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An attempt to refine the component masses of the very close Wolf-Rayet eclipsing binary system CX Cep

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Abstract. Using a more accurate value of the orbital period a repeat analysis of polarimetric CX Cep observations in 1987 obtained by Schult–Ladbec and Van der Hucht (1989) has been made. The new estimate of the orbit inclination ($i_{polar} = 53\overset{\circ}{.}9$) is in good agreement with the low value $i \approx 50^{\circ}$ expected from the shape of the light curve of the system and from the estimate of the spectral class of the companion given by Massey and Conti (1981). From the results of spectroscopic investigations the results obtained by Massey and Conti are the most trustworthy. At $i = 53\overset{\circ}{.}9$ they lead to masses ($M_{WR} = 10.0\,M_{\odot}, M_O = 23.1\,M_{\odot}$) which are in good agreement with the estimate of the spectral classes of the CX Cep components (WN5+O8V).

Key words: stars: Wolf-Rayet — stars: polarization — stars: individual: CX Cep

1. Introduction

CX Cep ((WN5+O8V) is a binary with a Wolf-Rayet component that takes the second place after CQ Cep in closeness of the stars. The orbital period of CX Cep found primarily by Hiltner (1948) ($P = 2\overset{d}{.}1267$) was refined in the 1980s by Lipunova and Cherepashchuk (1982) and also by Kurochkin (1985) in a special study ($P = 2\overset{d}{.}126897$). The system is rather faint ($V = 12\overset{m}{.}5$), which impedes its observation. Three series of spectroscopic investigations (Hiltner, 1948; Massey and Conti, 1981; Lewis et al., 1993), two photometric studies (Hiltner, 1948; Lipunova and Cherepashchuk, 1982) and the only study of linear polarization (Schult–Ladbec and Van der Hucht, 1989) of CX Cep are available at the present time. Besides, a paper of Arnal et al. (1999), which is devoted to the results of investigation of the neutral hydrogen distribution towards CX Cep, has recently appeared. A hydrogen bubble with an envelope bordering on it has been detected around the system.

A programme of studying long-term (years) variations of linear polarization of eclipsing binaries with a Wolf-Rayet type component, which was started at SAO RAS in 1994, incorporates CX Cep too. This is the reason for our particular interest in the results of the only, as yet, polarimetric study of the system. In scrutinizing the paper by Schult–Ladbec and Van der Hucht (1989) it was found that the authors analysed the results of their observations using the orbital period value derived by Hiltner (1948), probably being ignorant of the refined estimate of the period presented by Lipunova & Cherepashchuk (1982) and Kurochkin (1985). This resulted in a considerable error ($\Delta\Phi \approx 0\overset{p}{.}17$) in the computation of the orbital period phases, which strongly affected the results of the Fourier analysis of observations and consequently the estimates of the orbit parameters and the masses of the system components. Besides, a consideration of the three above-mentioned series of spectroscopic studies of CX Cep has shown that the results of the latest of them (Lewis et al., 1993) do not agree with the results of the earlier study of Massey and Conti (1981). Therefore, the aim of this paper is, firstly, to repeat analysis of the data of the polarimetric observations of Schult–Ladbec and Van der Hucht made with the use of the revised orbital period value of the system, secondly, to attempt to clear up which of the spectroscopic studies of CX Cep yields more correct estimates of the component masses.

2. Repeat analysis of the CX Cep polarimetric observations of Schult–Ladbec and Van der Hucht

The results of the polarimetric observations of CX Cep made by Schult–Ladbec and Van der Hucht (1989) corrected for the instrumental polarization with allowance made for the coefficient of efficiency of their apparatus (all the data required for this purpose were borrowed from the paper of the observers) were converted from the instrumental coordinate system to equatorial. After that the data over two channels ("A" and "B") were averaged. The orbital period phases were calculated by the formula taken from the

Table 1: *Transformed results of the polarimetric CX Cep observations obtained in 1987 (Schult-Ladbec and Van der Hucht, 1989)*

J.D.⊙ (2446900+)	Φ in frac. of P	$q_A(\%)$	$u_A(\%)$	$q_B(\%)$	$u_B(\%)$	$\bar{q}(\%)$	$\bar{u}(\%)$	$P(\%)$	$\Theta°$
77.62647	0.741	+0.344	5.988	+0.086	5.892	+0.215	5.940	5.944	44.0
78.57696	0.188	+0.109	6.245	+0.036	6.138	+0.073	6.191	6.192	44.7
79.41588	0.583	+0.039	6.456	−0.096	6.202	−0.028	6.329	6.329	45.1
79.59869	0.669	+0.265	6.397	+0.173	6.339	+0.219	6.368	6.372	44.0
80.54329	0.113	−0.119	6.386	−0.185	6.228	−0.152	6.307	6.309	45.7
81.55750	0.590	+0.047	6.444	−0.200	6.313	−0.077	6.378	6.379	45.3
83.46278	0.485	+0.005	6.153	−0.172	6.113	−0.084	6.133	6.134	45.4
83.61595	0.557	−0.020	6.365	−0.149	6.252	−0.085	6.309	6.310	45.4
84.41910	0.935	−0.174	6.223	−0.196	6.117	−0.185	6.170	6.173	45.8
84.61850	0.029	−0.017	6.385	−0.081	6.179	−0.049	6.282	6.282	45.2
85.44706	0.418	−0.223	6.088	−0.082	6.230	−0.152	6.159	6.161	45.7
85.61536	0.497	+0.264	5.809	+0.121	5.641	+0.193	5.725	5.728	44.0
88.51986	0.863	−0.186	6.267	−0.097	6.079	−0.142	6.173	6.175	45.7
88.61912	0.910	−0.164	6.128	−0.221	6.132	−0.193	6.130	6.133	45.9
90.38889	0.742	+0.199	6.040	−0.026	5.964	+0.087	6.002	6.003	44.6
90.58130	0.832	+0.082	6.117	+0.047	5.972	+0.064	6.044	6.044	44.7

paper by Kurochkin (1985):

$$T_{min} = 2444451^{d}_{.}423 + 2^{d}_{.}126897 \cdot E.$$

The results of the transformation done are presented in Table 1. The first column of the table gives the moments of observations in Julian dates, in the second column are presented the phases in fractions of the orbital period (Φ), in columns three–eight are collected the normalized Stokes parameters ($u = U/I$ and $q = Q/I$) over the channels "A" and "B" separately and the average over the channels. The nineth and tenth columns present the degree of linear polarization $P = (u^2 + q^2)^{1/2}$ and the position angle of the polarization plane Θ ($tg2\Theta = u/q$).

As usual, the u and q Stokes parameters were presented in the form of expansion into a Fourier series to the second harmonics, that is

$$u = u_0 + u_1\cos\lambda + u_2\sin\lambda + u_3\cos2\lambda + u_4\sin2\lambda,$$

$$q = q_0 + q_1\cos\lambda + q_2\sin\lambda + q_3\cos2\lambda + q_4\sin2\lambda,$$

where $\lambda = 2\pi\Phi$, Φ is the phase of the orbital period. The expansion coefficients defined by the least-squares method are presented in Table 2.

It can be seen from Table 2 that the decisive role in expansion is played by the second harmonics, which suggests a high degree of symmetry of diffusing matter about the orbital plane of the system according to the model computations of Brown et al. (1978). In Fig. 1 the observed curves of variation of the polarization parameters ($P, \bar{u}, \bar{q}, \Theta$) of CX Cep with the phase of the orbital period are presented, the theoretical curves are shown as solid lines. Fig. 2a displays the variations of the Stokes parameters in the (q, u) plane. Fig. 2b depicts the $(q_+ u_+)$ trajectory, which is an ellipse described by the second harmonics of expansion (see Brown et al., 1978).

To connect the expansion coefficients with geometric and physical characteristics of the system, the model of Brown et al. (1978), which had been elaborated for an optically thin envelope with an arbitrary density distribution rotating together with the binary system and diffusing light of an arbitrary number of point sources, was used. The orbit parameters of CX Cep derived as a result of application of the model mentioned above (i — the orbit inclination angle and Ω — the angle that characterizes the orbit orientation in space) and also the numerical values of some spatial integrals ($\tau_0\gamma_1, \tau_0\gamma_2, \tau_0\gamma_3, \tau_0\gamma_4$) and their combinations [$\tau_0\mathrm{G} = \tau_0(\gamma_1^2 + \gamma_2^2)^{1/2}, \tau_0\mathrm{H} = \tau_0(\gamma_3^2 + \gamma_4^2)^{1/2}, \mathrm{H/G}, \gamma_2/\gamma_1, \gamma_4/\gamma_3$], which characterize the features of matter distribution in the envelope, are presented in Table 3. The last but one line of Table 3 gives the differences $\Delta u'$ between the u'_C – coordinate of the centre of the ellipse described by the second harmonics and the u'_I — u parameter of interstellar polarization. In the $q'u'$ coordinate system, related with the binary system, these two values must be equal ($u'_C = u'_I$) in accordance with the theory of Brown et. al. (1978). Fulfilment (or not fulfilment) of the equality will permit us to judge that a constant component in linear polarization connected with the system itself is absent (or present). The last line of Table 4 shows the value of the semi-major axis of the ellipse described by the second expansion harmonics

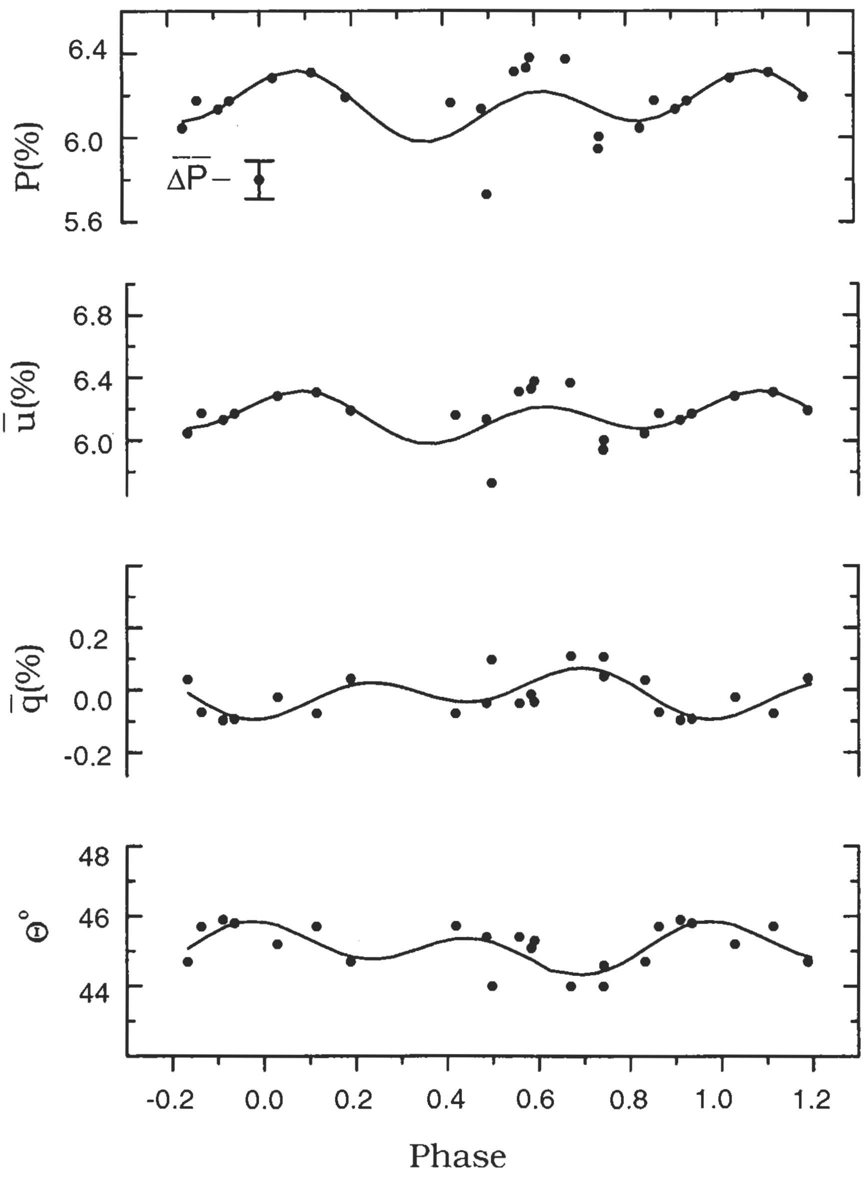

Figure 1: *The curves of variation of linear polarization (P), $\bar{q}$ and $\bar{u}$ Stokes parameters and polarization plane position angle (Θ) with the phase of the orbital period (the transformed results of observing CX Cep by Schult-Ladbec and Van der Hucht in 1987). The theoretical curves are shown by the solid lines.*

(A_p), which can be expressed in the theory of Brown and his colleagues via spatial integrals $\tau_0\gamma_3$ and $\tau_0\gamma_4$: $A_p = \tau_0(\gamma_3^2 + \gamma_4^2)^{1/2}(I + \cos^2 i)$. On the other hand, A_p can be represented by a function of several physical parameters of the system, $A_p \sim n_e \sim \dot{M}_{WR}$ (n_e is the electron density of the envelope, $\dot{M}_{WR}$ is the mass loss rate of the WR star) (St.-Louis et al., 1988).

When comparing the results of analysis of polarization observations of CX Cep with similar results obtained for other WR binaries (first of all, with the results derived for CQ Cep by Drissen et al. (1986), Kartasheva et al. (1998, 2000) and also with the results of St.-Louis et al. (1988)), one can interprete them as follows. It is seen from Table 3 that the H/G

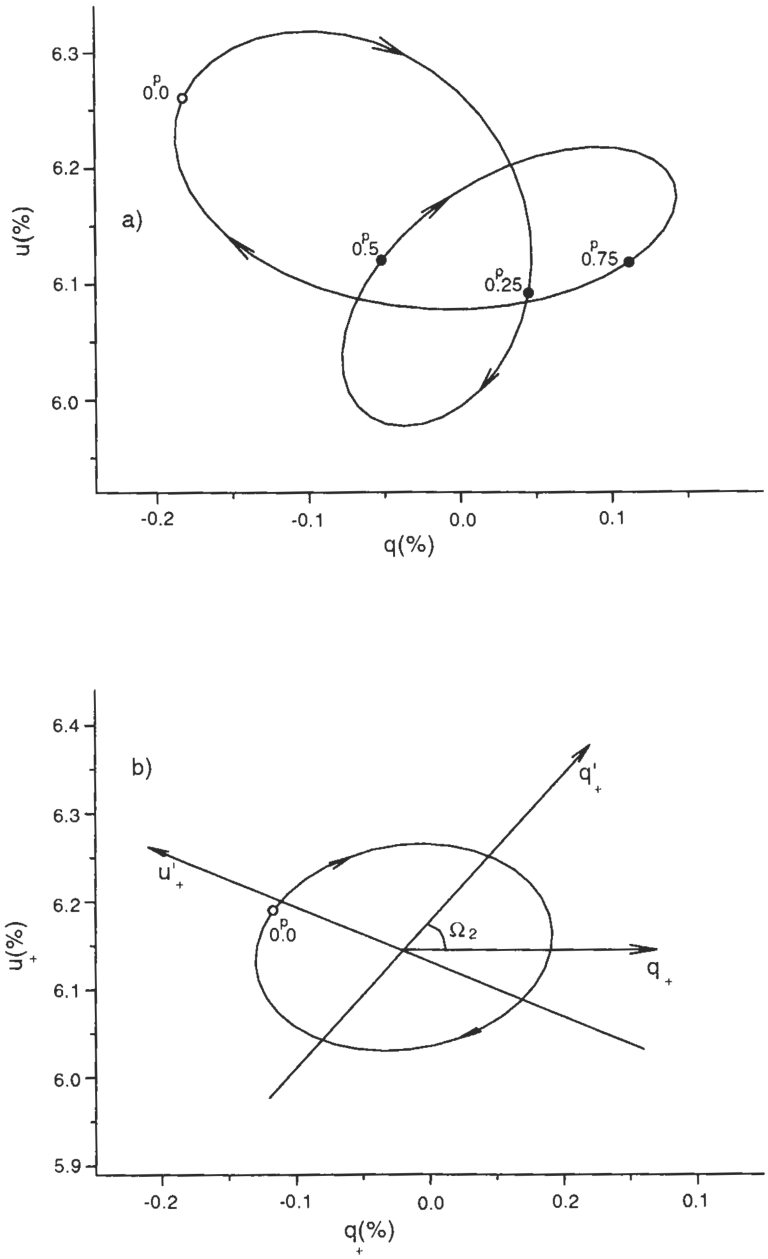

Figure 2: *Variations of the Stokes parameters in the q, u plane (a) and also the q_+, u_+ trajectory (b) derived from the repeat harmonic analysis of the results of the 1987 polarimetric observations by Schult-Ladbec and Van der Hucht (1989).*

ratio is not large. This is a consequence of the small concentration of diffusing matter to the orbital plane of the system ($\tau_0 H$). However, the degree of asymmetry of diffusing matter about this plane ($\tau_0 G$) and the value of $A_p \sim n_e$ are also small. All this suggests that during the observations (the summer of 1987) the system had a moderate quantity of diffusing matter, that is, the system was in a quiet state. The authenticity of the results of the analysis and, in particular, the reliability of the obtained geometrical parameters of the system ($i_{polar} = 53^\circ\!.9$ and $\Omega = \Omega_2 = 57^\circ\!.7$) are suggested by quite good fulfilment of the criterion $|\Delta\Omega| = |\Omega_1 - \Omega_2| \approx 90^\circ$ (Ω_1 and Ω_2 are the values of Ω derived from the analysis of the first and second harmonics). Our $\Omega_1 = -44^\circ\!.2, \Omega_2 = 57^\circ\!.7$, that is, $|\Delta\Omega| = 101^\circ\!.9$. Thus the repeat analysis of the

Table 2: *The coefficients of expansion of the q and u Stokes parameters into a Fourier series*

q_0	q_1	q_2	q_3	q_4
-0.0193	-0.0651	-0.0333	-0.0977	0.0525
u_0	u_1	u_2	u_3	u_4
6.1474	0.0703	0.0131	0.0427	0.1094

Table 3: *Geometrical and physical parameters obtained from the repeat analysis of polarization observations of CX Cep performed by Schult-Ladbec and Van der Hucht*

$i°$	53.9
$\Omega°$	57.7
$\tau_0\gamma_1$	-0.37×10^{-3}
$\tau_0\gamma_2$	-0.34×10^{-3}
$\tau_0\gamma_3$	0.12×10^{-3}
$\tau_0\gamma_4$	0.90×10^{-3}
$\tau_0 G$	0.51×10^{-3}
$\tau_0 H$	0.90×10^{-3}
H/G	1.76
γ_4/γ_3	7.5
γ_2/γ_1	0.92
$\Delta u'$	9.0×10^{-3}
A_p	1.2×10^{-3}

polarimetric observations of CX Cep carried out by Schult-Ladbec and Van der Hucht (1989), which was performed with a more accurate value of the orbital period, eliminated the discrepancies between i_{polar} and $i \approx 50°$, expected from photometric studies of CX Cep (two shallow minima on the light curve) and following from the fact that the companion belongs to spectral class O8V or earlier (Massey and Conti, 1981). According to the paper by Lipunova and Cherepashchuk (1982), $i_{phot} = 53° \pm 3°$.

Interstellar polarization in the direction of CX Cep was determined by means of investigation of polarizing capacity of interstellar matter (P/A_V) in the vicinity of the system. The procedure which is well described in the papers by Polyakova (1974, 1976) and Abramian (1982) was used. The data on the 8 neighbouring stars $(P, \Theta, E_{B-V}$ and $(V_0 - M_V))$ in a circle of radius 2° were taken from the catalogue by Hiltner (1956). The interstellar extinction for these stars $(A_V = RE_{B-V})$ was computed with $R = 3.1$. Since the investigated system contains a WR component, then, the same as in the case of single shell stars (Polyakova, 1974, 1976), the extinction A_V defined for the system from the colour excess includes not only interstellar extinction but also the shell absorption. For this reason, interstellar extinction towards CX Cep is found from the relation $A_V - (V_0 - M_V)$ plotted from the 8 neighbouring stars and approximated by the formula

$$A_V = -9.2151 + 2.0390(V_0 - M_V) - 0.0848(V_0 - M_V)^2.$$

Using the distance modulus $(V_0 - M_V = 13^m\!.9$ given for the CX Cep by Van der Hucht et al. (1988), we obtained $A_V = 2^m\!.7$ for the system, which is 1^m smaller than the value of A_V following from the colour excess presented for the system in the same catalogue (Van der Hucht et al., 1988).

$$(E_{b-v} = 0^m\!.98 \rightarrow E_{B-V} = 1^m\!.19 \rightarrow A_V = 3^m\!.7).$$

Next, relationships between polarizing capacity of interstellar matter $(q/A_V$ and $u/A_V)$ and interstellar extinction (A_V) were plotted from the neighbouring stars. The least-squares method yielded the following theoretical approximations of these relationships:

$$q/A_V = -0.8165 + 0.2647A_V$$
$$u/A_V = 0.2665 + 1.2762A_V - 0.3034A_V^2.$$

With the use of the latter formulae for CX Cep (at $A_V = 2^m\!.7$) the following parameters of interstellar polarization (in the equatorial coordinate system) were derived:

$$q_I = -0.27\% \pm 0.30\%$$

and

$$u_I = 4.05\% \pm 0.53\%.$$

In the coordinate system $q'u'$, related to the star, these parameters take the values $q'_I = 3.28\,\%$ and $u'_I = 2.40\,\%$. In the same system $q'u'$ coordinates of the centre of the ellipse described by the second harmonics of expansion are $q'_C = 5.18\,\%$ and $u'_C = 3.30\,\%$.

Thus, for the 1987 observations of CX Cep $\Delta u' = u'_C - u'_I \approx 0.9\,\%$, which essentially exceeds the error of determination of parameters of interstellar polarization. This suggests that linear polarization of CX Cep has a constant component related to the system itself.

3. Analysis of the results of spectroscopic study of CX Cep

The first detailed spectroscopic study of CX Cep was accomplished by Hiltner (1948) from low-dispersion (200 Å/mm at λ4686 Å) spectra, which allowed position measurement of only the strongest emission line, HeII λ 4686 Å.

Massey and Conti (1981) made an attempt to construct the radial velocity curve not only for the

WR star but also for the O component. For this purpose, they used eight spectra of the system obtained with the 4 m Mayal telescope with a dispersion of 26 Å/mm in 1978 September and 1979 September-October. The plates were measured with the NBS Grant machine in the forward and reverse directions with subsequent averaging the results. The emission line NIV λ 4058 Å, the relatively unblended absorption lines H10 and H9 and also the absorption lines H8, Hγ and HeII λ 4200 Å superimposed on the HeII emission lines were measured. Wilson's (1941) method of estimation of the ratio of the masses of the components (q) and the radial velocity of the system mass centre (γ velocity) from a small number of spectrograms was applied. Besides, it was assumed that the emission line NIV λ 4058 Å had an approximately the same half-amplitude of the radial velocity variation as the emission line HeII λ 4686 Å in Bracher's (1966) analysis of the observations caried out by Hiltner (1946) (K_{WR} = 300 km/s). Having determined that $q = M_O/M_{WR} = 2.34$, Massey and Conti found that K_O = 130 km/s. The γ velocities obtained separately for the WR component and O companion proved to be equal ($\gamma_{WR} = \gamma_O = -93$ km/s). However, these velocities were higher than the radial velocity caused by the Galactic rotation $V_{r(Gal)}$. When the distance to CX Cep is accepted to be r = 6 kpc (Van der Hucht et al., 1988; Arnal et al., 1999), the application of the formulae of Cruz-Gonzalez et al. (1974) yields $V_{r(Gal)} = -66$ km/s. The authors estimated the spectral class of the O companion as O8 or earlier. As a whole, the results obtained by Massey and Conti yielded acceptable estimates for the masses of the CX Cep components. At $i \geq 50°$ $M_{WR} = 5 - 12\,M_\odot$ and $M_O = 12 - 27\,M_\odot$. The shallow minima on the light curve of CX Cep and the spectral class of the O component allowed the authors to favour the larger mass values. It would be desirable to revise the results obtained by Massey and Conti on the basis of a larger body of observational data.

This objective was probably pursued in the work done by Lewis et al. (1993) based on 57 CCD spectra of CX Cep obtained with the 1.6 m telescope of the observatory Mont-Megantic with a resolution of 5 Å (i.e. with a resolution far worse than that of Massey and Conti (1981)) in 1987 August and October. The spectra were processed with the aid of standard procedures in the IRAF medium. The results obtained were analysed using the same medium. The position measurements of emission lines were made by both the method of "centroid" and the method of "peak" (the details of the procedure of measurements are in the paper being discussed). The radial velocity curves of the WR component were derived from measurements of the emission lines that form most closely to the WR nucleus (NV λ 4603 Å, λ 4640 Å and NIV λ 4058 Å), and also the emission lines HeII λ 4200 Å, λ 4542 Å, λ 4686 Å and λ 4859 Å. The results of measurements of the line NV λ 4603 Å (K_{WR} = 340 k/s) were preferred, although the γ velocity following from its radial velocity curve ($\gamma_{WR} = -2$ km/s) largely differed from the radial velocity caused by the Galactic rotation. As regards the lines of the companion, they mainly measured the O absorption lines superimposed on the WR emission lines because the CCD sensitivity was low in the region where "pure" O absorption lines (3700–4000 ÅÅ) were located. Position measurements of absorptions were performed by the "centroid" method which allows account to be taken of the slope of the "pseudocontinuum". Note, however, that the reconstruction of the emission profile above the absorption lines, which comes before this procedure, is a very difficult problem that requires high spectral resolution of observational data. As experience has shown, with the old method of position measurements of spectra on comparators, the radial velocities following from measurements of absorption lines superimposed on emission lines turned out to be overestimated by a few dozen km/s in the visible part of the spectrum. This entailed similar overestimation of the half-amplitude of the variation of V_r of the O component (K_O). Because of this, from the methodically more perfect position measurements of Lewis et al. (1993) it was expected that K_O < 130 km/s, i.e. smaller than the value of K_O which was obtained by Massey and Conti when measuring plates on a comparator. However, on the contrary, the half-amplitude of the radial velocity variation for the O companion of CX Cep in studies of Lewis et al. (1993) increased by more than a factor of 1.5 (K_O = 240 km/s). Besides, the revision of the spectral class of the O companion performed by Lewis and his colleagues is questionable. The authors themselves note in the paper that the absorption line HeI λ 4472 Å was hardly measurable on separate spectra. (There are no data on this line in Table 3 where all the results of position measurements are collected.) However, the authors considered it possible to measure the intensity of this line in the mean spectrum of the system and to use it for revision of the spectral class of the companion. There is an impression that despite the application of more advanced methods of measurements, the low spectral resolution of data used by Lewis and his colleagues did not allow the authors to make reliable position measurements of absorption lines of the O component and derive correct estimates of their intensities.

4. Conclusions

The repeated analysis of the polarimetric CX Cep observations of Schult-Ladbec and Van der Hucht (1989) that we have made with a more accurate orbital period value of the system ($P = 2^{d}.126897$) put i_{polar} = $53^{\circ}.9$ into correspondence with the low photometric estimate of the orbital inclination of CX Cep ($i_{phot} = 53^\circ \pm 3^\circ$, Lipunova and Cherepashchuk, 1982). As regards the spectroscopic investigations of the system, it is still desired to repeat them on the basis of a greater body of data obtained with good spectral resolution (1 Å/mm or better), using present-day procedures of position measurements. At the moment, the spectroscopic elements derived by Massey and Conti (1981) for CX Cep ($M_{WR}\sin^3 i = 5.3\,M_\odot, M_O\sin^3 i = 12.2\,M_\odot, A\sin i = 18.1\,R_\odot$) seem to be the most realistic. At $i_{polar} = 53\overset{\circ}{.}9$ they lead to the following masses of the system components and distance between them: $M_{WR} = 10.0\,M_\odot, M_O = 23.1\,M_\odot$ and $A = 22.4\,R_\odot$. Quite a good agreement is noted between the masses of the components and their spectral classification (WN5+O8V).

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