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## SUMMARY

Preliminary results of three X-ray surveys are presented. Out of a sample of 20 stars, X-rays were detected from four Wolf-Rayet stars and two O8f<sup>+</sup> stars. The detected stars have about the same mean value as O stars for the X-ray to total luminosity ratio,  $L_x/L = 10^{-7}$ , but exhibit a much larger variation about the mean. The spectral energy distributions are also found to be like that of O stars in that they do not exhibit large attenuation of X-rays softer than 1 keV. This indicates that for both the O stars and WR stars much of the X-ray emission is coming from hot wisps or shocks in the outer regions of the winds and not from a thin source at the base of the wind. The general spectral shape and flux level place severe restrictions on models that attribute the lack of hydrogen emission lines to extremely high temperatures of the gas in the wind.

## INTRODUCTION

Because this is the only paper on an X-ray survey of Wolf-Rayet stars scheduled for this conference, we have received permission from Richard White and Knox Long of Columbia University and Frederick Seward and Tomasz Chlebowski of the Harvard-Smithsonian Center for Astrophysics to discuss their preliminary findings in addition to our own observations. Consequently, we have the following results to discuss:

1) Our own observations were of eleven stars of the following two categories a) six WN7 and transition Of-WR stars including two O8f<sup>+</sup> stars; b) five high excitation WR stars which show O VI emission lines in their optical spectra (at  $\lambda 3811$ ,  $\lambda 3830$ ).

2) White and Long have observed seven WR stars including several of the nearest and brightest.

3) Seward and Chlebowski observed three WN7 stars in the Carina OB I association.

Table 1

## X-ray Observations of Wolf-Rayet Stars

Star	Spec Type	Distance <sup>a</sup> (kpc)	IPC Count Rate <sup>b</sup> (cts s <sup>-1</sup> )	log L <sub>x</sub>	L <sub>x</sub> /L (units:10 <sup>-7</sup> )
1) Survey of Sanders, Cassinelli and van der Hucht					
HD 104994	WN3pec(OVI)	8.71	<0.009	<33.2	
HD 191765	WN6	1.63	<0.014	<31.9	<0.7
HD 151932	WN7	1.76	<0.009	<31.8	<0.4
HD 86161	WN8	4.08	<0.018	<32.9	
LSS 4368	WC4pec(OVI)	5.58	<0.007	<32.7	
HD 17638	WC6 (OVI)	4.56	<0.005	<32.4	
HD 119078	WN7 (OVI)	8.56	<0.005	<32.9	
HD 192103	WC8 (OVI)	2.00	<0.005	<31.7	<1.1
HD 151804	O8f <sup>+</sup>	1.80	0.025	32.3	0.5
HD 152248	O8f <sup>+</sup>	1.50	0.037	32.3	0.4
2) Survey of White and Long <sup>d</sup>					
HD 50896	WN5	2.03	0.075	32.9	17.
γ <sup>2</sup> Vel	WC8+O9I	0.48	0.100	31.7	1.1
θ Mus	WC6+O9.5I	2.07	0.065	32.8	11.
3) Survey of Seward and Chlebowski					
HD 92740	WN7	2.28	0.007	32.1	0.7
HD 93131	WN7	2.77	<0.005	<32.0	<0.6
HD 93162	WN7	3.10	0.140	33.5	20.

a Distances from Hidayet et al. (1981)

b Upper limits are 3σ

c L from Barlow, Smith and Willis (1981) or Cassinelli et al. (1981)

d Not detected RGW58, CV Ser, HD 165763, HD 192641

The three surveys are summarized in Table 1. The observations have resulted in seven strong detections (intensity greater than 5 sigma): five Wolf-Rayet stars (HD 50896, γ<sup>2</sup> Vel, θ Mus, HD 93162, HD 92740) and two O8f<sup>+</sup> stars (HD 152248, HD 151804).

## OBSERVATIONS

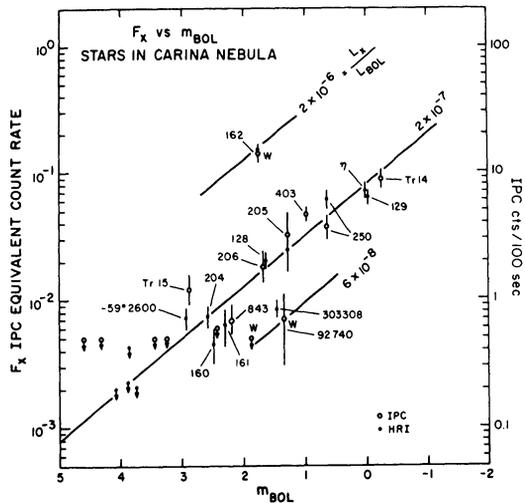
All of the observations were made with the instruments on the Einstein Observatory (Giacconi et al. 1979). The count rates and fluxes listed in Table 1 are from observations made with the Imaging Proportional Counter (IPC), which is sensitive to X-rays having energies between 0.2 and 4 keV and which has a spatial resolution of approximately 1 arcmin. The IPC also yields some spectral information ( $\Delta E/E \sim 1$  at

1.5 keV). Seward and Chlebowski have also observed the strong source HD 93162 with the High Resolution Imager (HRI). This instrument has a spatial resolution of approximately 3 arcsecs, but yields no spectral information.

It is useful to discuss the small number of WR detections in comparison with the more numerous O star detections (Seward *et al.* 1979; Harnden *et al.* 1979; Long and White 1980; Cassinelli *et al.* 1981; Seward and Chlebowski 1981; Pallavicini *et al.* 1981).

1.) The  $L_x/L$  ratio. The X-ray luminosity of early-type stars is proportional to the total luminosity. Long and White (1980), Seward and Chlebowski (1981), Pallavicini *et al.* (1981), and Cassinelli *et al.* (1981) have found that  $L_x/L$  is approximately  $10^{-7}$ , to within a factor of 2, over the spectral range O3 to B5. Wolf-Rayet stars appear to have an  $L_x/L$  of about  $10^{-7}$  but there is a larger spread in this ratio than is the case for O stars and OB supergiants. This is shown most directly in Figure 1 from Seward and Chlebowski's observations of stars near  $\eta$  Car.

Fig. 1 - Observed X-ray flux from early-type stars in the Carina Nebula as a function of apparent bolometric magnitude. The solid lines are loci of constant  $L_x/L$ . All stars are O stars except for three indicated WR stars and for  $\eta$  Car. (This is Fig. 6 of Seward and Chlebowski, *Ap.J.*, submitted.)



The WN7 star HD 93162 has an  $L_x/L = 2.2 \times 10^{-6}$ . This is a factor of 30 higher than the two other WN7 stars in the nebula. The O stars are seen to have a much smaller spread in  $L_x/L$  about the mean of  $2 \times 10^{-7}$ .

There is no obvious reason why HD 93162 should have such a large relative X-ray luminosity. Spectroscopic studies indicate that the star is probably a single (Moffat and Seggewiss 1978), and therefore it is unlikely that a compact companion is the source of X-rays. The

HRI observation of HD 93162 by Seward and Chlebowski is consistent with a point-like source and yields a diameter  $< 2 \times 10^{17}$  cm. This is much smaller than a wind-produced bubble that might be expected around a star with a strong wind. As is the case with O stars, we can conclude that the X-ray source is intrinsic to the star.

Seward and Chlebowski point out that the star shows weak WR emission features in the optical (Moffat and Segewiss 1979). They suggest that since WN7 stars are thought to be transition Of to WR stars that perhaps there is a maximum in the X-ray flux associated with the transition from an O3f like 93129 to a strong line WN7 like 93131. However the correlation of strong X-ray flux with weak optical emission lines might just mean that the X-rays are less attenuated by a smaller amount of wind material above the X-ray source region.

2.) The Spectral Energy Distribution. All three groups of observers find that, for those WR stars with count rates large enough to yield meaningful pulse height information, the spectra are like those of the O stars and OB supergiants shown and analyzed by Long and White (1980) and Cassinelli et al. (1981). The pulse height distributions do not show the strong depletion of X-rays less energetic than 1 keV that would be expected from a model with a slab thermal source at the base of a stellar wind (Cassinelli and Olson 1979).

Seward and Chlebowski (1981) indicate that the IPC spectra of both the O stars and the WR star HD 93162 in the Carina nebula can be fit with a thermal source model, characterized by a source temperature,  $T \sim 10^6$  K, and an attenuating column density,  $N_H$ , of a few times  $10^{21}$  cm<sup>-2</sup>.

White and Long inform us that the IPC spectra of HD 50896 and  $\Theta$  Mus are similar to that of  $\zeta$  Pup. Their thermal source fits to the data give  $T \sim 10^{6.6 \pm 0.2}$  and  $N_H \sim 10^{21.4-22.4}$  cm<sup>-2</sup>. As they found for  $\zeta$  Pup (Long and White 1980), they concluded that the X-ray source is not confined to a slab at the base of the wind, but is located out in the wind, perhaps in shocks as discussed by Lucy and White (1980). Their spectrum of  $\gamma^2$  Vel is noticeably harder,  $T > 10^7$  K, and they are considering the possibility that some of the hard X-rays are produced by colliding winds in the binary system.

3.) Constraints on Wind Temperatures and H/He Abundance Ratios. Smith (1973) argued that hydrogen is underabundant in many WR stars including the WN5 star HD 50896, for which there is now an X-ray detection. Smith showed that the hydrogen Balmer recombination emission lines contribute negligibly to the emission seen in the alternate lines of the He II Pickering series. She concluded that hydrogen is essentially absent in HD 50896.

Sahade (1980) has suggested an alternative explanation; one that we will call here the "heated wind" model. In this model the hydrogen has a normal abundance but the recombination lines are weak because

of high temperatures in the wind. Consider, for example, the H $\beta$  line in HD 50896. (We choose H $\beta$  because the atomic data is conveniently tabulated by Osterbrock (1974) and the strengths of higher Balmer lines are given relative to H $\beta$ .) The line contributes an equivalent width of no more than 2 Å to the  $\lambda$ 4860 emission of the  $n = 8$  to 4 transition of He II. Let  $EM_w$  be the emission measure ( $n_e^2 V$ ) of the warm wind and let  $T$  be the wind temperature. Then the equivalent width is

$$EW_{\beta} = L_{H\beta}^c / L_{\lambda}^c \approx (EM_w 5 \times 10^{-22} / T^{0.9}) / L_{\lambda}^c < 2 \text{ \AA} \quad (1)$$

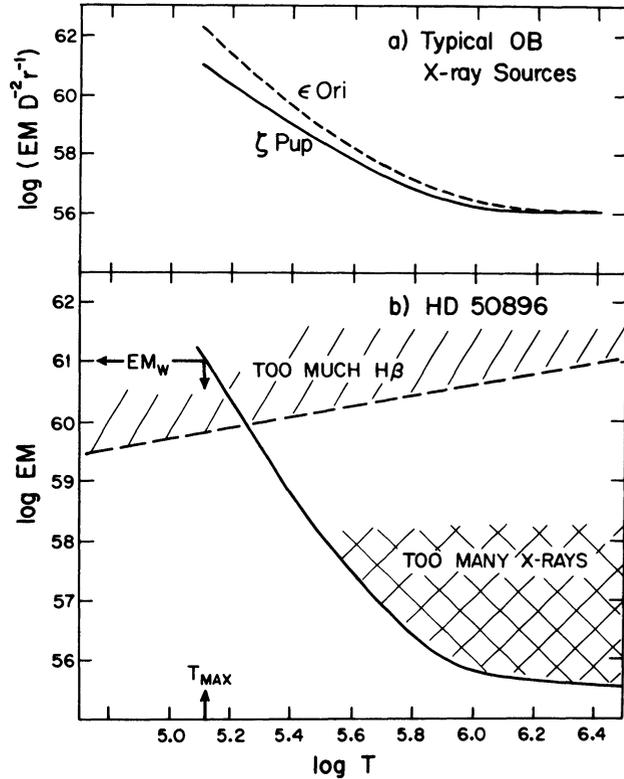
where  $L_{\lambda}^c$  ( $\approx 4 \times 10^{33}$  ergs  $\text{cm}^{-2}$   $\text{s}^{-1}$   $\text{\AA}^{-1}$ ) is the continuum luminosity at  $\sim \lambda$ 4860. The essential point of the heated wind model is that as  $T$  increases, the Balmer line equivalent widths decrease. For WR stars the mass loss rates are very large ( $\sim 2 \times 10^{-5} M_{\odot} \text{yr}^{-1}$ ) so the wind emission measures are also very large. Using the stellar data for HD 50896 of Rimpl (1980), we estimate from equation (19) of Cassinelli and Olson (1979) that the emission measure of the heated wind is  $EM_w \approx 10^{61} \text{cm}^{-3}$ . From equation (1) we can then derive that the wind temperature must be  $\geq 10^{6.4}$  K. At these temperatures and this  $EM_w$ , a heated wind will emit a very large flux of X-rays.

To quantify the X-ray flux, we have used the data of Long and White (1980) for  $\zeta$  Pup and of Cassinelli *et al.* (1981) for  $\epsilon$  Ori (B0Ia) to derive, as a function of assumed source temperature, the emission measure required to produce one IPC count per second by a star at 1 kpc. The results shown in Figure 2a are best fits to the pulse height distributions of the two stars. Thus a temperature of  $10^{6.4}$  K and  $EM_w = 10^{61} \text{cm}^{-3}$  would yield an IPC count rate for HD 50896 of  $2 \times 10^4 \text{s}^{-1}$  - far greater than the observed  $0.075 \text{s}^{-1}$ . Conversely, we may use  $EM_w$  and the observed count rate to estimate an upper limit to the temperature of a heated wind. From Figure 2a, if the pulse height distribution of HD 50896 resembles that of  $\epsilon$  Ori, the temperature is  $T < 2 \times 10^5$  K. This temperature is far below what is needed for the heated wind model to explain the low H/He emission ratio. Figure 2b summarizes the constraints discussed here on HD 50896.

Figure 2b indicates that HD 50896 probably does not have a heated wind and therefore the low H/He emission ratio is due to low hydrogen abundance. We see that X-ray observations of Wolf-Rayet stars provide useful constraints on this and related models.

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Fig. 2 - (a) Shows the dependence on source temperature of the source emission measure required to produce an IPC count rate of  $r = 1 \text{ sec}^{-1}$  by a star at a distance of  $D = 1 \text{ kpc}$ . Results are shown for two sources that have "typical" early-type star IPC spectra. (b) The average of the curves above was used to find a maximum heated wind emission measure as a function of wind temperature for the WN5 star HD 50896. If the star has a mass loss rate of  $2 \times 10^{-5} M_{\odot} \text{ yr}^{-1}$  the wind emission measure is  $EM_w = 10^{61} \text{ cm}^{-3}$ . This requires that the wind temperature be less than  $2 \times 10^5 \text{ K}$ . The emission measure required to produce an H $\beta$  line with an equivalent width of 2  $\text{\AA}$  is also shown.



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DISCUSSION FOLLOWING SANDERS et al.

Panagia: Among the X-ray detected WR stars how many are single and how many are binaries? Considering this aspect is important in order to establish the true level of the X-ray emission of WR stars separately from that of possible O-type companions.

Cassinelli: In the White and Long survey,  $\theta$  Mus and  $\gamma^2$  Vel are binaries, and HD 50896 may have a neutron star companion. In Seward's sample of stars in the  $\eta$  Carinae regions HD 93162 and HD 92740 are single. So maybe just 2 out of 5 are single stars.

Niemela: I would like to make a comment on HD 93162. This star has a close optical companion which is included in the published X-ray image, and the companion is an early O-type star. Therefore, the X-ray flux may be a combination from both stars.

Conti: One must be careful about duplicity in these WR stars; e.g.  $\gamma$  Vel detection is attributed to a colliding wind, merely consistent with the binary nature.  $\theta$  Mus, with similar type(s), does not show this, perhaps suggesting the supergiant component is not near the WR star. Is the X-ray flux of HD 50896 quantitatively consistent with the putative neutron star companion?

Cassinelli: The neutron star should be very close to the surface of HD 50896, and therefore the X-ray associated with it would be heavily attenuated by the overlying wind material, and only hard X-rays would get out. The IPC spectrum is not depleted in soft X-rays and looks like a typical O star X-ray spectrum. Therefore the observed X-rays are produced in the outer parts of the wind in hot shock wisps.