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X-RAY EMISSION FROM COLLIDING WIND BINARIES

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RESUMEN

Se presenta nueva evidencia de la producción de rayos X por colisión de vientos en sistemas binarios de tipo temprano, buscando cambios dependientes de la fase en la emisión de rayos X observada. Nuevas curvas de luz en rayos X derivadas para 18 binarias de tipo O, muestran que la variabilidad es mucho más común en estrellas de tipo O binarias que en estrellas O simples. Cuatro de los 18 sistemas estudiados muestran clara evidencia de variabilidad dependiente de la fase, sugiriendo que una gran parte de la emisión de rayos X se produce en una región localizada de colisión de vientos. Se examinan 3 importantes sistemas WR + O: WR140, γ^2 Vel y V444 Cyg, y se muestra que las variaciones observadas en rayos X son consistentes con las predicciones de los modernos modelos de colisión de vientos.

ABSTRACT

I present new evidence of X-ray production by wind collisions in early-type binary systems by looking for phase-dependent changes in the observed X-ray emission. Newly derived X-ray lightcurves for 18 O-type binaries indicate that variability is far more common for O-type binaries than for single O stars. Four of the 18 systems studied show clear evidence of phase-dependent variability, suggesting that a large fraction of the X-ray emission is produced in a localized wind collision region. I examine 3 important WR + O systems, WR140, γ^2 Velorum and V444 Cygni, and show that the observed X-ray variations are consistent with the predictions of modern colliding wind models.

Key words: **BINARIES: CLOSE — STARS: EARLY-TYPE — STARS: WOLF-RAYET — X-RAYS: STARS**

1. INTRODUCTION

X-ray emission is a natural consequence of wind collisions in early-type binaries as the high relative wind velocities (thousands of km s^{-1}) produce temperatures in excess of a million degrees in the shocked gas at the collision boundary. Early models (Tcherepashcuk 1967; Prilutskii & Usov 1976) suggested high intrinsic X-ray luminosities in excess of 10^{33} ergs s^{-1} for a WR + O binary system like V444 Cygni and emission temperatures in excess of 10^7 kelvins. Since the flux and spectrum of the colliding wind X-rays depend on the stellar wind mass loss rates and terminal velocities, analysis of colliding-wind X-rays provides valuable information on these important parameters. In reality colliding-wind X-ray emission has proved difficult to clearly identify. Circumstellar absorption in the unperturbed stellar wind greatly reduces the fraction of the intrinsic X-ray flux which reaches the observer. Individual O and WR stars are X-ray emitters (Chlebowski, Harnden, & Sciortino 1989; Pollock 1987), and it can be difficult to disentangle the colliding-wind emission from the "quiescent" emission of the individual component stars (Chlebowski 1989; Sciortino et al. 1990). In addition, the interaction of a star's radiation field with the wind from the companion can decelerate the wind in the impact region and greatly reduce the intrinsic X-ray luminosity (Owocki & Gayley 1995, Gayley 1996).

Nevertheless, X-ray observatories like *EINSTEIN* (Giacconi et al. 1979) and *ROSAT* (Trümper 1983) have already provided some indication that wind collisions can generate observable X-ray emission. Pollock (1987) found that WR binaries tended to have higher X-ray luminosities than single stars, and suggested that wind collision made a significant contribution to the observed excess. Stevens, Blondin, & Pollock (1992) showed that colliding-wind emission models could reproduce the observed X-ray luminosity of 10^{34} ergs s^{-1} from the WC7+O binary WR 140 (=HD 193793). However, their models overpredicted the observed X-ray luminosity from the WN5+O6 binary V444 Cygni by about an order of magnitude. More recently, Willis, Schild, & Stevens (1995) obtained an X-ray lightcurve of the WC8 + O9I binary γ^2 Velorum which showed a factor of 4 increase in luminosity near secondary minimum, perhaps the clearest example to date of colliding wind X-ray emission.

In this paper I re-examine the issue of X-ray production from colliding winds by looking for evidence of X-ray variability. I discuss a number of mechanisms which may cause colliding wind X-ray emission to vary with binary orbital phase. Using newly-available *ROSAT* data, I construct X-ray lightcurves for O-type binaries and look for evidence of variability as a signature of colliding wind emission. I find that the percentage of O binaries which shows significant variability is much larger than for single O stars and for some systems the observed variability is clearly phase-locked. I also examine variability in X-ray emission from 3 important systems, γ^2 Vel, WR 140 and V444 Cyg, using new *ROSAT* and *ASCA* (Tanaka, Inoue, & Holt 1994) observations. Each of these systems exhibits intensity and spectral variations which are consistent with colliding wind models.

2. X-RAY VARIABILITY IN COLLIDING WIND BINARIES

X-ray variability can be produced in many ways in colliding wind systems. In eccentric binaries, the density in the collision region and the wind collision velocity vary as the stellar separation changes from periastron to apastron. Since the luminosity and spectrum of the X-ray emission depend on the density and relative wind velocity along the collision boundary, changes in these quantities will result in phase-locked variations in the observed X-ray emission.

X-rays produced in the collision region are absorbed by the intervening wind material along the line-of-sight. If the absorbing material is distributed anisotropically, then the X-ray absorption will vary as the stars revolve in their orbits, causing a phase-dependent change in the observed X-ray emission (even if the intrinsic X-ray emission is constant). For example, in WR + O binaries, the wind from the O star is usually much less efficient at absorbing X-rays than the wind from the WR star. The decrease in absorption when the O star is towards the observer implies an increase in observed X-ray emission at these phases.

In addition, photospheric eclipse of the X-ray emitting region can occur if the size of X-ray emitting region is comparable to the stellar radii, and if the inclination is sufficiently high. Such photospheric eclipses can also produce phase-locked X-ray variability.

In general each of these effects can influence the observed X-ray lightcurve. Synthesis of colliding wind X-ray lightcurves can thus be quite complicated, but in principle can reveal a great deal about the dynamics of the stellar winds.

3. X-RAY LIGHTCURVES OF O-TYPE BINARIES

The *ROSAT* Public Data Archive (Corcoran 1992) offers an important resource for addressing the issue of X-ray variability of stellar sources. The *ROSAT* archive contains non-proprietary data from *ROSAT* pointed observations with the Position Sensitive Proportional Counter (PSPC) and the High Resolution Imager (HRI). Although only a small fraction of the sky is covered by the pointed observations, the average exposure of each observed field is on the order of 10 ksec, and observations currently available span the 1990–1995 interval. Data from the *ROSAT* archive can be used to examine X-ray variability in detected sources on timescales of minutes to years. A significant fraction of *ROSAT* time was devoted to direct observations of early-type stars. In addition to these targeted observations, early-type stars appear as serendipitous sources in many observations. The *ROSAT* archive thus provides the best survey of X-ray emission from hot stars yet available.

I searched the *ROSAT* archive for pointings near all early-type binaries listed in the 8th Catalogue of Spectroscopic Binaries (Batten, Fletcher, & MacCarthy 1989). In order to ensure uniformity, I restricted my search to those binaries in which both components are of spectral type O, and considered only PSPC observations. I found 18 O+O binaries detected by the PSPC in multiple observations currently archived. For comparison, analysis of X-ray variability using archived *EINSTEIN* observations of OB stars (Collura et al. 1989) was limited to 12 stars, only 3 of which are known binaries.

I extracted data for these 18 binaries from the archive and constructed X-ray lightcurves. I derived count rate as a function of time for all sources, correcting off-axis sources for vignetting. I generally binned the X-ray data at a resolution of a few thousand seconds to achieve sufficient signal to noise without masking real short-term variability. I phased the observations using the ephemerides given in the 8th catalogue (except for HD

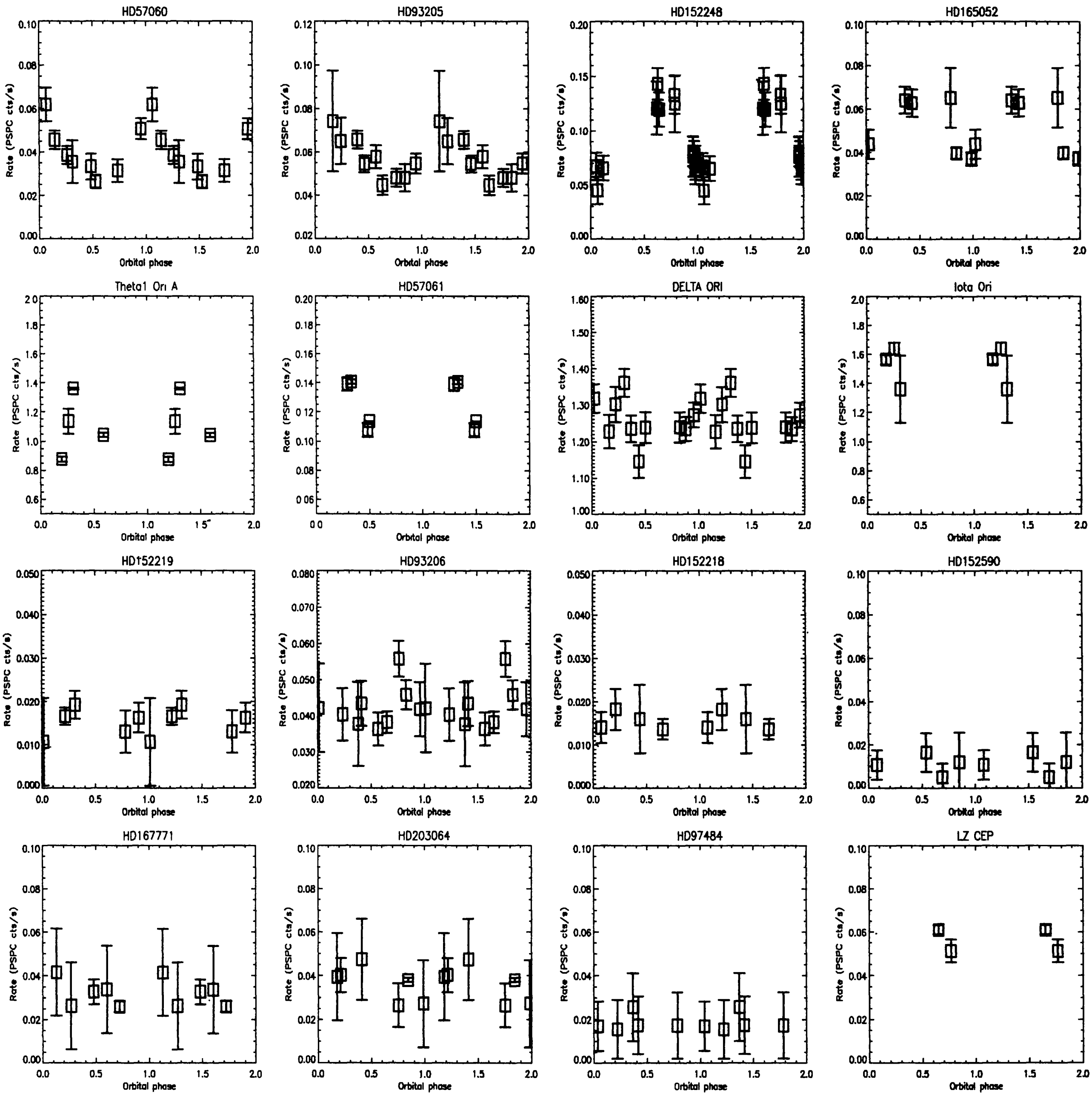

Fig. 1. X-ray "lightcurves" of O-type binary stars.

152248, for which I used the improved ephemeris of Mayer, Lorenz, & Drechsel 1992). I adjusted the phasing such that phase 0 corresponds to primary minimum or to the time when the less-massive star is in front for non-eclipsing systems. I binned the resulting lightcurves by orbital phase. Two cycles of the phase-binned lightcurves for 16 of the 18 star are shown in Fig. 1 (HD 206267 and V729 Cyg are not shown). Note that the lightcurve derived for UW CMa is nearly identical to the lightcurve previously reported by Berghöfer & Schmitt (1995a).

I found that 10/18 stars show significant X-ray variability, and in 4 cases (UW CMa, HD 93205, HD 152248 and HD 165052) the variability is clearly phase-locked. Variability in the other 6 X-ray variables is not clearly tied to orbital phase. The star δ Ori has a well-defined lightcurve that, while variable, does not seem to be tied to the binary orbit (Haberl & White 1993). However, the optical lightcurve for δ Ori is substantially contaminated by third light (Koch & Hrivnak 1981), and it may be that this contamination affects the X-ray lightcurve as well. The remaining 8 stars show no signs of significant variability in the archived data. This may be due to low counting rates which mask real variability, or poor phase coverage (especially in the long-period binaries like τ CMa and ι Ori).

Of the four phase-variable stars, HD 93205 (O3V + O8, $q = 0.4$) and UW CMa (O7Iab + O9.7Ib, $q = 1.2$, Bagnuolo, Jr., et al. 1994) are systems in which the wind from the primary is much stronger than the wind from the secondary. Both cases show an increase in X-ray emission near $\phi = 0$ when the weaker-wind star is in front, probably due to a decrease in X-ray absorption as the colliding wind emission is viewed through the less dense wind of the secondary. For the other 2 phase-variables, HD 152248 (O7f, $q = 0.9$) and HD 165052 (O6.5V, $q = 0.9$), the component stars possess winds of nearly equal strength. Here the wind collision region is nearly perpendicular to the line of centers of the binary, making X-ray absorption at 1st conjunction about the same as that at second conjunction. The emission maximum occurs at quadrature since the circumstellar absorbing column to the wind collision region is smaller at quadrature than at either conjunction.

Although not all stars in this sample showed phase-locked variability, the fraction of binary stars surveyed which showed any kind of variability is about 50%. This is about a factor of 2–3 higher than the fraction of O star variables derived from *ROSAT* All-Sky Survey observations (Berghöfer & Schmitt 1995b). This suggests that binarity influences the stability of the X-ray emitting structures in O stars winds.

4. X-RAY VARIABILITY IN WR + O BINARIES

In WR + O binaries the wind from the WR star is usually much stronger than the O star wind. This should lead to strong phase-dependent variations in the observed X-ray emission. Three systems seem especially promising candidates: WR 140, γ^2 Velorum, and V444 Cygni. WR 140 is known to undergo periodic radio and IR variations which have been ascribed to the interactions of the wind from the WC7 star with the wind from the O-type companion. *EXOSAT* (Taylor et al. 1981) observations indicated an extremely high X-ray luminosity (near 10^{34} ergs s^{-1}) which caused Pollock to suggest that some of the observed luminosity was produced by colliding winds. *ROSAT* observations of γ^2 Vel by Willis, Schild, & Stevens (1995) showed a phase-repeatable X-ray "flare" when the O9I star moved in front of the WC8 star. For V444 Cyg, Moffat et al. (1982) showed that the X-ray emission measured by the *EINSTEIN* Imaging Proportional Counter (IPC) was lower during a single observation when the WN5 star was in front of the O6 star.

New X-ray observations of these systems have recently been obtained, which allow us to examine in more detail the nature of the colliding wind X-ray emission.

4.1. WR 140

No complete X-ray lightcurve of WR 140 throughout its 8 year orbit yet exists. However, 4 recent observations have been obtained by the *ROSAT* PSPC (until the demise of the PSPC in July 1994). Two additional observations were obtained by the Solid State Imaging Spectrometer (SIS) on the *ASCA* observatory. These observations allow us to look in detail at the changes in the X-ray spectrum through periastron passage. I extracted X-ray spectra from the six WR 140 observations from the *ROSAT* and *ASCA* archives. I fit the extracted spectra with Raymond-Smith plasma models + cool absorption as components, using the fewest number of components necessary to achieve an adequate fit to the background-subtracted spectra.

In nearly all cases only one (emission + absorption) component was necessary to fit the observations. However, the PSPC observation nearest periastron passage required an additional component to fit the spectrum at $E \geq 1.5$ keV. The variation in observed flux, minimum absorbing column, and maximum observed temperature derived from the best fit models are shown in Fig. 2. Large changes in each parameter occur through periastron passage. These changes can be interpreted in terms of a colliding wind model. The observed column decreases abruptly at phase 0.96, when the line-of-sight passes through a conical region of low-density, solar abundance wind around the O star. This results in an increase in the observed flux since more low-energy photons reach the observer. Shortly thereafter, the observing column increases and the observed flux decreases. The observed flux variations are similar to the theoretical colliding-wind lightcurve calculated for WR 140 by Stevens, Blondin, & Pollock (1992, their Figure 21).

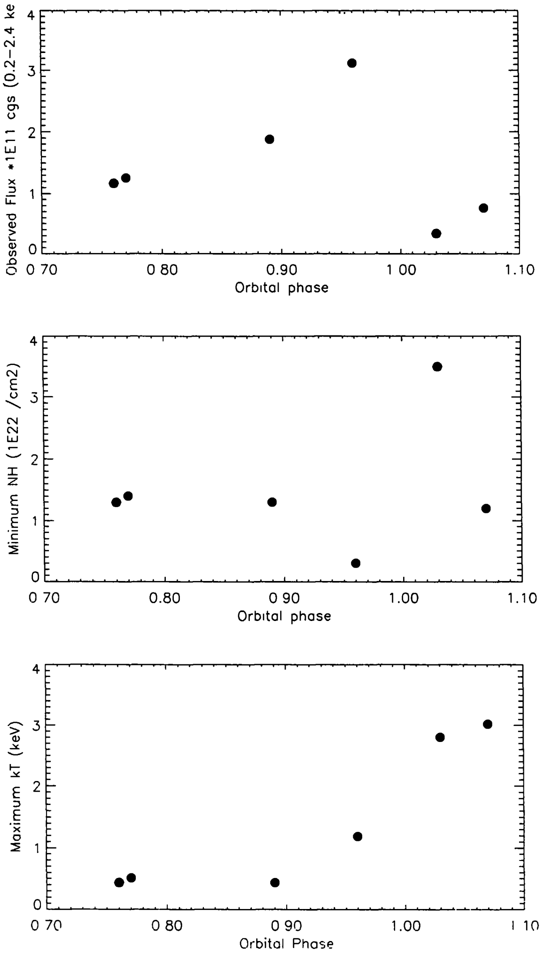

Fig. 2. WR 140: changes in f_x, N_H and kT through periastron passage.

4.2. γ^2 Velorum

In order to better understand the nature of the observed X-ray variations seen in the *ROSAT* observations of Willis, Schild, & Stevens (1995), Stevens et al. (1995) obtained *ASCA* spectra of γ^2 Vel at one phase prior to X-ray maximum and one phase during X-ray maximum. Stevens et al. showed that the observed spectra could be fit fairly well by colliding wind emission models which took into account both the emissivity of the wind collision region and the circumstellar wind absorption. The observed spectra, along with the best fit colliding wind models, are shown in Fig. 3. Stevens et al. used their X-ray spectral analysis to determine the mass-loss rate of the WR star, assuming a standard wind-velocity law. They derived a mass-loss rate from the WR star of $3 \times 10^{-5} M_{\odot}$ yr^{-1}, which is about a factor of three lower than the mass-loss rate derived from radio observations (Barlow, Roche, & Aitken 1988). This discrepancy may indicate that the radio mass-loss rate is overestimated, perhaps due to inhomogeneities in the wind, or that further refinements of the X-ray spectral models are needed.

4.3. V444 Cygni

Corcoran et al. (1996) obtained limited coverage of the X-ray lightcurve of V444 Cygni with *ROSAT*. Their lightcurve confirmed the X-ray variability seen in the *EINSTEIN* observations by Moffat et al. (1982). Fig. 4 shows the phase-binned *ROSAT* PSPC lightcurve, along with the *EINSTEIN* IPC lightcurve (which has been

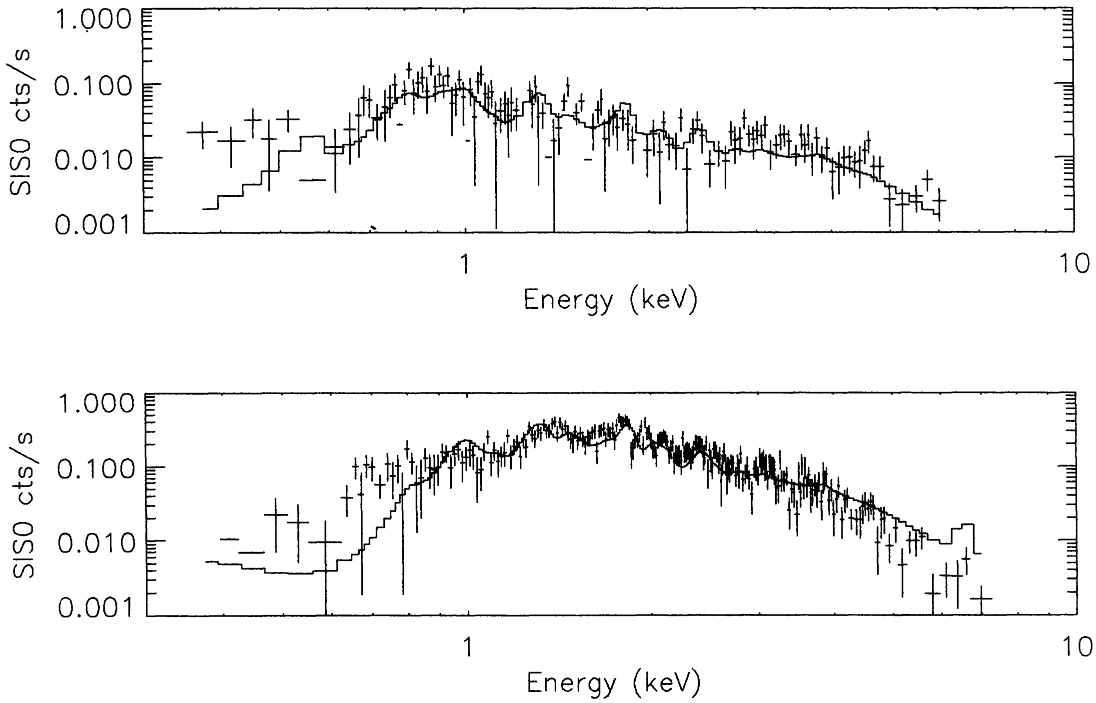

Fig. 3. *ASCA* SIS0 spectra of γ^2 Vel at $\phi = 0.4$ (pre-X-ray maximum, top) and $\phi = 0.5$ (in X-ray maximum, bottom) and colliding-wind model spectra (solid lines).

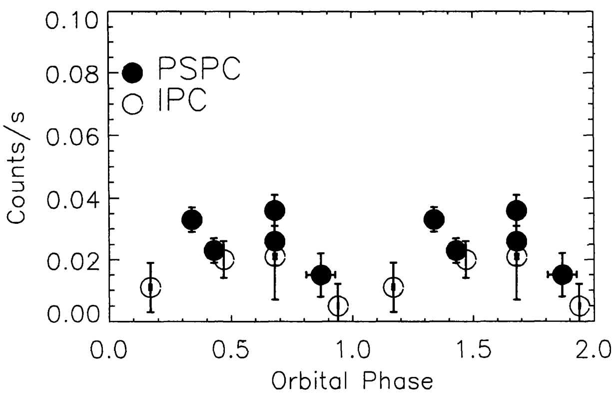

Fig. 4. IPC and PSPC lightcurves of V444 Cyg.

re-derived from the archived *EINSTEIN* data). Both the *ROSAT* and *EINSTEIN* datasets indicate a decrease in emission when the WN5 star is in front of the O6 star (at phase 0.0). This can be interpreted as an occultation of an X-ray emitting region by the wind from the WN5 star. Corcoran et al. showed that, if the *ROSAT* data are interpreted in terms of a colliding-wind model, the extent of the colliding wind region is more than 100 times the radius of the WN5 star. However, if some of the emission is produced in the wind of the O star by processes unrelated to the wind collision, then the size of the hot region produced by the colliding wind region could be much smaller. Corcoran et al. noted that the derived L_x/L_{bol} ratio for this system is only a factor of 1.5 or so larger than expected for a single O6 star. This means that the observed emission is substantially contaminated by X-rays from the O star. The colliding wind emission should make the largest contribution to the observed emission in a restricted phase interval near $\phi = 0.5$, when the O star is in front of the WR star. No such increase in emission is seen in the existing datasets, but phase coverage is poor.

5. CONCLUSION

I have re-examined the importance of colliding wind X-ray generation in early-type binaries. New *ROSAT* and *ASCA* observations show that colliding wind X-ray emission is an important process which occurs in some if not all of these systems. For the O+O binary systems, wind collisions seem to be revealed in the observed variability of the X-ray emission, and not by large overluminosities in the 0.1–2.5 keV energy range. It remains to be determined why some systems show predictable phase-locked variability, while others show sporadic variability and still others show no significant variability at all. On the other hand, the WR+O binary system WR 140 shows both a large X-ray overluminosity and phase-dependent X-ray variability which seems to be well described by the colliding wind picture. The X-ray lightcurve of the system is sampled only through a limited (though important) phase interval around periastron passage; monitoring the star's X-ray emission through the entirety of its orbit is sure to reveal new insights and refinements to current understanding. X-ray spectral variability is a new and important tool for understanding early-type binaries. Modeling the X-ray spectrum of the colliding wind emission gives a new handle on important wind and stellar parameters like mass-loss rate, as the analysis of the X-ray emission from γ^2 Vel shows, as well as letting us examine the details of important new physical processes like "radiative braking", which are best studied at X-ray energies. Clear identification of colliding wind emission is needed, though, and this can be difficult to obtain, as in the case of V444 Cyg. Although V444 Cyg is a laboratory to study wind interaction effects in the UV and optical, the X-ray data in hand indicate that the colliding wind emission from this system is intimately tangled up with emission produced by intrinsic instabilities in the O star wind.

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