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X-RAY OBSERVATIONS OF WOLF-RAYET STARS

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ABSTRACT

X-ray observations have been made of a very luminous O8f star, four late WN stars, and eight O VI Wolf-Rayet stars. The X-ray pulse height distributions of the O8f star is analyzed to obtain information on source temperature, emission measure and location relative to the stellar wind. Only upper limits are obtained for the X-rays from the Wolf-Rayet stars, but for the late WN stars the upper limits are well below the maximum L_x/L_{bol} detected in earlier surveys. For the O VI stars, the limits, used in conjunction with models for the production of the optical O VI lines, supply information about the excitation conditions in the winds.

Subject headings: stars: Of-type — stars: winds — stars: Wolf-Rayet — X-rays: sources

I. INTRODUCTION

Surveys with the *Einstein Observatory* have concluded that all O stars and early OB supergiants are X-ray sources with X-ray luminosities of order 10^{32} ergs s^{-1} (Harnden *et al.* 1979; Seward *et al.* 1979; Long and White 1980; Cassinelli *et al.* 1981). The X-ray luminosity of these stars is proportional to the stellar luminosity ($L_x = 10^{-7}\ L_{bol}$) and the characteristic temperature of the X-ray source is $10^{6.5 \pm 0.2}$ K. The energy distribution of the Of and OB supergiant X-ray emission indicates that the X-rays are more likely emitted by sources embedded within the wind rather than exclusively by a corona at the base of the wind (Long and White 1980; Cassinelli *et al.* 1981; Cassinelli and Swank 1983).

There is an indication that Wolf-Rayet stars behave differently from Of stars in regard to their X-ray emission. In their survey of the η Carinae region, Seward and Chlebowski (1982) found that Of and O stars have L_x/L_{bol} near 2×10^{-7} with not much scatter about this value. The two detected Wolf-Rayet stars in their sample indicate a larger range in L_x/L_{bol}, from 6×10^{-8} to 2×10^{-6}. This difference from the O stars could be caused by different amounts of extinction of the X-rays in the winds, different source mechanisms, or different locations of the sources relative to the winds.

In this paper, we consider direct X-ray observations and indirect evidence for X-ray emission from several classes of Wolf-Rayet stars and attempt to deduce the location of the X-ray–emitting sources in some of the objects.

Three classes of stellar objects were included in our *Einstein* surveys: transition Of stars, late WN stars, O VI Wolf-Rayet stars.

a) Transition Of Stars

These are massive stars which have optical emission lines (Walborn 1982). In the scenario of Conti (1976) these stars are evolving toward the WN7 stage. The scenario, which has been described quantitatively by Noels and Gabriel (1981), produces WR stars by pure mass loss during main-sequence evolution. Maeder (1982) and Chiosi (1982) have recently shown that this direct transition occurs only for very massive stars ($M > 60\ M_\odot$). Maeder (1982) argues that most Wolf-Rayet stars are produced not by mass loss alone but by internal mixing caused by convective overshoot and turbulent diffusion. Mixing can be more important than mass loss in bringing nucleosynthesis products to the stellar surface, and mixing may imply that mechanical energy release is occurring in Wolf-Rayet and related stars. The supergiant HD 151804 (O8 If) is an excellent example of a bright, massive ($M \gtrsim 60\ M_\odot$) star (Conti and Burnichon 1975) that is likely to be in the transition toward the WN stage via the Conti scenario.

b) Late WN Stars

These are among the brightest Wolf-Rayet stars, and according to Maeder (1983) they may be formed soon after the Of–OB supergiant stages in very massive stars. Several WN5–WN7 stars were detected in the surveys of Seward and Chlebowski (1982) and White and Long (1983), as summarized in the review of Sanders, Cassinelli, and van der Hucht (1982).

c) O VI *Wolf-Rayet Stars*

Emission of O VI $\lambda\lambda$3811, 3834 defines membership in this class. The stars can be divided into two groups (van der Hucht *et al.* 1981): those in which the O VI emission lines are stronger than the C III, C IV emission lines, and those in which the opposite is true. The former are classified as WO stars by Barlow and Hummer (1982), who suggest that their spectra reflect an actual enhancement of oxygen, relative to "normal" WC stars. Thus the WO stars would represent the next evolutionary phase after the WC stars, being either at the end of core helium-burning or already in the core carbon-burning stage. Of our selection of O VI stars, only LSS 4368 is of the WO type. The O VI stars were chosen for observation because the O VI λ1040 doublet is known to be a useful diagnostic of X-ray emission in hot stars and, in fact, was used to estimate the X-ray flux of O stars before the launch of the *Einstein* satellite (Cassinelli, Castor, and Lamers 1978; Cassinelli and Olson 1979). Superionization stages such as O VI can result from the Auger effect following the absorption of X-rays by ions in the wind. Given the presence of superionized stages, one can determine indirectly the X-ray luminosity from line strengths (Odegard and Cassinelli 1982).

A description of the X-ray observations is presented in § II. Discussion of the observations, including the indirect constraints on the location of X-ray emission in O VI stars, is presented in § III. Concluding remarks are in § IV.

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TABLE 1

PARAMETERS OF OBSERVED STARS

W-R No.[a]	Name	Spectral Type[a]	Distance (kpc)	log N(H I + H_2) (cm^{-2})	O VI EW (Å)
		Transition Of–WN Star			
...	HD 151804	O8 If	1.8	21.19	...
		WN6–WN8 Stars			
16	HD 86161	WN8 (SB1)	4.1	21.61	...
22	HD 92740	WN7 + abs (SB1)	2.3	21.29	...
78	HD 151932	WN7	1.8	21.51	...
134	HD 191765	WN6 (SB1)	1.6	21.55	...
		O VI Stars			
5	HD 17638	WC6	4.6	21.65	1
17	HD 88500	WC5	8.0	21.28	1
30	HD 94305	WC6 + O6–O8 V	8.0	21.54	1
46	HD 104994	WN3pec	8.7	21.17	1
57	HD 119078	WC7	8.6	20.62	1
102	LSS 4368	WC4pec/WO	5.6	21.67	500
135	HD 192103	WC8	2.0	21.49	3
154	HD 213049	WC6	7.3	21.57	1

[a] Catalog numbers and W-R spectral types are from van der Hucht *et al.* 1981.

II. X-RAY OBSERVATIONS

Thirteen stars were observed for this project using the imaging proportional counter (IPC), the most sensitive detector on the *Einstein* satellite. The IPC could provide arcmin spatial resolution and pulse-height spectral information at energies from 0.1 to 4 keV with energy resolution $E/\Delta E \sim 1$ at 1.5 keV (Giacconi *et al.* 1979). The observations were made from 1979 March to 1981 February with exposure times ranging from 300 to 8400 s.

The parameters for the observed stars are listed in Table 1. The X-ray emission from HD 151804, the transition Of–WN star, has been discussed briefly by Cassinelli *et al.* (1981), and references for the stellar parameters are given in Abbott (1978). The spectral types and distances to the Wolf-Rayet stars are from Hidayat, Supelli, and van der Hucht (1982). The interstellar hydrogen column density, N_H, is calculated from the relation of N_H to E_{B-V} (Bohlin, Savage, and Drake 1978). The extinction, E_{B-V}, is calculated from E_{b-v} using the average galactic extinction law (Savage and Mathis 1979) to correct for the differences in the bandpasses.

Table 2 contains a summary of the X-ray observations. Column (1) gives the name of the star, and column (2) gives the effective exposure time. The source counts for most stars were determined from a 2′ circle centered on the stellar position, and an annulus of inner radius 2′ and outer radius 6′ was used to determine the background. For HD 151804 a 5′ source circle and a 5′–8′ background annulus were used. Column (3) gives the net (background-subtracted) count rate over the approx-

TABLE 2

X-RAY DATA FOR OBSERVED STARS

Name (1)	Effective Exposure Time (s) (2)	Net Count Rate (counts s^{-1}) (3)	F_x (10^{-13} ergs cm^{-2} s^{-1}) (4)	L_x^0 (10^{32} ergs s^{-1}) (5)	L_x (10^{32} ergs s^{-1}) (6)	log EM (cm^{-3}) (7)
			Transition Of–WN Star			
HD 151804	9698	0.022 ± 0.003	4.4 ± 0.6	1.7 ± 0.3	2.7 ± 0.4	55.0
			WN6–WN8 Stars			
HD 86161	1775	<0.011	<2.2	<4.4	<20	<55.8
HD 92740	594	<0.023	<4.6	<2.9	<7.4	<55.4
HD 151932	1843	<0.008	<1.6	<0.62	<2.2	<54.9
HD 191765	1054	<0.011	<2.2	<0.67	<2.6	<54.9
			O VI Stars			
HD 17638	5487	<0.0036	<0.72	<1.8	<8.8	<55.4
HD 88500	5567	<0.0047	<0.94	<7.2	<18	<55.8
HD 94305	345	<0.027	<5.4	<41	<160	<56.7
HD 104994	5086	<0.0047	<0.94	<8.5	<19	<55.8
HD 119078	6324	<0.0039	<0.78	<6.9	<10	<55.5
LSS 4368	5690	<0.0044	<0.88	<3.3	<17	<55.7
HD 192103	8356	<0.0035	<0.70	<0.34	<1.2	<54.6
HD 213049	3880	<0.0047	<0.94	<6.0	<24	<55.9

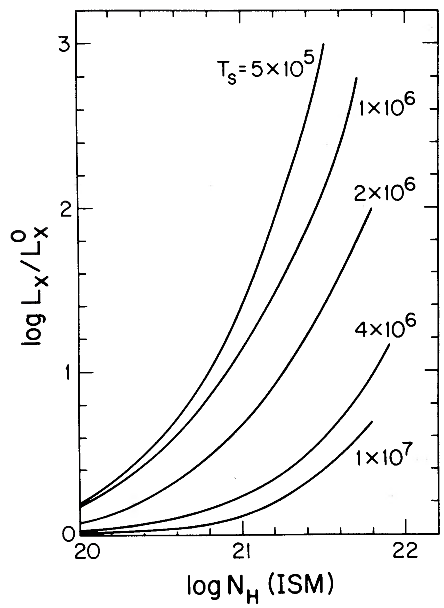

FIG. 1.—Shows the logarithm of the correction factor to convert the observed X-ray luminosity, L_x^0, to the X-ray luminosity leaving the outer boundary of the star plus wind, L_x, plotted against the hydrogen interstellar column density, N_H (cm^{-2}) as a function of source temperature, T_s.

imate energy interval 0.2–2 keV. Indicated uncertainties, based on counting statistics only, for the detected star are 1 σ. The 3 σ upper limits are given for the 12 stars not detected. The net count rate for HD 151804 is $\sim$0.01 counts s^{-1} higher than reported by Cassinelli *et al.* (1981).

The fluxes at Earth (col. [4]) are determined from the observed count rate or the 3 σ upper limit using the approximate sensitivity of 2×10^{-11} ergs s^{-1} cm^{-2} per IPC count (Vaiana *et al.* 1981; Cassinelli *et al.* 1981). The fluxes were converted to observed X-ray luminosities (col. [5]), L_x^0, using the distances to the stars from Table 1. L_x^0 is related to the X-ray luminosity leaving the outermost portions of the star's wind, L_x (col. [6]), by correcting for the absorption of interstellar gas. Figure 1 displays in graphical form the correction factors for interstellar X-ray absorption. The interstellar optical depth is calculated using the interstellar cross section per hydrogen nucleus of Brown and Gould (1970). On the basis of our experience with O stars, we assume for the purpose of calculating the absorption that the emergent flux from the star has an energy distribution proportional to the emissivity, $\Lambda(E)$, as given by Raymond and Smith (1977, 1979) for a hot plasma with a temperature of $T_s = 5 \times 10^6$ K. With this assumption, the computed emission measure (col. [7]) for the source is $\mathrm{EM} = L_x/\int\Lambda(E)dE = 3.2 \times 10^{22}\, L_x$.

The computed value of EM is a lower limit for the star actually detected, because there can be significant attenuation by wind material between the source and the observer that is not included in the interstellar absorption correction.

Figure 2 shows the X-ray luminosity for HD 151804 and the Wolf-Rayet stars plotted against total luminosity. The O star data are taken from Seward and Chlebowski (1982) and are corrected for interstellar absorption as discussed earlier. The three Wolf-Rayet stars in their survey, HD 93162, HD 92740, and HD 93131, are also shown. Our data are shown as squares for late-type Wolf-Rayet stars, as a diamond for HD 151804, and as open circles for the O VI Wolf-Rayet stars.

A best-fit line through the O star data is $L_x = 1.4 \times 10^{-7}\, L$, and is shown on the figure. This constant of proportionality differs slightly from that in Seward and Chlebowski (1982) because we have chosen to adjust all of the data, both theirs and ours, by the interstellar correction factors discussed above.

III. DISCUSSION

a) HD 151804 (O8 If)

The star HD 151804 has a sufficiently large count rate to permit us to carry out a simple spectral analysis. As in Cassinelli *et al.* (1981), we assume that there is a single region of hot gas at temperature T_s embedded in a wind under a column density of gas N_H(wind). The hot gas is assumed to emit an optically thin emission spectrum as calculated by Raymond and Smith (1977, 1979). Since there is little difference between stellar wind opacity and interstellar matter opacity at energies higher than 0.4 keV, we assume for simplicity that the material absorbs with the opacity per hydrogen nucleus given by Brown and Gould (1970). The spectrum incident on the detector is determined by T_s, by the emission measure of the source region, EM_s, and by the total column density of attenuating material, $N_H = N_H(\mathrm{wind}) + N_H(\mathrm{ISM})$. The resultant spectrum from a given set of these three parameters is folded through the IPC instrumental response and compared with the observed pulse-height spectrum via the chi-square test.

The 90% confidence region for HD 151804 is shown in Figure 3. The logarithm of the source emission measure that is consistent with a given T_s and total column density N_H is indicated by contours within the 90% confidence region. A wide range of models is consistent with the data. At one extreme, a model with the minimum emission measure as given in Table 2 with a source temperature of 5×10^6 K and a minimal column density $N_H = N_H$(ISM) is consistent with the data. Models in which the source is much deeper in the wind are also allowed, and these, of course, would have larger emission measures. Waldron (1983) in his base coronal models for OB stars typi-

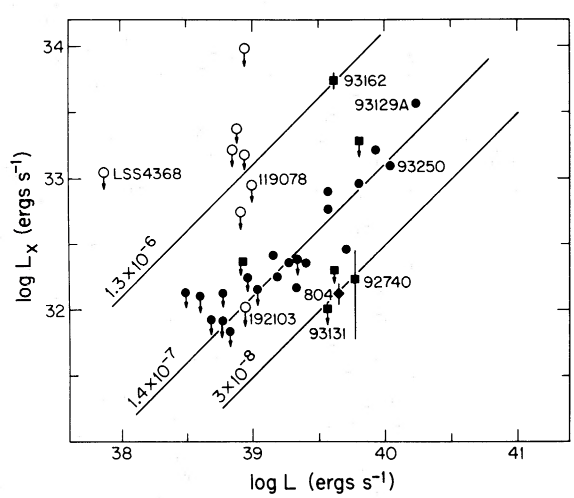

FIG. 2.—The stellar X-ray luminosity, corrected for interstellar absorption, plotted against the total luminosity. Solid circular dots refer to O stars in the Seward and Chlebowski (1982) survey. Solid squares represent late WN stars; the diamond corresponds to the extreme Of star HD 151804; and open circles represent the O VI Wolf-Rayet stars; LSS 4368 is a WO star. Three slopes of the (L_x, L)-relation are also shown, representing the extremes for detected Wolf-Rayet and O stars. The symbols with downward-directed arrows correspond to 3 σ upper limits.

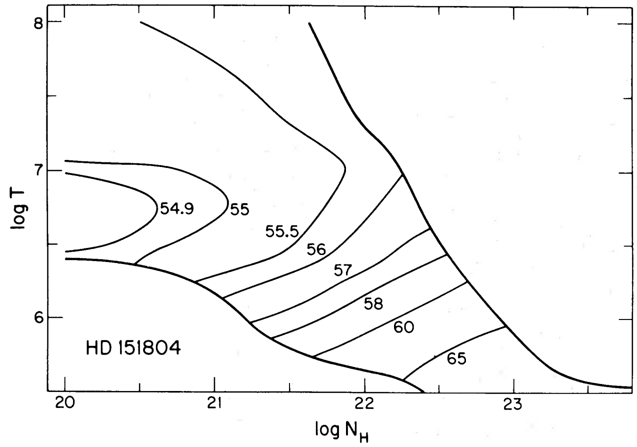

FIG. 3.—The results of the analysis of the IPC spectrum of HD 151804. In the analysis it is assumed that the X-rays are emitted from a single region that has a temperature T, and the X-rays are observed after passing through a column of interstellar gas with column density N_H (cm^{-2}). The outer boundaries are 90% confidence regions. Inside the 90% confidence regions are contours of the logarithm of the best-fitting source emission measure.

cally has a coronal emission measure that is one-tenth of the wind emission measure, EM_w, in order to match observed ionization conditions and X-ray luminosities. Using $EM_s \leq EM_w(\sim 10^{60}\ cm^{-3})$ as a plausible upper limit, Figure 3 then shows that the total column density is $N_H < 10^{22.7}\ cm^{-2}$. This upper limit is somewhat smaller than the column density to the base of the wind N_H(wind). If we use $\dot{M} = 10^{-4.78}\ M_\odot\ yr^{-1}$ as a mass loss rate for HD 151804 as obtained by Klein and Castor (1978) from Hα emission, then $N_H(\text{wind}) \approx 10^{23.2}$. Thus, the source of X-rays appears not to be confined only to the base of the stellar wind. A similar conclusion has been reached for other Of and OB supergiants by Long and White (1980), Cassinelli *et al.* (1981), and Cassinelli and Swank (1983). Waldron (1984), however, does not agree with that conclusion, because X-rays from a base corona can modify the wind opacity.

b) *The Late WN Stars*

None of the four late WN stars in our survey were detected in X-rays. This is possibly because of the short exposure times. For example, for HD 92740 we have an upper limit of 7×10^{32} ergs s^{-1}, whereas Seward and Chlebowski (1982) detected the star with a luminosity of 2×10^{32} ergs s^{-1}. Our other three Wolf-Rayet stars, shown in Figure 2, have 3 σ upper limits of several times 10^{32} ergs s^{-1}, including an allowance for interstellar absorption. The upper limits lie near the O star L_x/L line.

Both the data of Seward and Chlebowski (1982) and those of White and Long (1983) show IPC pulse-height distributions for Wolf-Rayet stars that are similar to those of typical O stars, as is discussed by Sanders, Cassinelli, and van der Hucht (1982). This suggests that gas at a temperature of a few million degrees is the source of the X-rays. The emission measures of Table 2, as well as those inferred from Seward and Chlebowski (1982) and White and Long (1983), are generally less than 10^{56} cm^{-3}, much smaller than the 10^{60} cm^{-3} emission measures typical of the winds of Wolf-Rayet stars. This suggests that the bulk of the outer winds of these stars is cool ($< 10^5$ K) material, in that it is not emitting the observed X-rays (otherwise the luminosity would be higher) or it is absorbing X-rays emitted deeper in the wind. In this regard the late WN stars are like the O8f star discussed above.

In Figure 2 the star HD 93162 now appears to be especially displaced from the other Wolf-Rayet stars. Thé and Groot (1983) have found a possible contributor to the X-rays attributed to HD 93162: the O4f star Trumpler 16−149, which is 15″ away. However, F. D. Seward (1983, private communication) has informed us of high spatial resolution observations with the high-resolution imager (HRI) that confirm that the X-rays are from within 2″ of HD 93162.

c) *The* O VI *Stars*

This class of Wolf-Rayet stars is particularly interesting because of the evidence in the optical spectra for energetic phenomena occurring in the winds. Although we expected that these stars would be X-ray sources, none of the O VI stars in our survey were detected. Nevertheless, the X-ray flux upper limits can be combined with information on the O VI λλ3811, 3834 line strengths to place constraints on models of these stars.

There are two basic mechanisms for the production of the O^{+5} ion that have been considered in discussions of early-type stars. Collisions can produce the ion in a gas with $T_e = 10^{5.5 \pm 0.3}$, as Lamers and Morton (1976) proposed in the "warm wind" model of Of stars. Alternatively, the ion could be produced radiatively in a cooler gas ($T_e \approx 10^{4.5}$) that undergoes K-shell ionization because of an influx of X-rays, as in the coronal plus cool wind model of Cassinelli and Olson (1979).

Hartmann and Raymond (1978) have discussed the collisional or radiative excitation of O^{+5} that leads to the production of the λλ3811, 3834 line emission.

i) *Collisional Excitation Models for the* O VI *Stars*

In the collisional excitation picture, the warm gas could in principle be located either in a transition region, analogous to the chromosphere-corona transition region of the Sun, or in an extensive warm wind, as in the Lamers and Morton (1976) model. Both possibilities will be considered.

Following Hartmann and Raymond (1978), the luminosity of the O VI lines in the optically thin case is

$$L_{3811} = X(\text{O VI})(\text{EM})qh\nu \frac{A_{3p-3s}}{A_{3p-3s} + A_{3p-2s}}, \tag{1}$$

where q is the collisional excitation coefficient to the $n = 3$ state, $\text{EM}(= n_e^2 V)$ is the emission measure of the warm gas, X(O VI) is the fractional abundance of O VI relative to n_e, and the ratio of A-values is the fraction of the radiative transitions producing the λλ3811, 3834 lines. The branching ratio would be 1/509 if the gas were optically thin to the $3p$–$2s$ transition. However, Hartmann and Raymond (1978) argue that the gas is very thick and the photons scatter until they escape via the $3p$–$3s$ transition. Thus, the branching ratio approaches 1, the value that we will use. A more convenient expression than equation (1) for the line luminosity is available using the emissivity calculations of Raymond and Smith (1977, 1979), which provide $n_e^2 P$, the power emitted per unit volume in the λλ3811, 3834 lines, as a function of gas temperature:

$$L_{3811} = (\text{EM})P(T). \tag{2}$$

The emission measure of the line emitting region can then be derived from the observed line strength, expressed as an equivalent width, EW, defined as

$$\text{EW} = L_{3811}/(4\pi R_*^2 \pi F_\lambda); \tag{3}$$

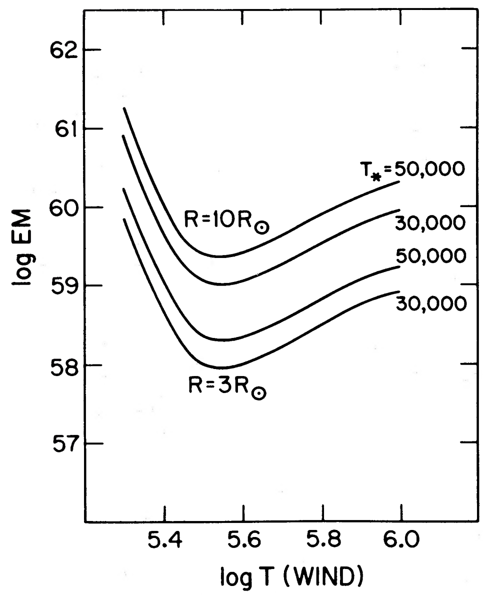

FIG. 4.—The emission measure of a "warm" gas needed to collisionally produce a line of unit equivalent width in the optical O VI lines (λλ3811, 3834). Results are shown for two assumed values of the stellar temperature, T_x = 30,000 K and T_x = 50,000 K, and for two plausible values for the stellar radius, 3 and 10 $R_\odot$.

here πF_λ is the continuum flux at $\lambda \approx 3820$ Å, which we take from the models of Kurucz (1979). Combining equations (2) and (3), we obtain the emission measure of the line emitting region,

$$\mathrm{EM} = (\mathrm{EW}/P) 4\pi R_*^2 \pi F_\lambda . \quad (4)$$

Figure 4 shows the emission measure required to produce a line of unit equivalent width determined by equation (4) as a function of emitting region temperature for photosphere temperatures of 30,000–50,000 K, and for two plausible values for Wolf-Rayet stellar radii, 3 and 10 $R_\odot$. Production of the λλ3811, 3834 line requires the smallest emission measure for an emitting region with a temperature near $10^{5.6}$ K. The minimum emission measures required to emit a line of a given equivalent width are presented in column (4) of Table 3.

If the O VI emitting volume is a transition region, the minimum emission measure indicates the thickness of the region, H, because

$$\mathrm{EM} = n_e^2 4\pi R_*^2 H . \quad (5)$$

TABLE 3

WARM WIND MODEL PARAMETERS[a]

Star (1)	O VI EW (Å) (2)	R ($R_\odot$) (3)	log $\mathrm{EM}_{\min}$ (cm^{-3}) (4)	log $\dot{M}$ ($M_\odot\ \mathrm{yr}^{-1}$) (5)	log L_{mech} ($L_\odot$) (6)
HD 119078[b]	1	3	58.00	−6.24	2.50
		10	59.05	−5.44	3.55
HD 192103	3	3	58.48	−6.00	2.98
		10	59.53	−5.20	4.02
LSS 4368	500	3	60.70	−4.89	5.20
		10	61.75	−4.09	6.25

[a] Values in table are derived assuming T_{eff} = 30,000 K and $T_{\mathrm{source}} = 10^{5.6}$ K.

[b] Data for HD 119078 are for a star with unit O VI EW and is applied to other stars with "weak" O VI.

Assuming the density to have the large value of 10^{12} cm^{-3}, and using the data of Table 3, we find that transition region thicknesses are many stellar radii. This is far too large for the emitting region to be pictured as a transition region, and we will no longer consider that model.

Let us assume instead that the O VI emission-line region is a warm stellar wind. In this case the minimum emission measure can be converted into a minimum mass loss rate, given a velocity law for the flow. For convenience we choose the velocity law and emission measure integrals used by Cassinelli and Olson (1979); $v^2 = v_0^2 + v_1^2(1 - R_*/r)$ with $v_0 = (1/20)v_1$. For this velocity law the wind emission measure is

$$\mathrm{EM}_w = 7 \times 10^{59} (\dot{M}/v_\infty)^2 / R_* , \quad (6)$$

where $\dot{M}$ is the mass loss rate in units of $10^{-6}\ \dot{M}_\odot$/yr, v_∞ is the wind terminal speed in units of 10^3 km s^{-1}, and R_* is the stellar radius in solar units. Using the minimum emission measures derived above, we derive from equation (6) the minimum mass loss rates, which are shown in column (5) of Table 3, for a wind terminal velocity of 2000 km s^{-1}. The warm wind explanation of O VI predicts satisfactory mass loss rates, except for the star LSS 4368. For this star [which has EW(O VI) = 500 Å] a model with $R_* = 10\ R_\odot$ would require an unacceptably large $\dot{M}$. Energy considerations can also provide useful constraints on line emission models. An example is the criticism of warm wind models (Cassinelli 1979) showing that an extremely large fraction of the stellar luminosity must be deposited mechanically in the wind to keep the wind at temperatures of $10^{5.5 \pm 0.3}$ K. The "mechanical" or "acoustic" luminosities required to maintain the winds at the temperature for the most efficient production of the O VI optical line ($10^{5.6}$ K) are given in column (6) of Table 3 (log L_{mech}). These luminosities are to be compared with the total luminosity characteristic of Wolf-Rayet stars, 10^5–$10^6\ L_\odot$. Again, only for LSS 4368 is there an obvious problem with the warm wind explanation.

All of these observational constraints on the warm wind model are shown in Figure 5 for three of the O VI stars. On a plot of emission measure versus warm wind temperature are shown the limits imposed by the X-ray upper limits, the O VI λλ3811, 3834 emission-line strengths, and a maximum plausible mechanical energy luminosity. For the two weak-line stars, HD 119078 and HD 192103, we see that certain temperature regimes are forbidden but that within a certain range in wind temperature and stellar size, the warm wind model for the O VI optical line emission is satisfactory. For example, for HD 119078, if $R_* \approx 3$, then the wind temperature may be in the range 2×10^5 to 4×10^5 K. Note, however, that for the WO star LSS 4368, the warm wind model explanation for the O VI emission lines is unacceptable either because too large a mechanical flux would be required to heat the wind or because X-ray emission would have been detected in our observations.

These conclusions have been reached assuming that the stars have the cosmic abundances (Allen 1973) that are used in the Raymond and Smith (1977, 1979) calculations. For the WO stars, Barlow and Hummer (1982) argue that the mass fraction of oxygen is larger than the cosmic mass fraction by almost an order of magnitude. The emission measure needed to account for the O VI emission is inversely proportional to the abundance. Thus, if we lower the O VI curves in Figure 5 for LSS 4368, we see that a warm wind solution could then be admitted.

There is sufficient uncertainty in the adopted abundances and stellar parameters for the warm wind models to explain the

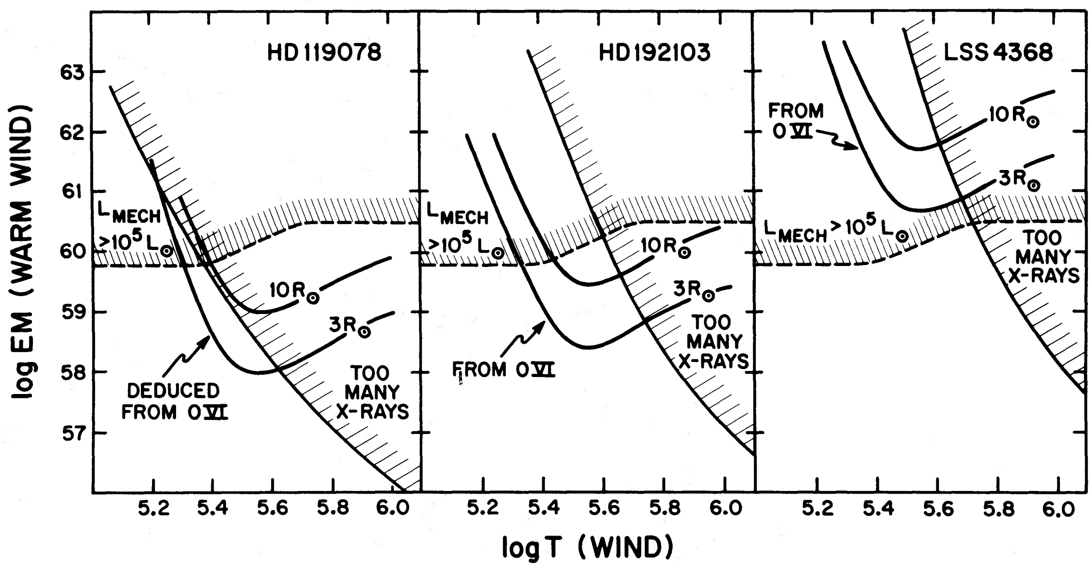

FIG. 5.—The constraints that can be placed on the "warm wind" explanation of the O VI λ3800 lines for three of the O VI stars. If the temperature is very high, too many X-rays would be produced to satisfy the IPC upper limits. If the warm wind emission measure is very large, too large a mechanical flux would need to be generated by the star. These two constraints are illustrated by the shaded regions. The limits derived for the O VI are replotted from Fig. 4. The warm wind model is unacceptable for the WO star LSS 4368.

data for all of the stars. Perhaps the distances are larger, or the interstellar column densities are larger, or there is X-ray absorption in the outermost parts of the stellar winds. Nevertheless, this analysis shows that the X-ray results should be accounted for in future model developments.

ii) *Coronal Models for the* O VI *Stars*

The O VI λλ3811, 3834 lines could be produced by photoexcitation as is described by Hartmann and Raymond (1978). Here we consider the possibility that the required radiation is produced in high-temperature coronal regions located somewhere in the winds of the stars. The observed strengths of the O VI lines are used to predict minimum X-ray luminosities. These results are then compared with the IPC observations.

We are interested in estimating the minimum X-ray luminosity that is required to produce the optical O VI lines by photoexcitation. Thus we assume the maximum efficiency for the production of the lines. This case is discussed in Hartmann and Raymond (1978). The population of the $3p$ state (82 eV above the ground state) may occur either by photoexcitation and cascade from levels with excitation energies ranging from 100 eV to the O VI continuum at 130 eV or by recombination following photoionization to O VII, which can occur up to energies ($E \approx 300$ eV) where the wind becomes optically thick because of the K-shell ionization of carbon. As in the collisional case it is assumed that every excitation to the $3p$ state eventually produces a λλ3811, 3834 photon. We further assume that all of the oxygen in the O VI emitting region is in the O^{+5} state. Under these limiting assumptions the line emission resulting from direct excitation and cascade is

$$L_{3811} < \mathrm{EM}\left[\int_{E_1}^{E_1+\Delta E_1} \Lambda(E)e^{-\tau}dE + \int_{100\ \mathrm{eV}}^{300\ \mathrm{eV}} \Lambda(E)e^{-\tau}dE\right], \quad (7)$$

where $\Lambda(E)$ is the monoenergetic emissivity and τ is the optical depth of the wind between the X-ray source and the O VI line emitting region. The upper limit on the first integral accounts for the range of energies that can excite the level directly, as determined by the range of Doppler shifts in the stellar wind. Equation (7) can be combined with equation (2) to obtain the coronal emission measure EM_c required to produce the λλ3811, 3834 lines. For this calculation we assume that the X-ray source has a temperature of 5×10^6 K and that there is no absorption between the source and the O VI line emitting region (i.e., $\tau = 0$). As was done for the collisional model, we also compute the mechanical energy required to maintain the X-ray source. The results are given in Table 4. Only for LSS 4368 is any problem apparent. If this star were to have a large radius, the corona would require an excessively large input of mechanical energy.

Given the minimum coronal emission measures in Table 4, it is straightforward to calculate the expected X-ray flux, f_x, and IPC count rate, r:

$$f_x = \mathrm{EM}_c \frac{1}{4\pi D_*^2} \int \Lambda(E)e^{-\tau(\mathrm{wind})}e^{-\tau(\mathrm{ISM})}dE . \quad (8)$$

First consider a model in which the X-rays are emitted by a source in the outer regions of the wind, i.e., with $N_\mathrm{H}(\mathrm{wind}) = 0$. Recall that such a model was found to be consistent with the IPC spectrum of the O8f star discussed earlier. We find here, however, that the implied X-ray fluxes are several orders of magnitude too large. This can be seen comparing EM_c in Table 4 with EM given in Table 2. Clearly this exterior coronal model is not valid for the O VI stars.

The column densities of wind material that the models require in order to match the observed X-ray fluxes are given in Table 4. If we assume a velocity law, we can convert these column densities into wind mass loss rates. Assuming the velocity law used earlier (eq. [7] with $v_\infty = 2000$ km s^{-1}), we obtain the mass loss values given in Table 4. These are all marginally satisfactory in the sense that they do not exceed the mass loss rate of $10^{-4.5}$ found to be typical of Wolf-Rayet stars by Bieging, Abbott, and Churchwell (1982) from radio observations. Winds with more gradual increases in v relative to r require even smaller mass loss rates. For example, if

TABLE 4

Corona Model Parameters

Star	EW (Å)	R ($R_\odot$)	log EM_c[a] (cm^{-3})	log L_{mech} ($L_\odot$)	Required N_H(wind)[b] (10^{23} cm^{-2})	log $\dot{M}_{min}$[c] ($M_\odot$ yr^{-1})
HD 119078	1	3	58.06	2.1	0.68	−6.10
		10	59.10	3.2	1.8	−5.12
HD 192103	3	3	58.53	2.6	2.9	−5.47
		10	59.58	3.6	5.1	−4.66
LSS 4368	500	3	60.75	4.8	5.5	−5.19
		10	61.80	5.9	8.3	−4.45

[a] The coronal emission measure needed to produce the observed O VI line strengths; assumes $T_c = 5 \times 10^6$ K.

[b] The column density of wind material required to attenuate the predicted X-ray flux to the observed value.

[c] The mass loss rate of a wind that is required to account for the attenuation in the previous column.

$v = (1 - R/r)^2$, $\dot{M}$ values are a factor of 3 less than those in Table 4. A wind is capable of accounting for the required attenuation in all cases. We conclude that the O VI optical line emission can be explained with a model in which the source of X-rays is at or near the base of a stellar wind.

Figure 6 shows the results for the coronal photoexcitation model for the O VI line emission for the two weak-line O VI stars and the WO star that were discussed earlier. For HD 119078 and HD 192103 a rather low coronal emission measure of $\sim 10^{58}$ cm^{-3} with cool wind column densities of $< 10^{23.5}$, would be sufficient to explain our failure to detect the X-rays. For the WO star LSS 4368, a much larger coronal emission measure is required to explain the O VI $\lambda\lambda 3811$, 3834 emission (EM $> 10^{60}$ cm^{-3}). The mechanical energy required to produce such a corona is very large, of the order of 10^5 $L_\odot$. Even for this star the nondetection of X-rays can be explained as the result of absorption in a cool wind with a column density $N_H \approx 10^{24}$ cm^{-2}. As was the case in our warm wind discussion, increasing the assumed abundance of oxygen would decrease the emission measure required to explain the O VI line. The tight constraints on LSS 4368 would be alleviated accordingly.

IV. CONCLUSIONS

The X-ray spectrum of the massive O8f star HD 151804 leads to results similar to those derived by a number of authors for O stars with weaker emission features. The X-rays could be explained as arising from sources in the wind. The simple corona plus cool wind model would encounter difficulties in explaining the data because the coronal emission would be heavily attenuated by the cool wind and an excessively large emission measure would need to be postulated. Waldron (1983) has shown that this argument against the base coronal model for Of and OB supergiants is open to criticism, however, because the corona affects the ionization structure in the wind and can reduce the cool wind opacity to X-rays.

For the late WN stars in our survey the L_x/L_{bol} ratio is at or below the 10^{-7} level appropriate for O stars. As a result the

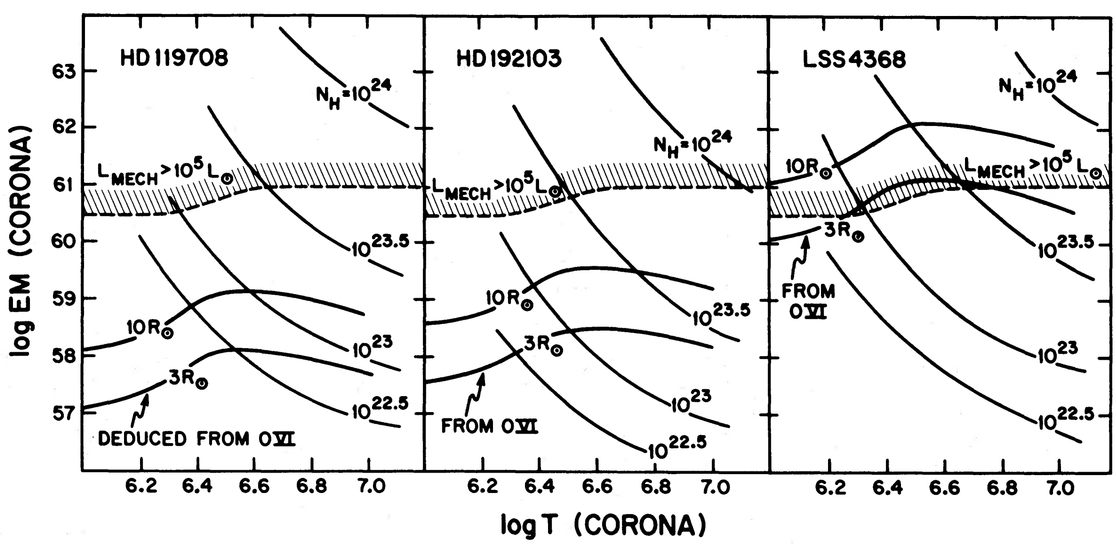

Fig. 6.—Constraints on the radiative excitation model for three of the O VI stars. The emission measure of the X-ray source region that is required to produce the equivalent width of the stellar optical O VI line is plotted against the source region temperature. The roughly diagonal lines show the column density of absorbing material required to satisfy the IPC X-ray upper limits. At very large emission measures excessively large mechanical fluxes would be needed to produce the stellar corona. This is indicated by the shaded region.

large L_x/L_{bol} ratio for HD 93162 of Seward and Chlebowski (1982) appears even more extreme.

We have developed procedures for interpreting the O VI optical line emission in Wolf-Rayet stars of the O VI and WO classes. Interesting constraints can be placed on models for the stars by accounting for the X-ray data and by the requirement that the mechanical flux be moderate. The WO stars pose interesting problems for either the warm wind or the corona plus cool wind model.

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