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# ON WINDS AND X-RAYS OF O-TYPE STARS

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## ABSTRACT

We investigate dependences between stellar wind and X-ray properties of the O-type stars. New *IUE*-based mass-loss rates and wind terminal velocities are obtained for 40 well-known, bright single stars or binaries. There is no evidence for enhanced mass loss from the binaries compared with the single stars. We suggest that a weak dependence between $L_x$ and $\dot{M}v_\infty$ found here for single stars at least partially accounts for the observed proportionality between $L_x$ and $L_{bol}$. Very tight, detached, massive binaries with kinetic energy of the wind exceeding $3 \times 10^{35}$ ergs s$^{-1}$ ($|\dot{M}| > 10^{-7}$ $M_\odot$ yr$^{-1}$) generate an excess X-ray flux which is in a qualitative agreement with simple theories of colliding stellar winds.

*Subject headings:* stars: binaries — stars: early-type — stars: mass loss — stars: winds — stars: X-rays — ultraviolet: spectra

## I. INTRODUCTION

The theory of line radiation-driven stellar winds, developed to explain mass loss from hot luminous stars (see Abbott 1988), has been very successful in explaining the winds from these stars. However, one of the major deficiencies in the theory is the discrepancy between the observed and predicted X-ray fluxes. Cassinelli and Olson (1979) suggested the possible existence of a corona at the base of the wind, but the predicted spectrum does not match the observations. Likewise, Lucy's (1982) theory of a shocked wind does not solve the problem. Little success has been achieved in the search for a connection between the X-ray fluxes, based on the preliminary *Einstein* results, and stellar properties. Vaiana (1980) pointed out a lack of correlation between X-ray flux level and mass-loss rates for hot stars. Abbott, Bieging, and Churchwell (1981) attempted to link X-ray luminosity with the wind luminosity and were not able to draw any general conclusions.

A massive binary system should influence its emergent X-ray flux as a result of colliding stellar winds. This was predicted by Cherepaschuk (1976), Prilutskii and Usov (1976), and Cooke, Fabian, and Pringle (1978). From the observational point of view, the possible effect of multiplicity upon the X-ray emission of OB stars has been discussed by Harnden *et al.* (1979), who concluded that no significant effect was discernible in the early data. Stewart and Fabian (1981) and Chlebowski (1984) came to the same conclusions. We reexamine this question in the present paper. We use the catalog published by Chlebowski, Harnden, and Sciortino (1989, hereafter Paper I) of the *Einstein* final X-ray fluxes of all known Galactic O-type stars. In addition, we have obtained new measurements of the mass-loss rates and terminal velocities of 40 stars based on the archival *IUE* observations. We have benefited from a preprint by Sciortino *et al.* (1990) which also uses Paper I and confirm some of their conclusions about wind kinetic energy and X-ray flux. The method of star selection and the new determinations of mass-loss rates from *IUE* data are described in § II. These rates are compared for single and binary stars in § III, and their relation to the X-ray fluxes is analyzed in § IV.

After this project was finished we learned about work by Howarth and Prinja (1989, hereafter HP), whose aim was partially similar to the UV part of our paper. Where possible we have compared their results with ours.

## II. STELLAR PARAMETERS

### *a) Selection of Stars*

We have selected a sample of stars that are known with some confidence to be either single stars or massive binaries. The single stars are taken primarily from Chlebowski (1989, hereafter Paper II) and include stars observed both with *Einstein* and with *IUE* in the high-resolution mode of the SWP camera. The criteria adopted in Paper II were as follows: (1) at least five radial velocity measurements were found in the literature, and (2) the amplitude of variation was smaller than 30 km s$^{-1}$. In this paper we have relaxed our criteria somewhat and included HD 93129A, found to be single by Conti, Niemela, and Walborn (1979) and also ξ Per, α Cam, 9 Sge, and 68 Cyg, since the unconfirmed reports that they contain compact companions are not convincing (see also Zeinalov, Musaev, and Chentsov 1987). In addition, we have included in the sample 14 bright stars found to be single by Garmany, Conti, and Massey (1980), unobserved with *Einstein*. Table 1 lists the luminosities and temperatures for our sample of 38 single stars. Absolute magnitudes are from the data presented in Paper I. The derivation of these luminosities and temperatures is discussed in § II*b*.

We have also chosen a sample of 34 well-known binary systems with O-type components, 26 observed with *Einstein*. Tables 1 and 2 contain *all* O-type stars observed in the high-resolution mode with the SWP camera of the *IUE* that we judge to be either single or binary. All spectral types are taken from Walborn (1971*a*, *b* 1972, 1976, 1982*a*, *b*). Three stars listed in Table 2 deserve a comment: HD 37468 (σ Ori A) is a spectroscopic binary with a period longer than 30 days (Bolton 1974, and private communication). Numerous radial velocity measurements of HD 152424 convince us that it also is a binary with a long period (Hill, Crawford, and Barnes 1974). Since from the radial velocity variations we can put only an upper limit on its period ($P < \sim 1$ yr), we will consider it as a binary but will not include any dependences on the orbital period. HD 152248, although observed with *Einstein*, is located

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TABLE 1

SINGLE STARS

| Name | Spectral Type | $10^{-5}L$ ($L_\odot$) | $10^{-3}$ $T_{\rm eff}$ (K) |
|---|---|---|---|
| HD 14434 ............ | O5.5 Vn((f))p | 2.30 | 43.2 |
| HD 24431 ............ | O9 III | 2.37 | 34.0 |
| HD 24912 ............ | O7.5 III(n)((f)) | 2.13 | 37.1 |
| HD 30614 ............ | O9.5 Ia | 6.46 | 30.0 |
| HD 36861 ............ | O8 III((f)) | 2.83 | 36.0 |
| HD 37742 ............ | O9.7 Ib | 8.20 | 32.0 |
| HD 38666 ............ | O9.5 V | 0.40 | 34.9 |
| HD 42088 ............ | O6.5 V | 1.71 | 41.2 |
| HD 46149 ............ | O8.5 V | 1.72 | 37.0 |
| HD 46223 ............ | O4 V((f)) | 7.21 | 46.0 |
| HD 46202 ............ | O9 V | 0.90 | 35.9 |
| HD 46966 ............ | O8 V | 1.88 | 38.0 |
| HD 47432 ............ | O9.5 I | 3.13 | 30.9 |
| HD 47839 ............ | O7 V((f)) | 2.01 | 40.1 |
| HD 54662 ............ | O6.5 V | 3.94 | 41.2 |
| HD 55879 ............ | O9.5 II–III | 1.14 | 32.9 |
| HD 57682 ............ | O9 IV | 0.94 | 35.0 |
| HD 66811 ............ | O4 I(n)f | 8.83 | 42.0 |
| HD 90273 ............ | O7 V[a] | 1.33 | 40.1 |
| HD 93129A .......... | O3 If* | 15.8 | 45.0 |
| HDE 303308 .......... | O3 V((f)) | 6.31 | 45.5 |
| HD 93843 ............ | O5 III(f)var | 6.80 | 42.3 |
| HD 96946 ............ | O6 V | 2.56 | 42.2 |
| HD 149757 ........... | O9.5 V(e) | 1.24 | 34.9 |
| HD 151804 ........... | O8 Iaf | 13.1 | 34.0 |
| HD 152408 ........... | O8 If | 10.2 | 34.0 |
| HD 155806 ........... | O7.5 V[n]e | 2.93 | 39.1 |
| HD 162978 ........... | O8.5 III((f)) | 3.67 | 35.0 |
| HD 175754 ........... | O8 II((f)) | 2.37 | 36.0 |
| HD 175876 ........... | O6.5 III(n)(f) | 3.97 | 39.2 |
| HD 188001 ........... | O7.5 Iaf | 13.2 | 35.1 |
| HD 188209 ........... | O9.5 Iab | 3.07 | 30.9 |
| HD 193514 ........... | O7 Ib(f) | 5.55 | 36.1 |
| HD 203064 ........... | O7.5 III:n((f)) | 2.99 | 37.1 |
| HD 207198 ........... | O9 I | 1.94 | 32.0 |
| HD 209975 ........... | O9.5 Iab | 2.03 | 30.9 |
| HD 210839 ........... | O6 I(n)fp | 9.00 | 38.0 |
| HD 214680 ........... | O9 V | 1.02 | 35.9 |

[a] Luminosity class based on Si IV lines.

in the open cluster NGC 6231 and was not resolved in X-rays, so we will not use the X-ray data for this star.

### b) *Effective Temperature Scale and Bolometric Corrections*

We have constructed a new conversion table for spectral types, effective temperatures, and bolometric corrections, because effective temperature determinations based on the analysis of high-precision line profiles using non–LTE model stellar atmospheres (Kudritzki 1980; Kudritzki, Simon, and Hamann 1983; Simon *et al.* 1983; Bohannan *et al.* 1986; Voels 1988; Voels *et al.* 1989) give systematically higher temperatures than those traditionally accepted. Plotting the temperatures versus the bolometric corrections derived for a total of 12 stars by these authors, we find that except for $\zeta$ Pup (for which Kudritzki derived a bolometric luminosity of BC = −4.32 mag, Bohannan *et al.* got BC = $-4.0 \pm 0.1$ mag, and Voels, Bohannan, and Hummer obtained BC = −3.92 mag), all of the stars are located on a nearly straight line (in the log-log plot). This is shown in Figure 1, which is a convincing argument that BC for the hot stars does not depend on the luminosity class.

HP obtained a very similar but slightly steeper BC scale as a linear function of $T_{\rm eff}$. Their values differ from ours everywhere by less than 0.1 mag.

Table 3 contains the adopted temperatures and bolometric corrections for each O subtype. Supergiants are almost exactly 4000 K cooler than dwarfs of a given spectral type. We have assumed that giants are located halfway between dwarfs and supergiants in temperature. Unfortunately, the only way to verify this assumption is by a comparison with $\delta$ Ori (O9.5 II), which was not used for fits (luminosity class II), and for which the interpolated $T_{\rm eff}$ and BC agree very well with the results of Voels *et al.* (1989). The relation between BC and temperature in Table 3 can be expressed as

$$\mathrm{BC} = 28.77 - 7.08 \log T_{\rm eff} .$$

The bolometric correction dependence derived in the present study can be spliced smoothly with the BC for cooler dwarfs ($T_{\rm eff} < 30{,}000$ K) from Malagnini *et al.* (1986).

### c) *The IUE Data*

*IUE* spectra were obtained from the archives at the Colorado Regional Data Analysis Facility. Where possible, we selected spectra obtained during 1979 and 1980, when the *Einstein* satellite was in operation, so that any long-term variability in the stellar winds would not affect our results (see, e.g., Drechsel *et al.* 1982). To improve our signal-to-noise ratio, especially for stars observed in the X-ray range, we summed several spectra before proceeding with the analysis. Based on the experience of earlier investigators (e.g., Harris and Sonneborn 1987), we selected up to seven of the best-exposed spectra from the merged *IUE* log. The list of images is presented in Table 4. When adding, the spectra were aligned in wavelength using interstellar lines, in most cases S II (1253.79 and 1259.53 Å) and Si II (1260.42 and 1526.70 Å), mapped onto a grid of uniform 0.1 Å intervals, and then summed together with bad data points removed. This technique minimized the effect of narrow absorption components in the P Cygni profiles (see Henrichs 1988), and possible periodic line shape changes in the binaries. For stars with only one image number listed in Table 4, we have selected the best exposed SWP spectrum or used the only one available.

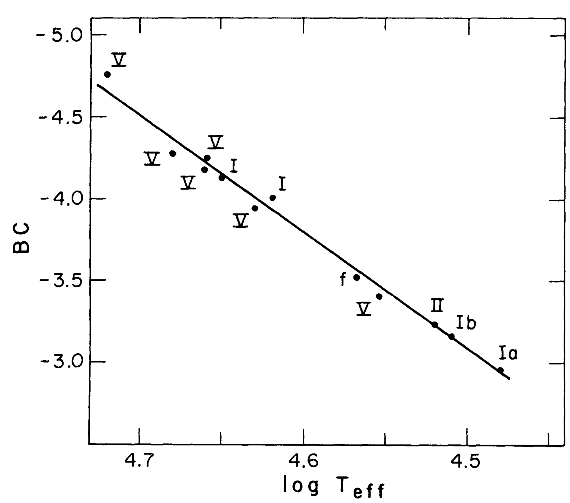


FIG. 1.—Relation between log $T_{\rm eff}$ and bolometric correction BC defined by line profile analyses using non–LTE model stellar atmospheres. The BC is seen to be independent of the stellar luminosity class.

TABLE 2

BINARY SYSTEMS AND TEST STARS

| Name | Spectral Type | $P_{orb}$ (days) | $10^{-5}L$ ($L_\odot$) | $10^{-3}T_{eff}$ (K) |
|---|---|---|---|---|
| HD 1337 | O9 III:(n)+O9 III | 3.52 | 8.97 | 34.0 |
| HD 12323 | ON9 V | 3.07 | 0.47 | 35.9 |
| HD 14633 | ON8 V | 15.34 | 1.31 | 38.0 |
| HD 15558 | O5 III(f) | 439.3 | 11.2 | 42.3 |
| HD 36486 | O0.5 II | 5.73 | 6.24 | 33.0 |
| HD 37041 | O9 V | 20.97 | 0.77 | 35.9 |
| HD 37043 | O9 III+O9 III | 29.14 | 3.78 | 34.0 |
| HD 37468 | O8.5 III | >30 | 1.67 | 35.0 |
| HD 47129 | O8p | 14.40 | 4.37 | 36.0 |
| HD 48099 | O7 V | 3.1 | 1.58 | 40.1 |
| HD 57060 | O7 Ia:fpvar | 4.39 | 15.9 | 36.1 |
| HD 57061 | O9 II | 154.90 | 9.91 | 34.0 |
| HD 75759 | O9 Vn | 33.31 | 4.50 | 35.9 |
| HD 93206 | O9.7 Ib:(n)+O9.5 III.. | 6.00+... | 9.96 | 30.5 |
| HD 93205 | O3 V+O8 | 6.08 | 8.43 | 48.5 |
| HD 93403 | O5 III(f)var | 15.09 | 15.4 | 42.3 |
| HD 100213 | O8.5 Vn | 1.39 | 1.14 | 37.0 |
| HD 135240 | O7.5 III((f)) | 3.90 | 3.05 | 37.1 |
| HD 152218 | O9.5 IV(n) | 5.40 | 2.10 | 34.0 |
| HD 152248 | O7 Ib:(n)(f)p | 5.97 | 8.14 | 36.1 |
| HD 152424 | OC9.7 Ia | Long | 7.74 | 30.5 |
| HD 152590 | O7.5 V | 4.49 | 1.31 | 39.1 |
| HD 153919 | O6.5 Iaf+ | 3.41 | 9.16 | 37.2 |
| HD 159176 | O7 V+O7 V | 3.37 | 2.26 | 40.1 |
| HD 165052 | O6.5 V(n)((f)) | 6.14 | 3.86 | 41.2 |
| HD 167771 | O7 III:(n)((f)) | 3.97 | 9.97 | 38.1 |
| HD 167971 | O8 Ib(f)p | 3.32 | 12.9 | 34.0 |
| HD 199579 | O6 V((f)) | 48.61 | 2.20 | 42.2 |
| HD 206267 | O6.5 V((f)) | 3.71 | 4.30 | 41.2 |
| HD 209481 | O9 Vn+O9 Vn | 3.07 | 2.17 | 35.9 |
| HD 215835 | O6 V(n)+O6n | 2.11 | 19.88 | 42.2 |
| Test Stars | | | | |
| HD 46150 | O5 V((f)) | n.a. | 5.29 | 44.3 |
| HD 152623 | O7 V(n)((f)) | n.a. | 6.26 | 40.1 |

For each spectrum we have removed the interstellar Lyα in a way similar to the method used by Shull and Van Steenberg (1985); modeling this line allowed us to determine an absorbing hydrogen column density ($N_{\rm H\,I}$) and at the same time recover the N V wind profile. This value of $N_{\rm H\,I}$, corrected for the molecular hydrogen contribution in the same way as in Paper I, was used correct the X-ray flux values for the stars whose X-ray absorption correction factors (published in Paper I) were based only on the gas-to-dust ratio of Bohlin, Savage, and Drake (1978) and the reddening values. The new values of $N_{\rm H\,I}$, $L_x$, and $L_x/L_{bol}$ are given in Table 4.

Our new log ($L_x/L_{bol}$) values are on average lower than those of Paper I by 0.06 ± 0.02 because we have used different BCs and new $N_{\rm H}$ values.

TABLE 3

ADOPTED SPECTRAL TYPE – $T_{eff}$ AND BC CONVERSION

| Type | V | −BC | III, II | −BC | I | −BC |
|---|---|---|---|---|---|---|
| O3 | 48500 | 4.36 | 46500 | 4.21 | 44500 | 4.07 |
| O4 | 46400 | 4.21 | 44400 | 4.06 | 42400 | 3.93 |
| O5 | 44300 | 4.06 | 42300 | 3.92 | 40300 | 3.78 |
| O5.5 | 43200 | 3.98 | 41300 | 3.85 | 39300 | 3.71 |
| O6 | 42200 | 3.91 | 40200 | 3.78 | 38200 | 3.62 |
| O6.5 | 41200 | 3.85 | 39200 | 3.70 | 37200 | 3.56 |
| O7 | 40100 | 3.77 | 38100 | 3.62 | 36100 | 3.48 |
| O7.5 | 39100 | 3.70 | 37100 | 3.55 | 35100 | 3.40 |
| O8 | 38000 | 3.62 | 36000 | 3.46 | 34000 | 3.31 |
| O8.5 | 37000 | 3.54 | 35000 | 3.40 | 33000 | 3.23 |
| O9 | 35900 | 3.46 | 34000 | 3.31 | 32000 | 3.14 |
| O9.5 | 34900 | 3.39 | 32900 | 3.22 | 30900 | 3.04 |
| O9.7 | ... | ... | ... | ... | 30500 | 3.00 |

### *d) Mass-Loss Rates*

The mass-loss rates and terminal velocities were determined from the UV resonance lines of N V and C IV using the method developed by Olson (1981*a*, *b*), which fits the observed profiles to parameterized model profiles and is described in Garmany *et al.* (1981). Olson's model assumes the existence of a hot corona, but this does not significantly affect the mass-loss determination (Olson and Castor 1981). It requires a knowledge of $T_{eff}$, stellar radius, and $v_\infty$ as well as the optical depth of the line integrated through the wind. The radii for the single stars were derived from their bolometric luminosities and effective temperatures.

The terminal velocities, $v_\infty$ were estimated at the point where the steep, blue edge of the P Cygni profile meets the continuum for the lines, N V, Si IV (for supergiants), and C IV. They were compared to each other to eliminate a possible influence of the photospheric line at 1533 Å. There has been some discussion in the literature about the definition of the terminal velocity (Lucy 1982; Abbott 1988; HP). We chose to define $v_\infty$ so as to

TABLE 4

*IUE*/SWP Images Used for Present Analysis

| HD (Name) | SWP Image | Exposure Time (minutes, seconds) | $10^{-21}N_{\rm H\,I}$ ($\rm cm^{-2}$) | $\log(L_x/L_{\rm bol})$ | $\log(L_x)$ (ergs $\rm s^{-1}$) |
|---|---|---|---|---|---|
| HD 1337 (AO Cas) | 7666 | 4, 30 | 0.80 | $-6.65 \pm 0.26$ | $32.90 \pm 0.28$ |
| HD 12323 | 9652 | 120, 0 | 1.61 | $< -5.37$ | $< 32.88$ |
| HD 14434 | 16094 | 90, 0 | 2.04 | Not observed with *Einstein* | |
| HD 14633 | 21583 | 14, 0 | 0.40 | Not observed with *Einstein* | |
| HD 24431 | 30166 | 60, 0 | 1.40 | Not observed with *Einstein* | |
| HD 37041 ($\theta^2$ Ori A) | 6420 | 3, 0 | 2.30 | $-6.40 \pm 0.20$ | $32.06 \pm 0.22$ |
| HD 37468 ($\sigma$ Ori A) | 7617 | 0. 19 | 0.40 | $-6.60 \pm 0.18$ | $32.22 \pm 0.21$ |
| HD 38666 ($\mu$ Col) | 6631 | 1, 15 | 0.12 | $-6.81 \pm 0.21$ | $31.37 \pm 0.24$ |
| HD 42088 | 22107 | 30, 0 | 2.23 | $-6.45 \pm 0.31$ | $32.38 \pm 0.32$ |
| HD 46150 | 10758 | 20, 0 | 2.20 | $-6.29 \pm 0.30$ | $33.02 \pm 0.36$ |
| HD 46202 | 8845 | 170, 0 | 3.18 | $-6.13 \pm 0.31$ | $32.40 \pm 0.31$ |
| | 30299 | 85, 0 | | | |
| HD 46223 | 8138 | 60, 0 | 2.00 | $-6.62 \pm 0.31$ | $32.62 \pm 0.31$ |
| HD 47432 | 9947 | 26, 0 | 1.51 | Not observed with *Einstein* | |
| HD 55879 (HR 2739) | 6298 | 5, 18 | 0.69 | $< -6.17$ | $< 32.53$ |
| HD 57060 (UW CMa, 29 CMa) | 6368 | 2, 4 | 0.58 | $-7.38 \pm 0.29$ | $32.43 \pm 0.31$ |
| | 6437 | 1, 30 | | | |
| | 6740 | 2, 7 | | | |
| | 6741 | 3, 0 | | | |
| | 6742 | 2, 54 | | | |
| | 6743 | 2, 44 | | | |
| | 6744 | 2, 34 | | | |
| HD 75759 (HR 3525) | 6397 | 6, 30 | 1.04 | $-6.67 \pm 0.28$ | $32.56 \pm 0.30$ |
| | 6419 | 6, 0 | | | |
| | 9619 | 6, 0 | | | |
| HD 90273 | 14832 | 100, 0 | 4.15 | $< -5.92$ | $< 32.83$ |
| HD 93205 | 6367 | 50, 0 | 2.60 | $-6.37 \pm 0.24$ | $33.14 \pm 0.25$ |
| | 6377 | 40, 0 | | | |
| | 6395 | 50, 0 | | | |
| | 6418 | 35, 0 | | | |
| | 9635 | 40, 0 | | | |
| HD 93206 (QZ Cr) | 9018 | 25, 0 | 1.96 | $-6.14 \pm 0.29$ | $33.43 \pm 0.30$ |
| HD 93403 | 6396 | 84, 0 | 3.67 | $-5.83 \pm 0.31$ | $33.96 \pm 0.31$ |
| | 9075 | 60, 0 | | | |
| | 9673 | 70, 0 | | | |
| | 9739 | 60, 0 | | | |
| HD 93843 | 14745 | 24, 0 | 1.93 | $-6.38 \pm 0.30$ | $33.06 \pm 0.31$ |
| HD 96946 | 28546 | 100, 0 | 1.58 | $< -6.37$ | $< 32.63$ |
| HD 100213 (TU Mus) | 19643 | 70, 0 | 1.55 | $< -5.95$ | $< 32.69$ |
| HD 152218 | 16203 | 40, 0 | 1.58 | $-6.11 \pm 0.31$ | $32.76 \pm 0.34$ |
| HD 152248 | 9621 | 21, 0 | 2.16 | Not resolved by *Einstein* | |
| HD 15290 | 16098 | 60, 0 | 2.09 | $< -6.20$ | $< 32.51$ |
| HD 152623 | 16096 | 17, 0 | 2.05 | $-6.27 \pm 0.31$ | $33.13 \pm 0.32$ |
| HD 153919 | 25616 | 21, 0 | 2.30 | Not observed with *Einstein* | |
| HD 155806 | 9851 | 3, 20 | 1.00 | Not observed with *Einstein* | |
| HD 159176 (HR 6535) | 6365 | 8, 0 | 1.50 | $-5.89 \pm 0.31$ | $33.07 \pm 0.33$ |
| | 6366 | 12, 0 | | | |
| | 6374 | 12, 0 | | | |
| | 6390 | 12, 0 | | | |
| | 9735 | 8, 0 | | | |
| HD 162978 (HR 6672) | 30502 | 8, 30 | 1.82 | Not observed with *Einstein* | |
| HD 165052 | 6392 | 21, 0 | 2.51 | $-6.00 \pm 0.24$ | $33.18 \pm 0.26$ |
| | 9734 | 20, 0 | | | |
| | 15306 | 16, 0 | | | |
| | 17106 | 15, 0 | | | |
| HD 175754 | 9320 | 9, 0 | 1.03 | Not observed with *Einstein* | |
| HD 175876 | 9321 | 8, 30 | 0.82 | Not observed with *Einstein* | |
| HD 193514 | 18145 | 140, 0 | 1.91 | $< -6.78$ | $< 32.58$ |
| HD 203064 (68 Cyg) | 29072 | 2, 30 | 1.11 | $-6.90 \pm 0.28$ | $32.18 \pm 0.30$ |
| HD 206267 (HR 8281) | 6572 | 15, 4 | 1.75 | $-6.47 \pm 0.29$ | $32.63 \pm 0.31$ |
| | 6599 | 15, 4 | | | |
| | 6604 | 15, 4 | | | |
| | 8979 | 13, 0 | | | |
| | 9651 | 25, 0 | | | |
| HD 209481 (14 Cep) | 6372 | 10, 0 | 1.30 | Not observed with *Einstein* | |
| HD 209975 (19 Cep) | 30515 | 5, 0 | 1.66 | Not observed with *Einstein* | |
| HD 215835 (DH Cep) | 14620 | 250, 0 | 5.63[a] | $-6.16 \pm 0.39$ | $33.73 \pm 0.38$ |
| | 27137 | 145, 0 | | | |

[a] Due to the large noise, no fitting was performed for HD Cep.

TABLE 5

MASS-LOSS RATES FOR SINGLE STARS

| Name | log(\|$\dot{M}$\|) ($M_{\odot}$ yr$^{-1}$) | Source | $10^{-3}v_{\infty}$ (km s$^{-1}$) | Source |
|---|---|---|---|---|
| HD 14434 | > −6.13 | 1, 2 | 2.30 | 1 |
| HD 24431 | −6.94 | 1 | 2.30 | 1 |
| HD 24912 | −5.77 | 3 | 2.55 | 6, 7 |
| HD 30614 | −5.42 | 3 | 1.83 | 6, 7 |
| HD 36861 | −6.40 | 3 | 2.47 | 6, 7 |
| HD 37742 | −5.94 | 3 | 2.22 | 6, 7 |
| HD 38666 | −8.31 | 1 | 1.20 | 1 |
| HD 42088 | −6.82 | 1, 4 | 2.30 | 1 |
| HD 46149 | −7.70 | 3 | 1.70 | 6 |
| HD 46202 | −8.10 | 1 | 1.15 | 1 |
| HD 46223 | −5.62 | 1, 4 | 3.10 | 1 |
| HD 46966 | −7.14 | 5 | 2.30 | 6 |
| HD 47432 | > −5.89 | 1 | 2.30 | 1 |
| HD 47839 | −6.72 | 3 | 2.65 | 5, 6 |
| HD 54662 | −6.70 | 3 | 2.50 | 6 |
| HD 55879 | −7.55 | 1 | 1.60 | 1 |
| HD 57682 | −6.73 | 5 | 1.70 | 5 |
| HD 66811 | −5.33 | 3 | 2.66 | 3 |
| HD 90273 | −6.87 | 1 | 2.60 | 1 |
| HD 93129A | −4.84 | 3 | 3.90 | 6 |
| HDE 303308 | −5.60 | 6 | 3.40 | 6 |
| HD 93843 | > −5.62 | 1 | 3.10 | 1 |
| HD 96946 | > −6.00 | 1 | 2.60 | 1 |
| HD 149757 | −6.70 | 7 | 1.64 | 7 |
| HD 151804 | −5.04 | 3 | 2.00 | 6 |
| HD 152408 | −4.91 | 5 | 1.80 | 6 |
| HD 155806 | −6.71 | 1 | 2.50 | 1 |
| HD 162978 | > −5.72 | 1 | 2.90 | 1 |
| | −6.08 | 5 | | |
| HD 175754 | > −5.90 | 1 | 2.70 | 1 |
| HD 175876 | > −5.22 | 1 | 2.90 | 1 |
| | < −4.68 | 8 | | |
| HD 188001 | −5.04 | 3 | 2.30 | 6 |
| HD 188209 | −5.72 | 5 | 2.10 | 6 |
| HD 193514 | −5.50 | 3 | 2.70 | 1 |
| HD 203064 | > −5.87 | 1 | 2.65 | 1 |
| HD 207198 | −6.13 | 5 | 2.30 | 6 |
| HD 209975 | > −6.33 | 1 | 2.30 | 1 |
| HD 210839 | −5.39 | 3 | 2.50 | 6 |
| HD 214680 | −7.18 | 7 | 1.38 | 7 |

REFERENCES.—(1) This work; (2) Garmany and Conti 1984; (3) de Jager, Nieuwenhuijzen, and van der Hucht 1988; (4) Garmany *et al.* 1981; (5) Leitherer 1988; (6) Garmany 1988; (7) Prinja and Howarth 1986; (8) Vallée and Moffat 1985.

be comparable with the majority of data available in the literature.

Table 5 gives our new mass loss rates and those we have adopted from the literature for the single stars, and Table 6 contains the same for the binary stars.

Our present determinations improve on those of Garmany *et al.* (1981) in two ways. First, by averaging spectra, we have obtained a better signal-to-noise ratio. Second, by eliminating the influence of the interstellar Lyα line we obtained a more accurate determination of N v P Cygni profile parameters. We have compared our results with the earlier UV mass-loss determination obtained by Garmany *et al.* for four stars common to both lists and two additional stars, HD 46150 and HD 152623, both having relatively large mass-loss rates. These six stars have mass loss in the range $-8.4 < \log |\dot{M}| < -5.7$ and neutral hydrogen column density $1.2 \times 10^{20} < N_{\rm H\,I} < 2.3 \times 10^{21}$ cm$^{-2}$. The differences between the earlier and the present mass-loss rate results are of the order of 0.2 in the $\log |\dot{M}|$, except for HD 46150, for which the difference is 0.44 (almost a factor of 3). Since we expect the accuracy of an individual mass-loss determination to be of this order, we conclude that the elimination of the Lyα does not introduce any significant systematic difference.

We also extracted Si IV (1393.75 and 1402.77 Å) in order to determine the luminosity class for those stars where it was unknown. This classification from Si IV is discussed by Walborn and Panek (1984).

We have plotted our new mass loss rates for the stars in common with HP in Figure 2. Mass-loss rates are dependent on the stellar radii and temperature, which is derived independently of the wind parameters. However, the temperature scale adopted by HP is very similar to ours, and the stellar absolute magnitudes differ by less than 0.2 mag, so the differences in the derived mass-loss rates of the stars in Figure 2 depend almost entirely on the treatment of the UV wind profiles and the assumptions made about wind terminal velocity and the ionization fraction. It is not our intent to examine which values are more correct, but only to indicate the type of scatter found in separate analyses of the UV line profiles.

## III. COMPARISON OF SINGLE AND BINARY STARS

Mass-loss rates depend critically on the physical conditions at the sonic point, which, in the case of hot stars, is located very close to the optical photosphere. Therefore, from the theoreti-

TABLE 6

MASS-LOSS RATES FOR BINARY STARS

| Name | log(\|$\dot{M}$\|) ($M_{\odot}$ yr$^{-1}$) | Source | $10^{-3}v_{\infty}$ (km s$^{-1}$) | Source |
|---|---|---|---|---|
| HD 1337 | −6.17 | 1 | 2.20 | 1 |
| HD 12323 | −8.37 | 1 | 1.30 | 1 |
| HD 14633 | −6.81 | 1 | 2.30 | 1 |
| HD 15558 | −5.43 | 2 | 3.00 | 5 |
| HD 36486 | −6.17 | 2 | 2.30 | 3, 5 |
| HD 37041 | −8.24 | 1 | 1.70 | 1 |
| HD 37043 | −6.33 | 2 | 2.50 | 3, 4, 5 |
| HD 37468 | −8.14 | 1 | 1.30 | 1 |
| HD 47129 | −5.91 | 3 | 2.645 | 3 |
| HD 48099 | −6.02 | 3 | 3.30 | 3 |
| HD 57060 | −5.35 | 2 | 1.80 | 1 |
| HD 57051 | −5.99 | 2 | 2.30 | 5 |
| HD 75759 | −7.49 | 1 | 1.60 | 1 |
| HD 93206 | > −5.85 | 1 | 2.50 | 1 |
| HD 93205 | > −6.23 | 1 | 3.60 | 1 |
| HD 93403 | > −5.82 | 1 | 3.00 | 1 |
| HD 100213 | −7.65 | 1 | 1.80 | 1 |
| HD 135240 | −6.21 | 3 | 2.70 | 3 |
| HD 152218 | −6.93 | 1 | 3.00 | 1 |
| HD 152248 | > −5.71 | 1 | 2.65 | 1 |
| HD 152424 | −5.50 | 2 | 2.24 | 5 |
| HD 152590 | −7.36 | 1 | 2.30 | 1 |
| HD 153919 | −4.82 | 2 | 2.70 | 1 |
| HD 159176 | −6.72 | 1 | 2.60 | 1 |
| HD 165052 | −6.65 | 1 | 2.70 | 1 |
| HD 167771 | −5.74 | 3 | 2.70 | 3 |
| HD 167971 | −5.15 | 4 | 3.10 | 4 |
| HD 199579 | −6.11 | 3 | 3.30 | 3 |
| HD 206267 | −6.16 | 1 | 3.10 | 1 |
| HD 209481 | −7.16 | 1 | 2.40 | 1 |
| HD 215835 | > −5.54 | 1 | 3.35 | 1 |
| Test Stars | | | | |
| HD 46150 | −6.51 | 1 | 3.10 | 1 |
| HD 152623 | −6.25 | 1 | 3.25 | 1 |

REFERENCES.—(1) This work; (2) de Jager, Nieuwenhuijzen, and van der Hucht 1988; (3) Prinja and Howarth 1986; (4) Leitherer 1988; (5) Garmany 1988.

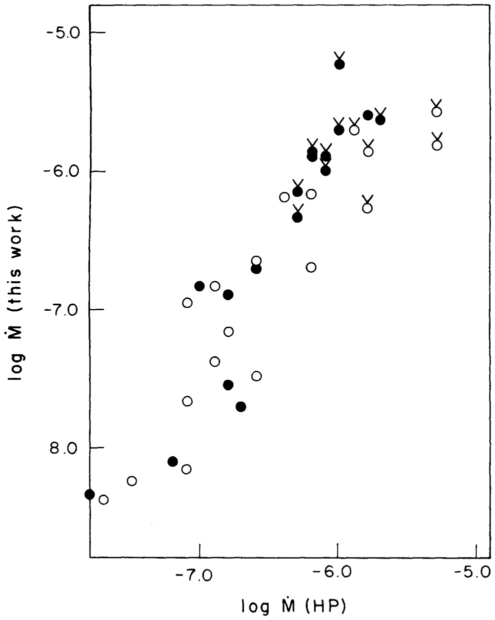


FIG. 2.—A comparison of our mass-loss determinations for the stars in common with HP. Filled circles refer to single stars; open circles refer to binaries.

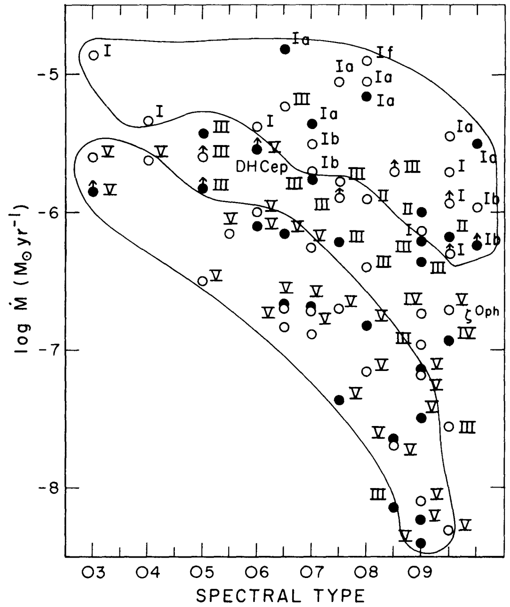


FIG. 3.—Mass loss as a function of spectral type. Filled circles are binaries; open circles are single stars. The luminosity classes of the stars are indicated, and the luminosity class V and I are enclosed, respectively.

cal point of view, there is only a remote possibility that mass-loss rates of binaries are different than those of single stars. Hutchings (1976, 1979) suggested that massive binaries have enhanced mass-loss rates although analyses of individual systems have proved inconclusive. Drechsel *et al.* (1982) found a large and variable mass loss of SV Cen (although probably a large part of the matter escapes through the outer Lagrangian point $L_3$, located close to the surface of the secondary of this contact system), whereas Howarth (1984), in an analysis of V861 Sco, could not support claims of enhanced mass loss from members of binary systems. HP also found no evidence for enhanced mass loss from binaries.

Figure 3 presents the derived mass-loss rates as a function of spectral type with different symbols for binaries and single stars. The stars are marked by their luminosity class. There is no difference in mass-loss values for single stars and binary systems. Two dwarfs are noted in Figure 3 for having larger than average mass-loss rates: one, ζ Oph, is discussed below, but the other, the very close binary DH Cep, has a bolometric magnitude −11.0, two mag brighter than the mean for O6 V stars, and an enhanced mass-loss rate. This system probably has an eccentric orbit ($e = 0.13$; e.g., Wu and Eaton 1981) but we were not able to average more than two *IUE* images for this star. The C IV line of this system is saturated, and the N V line is affected by the large Lyα interstellar absorption.

The dependence of mass loss on luminosity is shown in Figure 4, which plots log $|\dot{M}|$ versus log $L$. The solid line is the power-law dependence derived by Garmany and Conti (1984): $\log |\dot{M}| = -6.87 + 1.62 \log (L/10^5 L_\odot)$. It is clear that the dependence of mass loss on luminosity is no different for binary systems than for single stars. We have not attempted to account for the increased luminosity of the binary systems over single stars but note that summing the luminosities and mass-loss rates of two single stars will move the resultant binary father along this empirical relation. If our determinations are correct, then it appears that below log $L = 5.3$, the power-law relation changes slope, although this effect is not seen in the mass loss rates of HP.

## IV. X-RAY FLUXES FROM O-TYPE STARS

### *a) Single Stars*

According to the line radiation–driven wind theory, single, massive, hot stars emit X-rays produced in shocks that form in their winds (Lucy and White 1980; Lucy 1982). The amount of

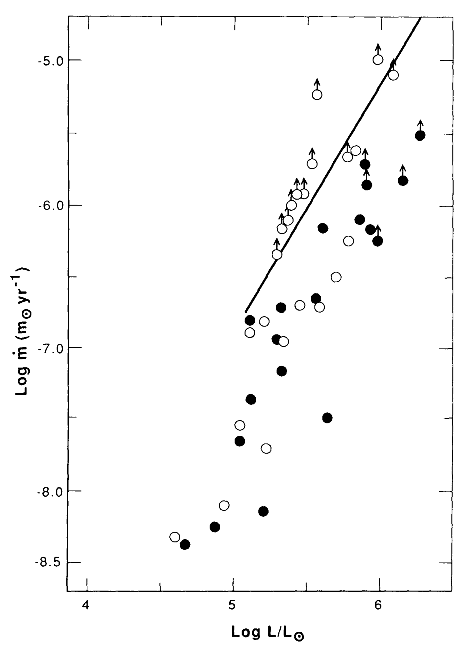


FIG. 4.—The dependence of mass loss on luminosity. Filled circles are binaries; open circles are single stars. The solid line is the relation derived by Garmany and Conti (1984).

the stellar wind X-ray (in the *Einstein* bandpass, 0.2–3.5 keV) emission should scale roughly as $\dot{M} \cdot u^2$ ($u$ is the amplitude of the chaotic velocity in the outer part of the wind) for winds of identical structure, if we assume that the X-ray self-absorption in the winds is negligible. This assumption is justified for at least less luminous O-type stars: in the IPC and SSS spectra of many O-type stars, we do not observe any significant excess of the X-ray absorption above the expected interstellar absorption. The velocity amplitude of the shocks scales as $(v_\infty)^{1/2}$ (Lucy 1982), so $L_x$ should roughly scale with $\dot{M} \cdot v_\infty$, which hereafter will be denoted $E_w$. Among the observed stars, $\dot{M}$ covers four orders of magnitude and $v_\infty$ covers only a factor of 3, so from the theoretical point of view $L_x$ should approximately scale with $\dot{M}$. On the other hand, it is well known that $\dot{M}$ scales with $\sim L_{\rm bol}^{1.6}$ (Garmany and Conti 1984; HP), and $L_x$ scales with $L_{\rm bol}$ (Harnden *et al.* 1979; Seward and Chlebowski 1982) therefore from the observational point of view $L_x$ should scale with $\dot{M}^{0.6}$.

For the 24 stars in Table 1 observed with *Einstein*, we found the relation $L_x \sim L_{\rm bol}^{1.03 \pm 0.25}$. To obtain this regression we used all the data, using upper limits for $L_x$, and the 1 $\sigma$ uncertainties are based on the bootstrap technique (Schmitt 1985) with 200 repetitions. This result agrees very well with the previously known proportionality. Figure 5 shows log $L_x$ versus log $E_w$ for the single stars in Table 5. Of 24 stars plotted in Figure 5, seven were not detected by *Einstein* and for the three we obtained only lower limits for the mass loss due to the line saturation. To fully use the information contained in these upper and lower limits, we followed Schmitt (1985) and performed the regression with doubly censored data. Using all our mass-loss data, we obtained the best power-law fit: $L_x \sim E_w^{0.34^{+0.14}_{-0.12}}$(1 $\sigma$): the dependence has less than a marginal significance, about 2.8 $\sigma$.

If we use the mass-loss rates and terminal velocities from HP for the faintest O-type dwarfs, which as already noted are larger than ours, we derive a steeper regression between the $L_x$ and log ($\dot{M} \times 0.85 v_*$). Using the singly censored data (HP give mass-loss values for all stars in our sample), the slope obtained is $0.41^{+0.13}_{-0.09}$ and the null hypothesis that $E_w$ and $L_x$ are not correlated can be rejected at a confidence level of 3.4 $\sigma$.

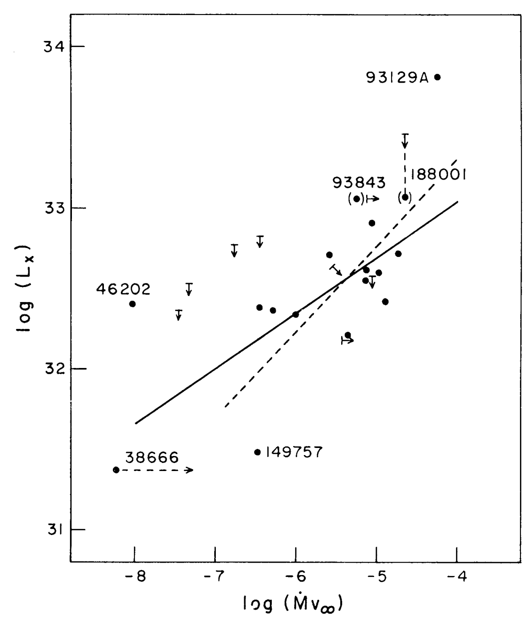


FIG. 5.—Log $L_x$ vs. log $E_w$ (see text for definition) for the single stars in Table 5. The solid line is the power-law fit to all the data; the dashed line is the fit to the stars with log $E_w > -6$.

Six stars are identified in Figure 5 which particularly affect the power-law fit. HD 93129A, the brightest star in the Galaxy, has extreme Of features and is considered to be evolving toward a Wolf-Rayet stage (Conti, Niemela, and Walborn 1979). Its X-ray flux obtained in Paper I does not account for a possible contribution from HD 93129B (O3 V), whose X-ray flux is *assumed* to be significantly smaller than the flux of the supergiant. The star 9 Sge (HD 188001) was detected at only 2.7 $\sigma$ level in Paper I, but it was detected at the 4 $\sigma$ level in the 1.0–4.5 keV energy band by Kumar, Kallman, and Thomas (1983). If we consider the 2.7 $\sigma$ detection as real, then the upper limit for 9 Sge becomes a detection as marked in Figure 5. We obtained only a lower limit for $E_w$ for HD 93843 due to the line saturation. However, HP's mass-loss value is very similar to our lower limit. If we replace this limit by $E_w$ derived from HP's mass-loss rate, then the star's position shifts slightly to the left, as shown.

Our mass loss for $\mu$ Col is the lowest among all O-type stars ($-\dot{M} \approx 5 \times 10^{-9}$ $M_\odot$ yr$^{-1}$). Olson and Castor (1981) derived log $|\dot{M}| = -7.35$, shown by the arrow in Figure 5, while HP's value is $-7.8$. The mass-loss rate of $\zeta$ Oph (HD 149757) is also extremely uncertain. We have adopted Prinja and Howarth's (1986) result which is smaller than the rate from the compilation of Lamers (1981), or Garmany (1988). But a radio upper limit obtained by Bieging, Abbott, and Churchwell (1989) is still smaller, log $|\dot{M}| < -6.78$ $M_\odot$ yr$^{-1}$. HP give log $|\dot{M}| = -7.2$ for this star. The last extreme is HD 46202, which has almost undetectable N V P Cygni resonance lines and a relatively large X-ray flux. HP also obtained a very small $\dot{M}$ for this star, but almost an order of magnitude larger than we did. There is no evidence in the literature that this star is a binary (see, e.g., Ogura and Ishida 1981; Pérez, Thé, and Westerlund 1987), although it might be face-on.

Let us consider the effect of removing selected stars from the fit $L_x \sim E_w^{0.34^{+0.14}_{-0.12}}$. Without HD 93129A the slope is 0.28; without HD 46202, it is 0.46. We have already noted that our smallest mass-loss rates are systematically lower than in HP. If we therefore reject the four stars in Figure 5 with log $E_w < -7$ from the regression analysis, then the power-law dependence becomes $0.53^{+0.19}_{-0.16}$ and 3.0 $\sigma$ confidence.

It is interesting to note that all stars located to the right of this fit line are either runaway stars and/or extreme Of stars (HD 151804). The Of and runaway stars form a right envelope in the plot presented in Figure 5. This suggests either that the efficiency of the X-ray production mechanism is smallest for Of and runaway stars or that any additional mechanisms generating X-rays are relatively ineffective. Their relatively low X-ray fluxes suggest that another mechanism of X-ray generation may be working in the winds of some stars, above the expected shocked wind emission, which is assumed to be present in Of and runaway stars. Chlebowski (1984, 1989) have suggested that perhaps there are remnants of protostellar condensations surviving deep in the winds for at least a part of the stellar lifetime, and interaction of the wind with such slowly destroyed condensations would contribute to the overall X-ray emission of some young, hot stars. Such condensations should be destroyed in the more massive winds but can survive quite a long time close to the less luminous stars (Shull and Chlebowski 1991).

If X-rays are enhanced by such a process than all runaway stars (which have left their environment when ejected from the parent association) should have smaller X-ray flux for a given wind energy. X-rays would be produced only in the shocked wind, according to Lucy's (1982) theory, and $L_x$ should scale with $E_w$. We note here that the weakest X-ray–detected stars ($\mu$ Col and $\zeta$ Oph) are runaway stars.

There are several reasons to expect that the stars with very small $E_w$ will obscure any $L_x$ versus $E_w$ dependence. There are both theoretical arguments (Abbott 1988, and private communication) and observational evidence that $v_\infty$ (and $v_\infty/v_{esc}$) dramatically decrease for luminosities smaller than $2 \times 10^5$ $L_\odot$. Also, for the faintest stars, the relation between $L_{bol}$ and $\dot{M}$ may break down, as shown in § III. Finally, as noted above, the mass-loss rates of less luminous stars are much more uncertain than those of more luminous stars (Garmany *et al.* 1981).

On the other hand, for more massive stars, X-ray self-absorption starts to play a role. Without knowing where most of the X-rays originate, it is hard to estimate for what mass-loss rates the X-ray self-absorption starts to be significant. Olson and Castor (1981) have shown that the optical depth $\tau(0.5$ keV) between the stellar surface and infinity for $\zeta$ Pup ($|\dot{M}| = 5 \times 10^{-6}$ $M_\odot$ yr$^{-1}$) $\approx 30$. If most of the X-rays originate at $R = 10 \times R_*$, then $\tau$ between this depth and the infinity will be of the order of 3, depending on the velocity law. From this simple approximation one can see that the X-ray self-absorption starts to be important for the stars losing mass at a rate comparable to that of $\zeta$ Pup (log $E_w \approx -5$).

It should be noted that no theoretical explanation has been given for the observed proportionality between $L_x$ and $L_{bol}$. The relation $L_x \sim E_w^{0.53}$ obtained above for the reliable mass-loss values may be at least a partial explanation of this dependence. Similar regression between $L_x$ and $\dot{M}$ (with the four lowest mass-loss stars rejected) gives the exponent $0.46^{+0.23}_{-0.14}$. If $\dot{M} \sim L_{bol}^{1.62}$ (or 1.69, as shown by HP) then we should expect $L_x \sim L_{bol}^{(0.75-0.78)+0.37}_{\phantom{(0.75-0.78)}-0.23}$, which is within 1 $\sigma$ of the observed proportionality between $L_x$ and $L_{bol}$ although the uncertainties are lower limits since we did not allow for errors in the $\dot{M}$ versus $L_{bol}$ relation.

### *b) Binaries*

It was shown in Paper II that the mean $L_x/L_{bol}$ of massive binaries is larger than the same ratio for single stars. Another result of that paper was that this excess is exhibited mainly by close binaries with the orbital periods shorter than 16 days. Here we show further that this enhancement is even better defined as a function of mean distance between the stars. Figure 6*a* shows the dependence of log ($L_x/L_{bol}$) on the mean distance between the stars expressed in units of the sum of the components' radii, and Figure 6*b* shows the dependence of log ($L_x$). The plots contains all massive systems observed with the *Einstein* satellite. Three more stars not observed with *IUE*, namely EM Car, RY Sct, and HDE 228766, have been added, and definite and probable nonthermal emitters have been rejected (see Paper II). See Bieging, Abbott, and Churchwell (1989) for a review of nonthermal emitters among the O-type stars. The stars included in Figure 6 are listed in Table 7, along with references. For the contact binaries we adopted $A/(R_1 + R_2) = 1$. For other stars the results from the references are used, or $A$ and radii have been calculated assuming equal masses, effective temperatures, and radii (or luminosities) of the components. The masses were obtained from a comparison of luminosity and $T_{eff}$ with evolutionary tracks of Meader and Meynet (1987). DH Cep and HDE 228766 need a comment: the discussion of Wu and Eaton (1981) suggests that DH Cep is not a contact binary, in spite of a very tight orbit ($P_{orb} = 2.11$ days), so for this system we adopt $A/(R_1 + R_2) = 1.1$. Similarly with HDE 228766: based on Massey and Conti's (1977) analysis, we adopted 1.2 for this system.

Figure 6 suggests that the mean distance between the components is an even more precise determinant of the excess X-ray flux than the orbital period (Chlebowski 1989). At least three out of four contact systems do not have enhanced emission (UW CMa, AO Cas, and RY Sct), and neither do the systems with mean distances larger than $5.5(R_1 + R_2)$. Excluding the four contact systems, we ran the regression analysis for all data points (including upper limits in $L_x$ and $L_x/L_{bol}$ and the lower limit for the period of $\sigma$ Ori A) and concluded that we can reject the null hypothesis that log ($L_x$) and log ($L_x/L_{bol}$) do

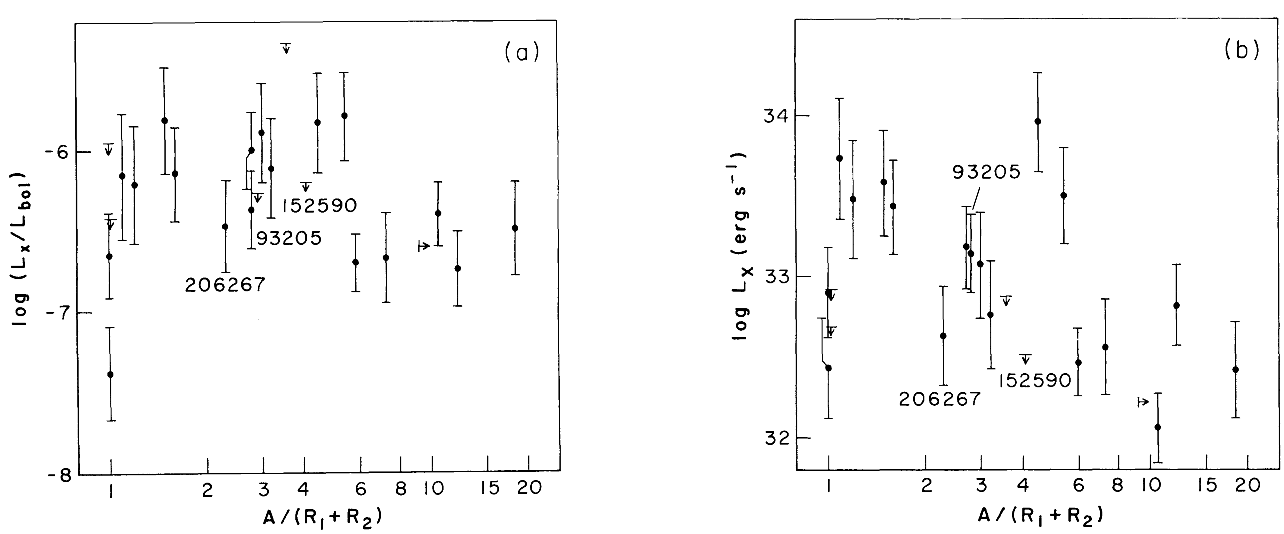


FIG. 6.—(*a*) log ($L_x/L_{bol}$) vs. the logarithm of the mean separation of the binary systems listed in Table 7, and (*b*) log ($L_x$) versus the logarithm of the mean separation of the binary systems in Table 7.

TABLE 7

MEAN DISTANCES OF BINARIES COMPONENTS

| HD | Name | $\frac{A}{R_1 + R_2}$ | Assumptions | Reference to Orbit |
|---|---|---|---|---|
| HD 1337 ............. | AO Cas | 1.0 | ... | 1 |
| HD 12323 ............. | ... | 3.6 | $M_1 = M_2 = 15\ M_\odot$ | 2 |
| HD 37041 ............. | $\theta^2$ Ori A | 10.6 | $M_1 = M_2 = 17\ M_\odot$ | |
| HD 37043 ............. | $\iota$ Ori | 5.9 | $M_1 = M_2 = 23\ M_\odot$ | 3 |
| HD 37468 ............. | $\sigma$ Ori A | >9.3 | $M_1 = M_2 = 20\ M_\odot$ | |
| HD 47129 ............. | Plaskett's | 5.4 | $M_1 = M_2 = 60\ M_\odot$ | 4 |
| HD 48099 ............. | HR 2467 | 2.9 | ... | |
| HD 57060 ............. | UW CMa | 1.0 | ... | 5 |
| HD 57061 ............. | $\tau$ CMa | 12.1 | $M_1 = M_2 = 38\ M_\odot$ | |
| HD 75759 ............. | HR 3525 | 7.3 | $M_1 = M_2 = 30\ M_\odot$ | |
| HD 93205 ............. | ... | 2.8 | $i = 50°$ | 6 |
| HD 93206 ............. | QZ Car | 1.6 | ... | 7 |
| HD 93403 ............. | ... | 4.5 | $M_1 = M_2 = 57\ M_\odot$ | |
| HD 97484 ............. | EM Car | 1.5 | $i = 70°$ | 8 |
| HD 100213 ............ | TU Mus | 1.0 | ... | 9 |
| HD 152218 ............ | ... | 3.2 | $i = 60°$ | 10 |
| HD 152590 ............ | ... | 4.1 | ... | 11 |
| HD 159176 ............ | HR 6535 | 3.0 | ... | 12 |
| HD 165052 ............ | ... | 2.8 | $M_1 = 30\ M_\odot$ | 13 |
| HD 169515 ............ | RY Sct | 1.0 | ... | 14 |
| HDE 228766 .......... | ... | 1.2 | ... | 15 |
| HD 199579 ............ | ... | 18.5 | $M_1 = M_2 = 26\ M_\odot$ | |
| HD 206267 ............ | HR 8281 | 2.3 | $M_1 = M_2 = 33\ M_\odot$ | |
| HD 215835 ............ | DH Cep | 1.1 | $i = 50°$ | 16 |

REFERENCES.—(1) Schneider and Leung 1978; (2) Bolton and Rogers 1978; (3) Stickland 1987; (4) Hutchings and Cowley 1976; (5) Leung and Schneider 1978; (6) Conti and Walborn 1976; (7) Leung, Moffat, and Seggewiss 1979; (8) Solivella and Niemela 1986; (9) Andersen and Grønbech 1975; (10) Hill, Crawford, and Barnes 1974; (11) Gieseking 1982; (12) Lloyd Evans 1979; (13) Morrison and Conti 1978; (14) Milano *et al.* 1981; (15) Massey and Conti 1977; (16) Theokas *et al.* 1985.

not correlate with log (mean distance) at the marginal confidence level of 99.1% and 97.5%, respectively.

Among all tight, detached binaries [those with $A < 5.5$ $(R_1 + R_2)$] three systems (HD 93205, HD 152590, and HD 206267) exhibit insignificant excess on both Figures 6*a* and 6*b*. It is interesting to note that these three systems are the only three tight binaries that possess significant eccentricity (larger than 4 $\sigma$; the eccentricity $e = 0.13$ found for DH Cep by Pearce [1949] was never confirmed). This is unlikely to be a possible selection effect due to the time of the X-ray observations. HD 93205, with the largest eccentricity among the tight binaries ($e = 0.49 \pm 0.03$; Conti and Walborn 1976) was observed 4 times with the HRI (see Seward and Chlebowski 1982) at different orbital phases (0.01, 0.15, 0.45, and 0.76) and did not show any signs of significant variability. More important, these three systems represent the binaries with the largest differences between the components in our sample.

It was shown in Paper II that for normal, single stars the mean log $L_x$ equals $-6.49 \times \log L_{\rm bol}$; using the new BC scale, this standard factor is $-6.55$. Figure 7 shows the dependence of an excess X-ray flux (above this mean value) versus the kinetic energy of the wind ($L_w = \frac{1}{2}|\dot{M}|v_\infty^2$) for all tight binaries that were observed with the *IUE* and whose mass-loss parameters have been determined. When plotting uncertainties we assume $\Delta \log (L_{\rm bol}) = 0.2$ and $\Delta \log (L_w) = 0.3$. For the systems with observed $L_x$ smaller than expected from single stars, we adopted an excess $L_x$ of less than 10% observed $L_x$. We realize that $v_\infty$ is not a precise measure of the wind velocity between the binary components, but assuming that the wind velocity laws are similar for the stars analyzed here, we use it as a scaled first approximation of colliding winds' velocity. According to current theories of stellar winds (Pauldrach, Puls, and Kudritzki 1986) the wind velocity at the typical shock distance (produced by the colliding winds) $r = 3R_*$ equals about $0.7v_\infty$.

We should expect that the X-ray flux scales with $L_w$, if the former is produced by colliding winds. Here we assume that

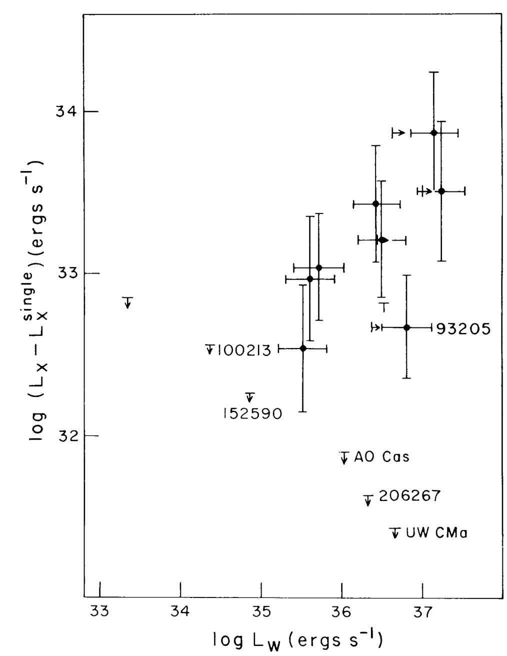


FIG. 7.—The excess X-ray luminosity of binaries above the expected $L_x$, obtained assuming that $\log L_x = -6.55 \log L_{\rm bol}$, as a function of their wind energy.

both components are losing mass at the same rate. Figure 7 confirms our expectations: if we exclude the contact systems (marked by their names) in which the winds do not collide, the general result is that only the stars with large $L_w$ have a noticeable excess X-ray flux. The relatively small number of stars makes this difficult to quantify, but we can estimate that between $4 \times 10^{-5}$ (for HD 206267) to $2 \times 10^{-3}$ (for HD 159176 and HD 165052) of $L_w$ is converted to the observed X-rays. The smallest efficiency of the X-ray flux generation for a given wind energy is found for HD 93205 and HD 206267. These two systems (and possibly the single-line binary HD 152590) exhibit the largest difference between the derived spectral types of the primary and secondary components, compared to all other binaries in our sample. For HD 93205 the spectral types are O3 V + O8 V (Conti and Walborn 1976) and for HD 206267 they are O6.5 V((f)) + O9 (Walborn 1973; Crampton and Redman 1975). To test our hypothesis that differences in the components affect the production of the excess X-ray flux, we have searched the literature to determine the luminosities of both components of each system. For eight stars, $\Delta M_{bol}$ was estimated, and we adopted $\Delta M_{bol} > 1.2$ for HD 152590 since the lines of the secondary are invisible in this system's spectrum. Figure 8 shows the difference in $M_{bol}$ between the components versus log $(L_x/L_{bol})$. Enhanced X-rays are found in binaries with equal luminosities, and for the systems with $\Delta M_{bol} > 0$, the primary component's wind overwhelms the secondary's wind and the collision is less violent.

Using a simple model of colliding winds from Prilutskii and Usov (1976), one can show that the efficiency of the X-ray generation due to collision of two winds in a binary system scales roughly as $\beta^3/(1-\beta)^4$, where $\beta = \dot{M}_2 v_2/(\dot{M}_1 v_1 + \dot{M}_2 v_2)$ and $\dot{M}_2$ and $v_2$ are less massive wind parameters. So the excess $L_x$ falls dramatically when $\beta$ departs from 0.5. For the three discussed systems (HD 93205, HD 206267, and HD 152590) the bolometric luminosity ratios for the binary components are approximately 10, 4, and at least 3 for the above systems, respectively. Using Garmany and Conti's (1984) $\dot{M}(L)$ relation, we can expect that an excess X-ray luminosity from these three systems will be at least an order of magnitude smaller than the excess $L_x$ for the binaries with $\beta = 0.5$. This also explains why the efficiency of the X-ray generation is smallest in these systems (Figs. 6 and 7). If we reject these three binaries and repeat the correlation analysis for the data presented in Figure 6, we obtain better correlations: log $(L_x)$ and log $(L_x/L_{bol})$ correlate with log $[A/(R_1 + R_2)]$ at the level 99.6% and 99.2%.

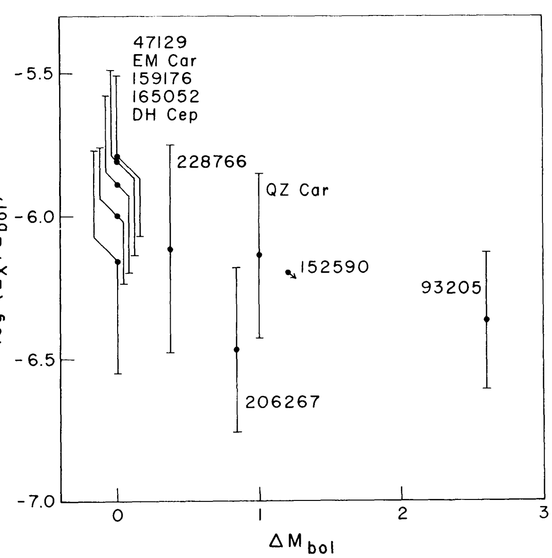


FIG. 8.—Log $(L_x/L_{bol})$ vs. the difference in $M_{bol}$ between both components of the binary systems.

We conclude that the enhancement of X-rays appears in the tight, detached binaries, whose components are of similar luminosity and are closer to each other than about 5 times the sum of their radii. The most natural interpretation of this dependence is that the excess X-ray emission is caused by colliding stellar winds.

There have been several attempts to estimate an expected X-ray flux from colliding stellar winds in massive binaries (e.g., Prilutskii and Usov 1976; Cooke, Fabian, and Pringle 1978). These theories result in much larger X-ray fluxes than those observed. The differences are between a factor of 4 (HD 159176, HD 165052) to almost a factor of 1000 (almost contact system DH Cep). The differences are probably caused by oversimplification of the estimates: stellar winds are probably not equal in most cases (which significantly decreases the expected X-ray flux) and the models do not take into account self-absorption of the X-rays. Additionally, *Einstein*-measured fluxes cover a relatively small range of energies (0.2–4.0 keV), while colliding winds with velocities of the order of 2000 km s$^{-1}$ will form a shock with the temperature in excess of 5 keV, and its X-ray radiation could be only partially detected by *Einstein*. If the X-rays from colliding stellar winds are produced via higher temperature thermal bremsstrahlung then their IPC and SSS spectra should mimic power-law shapes. This, or just higher temperatures derived from thermal spectra, may be another test confirming the production of the X-ray excess in the colliding stellar winds.

## V. CONCLUSIONS

We have searched for the dependence expected between stellar wind parameters and their X-ray fluxes. As mass loss depends on stellar radius, which is computed from the bolometric luminosity, we have examined bolometric corrections as a function of temperature. The new non–LTE model stellar atmospheres presented recently predict an almost linear correlation between the logarithm of the effective temperature and the bolometric correction, independent of the luminosity class. We propose a bolometric luminosity scale for the O type stars. It is not drastically different from the commonly used scales of Schmidt-Kaler (1982) and Humphreys and McElroy (1984).

To enlarge the sample of stars with known mass loss, we measured new mass-loss rates and terminal velocities of 40 well-known, bright single stars or binaries, mostly observed with the *Einstein* satellite. Moreover, for almost all stars we modeled the Ly$\alpha$ profile in order to determine the amount of X-ray–absorbing hydrogen with the greatest possible accuracy.

The mass-loss rates found for the latest O type dwarfs are significantly smaller than expected from the power-law dependencies known for brighter, hot stars. This problem should be addressed in the future since large differences of mass-loss rates obtained by different investigators suggest inaccuracies in the current method of mass-loss estimates for the late O type dwarfs. We find that the mass-loss rates of binary systems do not differ significantly from those of single stars, despite some earlier claims in the literature.

We find a dependence between the wind energy of the single stars and the X-ray luminosity and suggest that this dependence is at least partially responsible for the proportionality between $L_x$ and $L_{bol}$.

The X-ray fluxes from the close binaries behave in qualitative agreement with predictions from simple theories of colliding stellar winds. None of the contact binaries exhibit any enhanced X-ray flux, since their winds do not collide in a classical sense. The largest X-ray luminosity excess is found for the massive, very tight but detached binaries, where the effect of wind collision is expected to be largest; the excess is smallest for systems whose components significantly differ in luminosity, also in agreement with expectation that when a more massive wind overwhelms the wind of a less luminous star, the effect of the collision should be much smaller. The observed X-rays are smaller then expected from the simplest estimates, and it will be very interesting to compare those observations to two-dimensional hydrodynamical simulations, taking into account self-absorption and other effects influencing observability of the produced X-ray flux.

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