X-ray Variability in V444 Cygni - Evidence for Colliding Winds?

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ABSTRACT

Phase-resolved *ROSAT* observations of the soft X-ray flux from the WR+O star binary V444 Cygni confirm the orbital dependence of the flux suggested by *EINSTEIN* IPC observations, showing a drop in flux around primary eclipse, when the WR star is in front of the O-star. The observed X-ray variability can be modelled as a wind eclipse of an X-ray source by the Wolf-Rayet wind. If most of the X-rays from the system are produced in a region of shock heated gas formed by the wind collision between the two stars, then the shocked gas has a large physical extent ($r \sim 140R_{WR}$) if the observed variability is produced solely by the eclipse of the region by the WR wind. However, since the O star makes a significant contribution to the total X-ray flux from the system, the actual size of the shocked interaction region is probably much smaller. We discuss possible origins for the X-ray emission and conclude that it is probable that at least a fraction of the observed X-ray emission comes from the wind collision.

Subject headings: X-rays: stars — stars: Wolf-Rayet — stars: individual (V444 Cygni) — stars: early-type

1. Introduction

The importance of wind collisions in early-type binaries as a means to produce X-rays was first discussed by Cherepashchuk (1967) and Prilutskii and Usov (1976). The basic idea is that the wind from the primary star will collide with the wind (or surface) of the secondary somewhere in the region between the stars, shocking the gas to high enough temperatures ($T \sim 10^7 - 10^8$ K) that copious X-rays are emitted. Recent theoretical work (Stevens, Blondin and Pollock 1992, Usov 1992) has confirmed and expanded these results. Observationally, however, the situation is less clear. Single early-type stars are known sources of X-rays (Seward *et al.* 1979, Pollock 1987, Chlebowski *et al.* 1989), making it difficult to disentangle the contribution made by colliding winds from the X-ray emission of the individual components. Pollock's (1987) analysis of *EINSTEIN* IPC observations of Wolf-Rayet stars indicated that the L_x/L_{bol} ratio for WR binaries was as much as an order of magnitude higher than the known ratio for O stars and somewhat higher than the measured ratio for known single WR stars. From an analysis of IPC observations of O-type stars, Chlebowski (1989) and Sciortino *et al.* (1990) found that the L_x/L_{bol} ratio for O binaries was marginally higher than for single stars, an indication that wind-wind collisions can produce observable amounts of X-rays for at least some stars. In certain individual cases there is strong evidence that we are seeing X-rays produced by colliding winds (for example: WR 140 – Williams *et al.* 1990 and γ Velorum – Willis, Schild and Stevens 1995). However, at present we cannot say with certainty what fraction of the X-ray emission from early-type binaries is produced by colliding winds. This is an important question, since the X-rays produced by colliding winds offer a unique, localized probe of the wind flow. X-ray temperatures potentially provide a direct measure of pre-shock wind velocity at the point of collision, which in turn indicates the relative wind speeds and wind acceleration in the region between the stars. Emission measures can be used to determine densities of the shocked gas, and, since the shocked gas is buried deep in the systemic wind, photoelectric absorption of the X-rays as they pass through the wind can be used to determine the amount and nature of the

wind far from the binary system.

With this impetus, we have used the *ROSAT* (Trümper 1983) *Position Sensitive Proportional Counter* (PSPC) to look for evidence of X-rays from colliding winds in the WN5 + O6 binary V444 Cyg (HD 193576, WR 139). We chose this star for a number of reasons. It is a well-studied eclipsing binary with known physical parameters: orbital period $P = 4.21$ days, binary separation $a = 38 R_{\odot}$, stellar masses $M_{O6} = 28 M_{\odot}$, $M_{WR} = 9 M_{\odot}$, and stellar radii $R_{O6} = 10 R_{\odot}$, $R_{WR} = 2.9 R_{\odot}$ (Munch 1950, Cherepashchuk, Eaton and Khaliullin 1973, Hamann and Schwarz 1992, Marchenko, Moffat and Koenigsberger 1994). In addition, analysis of phase-resolved IUE spectra by Shore and Brown (1988) found evidence for the existence of a wind interaction region where the O and WR star winds collide. These authors showed that the variability of the He II $\lambda 1640\text{\AA}$ line can be explained by a simple model in which the O star wind carves out a conical shadow in the wind from the Wolf-Rayet star. Finally, analysis of an IPC observation of V444 Cyg by Moffat *et al.* (1982) and Pollock (1989) indicated (at about the 2.5σ level) that the X-ray flux decreased when the O star was eclipsed by the WR star. This variation could be produced by an eclipse of an X-ray emitting source between the stars, but it was impossible to rule out sporadic variability on the basis of the IPC data alone. We used the *ROSAT* PSPC to examine the X-ray variability of V444 Cyg. Our objectives were to compare our results with previous observations made with the *EINSTEIN* IPC, to explore the phase dependence of the X-ray variations, and to determine the location and origin of the observed X-rays.

In addition to a colliding wind origin it is likely that at least a fraction of the observed X-rays are generated within the winds of both stars, from shocks inherent to radiatively driven winds (Owocki, Castor and Rybicki 1988). The X-ray spectra and variability seen with *ROSAT* can in principle provide us with important clues to determining the origin of the X-ray emission.

The paper is organized as follows: in § 2 we describe the *ROSAT* observations of V444 Cyg, in

§ 3 we discuss the main results of the X-ray observations concerning the X-ray lightcurves and spectral fitting, in § 4 we discuss the implications of these observations on the size and origin of the X-ray emitting region, and in § 5 we summarize our findings.

2. *ROSAT* Observations of V444 Cygni

ROSAT observed V444 Cygni with the PSPC on five separate occasions, with a total integration time of about 20 ksec. A journal of these observations is listed in Table 1. In this table the orbital phases are calculated from the ephemeris of Kornilov and Cherepashchuk (1979):

$$\text{HJD (Pri. min.)} = 2,441,164.337 + 4.212435E$$

where E is the cycle count. Phase $\phi = 0$ corresponds to primary minimum (WR-star in front). The intense mass-loss from this system (primarily from the WR star) results in an increase in the orbital period. We have corrected the calculated phases for the measured change in the orbital period of V444 Cyg, ($\dot{P} = 0.222 \pm 0.019 \text{ s yr}^{-1}$, Cherepashchuk 1982). This correction results in a decrease of 0.02 and 0.004 in phase at the time of the *ROSAT* and *EINSTEIN* observations, respectively.

Table 1
Journal of *ROSAT* Observations of V444 Cygni

Sequence No.	Date (UT)	JD – 2,400,000	Orbital Phase (ϕ)	Exposure Time (sec)	Net count rate (cts s ⁻¹)
200057	6-May-91	48383.174	0.70	1846	0.036 $\pm$ 0.005
200063	9-May-91	48385.977	0.36	2073	0.033 $\pm$ 0.004
200058	9-May-91	48386.333	0.45	1931	0.023 $\pm$ 0.004
200062	22-Oct-91	48552.211 – 48552.726	0.82 – 0.95	12584	0.015 $\pm$ 0.007
200062	3-Nov-91	48564.319	0.70	1436	0.026 $\pm$ 0.008

V444 Cyg was observed on-axis in all cases, which minimised vignetting but which introduced flux variations on timescales below about 400 seconds due to the spacecraft wobble. Wobbling is necessary to avoid constant shadowing by the coarse wire mesh in front of the PSPC, but wobbling introduces short timescale variations in the observed source counting rate as the source is briefly shadowed by one of the wires in the coarse mesh which supports the PSPC window against vacuum. At timescales greater than the wobble timescale, the effect of the wobble is mainly to reduce the overall counting rate slightly, though slight pointing discrepancies and variations in the wobble can result in variations in the observed counting rate. We estimate the magnitude of these variations as follows. The wires in the PSPC coarse

mesh are 100 microns thick with a spacing of 2 mm. At the *ROSAT* focal plane scale, each wire subtends $9''$. The magnitude of the wobble is $\pm 3'$ in 400 seconds, or about $0.9''$ per second. This means it takes roughly 10 seconds for an on-axis source to cross 1 wire. During the wobble period, the source should intercept 2 wires which means that the total time that the source is shadowed is about $20/400$ seconds = 5 per cent of the observation. If each pointing were at exactly the same position on the detector, and wobbling done in exactly the same way each time, the observed rate from the on-axis wobbled observation would be 5 per cent less than the true source rate. We expect that variations in the counting rate due to slight pointing variations and variations in the wobble should be no larger than about 5 per cent.

3. Results from the ROSAT Observations

3.1. The X-ray Lightcurve

For each of the observations listed in Table 1, counting rates for the source were extracted from the photon event files using the PROS analysis package. Source counts were extracted from each data set using a circle of radius $3'$ centered on V444 Cygni. Background counts were extracted from a $3'$ circle centered at RA(J2000) = 20:19:20.9, Dec(J2000) = 38:49:33.0, as examination of the longest exposure (sequence number 20062) showed no obvious sources in this region. We binned the X-ray lightcurve in bins of about 1000 – 2000 seconds, ignoring bins which had an exposure of less than 500 seconds. This gave an average of 95 source counts and 70 background counts in each bin. Since background subtraction is important, we compared our derived counting rates with the rates derived by the standard processing software, which calculates an estimate of the background in the source circle from a derived background map. We found that our derived counting rates for the individual observations (200057, 200058 and 200063) and for the combined 200062 observation were not significantly different from the source counting rates derived by the automated processing system.

Figure 1 shows the lightcurve obtained with the *ROSAT* PSPC in the energy range 0.2 – 2.4 keV, in which the 22 October observation is broken up into 10 bins having lengths of 1500 – 2500 sec. Fitting the lightcurve with a constant value yielded $\chi^2 = 21.3$ with 13 degrees of freedom, which means that the lightcurve is variable at the 97 per cent confidence level.

Figure 2 shows the phase-binned PSPC lightcurve versus orbital phase ϕ . For comparison, we obtained the list of *EINSTEIN* IPC events for V444 Cygni (sequence number 7875) from the *EINSTEIN* On-Line database and extracted the lightcurve for the star with PROS in the same manner as for the *ROSAT* data. Figure 2 shows the resulting phase-binned IPC rates in the energy range 0.4 – 4.5 keV as a function of orbital phase. The resulting lightcurve is very similar to that published by Moffat *et al.* (1982). Fitting the unbinned *EINSTEIN* IPC lightcurve with a constant value yielded $\chi^2 = 20$ with 13 degrees of freedom (14 data points), which means that the IPC lightcurve is also variable at the 90 per cent confidence level.

The similarities between the PSPC and IPC lightcurves in Figure 2 are readily apparent: both PSPC and IPC lightcurves show a factor of 2 decrease in the counting rate when the WR star is eclipsing the O-star ($\phi \sim 0.0$). We used a χ^2 test to see whether the IPC and PSPC data were drawn from the same parent distribution. Before testing we resampled the phase-averaged IPC counting rates at the sampling of the phase-averaged PSPC data by linear interpolation. We then normalized each lightcurve by dividing by the average counting rate. This test yielded $\chi^2 = 0.72$ with 4 degrees of freedom, which means that the two lightcurves are drawn from the same distribution at greater than 95 percent confidence. Inspection of the IPC and PSPC data also suggests that some of the observed variability is not strictly locked to the orbital phase. For example, when the long PSPC pointing on 22 October is broken up into ~ 1500 second bins, one episode in which the X-ray counting rate approaches the non-eclipse level is apparent. Spectral fitting (§ 3.2 below) showed no significant differences in intrinsic luminosity between the IPC and PSPC observations, which suggests that the mean source luminosity is relatively constant over long time intervals.

3.2. X-ray Spectral Analysis

Figure 3 shows the derived hardness ratio curve as a function of phase for the *ROSAT* PSPC, where hardness ratio has been defined as the ratio of the counts in the 1.4 – 2.4 keV band to those in the 0.6 – 1.4 keV band. The PSPC hardness ratio suggests that the source is slightly harder outside primary eclipse. However, the hardness ratio derived from the IPC is nearly constant at a value of 1.82 ± 0.72 , where, to maximize signal to noise in each phase bin, the hardness ratio for the IPC data was defined as the ratio of counts in the 1.0 – 4.0 keV band to that in the 0.4 – 4.0 keV band.

To further investigate any apparent change in the observed spectrum we have constructed an “outside eclipse” spectrum from the 6 May and 3 Nov PSPC observations along with the 9 May observation obtained at phase $\phi = 0.36$ (sequence number 20063), and compared that to an “inside eclipse” spectrum constructed from the other observations. We fit both spectra with single-temperature absorbed Raymond-Smith models, using abundances appropriate for WN material (Prantzos *et al.* 1986) with a constant ISM absorption fixed at $N_H = 4.2 \times 10^{21} \text{ cm}^{-2}$ (using $E_{b,v} = 0.71$, Pollock 1987). This is only a gross approximation to the true X-ray spectrum since it ignores realistic modeling of intrinsic wind absorption and the detailed physics of wind collision in binary systems which will lead to a non-isothermal temperature distribution, but since the net spectra had fewer than 200 counts more detailed modeling was not warranted. The “outside eclipse” spectrum was fit with a nominally higher temperature ($> 1.7 \text{ keV}$ vs. 0.7 keV , with a He absorption column of about $3 \times 10^{21} \text{ cm}^{-2}$). However, neither the temperatures nor absorbing columns could be tightly constrained by the low count rate spectra. Figure 4 shows the PSPC spectra and best fit models. We found that a similar input spectrum (absorbed Raymond-Smith with N_{He} near 10^{20} cm^{-2} and $kT > 1 \text{ keV}$) also fits the spectrum extracted from the entire IPC observation.

Using the best fits to the *ROSAT* spectra, the inside-eclipse observed flux, corrected for

absorption, is $1.1 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the *EINSTEIN* band (0.4 – 4.5 keV) while the unabsorbed outside-eclipse observed flux is $2.5 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ in the same band. Adopting a distance to V444 Cyg of 1.7 kpc (Pollock 1987) we find that the unabsorbed X-ray luminosity is $3.8 \times 10^{32} \text{ erg s}^{-1}$ inside eclipse while out of eclipse the X-ray luminosity is $8.6 \times 10^{32} \text{ erg s}^{-1}$. For the IPC observation, we found that the unabsorbed flux in the *EINSTEIN* band was $1.6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, which gives an X-ray luminosity of about $5.5 \times 10^{32} \text{ erg s}^{-1}$. The derived luminosities are somewhat lower than the prediction of recent colliding wind models of V444 Cyg (Usov 1992, Stevens *et al.* 1992). In addition, we point out that the companion O6 star has $L_{bol} = 1.4 \times 10^{39} \text{ erg s}^{-1}$ which implies an X-ray luminosity of $6 \times 10^{32} \text{ erg s}^{-1}$ (assuming that $\log L_x = 1.08 \log L_{bol} - 9.38$ as appropriate for normal O stars, Sciortino *et al.* 1990). Thus the O star by itself is expected to make a significant contribution to the total X-ray flux from the system. Unfortunately it is impossible to determine the fractional contribution of the O star to the total systemic X-ray flux directly from the data in hand.

4. Discussion

4.1. The Size of the Interaction Region

In this section we shall develop a very simplified model of X-ray emission from colliding winds in an attempt to constrain the size of the X-ray emitting region. If we assume that all the observed X-rays from the system are produced in the region of wind interaction, and that the variation in counting rate between primary eclipse ($\phi = 0$) and quadrature ($\phi = 0.25, 0.75$) is produced solely by changes in the absorbing column, then the observed counting rate ratio can be used to estimate the ratio of optical depths for the two lines of sight. Figure 5 illustrates the assumed geometry. The weakening of the He II $\lambda 1640\text{\AA}$ absorption (which presumably traces the extent of the region of interaction) extends roughly over an interval of 0.2 in orbital phase (Shore and Brown 1988). We therefore approximate the shape of the contact surface as

a cone of total opening angle 72° centered on the line of centers (the shaded boundary around the O star in Fig. 4). This boundary separates the WR wind from the O star wind: we assume that the X-ray emitting gas originates close to this boundary. Lines of sight to the system at primary eclipse and at secondary eclipse are shown.

Assuming that the wind of the WR star consists mostly of helium, the optical depth τ through the wind is given by

$$\tau = N_{H\epsilon} \sigma \quad (1)$$

where σ is the absorption cross-section and $N_{H\epsilon}$ is the column density through the wind. The column density through the wind is given in the usual way by

$$N_{H\epsilon} = \int_{x_0}^{\infty} n \, dx \quad (2)$$

where n is the number density in the wind along the particular path under consideration, dx is the path length through the wind, and x_0 the location of the X-ray emitting gas. For a spherically-symmetric wind, the density $n(r)$ as a function of distance r from the wind-emitting star is

$$n(r) = \frac{\dot{M}}{4\pi r^2 V(r) \mu m_H} \quad (3)$$

with $\dot{M}$ the wind mass loss rate, μ the mean molecular weight of the wind ($=3.9$ for He rich material), and $V(r)$ the wind velocity law. For simplicity we assume a wind velocity law of the form

$$V(r) = V_\infty (1 - R/r)^\beta . \quad (4)$$

In the following we assume that for both winds $\beta = 1.0$.

At quadrature ($\phi = 0.25, 0.75$), the column depth N_H to a parcel of gas at (x_0, y_0) becomes

$$N_{H\epsilon} = \frac{\dot{M}}{4\pi V_\infty \mu m_H R} \int_{y_0}^{\infty} \frac{dy}{(x_0^2 + y^2) - \sqrt{x_0^2 + y^2}}, \quad (5)$$

while at primary eclipse ($\phi = 0.0$), the column depth is

$$N_{H\epsilon} = \frac{\dot{M}}{4\pi V_\infty \mu m_H R} \int_{x_0}^{\infty} \frac{dx}{(x^2 + y_0^2) - \sqrt{x^2 + y_0^2}}. \quad (6)$$

The total mass loss rate from the system is about $1.4 \times 10^{-5} M_\odot \text{ yr}^{-1}$; we assume that this is mainly due to the WR star and take the mass loss rate from the WR star $= 1.0 \times 10^{-5} M_\odot \text{ yr}^{-1}$, which is consistent with the location of the stagnation point in the model of Shore and Brown (1988) and near the value derived by St. Louis *et al.* (1993). Shore and Brown also determined that the terminal velocity of the wind from the WR star is about 2000 km s^{-1} . The ratio of the Eq. (5) to Eq. (6) gives the ratio of optical depths. For a wind eclipse, we have that

$$c_q/c_p = e^{-(\tau_q - \tau_p)} \quad (7)$$

where c_p , c_q , τ_p , τ_q are the counting rates and optical depths at primary eclipse and quadrature, respectively. Figure 6 shows the predicted counting rate ratio c_q/c_p as a function of x_0 if the variation in counting rate is totally due to the optical depth variations as the line of sight through the wind changes. The PSPC and IPC observations presented in Figures 1 and 2 show that $c_q/c_p = 1.7 - 2.5$. Our calculations indicate that the predicted c_q/c_p ratio falls to 2.5 only for $x_0 > 140 R_{WR} = 10a$ (where a is the binary separation). Thus the hot shocked region must be very large if all the variation observed results from the eclipse of the interaction region by the WR star wind.

As a check, we can calculate the column densities at quadrature and primary eclipse if the source is at $x_0 = 140 R_{WR}$, and compare those values to the columns obtained from the fits to

the PSPC spectra. Integrating (5) along the line of sight we find that $N_{H\epsilon} = 5 \times 10^{20} \text{ cm}^{-2}$ at $x_0 = 140R_{WR}$ at quadrature. This value is very close to our best fit value of $N_{H\epsilon} = 3 \times 10^{20} \text{ cm}^{-2}$ obtained by fitting the out-of-eclipse spectrum. Integrating (6) with $x_0 = 140R_{WR}$ yields $N_{H\epsilon} = 1.2 \times 10^{21} \text{ cm}^{-2}$. This value is somewhat above our best fit He column for the in-eclipse spectrum, though this value was very poorly constrained.

We can also calculate the expected column depth to the X-ray source at secondary eclipse to determine if the lower-density wind from the O star can cause an X-ray eclipse. Figure 5 shows the line of sight to the observer at secondary eclipse. We assume that the stellar wind from the O star has solar composition ($\mu = 1.3$) and we adopt $\dot{M} = 4.0 \times 10^{-6} M_{\odot} \text{ yr}^{-1}$ for the O star. Shore and Brown reported an increase in the terminal velocity of the C IV 1550 doublet to about 3000 km s^{-1} near phase $\phi = 0.5$, so we assume $V_{\infty} = 3000 \text{ km s}^{-1}$. Integrating along the line of sight through the O star wind from the X-ray source, we find that the column density is $N_H = 2.8 \times 10^{20} \text{ cm}^{-2}$. However, because the wind from the O star is mostly H, the absorption cross-section at 1 keV for the O star material is only $\sigma = 2.4 \times 10^{-22} \text{ cm}^{-2}$, which means that the optical depth through the O star wind is only 0.07 at 1 keV. Thus the O star wind will not significantly eclipse the X-rays produced in the wind interaction region if the region extends out as far as $x_0 = 140R_{WR}$ from the WR star. This also suggests that the observed X-ray flux of the system should increase at phases around $\phi = 0.5$, when the O star is towards the observer. The light curves in Figures 1 and 2 do not show an increase in flux close to phase $\phi = 0.5$. However, phase coverage in this portion of the orbit is poor and this conjecture cannot be tested with the current data.

4.2. The Origin of the X-ray Emission

4.2.1. Colliding Wind Origin

In the previous subsection we discussed simple estimates of the extent of the X-ray emitting region. Here we attempt to constrain possible models for the origin of the emission. The main observational properties of V444 Cyg that our *ROSAT* observations found are 1) systematic orbital variability, 2) short timescale variability in one of the pointings, 3) the X-ray luminosity and 4) the X-ray temperature. We can further investigate the origin of the X-ray emission by comparing these observed properties with theoretical models of the colliding wind phenomena (Stevens *et al.* 1992, Usov 1992).

At least some of the X-ray emission seems to repeat from orbit to orbit. This can be seen both in the agreement between the 3 November and 6 May observations, both of which were obtained near phase $\phi = 0.7$, and also the agreement between the PSPC and IPC X-ray lightcurves. As V444 Cyg has a circular orbit, a colliding wind model would predict that the intrinsic X-ray emission should be roughly constant throughout the orbit, while the changing line-of-sight to the region of wind interaction will cause changes in observed temperature, column and luminosity. This is qualitatively in agreement with the observed spectral changes seen in V444 Cyg. A further consequence of this model would be corresponding orbital variability in the hardness ratio, with the hardness ratio being at a minimum at phase $\phi = 0.5$. There is no clear evidence of such a feature in either the *ROSAT* or *EINSTEIN* hardness ratios, though the errors in these quantities are rather large and could mask such an effect.

The short-timescale variability seen during the 22 October observation, when the flux jumps by a factor 2 in one of the time-bins, does not fit too easily with a colliding wind mode, though some rapid variability can be expected from colliding wind systems for two reasons (Stevens *et al.* 1992). In close binary systems such as V444 Cyg the post-shock gas is dense enough so that substantial cooling can occur, and the intershock region is subject to dynamical instabilities.

These instabilities can give rise to variability on a dynamical timescale (a few hours in the case of V444 Cyg), though the magnitude of this variability is expected to be smaller than the observed factor 2. A second mechanism for generating short timescale variability occurs at epochs when the line-of-sight is down one arm of the interaction region. At this phase the line-of-sight passes through hot ionized material which is less efficient at absorbing X-rays, which could produce a short X-ray ‘flare’. However, in V444 Cyg this should occur at $\phi \sim 0.4$ and $\phi \sim 0.6$ rather than at $\phi \sim 0.9$. Thus, there is no clear explanation within the colliding wind model for this short-timescale variability. One speculative possibility is that the wind of the WR star is rather clumpy, consisting of dense clouds embedded in a diffuse background medium, rather than a more homogeneous wind. Such a cloudy configuration could lead to short timescale stochastic variability, both in terms of a wind collision model (dense clumps colliding leading to an increase in X-ray flux) and in an absorption model, where the low filling factor of the clouds could lead to epochs of lower absorption. Further phase resolved X-ray observations are needed, in particular to find out whether this feature repeats from orbit to orbit.

The observed X-ray luminosity of V444 Cyg, $L_x \sim 4 - 8 \times 10^{32} \text{ erg s}^{-1}$, is somewhat lower than theoretical predictions (Usov 1992; Stevens *et al.* 1992). However, as V444 Cyg is a rather close binary system ($a = 40 R_\odot \sim 4 R_{O6}$), the stellar wind of the O-star in particular will not have attained terminal velocity by the time the winds collide, if the wind obeys the assumed velocity law. There will be an additional effect produced by the detailed physics of the radiatively driven winds (Stevens and Pollock 1994) that will further reduce the velocity of both winds. Given the strong dependence of the luminosity on the pre-shock wind velocity (Stevens *et al.* 1992) this effect could remove the discrepancy between observed and theoretical luminosities (Usov 1992).

The characteristic X-ray temperature for V444 Cyg, $kT > 1.7 \text{ keV}$ for the “outside eclipse” spectrum, is higher than typical X-ray temperatures for single OB/WR stars

(Chlebowski *et al.* 1989), and would seem to be indicative of a colliding wind origin. Near eclipse the hottest regions of the wind collision are occulted, causing a decrease in the derived X-ray temperature similar to that derived from our analysis of the in-eclipse PSPC spectrum. A temperature of $kT > 1.7$ keV corresponds to a pre-shock wind velocity of $v > 750$ km s⁻¹ for WN material and $v > 1200$ km s⁻¹ for solar abundance material (the mean mass per particle being higher for WN abundances). In reality, the X-ray emission will be a combination of both shocked WN and O-star material, and will come from a range of temperatures, with the highest temperatures corresponding to the region where the winds collide head-on, near the binary line-of-centers. These inferred velocities are comparable to those derived from UV spectroscopy (Shore and Brown 1988).

4.2.2. Wind Instability Origin

An alternative hypothesis is that the origin of the observed X-ray emission from V444 Cyg is the same as that which occurs for all single early-type stars, most likely dynamical instabilities intrinsic to line-driven winds (Owocki *et al.* 1988), and basically unrelated to binarity. As all single early-type stars are X-ray sources then it is not unreasonable to expect that at least a fraction of the observed X-rays from V444 Cyg could be produced by such dynamical instabilities. As noted earlier, the observed X-ray flux seen from V444 Cyg is comparable to that expected for a star of similar bolometric luminosity as the O6 star (§ 3.2).

There are, however, several factors which suggest that radiative instabilities in the winds of either or both stars are not the dominant source of the observed X-ray flux. First, the X-ray emission varies systematically with orbital phase, which would seem to suggest a binary related origin. Second, while some variability in the X-ray flux from single OB/WR stars has been seen (Collura *et al.* 1989, Berghofer & Schmitt 1994) it has rarely been seen to occur on very short timescales. Third, the derived X-ray temperatures for V444 Cyg are substantially higher

than those typically seen for single OB stars (Chlebowski *et al.* 1989).

The X-ray lightcurve could be countered by a model where the O star wind is the dominant X-ray source in the system. In this case the observed variability could be produced as the O star is occulted by the wind of the WR star. Qualitatively, this model would mimic the observed variability. The second point concerning short timescale variability does not seem to fit easily into any model of V444 Cyg, but it still remains possible that it could be caused by intrinsic variations within one of the winds. Although rapid X-ray variability is typically not seen for most hot stars, a possible exception to this general rule is the WN5 star HD50896. White and Long (1986) have suggested that this system may show rapid variability on the timescale of less than an hour. However, Pollock (1989) has suggested that the statistical significance of this observed variability is low.

Perhaps the most important point is the third one, concerning the X-ray temperatures. The high derived values of kT for V444 Cyg outside eclipse ($kT \sim 1.7$ keV), compared to the lower temperatures of single O-stars ($kT \sim 0.5$ keV, Chlebowski *et al.* 1989) argues in favor of a colliding wind origin, and that binarity and colliding winds play a substantial role in generating the X-ray emission.

While neither hypothesis discussed above has been excluded, and indeed both have trouble explaining certain features of the X-ray emission (short timescale variability in particular), it does seem to be the case that the X-ray properties of V444 Cyg are different from that of single OB and WR stars. It is likely that both mechanisms mentioned above are at work in V444 Cyg, with a substantial fraction of the X-ray emission generated by the wind collision. Unfortunately it is difficult to quantify the amount using the available data. Further, some of the observed X-ray properties, such as the low luminosity and lower than expected X-ray temperature, do suggest some interesting refinements of the standard model of colliding wind systems. Higher spectral resolution observations, and enhancements in the theoretical models will likely lead to a better understanding of the system.

5. Summary

We have obtained new X-ray observations of the important colliding wind binary V444 Cyg, at a range of orbital phases. These observations, coupled with a re-analysis of earlier *EINSTEIN* observations have yielded new insights into the X-ray behavior of V444 Cyg. The main points are that the *ROSAT* and *EINSTEIN* lightcurves agree well, suggesting that the majority of the variability is phase repeatable. Secondly, variability on timescales of less than an hour was seen in one of the pointings. Modelling of the spectra has found that the source is comparatively hot ($kT \sim 1.7$ keV) with the spectra being hotter out of eclipse than during eclipse. An X-ray luminosity of $L_x \sim \text{a few} \times 10^{32} \text{ erg s}^{-1}$ was derived, which is somewhat lower than model predictions (Usov 1992, Stevens *et al.* 1992).

Efforts were made to constrain the size of the X-ray emitting region, and an estimate of $> 400R_*$ was made using the variation in flux at primary minimum and quadrature. If we could resolve the dip in the X-ray emission we could tightly constrain the size of the X-ray emitting region, although even the simple analysis above is sufficient to show that the hot gas has a large spatial extent. However, the above estimate of the size of the X-ray emitting region assumes that the X-ray flux is dominated by the emission of the wind interaction region, and an additional contribution from shocks intrinsic to either wind would tend to reduce the size of the emission region.

In summary, these *ROSAT* observations have not provided us with conclusive evidence for the origin of the X-ray flux from V444 Cyg. A colliding wind model remains perhaps the most plausible origin for at least part of the X-ray emission. Further observations, including higher spectral resolution observations and better phase coverage, are needed to solve this puzzle.

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Figure Captions

Figure 1. The *ROSAT* PSPC X-ray lightcurve of V444 Cyg, ordered by orbital phase. Each data point represents about 1500 s of data. The error bars are 1σ . Important points to note are the lower levels of emission at primary eclipse, and the factor of two variability seen close to phase $\phi = 0.9$. Thin dashed horizontal lines show the approximate durations of primary and secondary eclipse in the optical lightcurve.

Figure 2. The combined *ROSAT* PSPC and *EINSTEIN* IPC lightcurves of V444 Cyg. Data for the individual instruments have been binned by phase. The error bars are 1σ . The lightcurves are similar, suggesting that the orbital variability is real and repeats from orbit to orbit.

Figure 3. The hardness ratio curve ($1.4 - 2.4$ keV/ $0.6 - 1.4$ keV) for V444 Cyg constructed from phase-binned *ROSAT* PSPC data.

Figure 4. “In-eclipse” spectrum (top) and “out-of-eclipse” spectrum (bottom) from the *ROSAT* PSPC data, along with best fit models described in § 3.2.

Figure 5. Cartoon of V444 Cyg system based on the model presented in Shore and Brown (1988). The X-ray emitting gas is assumed to be located in the dark shaded region between the 2 stars. The wind of the WR star is assumed to be more massive and composed predominantly of helium, while the wind of the O-star has solar abundances. The various distances defined in this diagram are described in more detail in § 4.1.

Figure 6. The predicted variation in the counting rate at quadrature c_q (orbital phase $\phi = 0.25$ and $\phi = 0.75$) compared to the counting rate at primary eclipse c_p ($\phi = 0$) due to wind eclipse.

The observed value of $c_q/c_p = 1.7 - 2.5$ (§4.2) leads to a lower limit for the size of the emitting region.