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# Brightness ratio of the WR eclipsing binary CQ Cep components

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**Abstract.**
The equivalent widths of ten companion absorption lines and five WR–emissions were measured in three CQ Cep spectra taken in 1981 and 1987, using the camera 2 of the Main Stellar Spectrograph of the 6 m telescope, at phases close to the first brightness maximum. The most reliable result obtained from the absorption lines of the companion star in the system's spectrum in 1981 allowed us to conclude that the brightness of the WR star approximately twice exceeds the brightness of the O companion, which is probably a faint giant. We managed to obtain a more accurate estimate of the brightness ratio of the components of CQ Cep ($L_{WR}/L_O = 1.81$), involving the additional information from a photometric investigation of the system (comparing the amplitude of light curves obtained in 1937 and 1981). On the whole, the results of the work confirmed the assumption (going from the photometric investigations) about an appreciable variable addition in the system's continuum radiation, due probably to the hot gas condensation between the components of this very close pair. In the framework of this hypothesis it was shown why absorption lines of the O companion are situated on the edge of visibility.

**Key words:** stars: individual: CQ Cep – absorption lines: Wolf–Rayet stars – brightness ratio

## 1. Introduction

The need to obtain a reliable solution of the light curve of the Wolf–Rayet eclipsing binary CQ Cep demanded knowledge of the brightness ratio of its components.

In connection with this we undertook a spectrophotometric investigation of lines in the system's spectra, obtained at phases close to the primary light maximum. Two spectra of the system from the 9 and 14 August 1981 (phase $0^p.28$, λλ5300 – 6800 ÅÅ and λλ3350 – 5000ÅÅ) and a spectrum from the 13 October 1987 ($0^p.265$, λλ3600 – 6800 ÅÅ), taken with the camera 2 of the Main Stellar Spectrograph (MSS) of the 6 m telescope with a dispersion of 28Å/mm, were processed with the photometric complex AMD–I. The definition of the brightness ratio of the components ($q = L_{WR}/L_O$) was based on the method of defining $q$ from measurements of the equivalent widths of absorption lines of the companion star and WR–emissions, described in the paper by Beals (1944) and applied by him to another WR binary, V444 Cyg.

First, it is necessary to note that up to now CQ Cep has been considered as one–spectrum system, since only a few researchers have seen the lines of the companion (Niemela, 1980; Kartasheva and Snezhko, 1985a,b). In previous works (Kartasheva and Snezhko, 1985b; Kartasheva and Svechnikov, 1988) we had already tried to analyse all available CQ Cep spectral material from the viewpoint of visibility of the companion's absorption lines. We concluded that due to the weakness of the companion's absorptions their disclosure requires high dispersion spectra (with $D \leq 30$Å/mm). Moreover, the complexity of the absorption–emission spectrum of the system (the presence of WR intrinsic absorptions along with the companion's absorptions and those of P Cyg (Kartasheva and Snezhko, 1985b)) makes a direct disclosure of the companion's lines at the phases of the second-half of the orbital period (when all the absorptions, being located on the blue wing of the emission, merge into one absorption blend) almost impossible.

It is clear that the probability of detecting weak absorptions of the companion superimposed onto strong emission lines is small. Our 1981 spectra are an example of this, in which the absorptions of the companion projected onto strong emission bands He II 4686 Å, He II 5441 Åand He II 6560 Åare visible only at the phase $0^p.28$ and at best showing traces at other phases of the first–half of the orbital period.

Our experience also shows that the visibility of weak lines of the companion varies with time. From Fig.1, which compare the identical areas of the CQ

Cep spectra, obtained with an interval of six years at close phases, it is obvious that the companion's lines in the 1987 spectrum are present only in projection onto weaker emission lines of the blue spectrum range. Note, that the absence of absorptions of the companion in the region $\lambda\lambda 4500-6800$ÅÅ of our spectrum (1987) agrees with the results of Anderhill et al. (1990) who also did not discover traces of the companion in the spectra of CQ Cep which they obtained from 1986 to 1988 within $\lambda\lambda 5200-6000$ ÅÅ with the dispersion D=30 Å/mm.

Based on our interpretation of the CQ Cep light curve (stated most distinctly in the paper of Kartasheva and Svechnikov (1996)), we suggested that the visibility of the companion's weak absorption lines varies due to the alteration in the physical condition of the gaseous condensation, created by interacting winds of the components, which produces an appreciable variable addition in the continuum radiation of the system. It is for this reason that we investigated the spectra of 1981 and 1987, separately.

Spectral investigations of the CQ Cep carried out in 1983 (Kartasheva and Snezhko, 1985a,b) allow us to relate O companion to the spectral class O9–B0, and show that the mass of the companion (at $i \gtrsim 60°$) does not exceed $22\mathcal{M}_{\odot}$. Proceeding from this, for a definition of the standard equivalent width ($\overline{W}_\lambda$) we used the lists of $W_\lambda$ for stars of O 8.5 — B 0.5 spectral classes, V and III luminosity classes, taken from the works of Boyarchuk (1957); Kopylov (1958); Conti et al. (1971); Conti (1973, 1974); Didelon (1982); Klochkova and Panchuk (1987).

The comparison results of the measured equivalent widths of the CQ Cep companion's absorption lines with the standard ones ($\overline{W}_\lambda$) for the stars of O 8.5 — B 0.5 spectral classes and V, III luminosity classes are presented in Tables 1 and 2, respectively. The first columns of Tables 1 and 2 give the wavelengths of the absorption lines, the second columns cite $\overline{W}_\lambda$ of the standard stars. Columns 3 to 6 (incl.) contain the results of the investigation into the absorption lines of the system's companion in the 1981 spectra. In columns 7 to 10 (incl.) the same information is for the 1987 spectrum. In the third and seventh columns the results of absorption line equivalent width measurements for the companion are shown. The values of $(\frac{\overline{W}_{\lambda\, stand}}{W_{\lambda\, CQCep}}-1)$ are presented in the fourth and eighth columns. Since the absorption lines of the companion are superimposed on the emission bands, then

$$\frac{\overline{W}_{\lambda\, stand}}{W_{\lambda\, CQCep}}-1=\frac{I_{cont\, WR}+I_{em\, WR}+I_*}{I_{cont\, O}}=q''_{ab}\neq$$
$$\neq q'_{ab}=\frac{I_{cont\, WR}+I_*}{I_{cont\, O}}=\frac{L_{WR}+L_*}{L_O},$$

where

$I_{cont\, WR}$ is the intensity of continuum of the WR star,
$I_{em\, WR}$ — the intensity of WR-emission,
$I_{cont\, O}$ — the intensity of continuum of the O companion,
$I_*$ — the intensity of continuum radiation of the hot gas condensation between components.
$L_{WR}$, $L_O$ and $L_*$ are the brightnesses of the WR star, the companion and the hot gas condensation, respectively. ($L_{WR}=L_{WR\, photosph}+L_{WR\, env}$; $L_O+L_{WR}+L_*=1$). It is obvious that

$$q'_{ab}=\frac{q''_{ab}}{\frac{I_{cont\, WR}+I_{em\, WR}+I_*}{I_{cont\, WR}+I_*}}=\frac{q''_{ab}}{k},$$

where the correction coefficient "$k$" is usually taken from the spectrum of a single WR star of the same spectral class. Since we do not have at our disposal spectra of single WN7 stars, and moreover, we have an additional contributor to the radiation of the system in the continuum ($I_*$), we have had to be satisfied with a rough definition of the "$k$" coefficients through the available values

$$k'=\frac{I_{cont\, WR}+I_{em\, WR}+I_{cont O}+I_*}{I_{cont\, WR}+I_{cont\, O}+I_*},$$

measured in the centre of the absorption lines, and the values of $q'_{ab}$ which were taken by us in a first approximation equal to $q''_{ab}$. It is easy to show that the quantities of $k'$, $q'_{ab}$ and $k$ are connected by a simple formula:

$$1+\frac{(k'-1)(1+q'_{ab})}{q'_{ab}}=1+\frac{I_{em\, WR}}{I_{cont\, WR}+I_*}=k.$$

The values of "$k$" thus found are presented in the fifth and ninth columns of Tables 1 and 2. The sixth and tenth columns show the corrected values

$$q'_{ab}=\frac{q''_{ab}}{k}=\frac{L_{WR}+L_*}{L_O}.$$

In the lower lines of Tables 1 and 2 the mean values of $\bar{q}'_{ab}$, together with the mean square errors of their definition, are presented.

Examining Tables 1 and 2 it is clear that the equivalent width values of the companion's absorption lines are smaller in the 1987 spectrum, leading to $\bar{q}'_{ab\,1987}>\bar{q}'_{ab\,1981}$. However, in view of the small number of companion's absorption lines visible in the system's spectrum, and consequently the low accuracy of the definition of $\bar{q}'_{ab}$, within the errors $\bar{q}'_{ab\,1981}$ does agree with $\bar{q}'_{ab\,1987}$.

The mean of $\bar{q}'_{ab}$ in Tables 1 and 2, obtained under different assumptions about the luminosity class of the companion, coincide within the error limits. However, the dispersion of results from individual lines is two times less in the second case: the case which conjectures that the companion belongs to faint giants. Proceeding from this, the quantities $\bar{q}'_{ab\,1981}=2.38\pm0.18$ and $\bar{q}'_{ab\,1987}=2.92\pm0.34$ were taken in

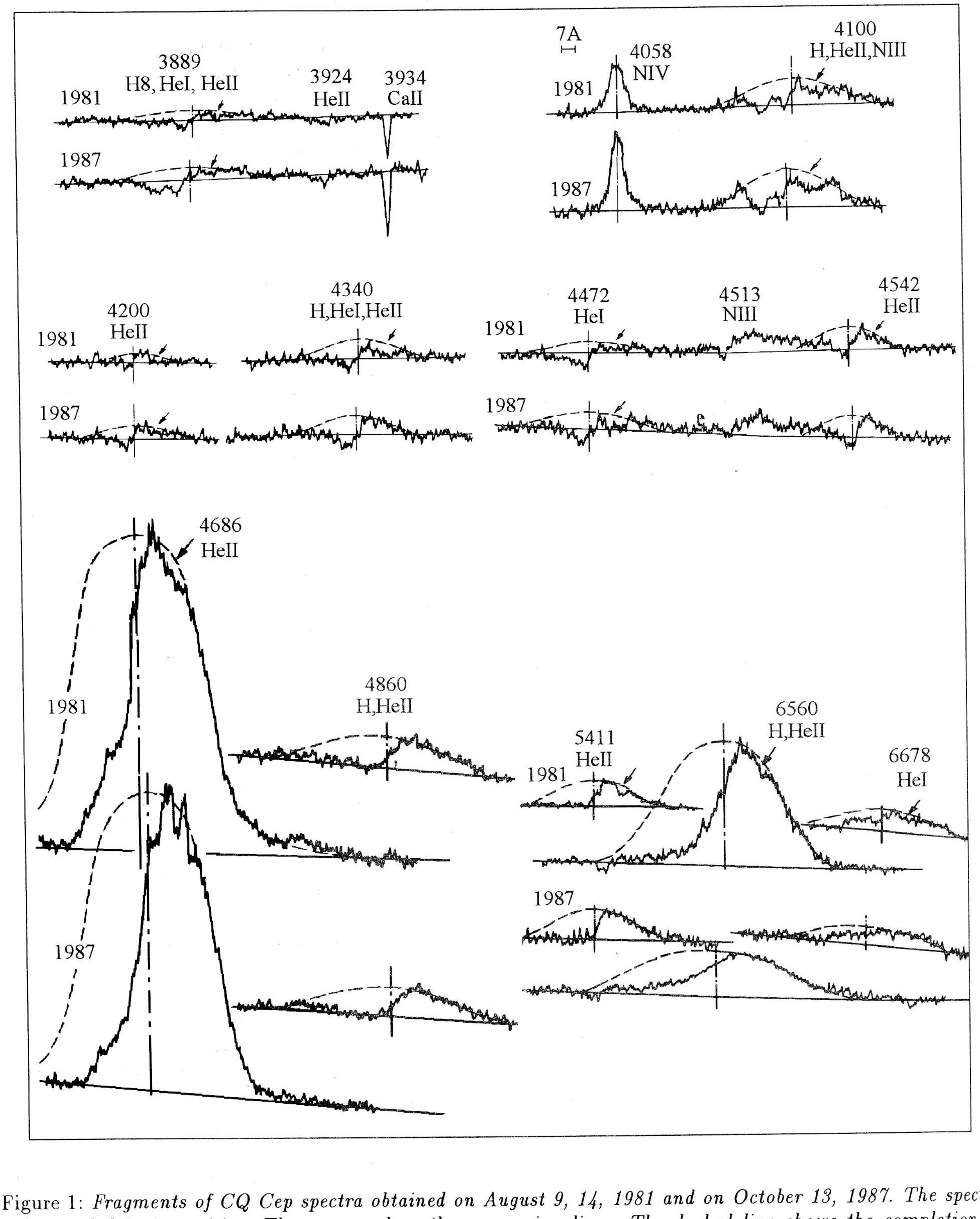


Figure 1: *Fragments of CQ Cep spectra obtained on August 9, 14, 1981 and on October 13, 1987. The spectra are recorded in intensities. The arrows show the companion lines. The dashed line shows the completion of emission profiles (Kartasheva and Snezhko, 1985a,b).*

the capacity of a final result together with an acceptance that the companion, in all probabilities, belongs to the luminosity class III.

A definition of the brightness ratio of the components of CQ Cep from the intensive emission lines of the WN7 component seems very problematical. The existence in late WN stars of intrinsic absorptions creates uncertainty in measuring the equivalent widths

Table 1:

| $\lambda$(Å) | $\overline{W}_{\lambda\, stand}$(Å) | 1981 | | | | 1987 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $W_{\lambda\, CQCep}$ | $q''_{ab}$ | $k$ | $q'_{ab}$ | $W_{\lambda\, CQCep}$ | $q''_{ab}$ | $k$ | $q'_{ab}$ |
| H8 3889 | 2.33 | 0.41 | 4.68 | 1.10 | 4.25 | 0.35 | 5.66 | 1.10 | 5.15 |
| H$\delta$ 4100 | 2.67 | 0.55 | 3.85 | 1.28 | 3.01 | 0.54 | 3.94 | 1.24 | 3.18 |
| HeII 4200 | 0.32 | 0.14 | 1.28 | 1.05 | 1.22 | 0.12 | 1.67 | 1.06 | 1.58 |
| H$\gamma$ 4340 | 2.76 | 0.58 | 3.76 | 1.11 | 3.39 | | | | |
| HeI 4472 | 1.15 | 0.22 | 4.23 | 1.08 | 3.92 | 0.27 | 3.26 | 1.13 | 2.88 |
| HeII 4541 | 0.40 | 0.14 | 1.86 | 1.17 | 1.59 | | | | |
| HeII 4686 | 0.59 | 0.09 | 5.55 | 2.02 | 2.75 | | | | |
| HeII 5411 | 0.43 | 0.15 | 1.87 | 1.21 | 1.54 | | | | |
| $H\alpha$ 6560 | 2.78 | 0.30 | 8.27 | 1.77 | 4.67 | | | | |
| HeI 6678 | 0.52 | 0.12 | 3.33 | 1.16 | 2.87 | | | | |
| | | $\overline{q'}_{ab\,1981} = 2.92 \pm 0.34$ | | | | $\overline{q'}_{ab\,1987} = 3.19 \pm 0.70$ | | | |

Table 2:

| $\lambda$(Å) | $\overline{W}_{\lambda\, stand}$(Å) | 1981 | | | | 1987 | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | $W_{\lambda\, CQCep}$ | $q''_{ab}$ | $k$ | $q'_{ab}$ | $W_{\lambda\, CQCep}$ | $q''_{ab}$ | $k$ | $q'_{ab}$ |
| H8 3889 | 1.76 | 0.41 | 3.29 | 1.10 | 2.99 | 0.35 | 4.03 | 1.10 | 3.66 |
| H$\delta$ 4100 | 2.30 | 0.55 | 3.18 | 1.30 | 2.45 | 0.54 | 3.26 | 1.24 | 2.63 |
| HeII 4200 | 0.37 | 0.14 | 1.64 | 1.05 | 1.56 | 0.12 | 2.08 | 1.06 | 1.96 |
| H$\gamma$ 4340 | 2.29 | 0.58 | 2.95 | 1.12 | 2.63 | | | | |
| HeI 4472 | 0.87 | 0.22 | 2.95 | 1.09 | 2.71 | 0.27 | 2.22 | 1.13 | 1.96 |
| HeII 4541 | 0.36 | 0.14 | 1.57 | 1.18 | 1.33 | | | | |
| HeII 4686 | 0.49 | 0.09 | 4.44 | 3.11 | 1.43 | | | | |
| HeII 5411 | 0.52 | 0.15 | 2.47 | 1.20 | 2.06 | | | | |
| H$\alpha$ 6560 | 1.99 | 0.30 | 5.63 | 1.68 | 3.35 | | | | |
| HeI 6678 | 0.59 | 0.12 | 3.92 | 1.15 | 3.41 | | | | |
| | | $\overline{q'}_{ab\,1981} = 2.38 \pm 0.18$ | | | | $\overline{q'}_{ab\,1987} = 2.55 \pm 0.37$ | | | |

of the emission bands and calls for, in our opinion, prior completion (correction) of the emission profile. This is probably one of the reasons for the big dispersion in equivalent width line values within the WN7 class. Inspite of this we tried to make use of the emission line equivalent widths in the CQ Cep spectra to define the component's light ratio. However, the comparison was carried out with the equivalent widths of the emission spectrum of the single WN7 star HD151932, not with the mean value of $\overline{W}_{\lambda}$ for the WN7 class. The spectrum of this single WN7 star was very similiar to the CQ Cep spectrum in line intensity, but did not possess, in the opinion of Seggevis and Moffat (1979), intrinsic absorptions. The results of the produced comparison are presented in Table 3. The first column shows the emission line wavelengths, the second — the equivalent line widths in the spectrum of HD 151932, taken from the paper of Conti (1973). The third and fifth columns of Table 3 cite the equivalent widths of emissions in 1981 and 1987 spectra of CQ Cep, respectively. Emission lines were picked out for the measurement which allowed a confident completion of the contour in the spectra of CQ Cep while also being contained in the list of the lines measured by Conti in the spectrum of HD 151932. In the fourth and sixth columns of Table 3 are cited the values of

$$q'_{em} = \left(\frac{W_{\lambda\, HD151932}}{W_{\lambda\, CQCep}} - 1\right) = \frac{L_O + L_*}{L_{WR}}.$$

In the lowest line of Table 3 the mean values for $\bar{q'}_{em}$ together with the mean square errors of their definition are given.

Because of the existence of an additional continuous radiation of the system ($L_*$) we were not able to produce a direct comparison of the results, following from the measurements of the companion's absorption lines, with the results obtained from WR-emissions

$$\left(q'_{ab} = \frac{L_{WR} + L_*}{L_O} \neq \frac{I}{q'_{em}} = \frac{L_{WR}}{L_O + L_*}\right).$$

Table 3:

| $\lambda$(Å) | $W_{\lambda\, HD151932}$ (Å) | 1981 | | 1987 | |
|---|---|---|---|---|---|
| | | $W_{\lambda\, CQCep}$ | $q'_{em}$ | $W_{\lambda\, CQCep}$ | $q'_{em}$ |
| NIV 4058 | 3.02 | 2.02 | 0.50 | 1.96 | 0.54 |
| HeII 4200 | 1.78 | 0.97 | 0.84 | 0.97 | 0.84 |
| HeII 4339 | 5.62 | 2.42 | 1.32 | 2.20 | 1.55 |
| HeII 4542 | 5.13 | 2.87 | 0.79 | 2.68 | 0.91 |
| HeII 4861 | 8.51 | 5.52 | 0.54 | 5.10 | 0.67 |
| | | $\overline{q'}_{em\,1981} = 0.80 \pm 0.11$ | | $\overline{q'}_{em\,1987} = 0.90 \pm 0.18$ | |

Such a comparison will be produced later using the results of the 1981 and 1987 photometrical investigation of the system.

In all further calculations we relied for certainty on the value

$$\bar{q'}_{ab1981} = \frac{L_{WR} + L_{*\,1981}}{L_O} = 2.38, \qquad (1)$$

obtained from a large number of companion absorption lines and thus, in our opinion, the most reliable result. In order to find the brightness ratio which describes the state of the system in the middle of 1937 ($L_{*\,1937} = 0, q_{ab\,1937} = L_{WR}/L_O$), essential for obtaining a more precise solution for the light curve of July–August 1937, we included for examination the B light curve of the system, observed by Stickland and his colleagues in September 1981 (Stickland et al., 1984), the closest to the 1981 spectra with relation to the time of receipt. The light variation amplitude for this in the main minimum was worked out as $0^m.40$, which was by $0^m.20$ more than the same parameter of the light curve of July–August 1937. Based on the result of Kurochkin (1979) that the light curve amplitude increases due to the increase of the light in maxima, we have:

$$\frac{L_{WR} + L_O + L_{*\,1981}}{L_{WR} + L_O} = 1.202. \qquad (2)$$

Accepting $L_{WR} + L_O = 1$ and using (1) and (2) for 1937 we derive the contributions of the CQ Cep component's brightnesses ($L_O = 0.356, L_{WR} = 0.644$) into the general brightness of the system, which leads us to $q_{ab1937} = L_{WR}/L_O = 1.81$. Based on this value we found the correct value $L_3 = L_{WR\,env} = 0.27$ for the light curve of CQ Cep 1937 (considering the light of the WR envelope invariable with time) and the corresponding solution of the light curve (see the paper of Kartasheva and Svechnikov, 1996).

From this solution we are interested further in the contribution of the component's brightnesses into the general brightness of the system in the middle of 1937. This is shown in the first column of Table 4.

By involving the information about the depths of the main minimum of the CQ Cep light curves obtained in 1980, 1981 and 1987, and comparing these with the depth of the main minimum of the 1937 photographic light curve, [1] while still assuming the light of the WR envelope to be constant, we were able to calculate the contribution of the system component's brightnesses into the general brightness of the system for another three interesting moments of time (1980, 1981 and 1987). The results are displayed in the second, third and fourth columns of Table 4.

Table 4:

| | 1937 | 1980 | 1981 | 1987 |
|---|---|---|---|---|
| $L_{WR\,env}$ | 0.270 | 0.240 | 0.225 | 0.216 |
| $L_{WR\,photosph}$ | 0.374 | 0.332 | 0.311 | 0.300 |
| $L_O$ | 0.356 | 0.316 | 0.296 | 0.285 |
| $L_*$ | 0.0 | 0.112 | 0.168 | 0.199 |

Using the results of Table 4 we were able to further calculate the expected values of $q'_{ab}$ and $q'_{em}$ for 1937, 1980, 1981 and 1987, and also the value of $\Delta m = m_O - m_{WR+*}$ for these moments of time. The obtained results are shown in Table 5.

As is obvious from Table 5 the calculated values for $q'_{ab1987}$, $q'_{em1981}$ and $q'_{em1987}$ turned out similar to the values for $\bar{q'}_{ab1987} = 2.55 \pm 0.37$, $\bar{q'}_{em1981} = 0.80 \pm 0.11$, and $\bar{q'}_{em1987} = 0.90 \pm 0.18$, obtained from analysis of the system's spectra. This testifies to the harmony of both the measurement results of the companion's absorption lines and WR–emissions and the

[1] $\Delta m_{min\,I} = 0^m.33$ for B curve, obtained in 1980 (Antokhina et al., 1982).
$\Delta\,\Delta\, m = 0^m.33 - 0^m.20 = 0^m.13$ gave:

$$\frac{L_{WR} + L_O + L_{*\,1980}}{L_{WR} + L_O} = 1.127.$$

$\Delta m_{min\,I} = 0^m.47$ for V curve in 1987 observations (Stickland et al., 1984). The latter amplitude needs to be reduced by $\approx 0^m.03$ to obtain the amplitude of the light curve in B system.
$\Delta\,\Delta\, m = 0^m.44 - 0^m.20 = 0^m.24$ gave:

$$\frac{L_{WR} + L_O + L_{*\,1987}}{L_{WR} + L_O} = 1.248.$$

Table 5:

| | 1937 | 1980 | 1981 | 1987 |
|---|---|---|---|---|
| $q'_{ab} = \frac{L_{WR}+L_*}{L_O}$ | 1.81 | 2.16 | 2.38 | 2.51 |
| $\Delta m = m_O - m_{WR+*}$ | $0^m.65$ | $0^m.84$ | $0^m.94$ | $1^m.00$ |
| $q'_{em} = \frac{L_O+L_*}{L_{WR}}$ | 0.55 | 0.75 | 0.87 | 0.94 |

results obtained for spectra of different years (1981 and 1987).

The results of Table 4 and the second line of Table 5 clearly explain the reason for the poor visibility of the companion's lines in the system's spectra. The large contribution to the general light of the system (> 20%) from the homogeneous in density part of the envelope's light ($L_{WR\,env}$), in combination with a smaller contribution ($0 \div 20\%$) of light from the gas condensation between the components ($L_*$), leads to the situation that the absorptions of the O companion turn out at the limit of visibility ($\Delta m = m_O - m_{WR+*} \rightarrow 1^m$!). Only due to the sporadic weakening of the light of the gas condensation $L_*$ does the possibility occasionally emerge to see the weak absorptions of the O companion in the system's spectrum.

From Table 5 it is obvious that the most favourable year for detecting the companion's lines in the high dispersion spectra of the system was 1980, the year of an essential weakening of the light of the gas condensation $L_*$, that manifested itself in the photometry by reduction of the system's light curve amplitude (Kartasheva and Svechnikov, 1996), and, possibly, two previous years. This is indicative in favour of the fact that the CQ Cep spectra obtained by Niemela in 1979 (Niemela, 1980) are, probably, with respect to the O companions absorption, the most informative. It is not surprising that in these spectra the absorption of the O companion projected onto the strongest emission band He II 4686 Å is clearly seen. As a result of the analysis, one can conclude that at the moments when the depth of the main minimum of the B light curve of the system is $\lesssim 0^m.4$ we can fairly clearly see the absorptions of the O companion on the high dispersion spectra of the system, referring to the phases of the first–half of the orbital period.

On the whole, the results of this paper confirmed the assumption, proceeding from the photometrical investigation, about the existence of an appreciable variable addition in the system's continuum radiation, due probably to the hot gas condensation between the components of this very close pair.

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