TIME-DEPENDENT X-RAY OBSERVATIONS OF WOLF-RAYET BINARIES WITH O-TYPE AND WITH SUSPECTED COMPACT COMPANIONS

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ABSTRACT. Each of four WR binaries has been observed in the 0.1 -5 keV range on four consecutive days for a total of $\sim 10^4$ sec with the IPC on the Einstein Observatory. One of the stars is the well-known WN5 + 06 binary V444 Cyg; the other three have suspected compact companions; all have periods close to four days.

Neither HD 197406 (WN7) nor HD 96548 (WN8) was detected; hence L_x (0.5 - 3.0 keV) $\lesssim 10^{32}$ erg s^{-1}, which is on the low side, even for O-stars. EZ CMa (WN5) and V444 Cyg are moderately strong, variable X-ray sources with L_x (0.5 - 3.0 keV) $\simeq 10^{33}$ erg s^{-1}, kT $\simeq$ 0.5 keV and $N_H \simeq 10^{22}$ cm^{-2}. These values suggest that the X-ray flux arises in the outer part of the wind. The variable component may be produced by collision of two winds.

There is no evidence of harder X-rays coming from accretion onto a compact star. Nevertheless, the presence of a collapsar is not excluded at $h\nu \lesssim 5$ keV, where absorption in the WR wind would likely reduce the X-ray flux to a level which is masked by the flux coming from the hot stellar wind.

I. INTRODUCTION

The existence of Wolf-Rayet binaries with low-mass, probably compact companions (WR + c) is strongly suggested by optical observations. These relate to single-line systems with orbits of low mass-function, unusually high systemic velocity or separation from the galactic plane, and ejected ring nebulae, of about a dozen WR stars found so far (cf. Moffat 1982). Such stars will have evolved from a previous OB + c stage. Several OB + c systems are well-known X-ray emitters due to accretion of matter from the OB-star onto the compact star. In the case of a WR + c binary, the estimated minimum column density along the line of sight through the WR wind to the compact companion is typically $N_H \gtrsim 10^{24}$ cm^{-2} (Moffat and Seggewiss 1979), much greater than the interstellar values ($\lesssim 10^{21}$ cm^{-2}). Thus, if 1-10 keV X-rays are produced by

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accretion onto the supposed compact object at kT $\sim$ 8 keV, the softer ones ($\lesssim$ 5 keV) will be progressively absorbed at lower energies. Despite this limitation, we decided to monitor several WR + c candidates to look for phase-dependent X-ray fluxes due to accretion, with the Einstein Observatory: its IPC imaging mode was the most sensitive instrument available for detection of X-rays in the range 0.1 - 5 keV.

II. OBSERVATIONS

The most convincing, optically studied WR + c candidates known at the time of application were HD 50896 = EZ CMa, WN5 (Firmani et al. 1980; McLean 1980), HD 197406, WN7 (Moffat and Seggewiss, 1979, 1980; Bracher, 1979)* All appear to be single-line spectroscopic binaries with low mass-functions and high displacements from the galactic plane. In particular, HD 197406 is located Z $\sim$ 800 pc above the plane (Hidayat et al. 1981). As a test object, we also selected a well-known WR + OB (eclipsing) binary with a normal mass function and low Z: HD 193576 = V444 Cygni, WN5 + 06.

All four stars have similar periods, P $\simeq$ 4d, a fortuitous but useful coincidence. None was detected by Uhuru, implying I_x (2-6 keV) $\lesssim$ 2.10^{-11} erg cm^{-2} s^{-1} and, for d $\gtrsim$ 1.5 kpc, L_x < 5.10^{33} erg s^{-1}, compared to $L_x \simeq 10^{37}$ erg s^{-1} for the massive OB binary X-rays sources. The large difference could be due to the greater smothering effect in the denser wind of the WR-stars, if in fact the WR + c candidates do have compact companions.

All four stars were observed using the IPC mode for $\sim$ 2500 sec each on 4 consecutive days, except V444 Cygni for which there was an unfortunate gap of $\sim$ 40 days between the two-day pairs. This is a bare minimum to detect any phase-dependent X-ray flux.

III. RESULTS

Most noteworthy are the following:

(1) Clear detection of both WN5 stars, EZ CMa and V444 Cygni as moderately strong X-ray sources located at the centres of their respective search fields (see below).

(2) Neither of the WNL stars HD 96548 nor HD 197406 was detected. Adding the four days' data together, this implies L_x (0.5 - 3 keV) $\lesssim$ 10^{32} erg s^{-1}, somewhat low even for normal O-stars, which all appear to be moderately soft X-ray sources (Vaiana et al. 1981; Pallavicini et al. 1981). However, WR stars may show a much greater spread in L_x/L_{opt} than O-stars (Chlebowski & Seward 1981:Cassinelli et al. 1982). If accretion-type X-rays are produced in these two stars, they are not getting out, at least below $\sim$ 5 keV.

(3) Several serendipitous, off-centre sources were detected in each field, probably unrelated to the WR stars.

(4) The ring nebulae S 308 around HD 50896 and RCW 58 around HD 96548 were not seen in 0.1-5 keV X-rays during a total integration time of $\sim 10^4$ sec.

In Figure 1 we show the average X-ray spectra of the two detected WR sources. Fitting thermal spectra yields approximate values kT $\simeq$ 0.5 keV (T $\simeq 6.10^6$ K) and $N_H \simeq 10^{22}$ cm^{-2} for both stars. There is no indi-

* and HD 96548, WN8 (Moffat and Isserstedt 1980, A & A 91, 147).

cation below $h\nu \simeq 5$ keV of a hotter source suffering higher absorption. The total average luminosity is L_x (0.5-3.0 keV) $\simeq 10^{32-33}$ erg s^{-1}, as in the range for O-stars of the same bolometric luminosity (see above).

Figs. 2 and 3 indicate how the net count rates and softness ratios vary with phase (obtained for V444 Cygni from Kron and Gordon 1950 and Münch 1950, and for EZ CMa from Firmani et al. 1980, with more recent unpublished optical data). For either star there is a fairly clear trend: minimum X-ray flux occurs when the WR component is in front in its orbit; also near this phase, the spectrum tends to become harder. This implies in either case that, superimposed on a constant, soft component, we are observing an additional soft source on the companion side of the WR star, which is modulated in flux by phase-dependent absorption. This interpretation assumes an otherwise constant wind and is subject to further confirmation.

IV. CONCLUSIONS

Both EZ CMa and V444 Cygni show similar behaviour in X-ray flux; this is probably related to their binary nature. The presence of a compact companion in HD 50896 is not excluded at $h\nu \lesssim 5$ keV, where photoelectric absorption in the dense wind could reduce the accretion-induced X-ray flux to $\lesssim 10^{33}$ erg s^{-1}. This could be further masked by a $\sim$ constant component from the wind, similar to that seen in O-stars. Looking for modulation of harder X-rays may help, although the intrinsic X-ray luminosity will decrease rapidly towards higher energies for an expected thermal source.

The present observations can only give a crude indication of the X-ray processes occuring in these two systems. Possibly, we are seeing X-rays which are produced indirectly by the collision of two winds, one wind from the WN5 star, the other from the O6 star in V444 Cygni or the suspected compact companion in EZ CMa (Firmani et al. 1980 give optical evidence for such a wind). In either case, the WR wind is expected to dominate, ramming any compressed, shocked matter out beyond the WR star in the direction of, or even beyond, its companion. However, at the position of the collision, this matter can be expected to produce L_x (1-10 keV) $\simeq 10^{34-35}$ erg s^{-1}, neglecting absorption, in the case of V444 Cygni (Prilutskii and Usov 1976; Cherepashchuk 1976) and possibly similar in EZ CMa. Behind the shock, the temperature, T_x, should rise to $\sim 10^8$K, for $\dot{M} \sim 10^{-5}$ $M_\odot$ y^{-1} and $v_\infty \simeq 2000$ km s^{-1} for the WR wind. With $N_H \simeq 10^{24}$ cm^{-2}, L_x will be considerably reduced, but T_x should remain high. The fact that we do not observe a high T_x suggests that the X-rays may originate in expanding hot blobs produced by collision as noted above, but which are blown out mainly by the stronger WR wind. They subsequently cool and we observe X-rays from them mainly in the outer regions of the wind, where N_H has fallen to $\simeq 10^{22}$ cm^{-2}. More details must be worked out, perhaps along the line of a 2-component wind model (cf. Lucy and White 1980): For EZCMa and V444 Cygni, X-rays may come primarily from all outer regions of the general wind, but in excess beyond the companion side of the WR component.

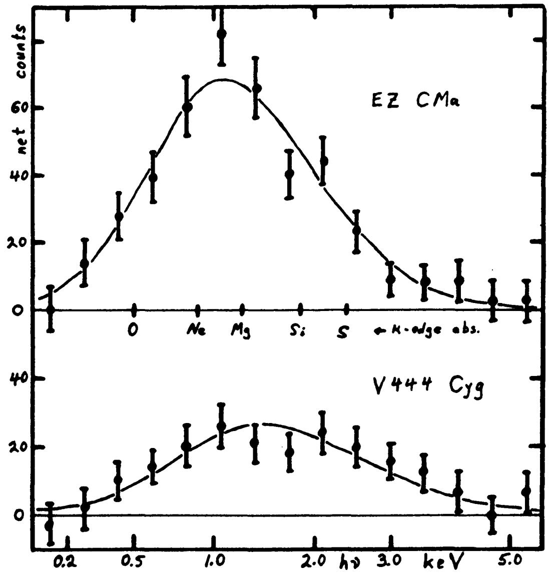

Figure 1: Einstein mean IPC X-ray spectra of EZ CMa and V444 Cygni. Net counts are shown with ± σ error-bars and thermal fits.

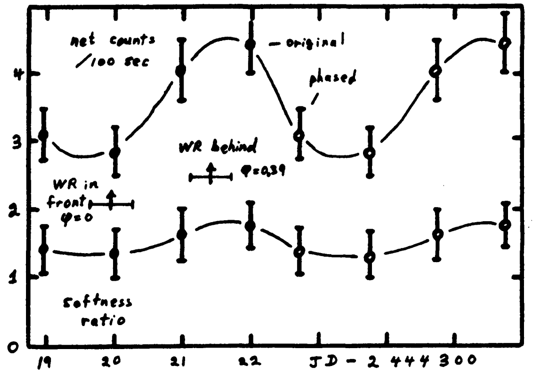

Figure 2: Net count rate (0.3-3.5 keV) and softness ratio ((0.3-1.4)/(1.4-3.5) keV) versus time for EZ CMa

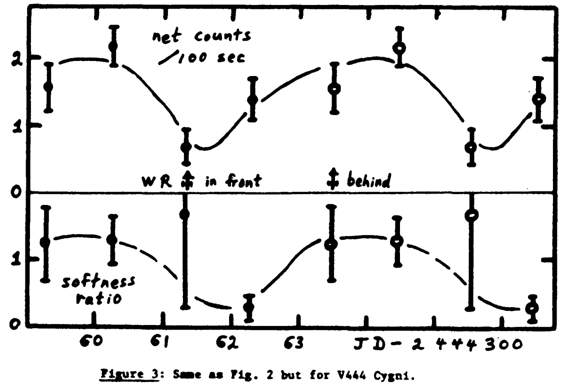

Figure 3: Same as Fig. 2 but for V444 Cygni.

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DISCUSSION FOLLOWING MOFFAT et al.

Kwitter: Can you use your non-detection of the rings around HD 50896 and HD 96548 to obtain upper limits to the X-ray flux, and then to see if these can be used to constrain or distinguish between the specific wind-blown bubble models by Weaver et al. (1977) and by Steigman et al. (1975)?

Moffat: This is a good idea and has not been done yet. However I suspect that contamination by faint, unresolved stellar sources in the Einstein field (into which the nebulae just nicely fit) may cause significant confusion.

Perry: I'm worried about the separations in the two systems you didn't detect, HD 197406 and HD 96548. Are these really deep enough in the wind to expect column densities of 10^{24} cm^{-2}?

Moffat: The a sin i's are all about 30 $R_{\odot}$ in the four stars observed. The calculation of $N_H \simeq 10^{24}$ cm^{-2} was already made by Moffat and Seggewiss (1979, Astron.Astrophys. 77, 128).

Massey: If you're seeing the collision of two winds in V444 Cyg, why do you only see one dip in the X-rays (when the WR star is in front) rather than two? What possible geometry could give you this? Couldn't you just be seeing X-rays just from the O star?

Moffat: We assumed that the WR wind dominates over the O star (or compact star) wind and pushes the hot blobs out beyond the O star in a direction ~ opposed to the WR star, before they become observable in X-rays.

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