WIND-WIND COLLISION EFFECTS IN CLOSE MASSIVE WR+O BINARIES

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Abstract. A detailed description of the wind-wind collision (WWC) zones in the Wolf-Rayet binaries V444 Cyg (WN5+O6III-V, P = 4.21 d) and CX Cep (WN5+O5V, P = 2.13 d) is presented. In V444 Cyg, parameters of the WWC zone can be derived from variations of HeI line profiles. There is some evidence for a highly unstable character of the WWC zone. In CX Cep, the complicated dependence of equivalent widths for emission lines of different ionization potential on orbital phase can be explained by a combination of several factors, *e.g.*, (a) additional ionization from the bow shock region; (b) reheating of the WR wind by the O-star companion; and (c) an emission component arising in the WWC region. Some preliminary indications of WWC are revealed in the WR+OB system CQ Cep (WN7+O9I-II?) with the shortest known orbital period: P = 1.64 d.

1. Introduction

In general, theoretical results are much more numerous than observations for wind-wind collision (WWC) effects in a binary systems. This is quite explainable by the complexity of the phenomena (different emission and absorption lines are involved in different manners in the wind collision process) and the necessity to cover a large spectral region with high signal-to-noise ratio for a complete set of phases in a binary. Practically all the studied systems are mentioned in the reviews of St-Louis, Gies and Bartzakos & Moffat (these proceedings), and all theoretical results are summarised by Walder, Lührs, Usov and Stevens (these proceedings). In this review I would like to describe in detail the WWC effects in three binary WR+O systems: CX Cep, V444 Cyg and CQ Cep. All of them are close, massive and have strong enough winds to expose WWC features in the optical region.

2. CX Cep = WR151 (WN4-5+O5V, $P = 2.^{d}13$)

This system has been investigated in detail by Lewis *et al.* 1993. In the lines of different excitation/ionization potential, He I 3889Å, N IV 4058Å, N V 4604Å, He II 4686Å, all measured equivalent widths (EW) reveal coherent variations with orbital period.
HeII 4686Å : we assume that some excess emission, $\sim$ 15% of the total emission flux, arises mainly in the long bow-shock arm, where the O star is 'ploughing' through the WR wind. The EW variations are caused by the

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eclipses of this extra-emissivity zone at $\phi \simeq 0.5$ and around $\phi \sim 0$. The line asymmetry is phase-dependent too: the top of the line is affected by the relatively narrow 'travelling' emission peak, in complete agreement with the He II 4686Å line of V444 Cyg.

NIV 4058Å and NV 4604Å: the EW variations are caused by eclipse effects at $\phi = 0.0$ and $\phi = 0.5$, and heating of the WR wind by the O star. The WWC zone has negligible influence on the line profiles.

HeI 3889Å, P-Cygni absorption: the EW is anticorrelated with the EW of He II . The intense ionization from the bow-shock diminishes the supply of neutral He at $\phi \sim 0.3$. On the contrary, at this phase, He II emission is near maximum because that part of the bow shock is viewed through the smallest amount of intervening gas.

3. V444 Cyg = WR139 (WN5+O6V-III, $P = 4.^{d}21$)

In 1992-1993, during campaigns of simultaneous photometry and spectroscopy of V444 Cyg at San Pedro Martir Observatory (México), large numbers of good quality spectra ($\Delta\lambda = 0.41$ Å/pixel, S/N $\sim$ 150-200) were obtained (Marchenko *et al.* 1994b).

Fig. 2 shows the N V 4604Å and He II 4686Å profiles of V444 Cyg at phases 0.0 and 0.5. All intensities are corrected for the variable eclipsing continuum level. Koenigsberger & Auer (1992) have mentioned four factors which cause the profile variations in an eclipsing binary: 1) Geometrical eclipse by an O-star companion; actually, any pure geometrical eclipse could be interpreted in a wider sense, taking into account the 'shadowing' (*i.e.,* lack of the part of WR wind) by the bow-shock cone. 2) 'Atmospheric eclipse' by the WR wind at $\phi \approx 0.0 \pm (0.10 - 0.15)$: the light from the O star is absorbed and redistributed by the He II atoms of WR star wind; mainly the blue side of the line profile is affected. 3) Photospheric absorption component from the O-type companion. 4) Wind-wind interaction features. Factors 2–4 seem to dominate. The most spectacular feature is the narrow emission peak travelling across the He II profile. This peak was mentioned for the first time by Wilson (1940) and investigated in detail by Sahade (1958) and Guseinzade (1969). As shown by Marchenko *et al.* (1994a), this travelling emission peak can be explained as arising from the heated and excited bow shock gas. Evidently (*cf.* Fig. 1), the qualitative appearance of this phenomenon is the same for lines of different ionization stages. Compared to the radial velocity full amplitude of the travelling emission of He I 5876Å , $\Delta RV \sim +600 - -800$ km s^{-1} (Marchenko *et al.* 1994a), the He II narrow emission feature has smaller $\Delta RV \sim \pm 500$ km s^{-1}. The latter can be explained by the difference in the formation zones of He I and He II : the lines of higher excitation arise closer to the bow-shock head where the velocity of the outstreaming gas is lower (Stevens *et al.* 1992). Comparison of our Figs. 1 and 2 with Figs. 2 and

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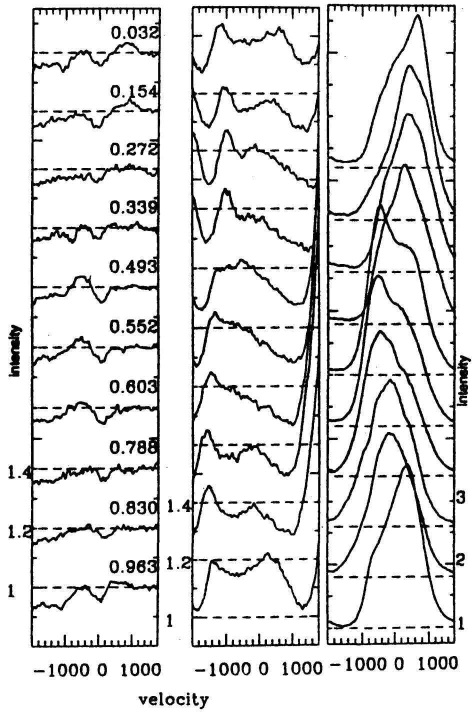

Fig. 1. V444 Cyg. Variations of He I 4471Å (left), N III 4634,4641,4642Å (centre) and He II 4686Å (right). Phases according to Khaliullin *et al.* (1984)

3 of Shore & Brown (1988) reveals a blue-shifted peak for He II 1640Å at $\phi = 0.60$, which moves toward the red side of the He II profile for $\phi = 0.84$, in full consistency with the He II 4686Å line. However, the travelling emission of He II 1640Å is absent at $\phi \sim 0.0$. Due to the larger extension of the He II 1640Å formation zone (transition 3-2) in comparison with He II 4686Å zone (4-3), the bow-shock region seen in He II 1640Å may be completely occulted at $\phi \sim 0.0$.

Fig. 3 shows rapid changes (the time between the exposures is about 6 hours) of the blue-shifted absorption component of He I 4471Å formed in the WWC zone. Similar variations (at the same phase) were reported earlier (Marchenko *et al.* 1994a). Are they caused by numerous instabilities of the WWC zone (Stevens *et al.* 1992) or do they reflect the moment of intersection of the line-of-sight by the bow-shock arm? If the latter is true, the bow-shock cone half-angle would be $\Theta \simeq 70^o$. A lower limit for Θ can be derived by taking the velocity of the He I blue-shifted component, $v_{sh} = -1000$ km s^{-1} at $\phi = 0.75$, as due to the geometrically projected velocity of the bow-shock arm with $v = v_\infty$. This gives $\Theta \simeq 40^o$, in complete coincidence with the estimation of Shore & Brown (1988). The half-angle of the bow-shock cone can be approximated by the following analytic equation (Eichler &

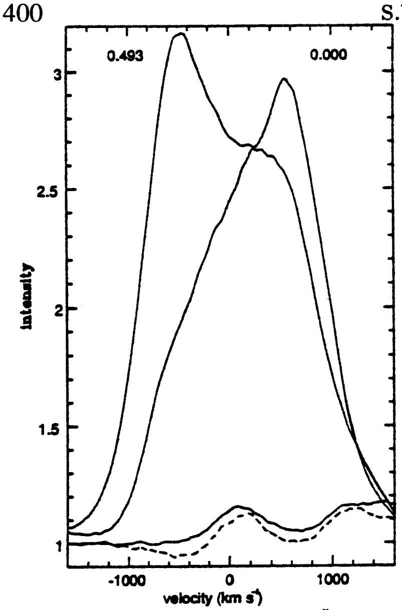

Fig. 2. V444 Cyg. He II 4686Å, NV 4604Å profiles at $\phi = 0.0$ and 0.5. Dashed line: N V($\phi = 0$)

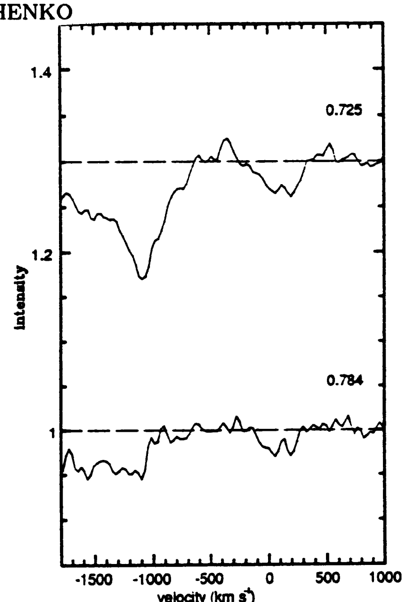

Fig. 3. V444 Cyg. The variations of the blueshited component of He I 4471Å

Usov 1993): $\Theta \simeq 2.1(1 - \eta^{2/5}/4)\eta^{1/3}$ (in radians), for $10^{-4} \leq \eta \leq 1$ and with accuracy $\sim 1\%$, where $\eta = (\dot{M}v_\infty)_{OB}/(\dot{M}v_\infty)_{WR}$. For $\Theta = 40^o - 70^o$, $\eta \simeq 0.05 - 0.30$ and $\dot{M}_{OB} \simeq (0.3 - 1.6) \times 10^{-6}$ $M_\odot yr^{-1}$, taking $v_\infty^{OB} = 2560$ km s^{-1}, $v_\infty^{WR} = 1785$ km s^{-1} (Prinja *et al.* 1990), and $\dot{M}_{WR} = 0.75 \times 10^{-5}$ $M_\odot yr^{-1}$ (St-Louis *et al.* 1993). This value of $\dot{M}_{OB}$ is close to the mean value of $\dot{M}_{OB} = 0.6 \times 10^{-6}$ $M_\odot yr^{-1}$ for the O6V-III spectral class (Leitherer 1988).

4. CQ Cep = WR155 (WN7+O9I-II(?), $P = 1.^d64$)

Our discussion is based on the 17 spectra obtained and briefly discussed by Grandchamps & Moffat (1991). The wavelength range of the spectra is 3600-4300Å with 1.4Å /pixel resolution and S/N = 100-200. Further careful inspection of the dataset reveals some interesting details. First of all, two absorption dips superposed on the He II 4100Å emission profile can be identified a Si IV 4089Å and Si IV 4116Å. They move clearly in antiphase with the WR emission features (*cf.* Figs. 4,5). At $\phi \sim 0.1 - 0.4$ one can even see the Hδ absorption of the O-type companion.

In an attempt to classify the companion, we cannot apply the usual luminosity criteria (Conti & Alschuler 1971) due to the lack of other visible O star lines. Comparison of the relative strengths of Hδ, Si IV 4089,4116Å and He I 4121Å in the digital atlas of Walborn & Fitzpatrick (1990) leads to the following conclusions: if the O star has luminosity class V-III, the spectral class can be defined as O8-8.5 due to the fast disappearance of Si IV

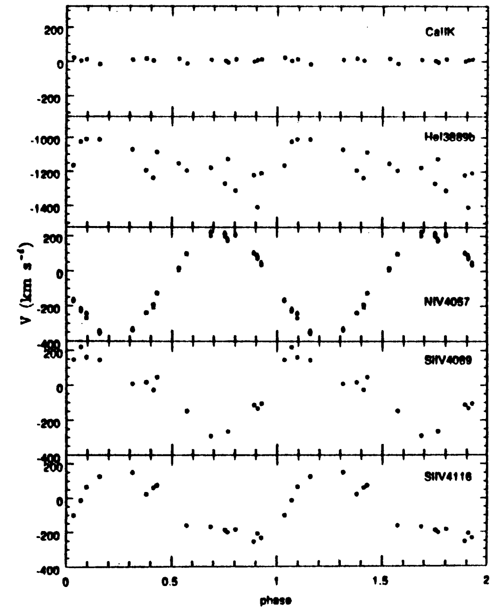

Fig. 4. CQ Cep. The radial velocity variations with phase. For the N IV 4058Å emission the RV measured on the upper part of the profile ($(0.5-1.0)I_{max}$) are marked by triangles, and filled dots denote the full profile measurements.

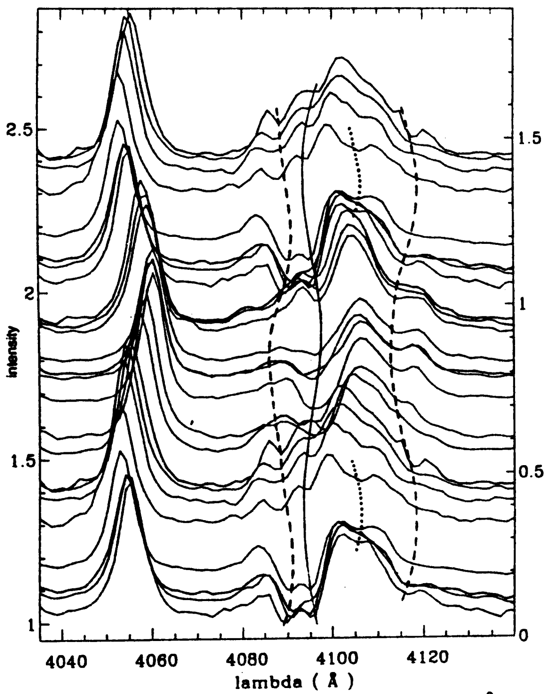

Fig. 5. CQ Cep. Montage of the spectra for the 4035-4140Å region. The orbits of the Si IV 4089,4116Å absorptions are marked by dashed lines and Hδ position by a dotted line. The movement of the He II+H I 4100Å absorption of the WR star is shown as a full line.

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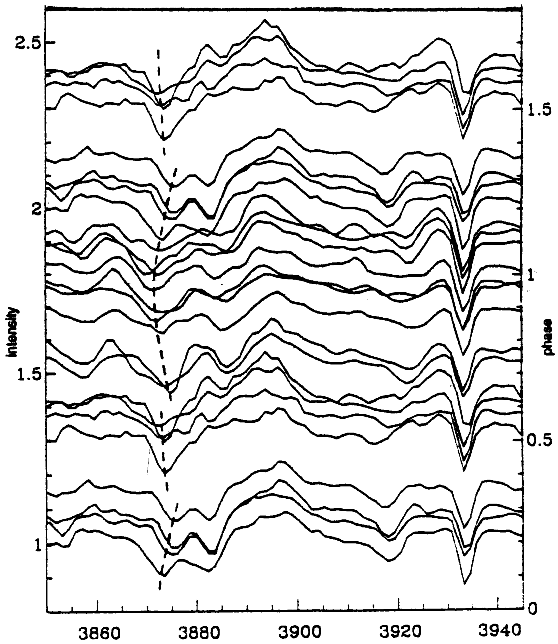

Fig. 6. CQ Cep. The same as Fig. 5, but for He I 3889Å. The dashed line denotes the position of the blue-shifted component.

in the hotter stars and rapid growth of the He I 4121Å intensity in O9-BO subclasses. If the luminosity class is I-II, then the most probable spectral class is O8.5-O9.5: the EW of the Si IV features is (very roughly!) 3-4 times less than the Hδ O star absorption component, and He I 4121Å is practically absent.

The most reliable EW of Si IV 4116Å can be obtained at $\phi \approx 0.4$ and $\phi \approx 0.7 - 0.8$ (*cf.* Fig. 5). After allowing for the variable continuum level (computed V-filter light-curve: Leung *et al.* 1983) and correction for the intensity of underlying emission (Beals 1944), the final value is: W_{bin}(Si IV4116) $= 0.30 \pm 0.05$Å and FWHM = 6.4Å, *i.e.*, $v_e sini(O) \leq 230$ km s^{-1} (blending with He I 4121Å); from Si IV 4089Å, although less reliable, $v_e sini(O) \approx 210$ km s^{-1}. The mean standard values of EW for Si IV 4116Å in single O8-O8.5V-III and O8.5-O9.5II-I stars are $W_{stand} = 0.17$Å and $W_{stand} = 0.35$Å, respectively (Conti & Alschuler 1971). The classification of the companion as O8-O8.5V-III must be rejected because $W_{bin} \gg W_{stand}$. Combining W_{stand}(Si IV4116) = 0.35Å with mean EW W_{stand}(He I4121) = 0.16Å (Conti & Alschuler 1971), and applying Beals' (1944) method, we obtain the luminosity ratio: $L_{WR}/L_O = W_{stand}/W_{bin} - 1 = 0.70 \pm 0.28$, in sharp contradiction with $L_{WR}/L_O \geq 3.3$ from Stickland *et al.* (1984).

Sine-wave fitting to the RV curves of N IV 4058Å and Si IV 4116Å yields semi-amplitudes $K_{WR} = 305$ km s^{-1}, $K_O = 180$ km s^{-1} and $M_{WR} = 8.1$ M$_\odot$,

$M_O = 13.7\ \mathrm{M}_\odot$, for $i = 74^o$ (Drissen *et al.* 1986). This M_O value seems to be too low for an O9II-I star. The K_O value might be affected by the blending of relatively weak Si IV with the underlying WR emission feature (note the distorted non-sinusoidal shape of the Si IV RV curve). An independent estimation of K_O can be performed by measuring the Hδ position at $\phi = 0.313$, when it is most prominent. We have $v(\mathrm{H}\delta) \simeq 220\ \mathrm{km\,s^{-1}}$ and $K_O \simeq 275$-310 $\mathrm{km\,s^{-1}}$ due to some uncertainty in the γ-velocity, $-53 - 87\ \mathrm{km\,s^{-1}}$ (Underhill *et al.* 1990), and, consequently, $M_{WR} sin^3 i = 17.4\ \mathrm{M}_\odot$, $M_O sin^3 i = 18.3\ \mathrm{M}_\odot$ and the total mass function $f(M) = 4.8 \pm 0.9$. For $i = 74^o$, the value of $M_O = 20.6\ \mathrm{M}_\odot$ fits nicely the mean ZAMS masses for the O8.5-O9.5 stars, (21-18) $\mathrm{M}_\odot$ (Conti & Underhill 1988). The main problem is that there is not enough room in the CQ Cep system for a bright giant/supergiant with expected $R_\star \sim (20 - 25)\ \mathrm{R}_\odot$ (Conti & Underhill 1988). The problem could be solved only if we accept a small radius for the WN7 component, by analogy (though far from direct) with Cyg X-3 (van Kerkwijk *et al.* 1992).

Now, we explore the WWC effects in CQ Cep. First, we can confirm the results of Niemela (1980): the blueshifted absorption component of He I 3889Å moves in antiphase with the WR emission lines (Fig. 6). The v_∞ of the O9II-I wind is 250-300 $\mathrm{km\,s^{-1}}$ higher than the v_∞ of the WN7 star in CQ Cep (mean values from Prinja *et al.* 1990). For the phases of the WR star eclipse, the faster O star wind dominates at the $v \geq v_\infty(WR)$ parts of the P-Cygni absorptions (*cf.* Fig. 1 of Shore & Corcoran 1992). The same could be true for He I 3889 Å: the λ3889 absorption feature from the O component should be strongly developed at the compressed parts of the O star wind. Note that the value of $\dot{M}_O$ is compatible with $\dot{M}_{WR}$ in CQ Cep (Kartasheva & Svechnikov 1990). The wake in the WR wind behind the O star could explain the reduction of the strengths of the absorption components of He I 5876Å (Underhill *et al.* 1992) and N IV 1718Å (Stickland *et al.* 1984) at the phases when the O-star is in front. The wake could cause the variations of the asymmetry of N IV 4058Å seen on Fig. 4 in a form of systematic deviations of the RV measured on a full line profile from the RV measured on the uppermost part.

5. Conclusions

A. The most spectacular evidence of the WWC in V444 Cyg and CX Cep is the relatively narrow emission peak travelling on the uppermost parts of broad underlying emission lines. In addition, the absorption component arises in the densest parts of the WWC zone, permitting us to derive lower and upper limits of the bow shock cone half-angle in V444 Cyg, $\Theta = 40^o - 70^o$.

B. The classification of the O-type component in the CQ Cep system as O9II-I leaves some hope of detecting WWC effects. However, they are expected to be less pronounced due to the closeness to unity of the key parameter $\eta = (\dot{M} v_\infty)_{OB}/(\dot{M} v_\infty)_{WR}$.

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DISCUSSION:

Cherepashchuk: First of all I would like to express my congratulations to you for such a nice spectroscopic investigations. I have a lot of questions and I will pose them to you during the coffee break. Just now I have only three short questions. 1. Several years ago Virpi Niemela claimed about detection of absorption line HeII 4686 in CQ Cep which belong to the O-star. Did you confirm this result?

2. It is well known that the CQ Cep system clearly shows the decreasing of orbital period. Because you know now the value of mass ratio of the components in CQ Cep system, you can estimate the value of mass loss rate for WN7 star. Did you do it?

3. And final question: Your data on CQ Cep system strongly suggests a small core radius from WN7 star. Am I right?

Marchenko: 1. I cannot say anything about 4686Å absorption, because we are limited by λ 4200Å in our observable range, but we can confirm V Niemela's result in the sense that the most blueshifted part of λ 3889Å profile moves definitely in antiphase with the Wolf-Rayet star emissions. But, there is nothing to do with the O star: the γ-velocity of this absorption is about -1200 km s^{-1}. I would suspect the wind-wind collision effect.

2. We have finished the analysis of the available spectra just a couple of weeks ago. We plan to obtain additional data this summer in order to fill the gaps on the phase diagram. I evaluate our mass ratio estimation as preliminary one.

3. It seems to be a problem: there is not enough room for a supergiant in the system with the separation between the components about (20-22)$R_\odot$. Of course, the problem should be solved, if we accept the small radius for the WN7 component, in somewhat dangerous analogy with Cyg X-3.

Stickland: It's nice to see that the schematic model of CQ Cep we presented ten years ago has now been fleshed out. But a word of caution: don 't rely too much on results from the HeI absorption unless you can get a continuous run of data. On Hiltner's plates from the 1950's, one can see on one night only, a "blob" of HeI accelerating out through several hundred km/s, but the same lines did nothing special on other plates.

Moffat: One cannot overemphasize the importance of carefully determining the spectral type and luminosity class of the O-type companion in WR + O binaries. Your work using high quality data is exemplary in this respect. If, for example, the companion is a main sequence star and thus non (or little) evolved, mass transfer may be needed to "rejuvenate" the O-star secondary.

Marchenko: The CQ Cep system looks for me like "yardstick" binary number two, after V444 Cyg, due to two reasons. First, astromers spent around 40 years trying to find any trace of the O star companion, hidden by the strong WR absorptions. Second, the system seems to have a really unusual parameters.