# OPTICAL AND X-RAY OBSERVATIONS OF STELLAR WINDS IN WOLF-RAYET BINARIES

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**Abstract.** New spectrophotometric, photometric and polarimetric observations of V444 Cygni confirm the basic conclusion that the WN5 star has a small core radius ($r_c < 4$ R$_\odot$) and a high core temperature ($T_c > 60\,000$ K), which are characteristic of massive helium stars. Values of $r_c < 3 - 6$ R$_\odot$ and $T_c > 70\,000 - 90\,000$ K for the core of the WN7 star in the Cygnus X-3 system agree well with this conclusion. A clumping structure of WR winds is suggested. X-ray observations of colliding winds in WR+O binaries suggest radial expansion and anomalous chemical composition of WR winds.

**Key words:** stars: Wolf-Rayet – binaries – winds – X-rays

## 1. Optical observations: structure of WR extended atmospheres

### 1.1 Photometry

In Fig.1 narrow-band ($\Delta\lambda \simeq 75$Å) continuum ($\lambda$4224Å, 7512Å) simultaneous photoelectric observations (Cherepashchuk & Khaliullin 1975) for the V444 Cyg system (WN5+O6) are presented which include $\sim 500$ individual measures in each filter. A considerable increase of the width and depth of secondary minimum (WN5 star is eclipsed by O6 star) with $\lambda$ is clearly seen. Such an effect had been suggested by Kuhi (1968). A strong increase with $\lambda$ of the radius of the continuum-emitting extended atmosphere of the WN5 star is clearly seen. Such an increase can not be explained by the modern theory of homogeneous extended WR atmospheres (Hamann & Schwarz 1992, hereafter HS92) and presumably is due to a clumpy structure of the WR wind (Cherepashchuk *et al.* 1984). Recent results of light-curve solutions for V444 Cyg, obtained by HS92 strongly disagree with our results (Cherepashchuk 1975, Cherepashchuk *et al.* 1984). The most striking disagreement is in the luminosity ratio: $q = L_{\rm WR}/L_{\rm O6} = 0.25$ (determined by us directly from the light-curve solution) and $q = 3.1$ (which is found by HS92 from the joint interpretation of the light-curve and He I/He II emission line spectrum). To check the value of $q$ we applied the Beals (1944) spectrophotometric method to our high quality spectroscopic observations of V444 Cyg. The results are published in the paper of Cherepashchuk *et al.* (1994). The overall mean value obtained for absorption lines from our data is $q = 0.60 \pm 0.06$.

Thus, the conclusions of Beals ($q = 0.20$) and Cherepashchuk ($q = 0.25$) are qualitatively confirmed: the main contribution to the total luminosity of the V444 Cyg system in the optical range come from the O6 star. This result



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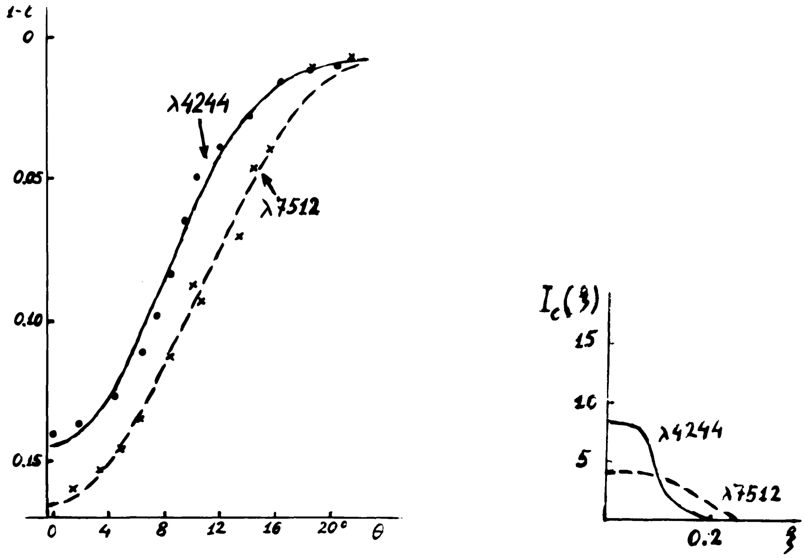


Fig. 1. Simultaneous narrow band continuum light-curves of V444 Cyg.

is in strong contradiction with the light curve solution of HS92 ($q = 3.1$). Consistent solution of both λ4244Å and λ7512Å narrow band continuum light-curves with a fixed value of $q = 0.6$ for λ4244Å yields the following parameters of V444 Cyg (Cherepashchuk 1994): $i = 76^\circ.6, R_{O6} = 0.22$ a $=$ 8.4 $R_\odot$ (radius of O6 star, where a $=$ 38 $R_\odot$ - separation of the components); $R_c^{WR} < 4$ $R_\odot$ and $T_c^{WR} > 60\,000$ K. ($R_c^{WR}$ is the radius of the WN5 core at $\tau_{es} = 1$ and $T_c^{WR}$ the brightness temperature of the central parts of the WN5 disk.) The values of residuals of (O-C) in this case are $\sim 0.0044$, twice those in the solution of Cherepashchuk (1975). The new results are insignificantly different from our published data (Cherepashchuk 1975; Cherepashchuk *et al.* 1984): $i = 78^\circ$, $r_{O6} = 0.25$, $R_c^{WR} < 3$ $R_\odot$, $T_c^{WR} > 70\,000$ K.

An increasing orbital period for V444 Cyg was discovered by Khaliullin (1974). This effect cannot be due to the presence of a third body in the system (Kornilov & Cherepashchuk 1979). The mass loss rate of the WN5 star determined from these data is $\dot{M} \sim (0.6 - 1)10^{-5}$ $M_\odot$/yr (Khaliullin *et al.* 1984; Underhill *et al.* 1990a). This value of $\dot{M}$ is close to that determined from polarimetric analysis of V444 Cyg (St-Louis *et al.* 1993) and several time less than that obtained from radio data. This is due to the clumping structure of the WN5 stellar wind. Direct evidence for clumping structure of WR wind come from investigations of rapid spectroscopic and photometric

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variability of WR stars (Moffat *et al.* 1988; Antokhin *et al.* 1992). The density distribution derived from our analysis of the 4244Å light-curve of V444 Cyg system suggests the acceleration of the matter in WR wind (Cherepashchuk 1975; Cherepashchuk & Khaliullin 1975; Cherepashchuk *et al.* 1984). This result agrees with the conclusion of Koenigsberger (1990). New photometric observations of the eclipsing binary HD 5980 (WN4+O7) and results of light-curve solution have been published by Breysacher & Perrier (1991). Recently Koenigsberger *et al.* (1994) provided some arguments for the triple nature of HD 5980.

Note also the very peculiar and puzzling deep ($\sim 0^m.5 - 1^m.2$) minima of light observed for WC7+O and WC9+O binaries CV Ser and HD 164270 (Hjellming & Hiltner 1963; Massey *et al.* 1984; Moffat *et al.* 1986).

Note that the position, shape and orientation of the region of wind-wind collision in V444 Cyg determined by Shore & Brown (1988) from *IUE* high-resolution spectra agree well with the model of radially expanding WR extended atmosphere. Also Aslanov & Cherepashchuk (1990) did not find any orientation effects in the radiation of WR+O binaries with known $i$.

### 1.2 Spectroscopy

A large accumulation of high S/N moderate-resolution optical spectra of V444 Cyg and CX Cep systems have been used by Marchenko *et al.* (1994) and Lewis *et al.* (1993) to obtain the new spectroscopic elements, study the properties of components, and the effects of colliding winds. Improved orbital elements are obtained. Monte Carlo simulation of line profile variability due to effects of colliding winds in WR+O binaries was carried out by Stevens (1993). New spectroscopic investigations of CQ Cep and HD192641 have been carried out by Underhill *et al.* (1990b) and Underhill (1992).

### 1.3 Polarimetry

Much effort on the polarimetric investigations of WR+O binaries has been applied by Moffat and collaborators (*e.g.,* Robert *et al.* 1989; Robert & Moffat 1989; Moffat *et al.* 1990; Robert *et al.* 1990; St-Louis *et al.* 1993). For V444 Cyg, the interpretation of polarimetric observations (Robert *et al.* 1990; St-Louis *et al.* 1993) yields the following values of the parameters: $i = 78°.7 \pm 0.5$, $R_{O6} = (8.5 \pm 1)\ \mathrm{R}_\odot$, $R_\mathrm{c}^\mathrm{WR} < 4\ \mathrm{R}_\odot$ which are in good agreement with the results of our light-curve solutions. The value of $\dot{M}$ for WN5 star derived from polarimetric data, $\dot{M} \simeq 0.75 \cdot 10^{-5}\ \mathrm{M}_\odot/\mathrm{yr}$, is close to that determined from period change $(0.6 - 1) \cdot 10^{-5}\ \mathrm{M}_\odot/\mathrm{yr}$ and is 3 times lower than $\dot{M}$ derived from free-free radio flux. All these results strongly support the idea that clumping structure exists in the WR winds (Cherepashchuk *et al.* 1984; Cherepashchuk 1992). An intensive program of spectropolarimetric investigations of WR stars has been realized by Schulte-Ladbeck and collaborators (*e.g.,* Schulte-Ladbeck *et al.* 1990, 1992, 1994).

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This program is very important for investigation of the occurrence of wind asymmetries and/or inhomogeneities (Taylor & Cassinelli 1992).

## 2. X-ray observations: colliding winds

### 2.1 X-RAY LUMINOSITIES

X-ray radiation in the range 0.2–4 keV due to wind-wind collision has been discovered recently from WR+O and O+O binaries (Pollock 1987; Chlebowsky & Garmany 1991). From early works (Cherepashchuk 1967, 1976; Prilutsky & Usov 1975, 1976) to the present there have been many theoretical investigations of the effects of wind-wind collisions (Luo *et al.* 1990; Bayramov *et al.* 1990; Myasnikov & Zhekov 1991, 1993; Usov 1991, 1992; Eichler & Usov 1993; Stevens *et al.* 1992; Cherepashchuk 1990; Bychkov and Cherepashchuk 1993; Kallrath 1991). In the fundamental work of Pollock (1987), results of the analysis of 48 WR stars observed with the *IPC* of the *Einstein* observatory are presented. The X-ray luminosities of WR stars cover a range from less than $10^{32}$ erg/s to more than $10^{34}$ erg/s. There is a significant difference between the individual single WR stars. Mean $L_{\rm x}$ of single WR stars is $\sim 5 \cdot 10^{31}$ erg/s which is several time fainter than $L_{\rm x} = 10^{32} - 10^{33}$ erg/s for single O3 – O6 stars (Chlebowski & Garmany 1991). Comparison of X-ray luminosities of shocks in WR+O and O+O binaries was carried out by Bychkov & Cherepashchuk (1993). Values of $L_{\rm x}$ for binary WR+O stars range from $(1.1 \pm 0.1) \cdot 10^{32}$ erg/s ($\gamma$ Vel, WC8+O9I, $P = 78^{\rm d}.5$) to $(34 \pm 10) \cdot 10^{32}$ erg/s (HDE 320102, WN3+O5-7, $P = 8^{\rm d}.8$) and even $4 \cdot 10^{34}$ erg/s (HD 193793, WC7+O4-5, $P = 7.94$ yr). This excess of $L_{\rm x}$ for WR+O binaries is due to wind-wind collisions. There are WR stars associated with non-thermal radio sources. Values of $L_{\rm x}$ for 27 WN stars have a mean X-ray luminosity $\sim 4$ times that of the 17 WC stars. According to Pollock (1987) this effect could reflect real differences in chemical composition and X-ray opacity of WN and WC winds.

Williams *et al.* (1990) have demonstrated that, in wide WR+O binaries, processes are observable which are hidden in close binaries due to the free-free opacity of the WR wind. The first X-ray selected WR star Th35-42 related to the X-ray source 1E 1024.0-5732 has been discovered from *ROSAT* PSPC observations by Mereghetti *et al.* (1993). X-rays with $L_{\rm x} = 10^{33} - 10^{34}$ erg/s in the 0.1–2.4 keV range are presumably generated in the shock formed as a result of wind-wind collision in this suspected WN6+OB binary. The possibility of discovering new WR+O binaries from X-ray observations of their colliding winds has been pointed out by Cherepashchuk (1976). In this respect, great potential is offered by *ROSAT* All Sky Survey. In these cases, behind the shock front the gas of the winds is heated to $10^7 - 10^8$ K and X-ray emission via bremsstrahlung is generated (Usov 1991, 1992; Stevens *et al.* 1992).

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## 2.2 X-RAY SPECTRA

Average X-ray spectra of EZ CMa and V444 Cyg are presented by Moffat *et al.* (1982). Fitting thermal spectra yields approximate values $kT \simeq 0.5$ keV ($T \approx 6 \cdot 10^6$ K) and $N_{\rm H} = 10^{22}{\rm cm}^{-2}$ for both stars. Observations from *GINGA* (Koyama *et al.* 1990) show that the spectrum of the colliding wind binary HD 193793 can be fitted in the 2–6 keV range by a power law with photon index $2.5 \pm 0.2$, with an X-ray luminosity $\sim (3.1 \pm 0.2) \cdot 10^{34}$ erg/s and $N_{\rm H}$ value $\leq 5 \cdot 10^{21}{\rm cm}^{-2}$. An emission line of iron at $6.6 \pm 0.2$ keV with equivalent width of $0.3 \pm 0.1$ keV was discovered. The power low X-ray spectrum of HD 193793 can be explained in term of multi-temperature thin thermal plasma (Stevens *et al.* 1992; Koyama *et al.* 1990).

## 2.3 RAPID X-RAY VARIABILITY

It was shown by Pollock (1989) that the statistical significance of the apparent rapid variability of the Einstein IPC X-ray flux of HD 50896 reported by White & Long (1986) was low. The other X-ray bright WR stars are also constant within a factor of 2 on time scales ($\sim$ 1000 sec – 1 hour), although there is some evidence of rapid variability in one of the observations of HD 93162 ($L_{\rm x} \simeq 3 \cdot 10^{34}$; variability of $L_{\rm x}$ by factor 2–3 for $\Delta t \simeq 1^{\rm h}$).

## 2.4 ORBITAL X-RAY VARIABILITY

There are the only five WR binaries for which several X-ray measurements were obtained at different orbital phases: V444 Cyg, HD 50896, HD 193793, HD 92740 and $\gamma$ Vel. According to Moffat *et al.* (1982), the X-ray flux from V444 Cyg changes by factor $\sim 2$ during the orbital period, one minimum of X-ray is observed at phase $\varphi = 0$ (WN5 star in front). The most recent *ROSAT* observations show the attenuation of the wind-wind collision region by both the O6 (phase$\varphi = 0^{\rm p}.45$) and WN5 components ($\varphi = 0^{\rm p}.8 - 0^{\rm p}.96$) (Corcoran *et al.* 1993). The mean X-ray luminosity for V444 Cyg in the range 0.5–4 keV is $L_{\rm x} \simeq 7.7 \cdot 10^{32}$ erg/s (Moffat *et al.* 1982; Pollock 1987). Part of X-ray flux may arise from intrinsic wind shocks of the O6 and WN5 stars and not necessarily from the colliding winds. According to gas-dynamic calculations of Stevens *et al.* (1992), the post-shock regions for colliding winds of both stars in V444 Cyg are not adiabatic but partly cooled. The total mean intrinsic unattenuated theoretical luminosity is $L_{\rm x} \simeq 10^{36}$ erg/s. Soft X-rays with $kT < 1$ keV are severely suppressed. Attenuated mean value of $\rm L_x$ for the *Einstein* range (0.2-4 keV) is $L_{\rm x} \simeq 3.2 \cdot 10^{34}$ erg/s. So the theoretical value of $L_{\rm x}$ is an order of magnitude higher than observed ($\sim 10^{33}$ erg/s). The theoretical spectrum is harder (few keV) than observed ($\sim$ 0.5 keV). Possible explanations of this discrepancy (Stevens *et al.* 1992) are: uncertainty of the spectral range for *Einstein Observatory*, possible collapse of the shock down to the O-star. Cherepashchuk (1990) suggested that the winds in WR+O binaries are of a clumpy nature. The "clumps" can pass through the shock and impact the photosphere of the O-star. The kinetic energy of blobs is then re-radiated at optical energies; X-rays are generated by collision of intercloud matter of the WR and O star winds and should be about order of magnitude less than in the case of smooth winds. Cherepashchuk (1976) also took into account inverse Compton cooling of hot plasma in the shock by optical radiation of O and WR stars. HD 193793 shows only weak ($\leq 30\%$) orbital X-ray variability (Koyama *et al.* 1990), but shows extremely remarkable variability in IR and radio ranges (Williams *et al.* 1990). *EXOSAT* and *GINGA* observations (Williams *et al.* 1990; Koyama *et al.* 1990) cover a considerable time interval: from 1984 to 1988, *i.e.*, before and after periastron passage (1985) which coincided with the onset of grain formation. The observed $L_{\rm x}$ ( 0.5–4 keV) in 1984–85 was $4 \cdot 10^{34}$ erg/s (Williams *et al.* 1990) and in 1987-88 long after periastron passage $L_{\rm x}$ (2–6 keV) $\simeq (3.1 \pm 0.2) \cdot 10^{34}$ erg/s. Detection of an emission line of iron at 6.6 keV suggests a thermal origin of X-ray spectrum. The overall power law spectrum can be explained in terms of a multi-temperature thin thermal plasma (Koyama *et al.* 1990; Stevens *et al.* 1992; Usov 1992). According to Stevens *et al.* (1992) and Usov (1992) the post-shock regions for both winds of the components in HD 193793 are adiabatic. The non-attenuated spectra for periastron and apastron have the same shape and differ only in the luminosity: $L_{\rm x} \simeq 1 \cdot 10^{36}$ erg/s at periastron and $L_{\rm x} \simeq 9 \cdot 10^{34}$ erg/s at apastron. Total attenuated theoretical value of $L_{\rm x}$ in (0.5-4 keV) range is $L_{\rm x} = 1.6 \cdot 10^{34}$ erg/s at periastron and $2.6 \cdot 10^{34}$ erg/s at apastron.

## 3. X-ray observations: accretion. Properties of the WR star in the Cyg X-3 system

This well-known and very active short-period ($P \simeq 4^h.8$) X-ray binary ($L_{\rm x} = 10^{38}$ erg/s, for 1–60 keV) is carefully investigated (*e.g.*, Bonnet-Bidaut & Chardin 1988; Aslanov *et al.* 1989) The powerful X-ray source is due to accretion of matter onto a relativistic object. Outstanding spectroscopic infrared investigations of Cyg X-3 carried out recently by van Kerkwijk *et al.* (1992) and van Kerkwijk (1993) clearly show that the optical companion of this peculiar X-ray binary is a WR star of $\sim$ WN7 subtype. The change of emission line ratios corresponding to a change of spectral subtype from WN6/7 to WN4/5 was observed (van Kerkwijk *et al.* 1993), which may be due to the variable X-ray heating effect and clumping of matter. Investigation of X-ray spectra and the ionization structure of Cyg X-3 (Terasawa & Nakamura 1993, 1994) clearly shows that the companion star is fairly massive ($5 \leq m_{\rm WR} \leq 10$ $M_{\odot}$) and that iron in the stellar wind is somewhat depleted to $0.1 - 0.5$ times the cosmic abundance. The wind matter in Cyg X-3 is enriched in any one of C, N, O. These results strongly support the results of van Kerkwijk (1993). The Cyg X-3 system provides for the first time a direct, model-independent method of determining severe limits on the core radius $r_c$ and effective temperature of a WR star (Cherepashchuk & Moffat 1994): $r_c < (3.2 - 5.6)\ R_\odot$ and $T_{\rm eff} > (70\,000 - 90\,000)$K for the wide range of Population I WR star masses $m(WR) = 10 - 50\ M_\odot$. It is also the first time that a relativistic companion has been detected with certainty in a WR system. The small core radius and high $T_{eff}$ of the WN7 star are in excellent agreement with models of massive helium stars (Langer 1989).

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**DISCUSSION:**

**Hamann:** I have no objections against your parameters for V444 Cyg. The main point in our earlier paper (Hamann & Schwarz 1992) was that from the light curve alone the parameters cannot be determined uniquely. But when you are sure you have fixed the brightness ratio reliably, you can pick out one particular solution out of the manifold of possible light-curve solutions. In our paper we had picked out the particular solution which fitted best the observed helium spectrum with our model, but I admit that this might depend critically on details of the model.

**Cherepashchuk:** I agree with you, but I would like to make some comments on my method of light curve solution. For the small values of $r_{06}$ we have two integral equations and one algebraic equation describing the normalisation of total luminosity of the system to unity. In this case you are right: four unknown values (two functions and two parameters $r_{06}$, i) have to be determined from three equations and the light curve solution may be not unique. But for high values of $r_{06}$ (> 0.1) integral equations are overdetermined and unique values of $r_{06}$ and i can be obtained from light curve solution without a spectroscopic estimate of the luminosity ratio, simply by the minimisation of the $(O\text{-}C)_{rms}$ residuals. The minimum of $(O\text{-}C)_{rms} = 0.0022$ is reached for the values of $i = 78°$ and $r_{06} = 0.25$. Therefore for high accuracy light curve, for high values of $r_{06}$ our method allows to determine both $r_{06}$, i, brightness and absorption distribution over the WR star disk and luminosity ratio of the components. This is the case which was realised in our yearly publications on V444Cyg. It is natural that including in our new light curve solution spectroscopic determination of luminosity ratio improves the reliability of the results. New results of our light curve solution for V444Cyg are insignificantly different from our earlier results.

**Magalhaes:** I would like to comment that Claudia Rodrigues and myself have a poster at this meeting, where we illustrate our Monte Carlo code with a fit to the light curve and polarisation of V444Cyg simultaneously. We found that the radius of the WR component is close to $4R_\odot$, consistent with the value you have just presented us, which is revised upwards from your earlier 1984 solution.

**Cherepashchuk:** Yes, I saw your poster. Our results concerning the upper limit for WN5 star core are in agreement; $r_c < 4R_\odot$ as an upper limit for WN5 star core at the electron scattering optical depth close to unity. Hydrostatic WN5 star core may be smaller.

**Antokhin:** I have applied Cherepashchuk's method to the light curve of V444 Cyg, using the luminosity ratio, obtained by Hamann and Schwarz from their modelling. Resulting parameters of the WR and O stars are essentially identical to those from Hamann and Schwarz's paper. This means that there is in fact no contradictions between two approaches. Thus, the reason for discrepancies between the two is not invalidity of one of them. The observed luminosity ratio must be used to make a choice between the two solutions.