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X-ray properties of bright OB-type stars detected in the ROSAT all-sky survey

T.W. Berghöfer[1,2]⋆, J.H.M.M. Schmitt[1], R. Danner[1,3], and J.P. Cassinelli[4]

[1] Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstr, 1, D-85740 Garching, Germany
[2] Center for EUV Astrophysics, 2150 Kittredge Street, University of California, Berkeley, CA 94720, USA
[3] Division of Physics, Mathematics, and Astronomy, Caltech 105-24, Pasadena, CA 91125, USA
[4] University of Wisconsin - Madison, Department of Astronomy, 475 North Charter Street, Madison, WI 53706-1582, USA

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Abstract. The ROSAT all-sky survey has been used to study the X-ray properties for all OB-type stars listed in the Yale Bright Star Catalogue. Here we present a detailed astrophysical discussion of our analysis of the X-ray properties of our complete sample of OB-type stars; a compilation of the X-ray data is provided in an accompanying paper (Berghöfer, Schmitt & Cassinelli 1996).

We demonstrate that the "canonical" relation between X-ray and total luminosity of $L_x/L_{Bol} \approx 10^{-7}$ valid for O-type stars extends among the early B-type stars down to a spectral type B1–B1.5; for stars of luminosity classes I and II the spectral type B1 defines a dividing line for early-type star X-ray emission.

We discuss the X-ray properties of X-ray detected B2-B9 stars (LC III–V) in the context of possible companions.

We also compare our results to the results obtained from *Einstein Observatory* data and ROSAT pointed observations. We show for our sample of stars that X-ray variability is generally not common for O-type stars as well as early B-type stars.

Key words: stars: early-type – X-rays: stars – stars: mass loss

1. Introduction

X-ray observations of stars clearly showed the presence of stellar X-ray emission over almost the entire Hertzsprung-Russell diagram. In addition to stars of late spectral type, which constitute the bulk portion of stellar X-ray emitters, early-type stars are also known as a separate class of soft X-ray emitting stars. After the first discovery of X-ray emission from O-type stars (Seward *et al.* 1979 , Harnden *et al.* 1979) with the *Einstein Observatory* almost all bright O-type stars have subsequently been observed with the *Einstein Observatory*. O-type stars emit $\approx 10^{-7}$ of their total luminosity in the soft X-ray band (Seward *et al.* 1979, Pallavicini *et al.* 1981, Chlebowski *et al.* 1989, Sciortino *et al.* 1990). However, the scatter for values of individual stars, 2 orders of magnitude, around the mean value is quite large. The widely accepted model for the X-ray emission from O stars assumes that it is produced by shock-heated gas propagating in the strong winds of these stars. In a phenomenological model Lucy & White (1980) and Lucy (1982) postulate the existence of shocks in the radiation driven winds of hot stars which are formed as a consequence of a strong hydrodynamic instability (e.g., Lucy & Solomon 1980). Hydrodynamical calculations for hot star winds (e.g., Owocki, Castor & Rybicki 1988) provide strong support for such a model. The base corona source of X-ray emission - prior to the launch of the *Einstein Observatory* - proposed by Cassinelli & Olson (1979) to explain the superionisation in hot star spectra, led to the correct prediction of the X-ray emission of early-type stars, but cannot explain their X-ray spectra. One argument against the coronal idea is that there are no convection zones in the hot stars that would provide mechanical energy for the heating of coronae. On the other hand, there are observations indicating connections between the optical variability of photospheric features and the UV variability of discrete absorption components (DACs) in lines formed in the winds of some hot stars (Prinja & Howarth 1988). So the most important argument against a coronal origin for the X-ray emission is that the soft X-ray flux would be absorbed by the overlaying wind layers, and such absorption is not seen. MacFarlane *et al.* (1993) studied observational constraints on a coronal model for the prototypical O-type star ζ Puppis. They found that the wind mass lass rate would need to be reduced to a third of the lowest observational estimate in order for the base coronal model to provide an adequate fit to the UV wind lines and X-ray spectrum. Another piece of evidence comes from the analysis of the ROSAT PSPC spectrum of ζ Puppis (Hillier *et al.* 1993). Hillier *et al.* showed that the X-ray spectrum of ζ Puppis can be explained by a distribution of X-ray sources throughout the cool "self absorbing wind". So at least for the O-type stars with thick winds, source models with shocks embedded in the wind provide the best explanation for the X-ray emission.

Send offprint requests to: T.W. Berghöfer
⋆ *On the leave to: Center for EUV Astrophysics*

One would expect the soft X-ray emission of early-type stars to be variable, as variability has been seen at almost all other wavelength and as the supersonic wind flow is intrinsically unstable (cf. Owocki 1992). However, time variability studies with ROSAT have shown that X-ray time variability of hot stars is not common (Berghöfer & Schmitt 1994a 1994b 1994c 1995). So far, only in the case of the O supergiant ζ Orionis a moderate increase in X-ray count rate by $\approx$ 20% over 2 days has been found and could be explained by an extraordinarily strong shock wave propagating in the wind of this star. Recently, Berghöfer *et al.* (1996) found evidence for correlated variability in the X-ray and Hα emission from the O-type star ζ Puppis which is attributed to a modulation of the wind density extending to the lower X-ray emitting wind layers and consequently modulating the emitted X-ray flux. Note that the amplitudes of the observed X-ray variations are small and amount to only $\pm$6% in the X-ray band pass between 0.9 and 2.0 keV.

In addition to O-type stars a small number of B-type stars has been identified with X-ray sources detected in the *Einstein Observatory* archival data (Grillo *et al.* 1992). However, the obtained detection rate was less than 5% and the inhomogeneous sample did not allow an in-depth study of the X-ray properties of B-type stars. Cassinelli *et al.* (1994) and Cassinelli & Cohen (1994) began to investigate B-type star X-ray emission with ROSAT observations in a more systematic way. They find a drop in X-ray luminosity for 12 nearby near-main-sequence B-type stars of spectral type later than B1–B1.5. Conversely, B-type stars of earlier spectral type show X-ray properties typically observed in O-type stars. They argue that lower X-ray luminosities are consistent with vanishing stellar wind activity in later B-type stars. However, a definite model for B-type star X-ray emission is so far not present and it is yet not clear whether a model of X-ray emitting shocks in the stellar winds – as in the case of O-type stars – is the only model that is applicable to B-type stars and contains all relevant physical processes.

Concerning the X-ray emission of early-type stars there are various open items that we want to address with the here presented study of early-type stars detected in the ROSAT all-sky survey:

- How far does the "canonical" relation between X-ray and total luminosity ($L_x/L_{Bol} \approx 10^{-7}$) extend among B-type stars?
- What can explain the large scatter in this relation?
- Are late B-type stars soft X-ray emitters?
- Do early-type stars show long-term X-ray variability?

2. Observational summary

We investigated the ROSAT all-sky survey (RASS) data to study the X-ray properties of early-type stars. In an accompanying catalogue paper (Berghöfer, Schmitt & Cassinelli 1996) we provide a compilation of the X-ray properties for our program stars and describe in detail our method to extract the X-ray data from the RASS. The purpose of this paper is to provide a detailed astrophysical discussion of the results.

First we want to summarize the results of our catalogue paper (Berghöfer, Schmitt & Cassinelli 1996). We define the OB-type stars listed in the Yale Bright Star Catalogue (Hoffleit & Warren 1991) as our base optical sample. This sample of 1838 OB stars is complete to the limiting magnitude of V = 6.5. In the RASS data we searched for counterparts of our program stars. Since the sky coverage of the RASS data is almost complete (99%), the sample of RASS detected OB star is only X-ray flux limited and allows for the first time to study the X-ray properties of OB-type stars on the basis of a complete sample of stars. Only 16 of our sample stars are not covered by any RASS observations and, therefore, had to be removed from further analysis. Since there are no plans for further satellite missions to perform an all-sky survey in the soft X-ray spectral range, the results presented here will be definitive for a long time to come.

Our criteria for an identification of an X-ray source with the respective sample star are a) the X-ray count rate exceeds the X-ray background level by more than 3 σ and, b) the offset between the X-ray and optical source position is below 75″. In the case of 21 OB-type stars we detected an X-ray source at a distance between 75–150″(cf. Berghöfer, Schmitt & Cassinelli 1996). Since the X-ray properties of these stars do not differ from the other (secure) identifications, we also include these 21 OB stars to the sample of detections. We identified a total of 237 out of 1822 OB sample stars (covered by RASS observations) with an X-ray source corresponding to a mean detection rate of $\approx$13%. For a detailed discussion of the detection rate we refer to Section 3.

For all detected stars we determined the respective X-ray count rate and hardness ratio from the RASS data; for the undetected stars we derived an upper limit for their X-ray count rates. In contrast to Table 3 in Berghöfer, Schmitt & Cassinelli (1996) giving the upper limits computed as a 3 σ upper limit above the respective background level, we here used a minimum number of 5 counts to compute upper limits. The hardness ratios which compare the source counts detected in the hard (0.5–2.0 keV) and soft (0.1–0.4 keV) energy band of the ROSAT PSPC were used to estimate the X-ray temperatures and an energy conversion factor to convert the observed count rates in fluxes. For a detailed description we again refer to Berghöfer, Schmitt & Cassinelli (1996).

Please note that the X-ray fluxes and X-ray luminosities reported in Table 2 and 3 in Berghöfer, Schmitt & Cassinelli (1996) are not dereddend (as claimed in the table headings). In order to compute the appropriate dereddened flux and luminosity values of individual stars we present a correction method in Berghöfer, Schmitt & Cassinelli (1997). However, the here presented paper bases on the corrected, properly dereddend X-ray fluxes and luminosities.

3. Detection rate

Since our sample of detected OB-type stars is flux limited in both X-ray flux and optical brightness, we need to investigate the detection rate in more detail. The relatively short RASS exposure times of typically 500 s restrict source detection to X-ray

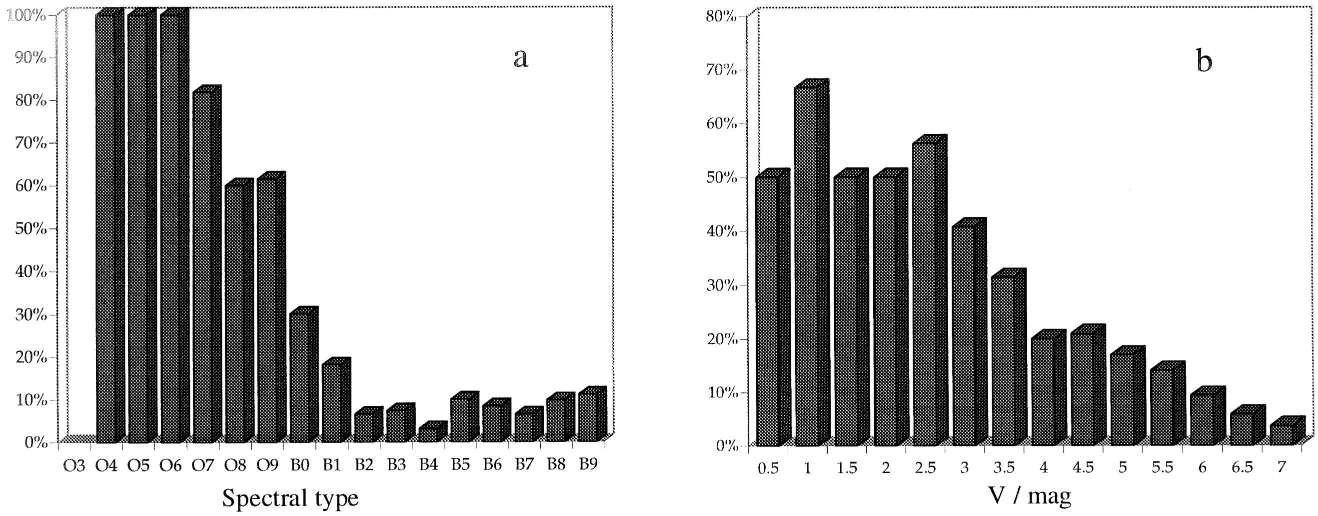

Fig. 1a and b. Histograms of the detection rate as a function of spectral types **a** and V magnitudes **b**.

sources with count rates $\gtrsim 0.02$ cts/s corresponding to a minimum X-ray flux of $\approx 2 \times 10^{-13}$erg s^{-1}cm^{-2}. Given the known "canonical" relation $L_x \sim 10^{-7} \times L_{Bol}$ the detection rate is expected to depend on spectral type and apparent visual brightness (respectively the distance) of the stars. These expectations are confirmed by Fig. 1, where we plot the detection rate (in percent) as histograms of the stars' spectral types and V magnitudes.

All O-type stars earlier than O7 listed in the Yale Bright Star Catalogue were detected in the RASS. Towards later O and early B-type stars the detection rate continuously decreases and amounts to only 6.5% in the case of B2 stars. In the spectral range B3–B9 between 3% (B4) and 11.2% (B9) of the Bright Star Catalogue stars have been found in the RASS. The detection rate also shows a significant decrease with visual brightness. For $V \leq 2.5$ at least every second OB-type star has been detected, whereas towards optically fainter stars the detection rate continuously decreases.

4. Data quality

4.1. Comparison: RASS vs. ROSAT pointed observations

In order to compare the RASS data with its relatively short exposure times of typically 500 s, to the longer exposed ROSAT pointed observations, we selected all of our program stars also observed during the ROSAT pointing program and determined their X-ray count rates by analyzing ROSAT archival data. For a detailed description of the selection and reduction of the observations we refer to Danner (1996). In Fig. 2 we compare for these stars the PSPC count rates during the RASS to those observed during the later pointing program of ROSAT. As is clear from Fig. 2, almost all O and early B-type stars show about the same count rate during RASS and pointing. Larger variability can only be found for some late B-type stars of spectral types B6–B9, which might indicate a principle difference for the X-ray emission of late B-type stars compared to the earlier spectral types. On the one hand, this finding confirms the excellent data quality of the RASS observations (note that the RASS observations have been obtained with a detector different (but very similar) from that used for the pointed observation); on the other hand, this shows on the basis of a larger number of stars that X-ray variability at least on a time scale of (1–4) years is not common for O and early B-type stars (Berghöfer & Schmitt 1994a, 1994b, 1994c, 1995).

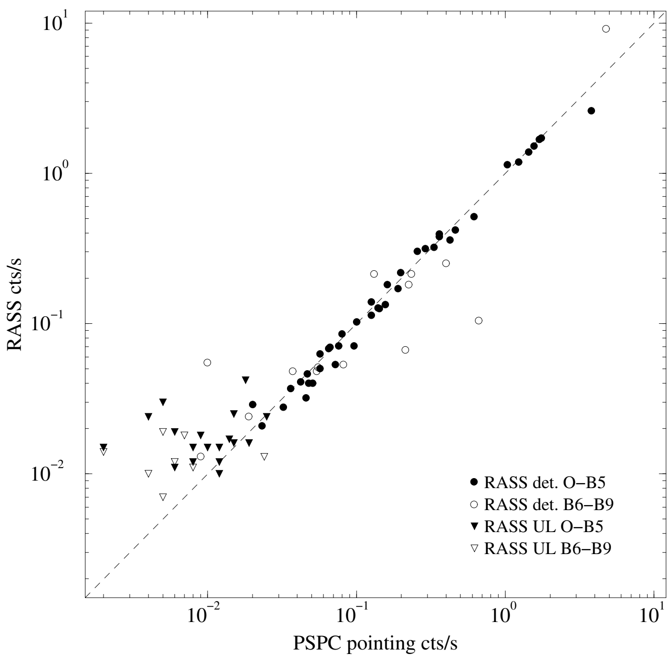

Fig. 2. Comparison between observed pointing and RASS count rates; filled circles show stars in the spectral range O–B5, open circles indicate late B-type stars of spectral type B6–B9, in the cases of RASS upper limits the respective stars are plotted with filled triangles (O–B5) or open triangles (B6–B9).

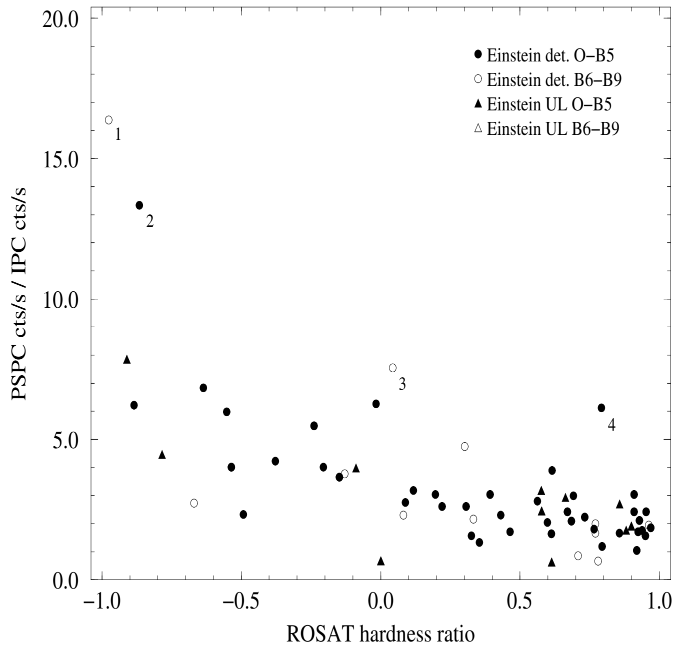

Fig. 3. Ratio between observed RASS and *Einstein* count rates as a function of ROSAT hardness ratio; triangles indicate RASS detections for which the *Einstein* data can only provide an upper limit, filled and open symbols distinguish between stars of spectral type O–B5 and B6–B9, stars showing unusually high count rate ratios are marked by numbers (see Sect. 4.2).

4.2. Comparison: RASS vs. Einstein *observations*

We now compare our results for the detected OB-type stars to those derived from the observations with the *Einstein Observatory*. In order to avoid ambiguities due to flux-conversion factors, we decided to compare the model-independent X-ray count rates. For all OB-type stars observed during both X-ray missions we show in Fig. 3 the ratios between ROSAT PSPC and *Einstein* IPC count rates plotted against ROSAT hardness ratios (HR = $(H - S)/(H + S)$); the *Einstein* IPC count rates are taken from the publications of Chlebowski *et al.* (1989) and Grillo *et al.* (1992). For the bulk portion of the stars plotted in Fig. 3 the count rate ratios are directly related to the energy dependent ratio of the effective areas of both detectors. In the case of very soft X-ray emitting OB-type stars as well as in the case of stars with low interstellar absorption column density, the higher sensitivity of the ROSAT PSPC in the soft energy range below 0.5 keV leads to higher count rate ratios.

The extremely large count rate ratios of 16.4 and 13.3 for λ Cen and λ Sco (marked with 1 and 2 in Fig. 3) suggests that these are "contaminated" by the presence of a white dwarf companion; note that it is impossible to explain such large count rate ratios between PSPC and IPC only by a low temperature thermal line spectrum. In the case of the late B-type star λ Cen (B9III), which is also detected in the all-sky survey data of the ROSAT Wide field camera (WFC) (Pye et al. 1995) and is listed in the first EUVE source catalog (Bowyer et al. 1994), a white dwarf companion provides a natural explanation for the X-ray and EUV observations. A ROSAT HRI observation centered on λ Cen confirms that the X-ray emission is associated with λ Cen. The count rate ration between PSPC and HRI of 7:1 is consistent with that measured for HZ 43. Thus the X-ray data are consistent with but cannot prove the presence of a white dwarf companion. λ Cen is known as a spectroscopic binary (Eggen 1984) with a so far unknown companion, however, the observational facts are similar to other known binary systems with white dwarfs (e.g, β Crt, an early A-type star with a white dwarf companion that also has been discovered by X-ray observations (Fleming, Schmitt, Barstow & Mittaz 1991)).

In the case of the early B-type star λ Sco, one might argue in the same way about the presence of a white dwarf companion. However, there is no other evidence for a White Dwarf and in the PSPC observation of λ Sco, Cassinelli *et al.* 1994 found the star to have spectral properties and an X-ray luminosity quite similar to other stars of that spectral type. If we consider a factor of 4–5 as a realistic conversion factor between IPC and PSPC count rates for an X-ray source with the spectral properties of λ Sco, the PSPC count rate is by a factor of 3 larger than expected for the observed IPC count rate. Since the PSPC count rates observed during the RASS and the pointing performed 6 weeks later does compare within 20% it is hard to believe that intrinsic variability can explain this large discrepancy between *Einstein* and ROSAT observations.

In Fig. 3 we also marked the data point of Algol (3) which is a spectroscopic binary system consisting of a late B primary and a co-rotating K star that is responsible for the X-ray production; a detailed discussion of this system can be found in Ottmann (1994). It is clear that the large count rate ratio between PSPC and IPC count rate is due to variability of this system and for the discussion of OB-type star X-ray emission we can ignore this case.

In the case of the B1V star 42 Ori (No. 4 in Fig. 3) the ratio between PSPC and IPC count rate is much larger than one might expect for the observed ROSAT hardness ratio. Note that 42 Ori is a rather hard X-ray source, however, the X-ray luminosity of $\log(L_x)$=30.9 derived from the RASS count rate is typical for stars of that spectral type and the RASS count rate of 42 Ori directly compares with the count rate observed in a later PSPC pointing. Additionally, the analysis of the highly resolved ROSAT HRI images of the Orion Nebula by Caillault, Gagné & Stauffer (1994) confirms 42 Ori as the optical counterpart for the observed X-ray source, thus, suggesting a long-term change in the X-ray count rate of 42 Ori by a factor of ≈ 2.

5. Analysis of the X-ray luminosities

We next turn attention to the observed X-ray luminosities and their relation to other stellar and stellar wind parameters of our program stars. As a first step we compare the observed properties for all our program stars, then we investigate luminosity class dependent properties.

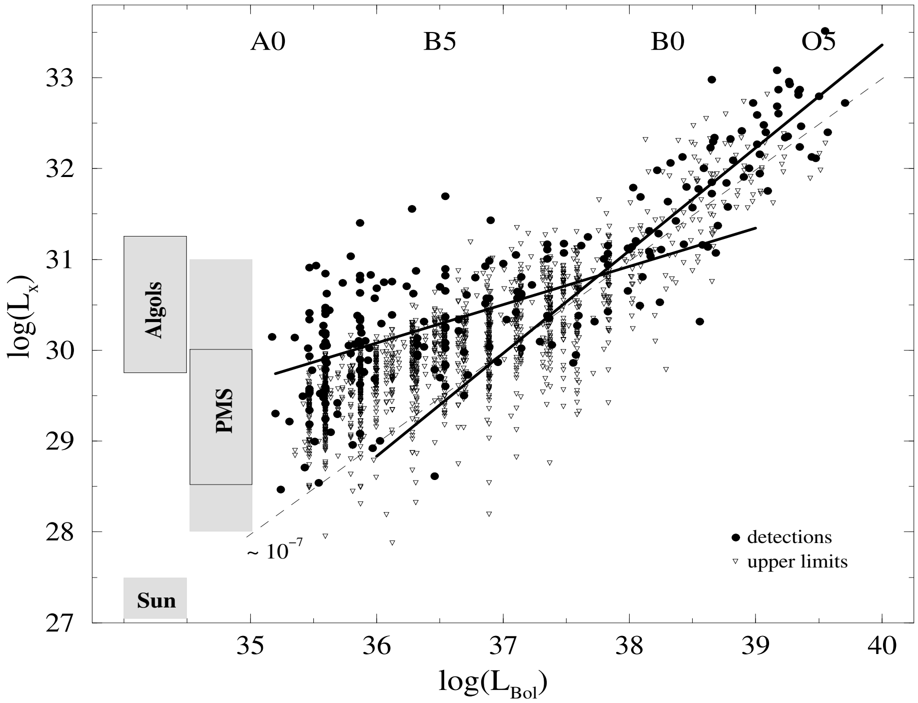

Fig. 4. X-ray luminosities L_x plotted versus bolometric luminosities L_{Bol}; solid lines represent regression lines for $L_{Bol} < 10^{38} erg\, s^{-1}$ and $L_{Bol} > 10^{38}$erg s^{-1}, whereas the dashed line shows $L_x = 10^{-7} \times L_{Bol}$, grey bars at the left side show typical ranges for the X-ray luminosity of Algol-type systems, pre-main sequence stars (PMS), and our Sun.

5.1. All stars

In Fig. 4 we plot the X-ray luminosities versus bolometric luminosity for all our program stars including the upper limits (plotted as triangles). The dashed line in Fig. 4 corresponds to the "canonical" relation $L_x = 10^{-7} \times L_{Bol}$. As is clear from Fig. 4, at least the most luminous OB-type stars ($L_{Bol} > 10^{38}$erg s^{-1}) do follow this relation on average. However, compared to their bolometric luminosities the detected late B-type stars ($L_{Bol} < 10^{38}$erg s^{-1}) show significantly larger X-ray luminosities, whereas in the case of a larger number of late B-type stars we determined upper limits well below $L_x/L_{Bol} = 10^{-7}$. In order to determine the spectral type where the "canonical" relation $L_x = 10^{-7} \times L_{Bol}$, valid for O-type stars, breaks down we performed a linear regression analysis for all detected stars with bolometric luminosities above and below $L_{Bol} = 10^{38}$erg s^{-1} separately. Considering only the detected OB-type stars the regression analysis yields the following result:

$L_{Bol} > 10^{38}$erg s^{-1}:

$$\log(L_x) = (1.13 \pm 0.10) \cdot \log(L_{Bol}) - 11.89 \pm 0.38$$
standard deviation: 0.40

$L_{Bol} < 10^{38}$erg s^{-1}:

$$\log(L_x) = (0.42 \pm 0.05) \cdot \log(L_{Bol}) - 14.87 \pm 0.46$$
standard deviation: 0.55

Both regression lines, overplotted in Fig. 4, intersect at [$\log(L_{Bol}) = 37.7$, $\log(L_x) = 30.8$]. The bolometric luminosity at this point is equivalent to a main-sequence star of spectral type B1.5V. Including the upper limits in the analysis leads to lower regression lines around $L_{Bol} = 10^{38}$erg s^{-1} with a steeper slope towards larger L_{Bol} and a flatter slope towards lower L_{Bol}. However, the L_{Bol} at the intersection of both regression lines does not change. As is evident from Fig. 4, the large number of low upper limits (compared to the L_x of the detected stars) in the range of the B-type stars is responsible for the different results with and without including the upper limits in the regression analysis. Therefore, we compared the distribution functions for the X-ray luminosity of the detected stars and the upper limits. For stars of $L_{Bol} > 10^{38}$erg s^{-1} the distribution function of the upper limits does compare with the distribution of the detections. Including the upper limits to a regression analysis lead to almost the same results as for the detected stars only. In the case of the B-type stars of $L_{Bol} < 10^{38}$erg s^{-1} the distribution function of the upper limits is by a factor of 3.5 lower than the distribution function of the X-ray luminosities of the detected stars. However, in order to include upper limits to any regression analysis, the detections and the upper limits necessarily must have about the same distribution function. Therefore, the methods provided, e.g., by the ASURV (*Astronomy SURVival Analysis*, Feigelson 1992) package cannot be used to include the upper limits to our analysis of the later B-type stars.

The main-sequence stars constitute the bulk portion of the investigated OB-type stars and therefore, Fig. 4 evidently demonstrates that the "canonical" relation between bolometric and X-ray luminosity known for the O-type stars does hold among the early main-sequence B-type stars down to a spectral type B1.5V. In the following we want to investigate whether this relation significantly differs for different luminosity classes or is typical for all stars in that spectral range.

5.2. Main-sequence stars (V) - normal giants (III)

For $L_{Bol} < 10^{38}$erg s^{-1} and $L_{Bol} > 10^{38}$erg s^{-1} and all luminosity classes separately, we tested the respective distribution

Table 1. Selected results for our statistical analysis of the relations between bolometric and X-ray luminosity.

LC	$(B-V)_0$	N	$\log(L_x/L_{Bol})$	σ	χ^2_ν	P(%)
I–II	≤ -0.20	18	-6.92	0.36	1.19	75
III–V	≤ -0.25	49	-6.81	0.38	1.63	99.5
III–V	> -0.25	170	-6.01	0.66	4.50	100

of L_x/L_{Bol}-values against the null hypothesis that the distribution is equal to that of the main-sequence stars (luminosity class V). However, our statistical tests do not provide any evidence for luminosity class dependent differences in the L_x/L_{Bol} distribution. In a next step we fitted the L_x/L_{Bol}-ratios with a Gaussian and looked for differences in the mean and dispersion of the distribution as a function of luminosity class. Table 1 summarizes our fit results and provides information on the best fit mean $\log(L_x/L_{Bol})$-value, the respective 1σ standard deviation, and the test results of a χ^2-test; column $(B-V)_0$ indicates which stars have been included to the distinct tests and P gives the probability against a Gaussian distribution for the L_x/L_{Bol}-ratios. Compared to the L_x/L_{Bol}-ratios for our sample stars of luminosity classes I–II and $(B-V)_0 \leq -0.2$ (O–B1), which can be explained by a Gaussian distribution, the O and early B-type stars of luminosity classes III–V show slightly larger $\log(L_x/L_{Bol})$-ratios and also show a larger scatter around the mean value. However, the significance for these different values is low and can be attributed to the different sample sizes. Note that the scatter (σ) in $\log(L_x/L_{Bol})$ is of the order of the errors for the individual values.

For stars of luminosity classes III–V we plot in Fig. 5 the L_x/L_{Bol}-ratios versus color index $(B-V)_0$. Compared to the hotter stars of these luminosity classes, B-type stars of spectral type later than B1.5 ($(B-V)_0 > -0.25$) obviously show a larger mean as well as a larger scatter in L_x/L_{Bol}-values. Our fits confirm that a Gaussian distribution does not provide a reasonable description of the observed L_x/L_{Bol}-ratios.

The survey of Cassinelli and Cohen (1994) indicates that the L_x/L_{Bol}-ratio decreases to values below 10^{-8} for stars of spectral type B1.5 (III–V) and later. There are many stars in Fig. 5 with $(B–V)_0 > -0.25$ with upper limits, so perhaps the intrinsic fluxes of these stars are very low and the large values indicated by the fit shown in Fig. 5 are due to companions and other causes.

However, only on the basis of the moderately resolved RASS data we cannot decide whether the observed X-ray emission in fact is produced by the respective B-type star or originates from a nearby unresolved companion. For a further discussion, Fig. 4 also provides information about typical X-ray luminosity ranges observed for possible companions. For example, Algol-type systems, consisting of an optically dominant early-type star and a co-rotating, X-ray emitting late-type star, show the largest X-ray luminosities ($\approx 10^{30} - 10^{31}$ erg s^{-1}) and L_x/L_{Bol}-ratios of typically $\log(L_x/L_{Bol}) \approx -5$. In the case of an observed X-ray luminosity of $L_x \leq 10^{30.5}$ erg s^{-1} also a young late-type star (e.g., a T Tauri star) can be responsible for the X-ray emission which is difficult to detect in the optical. Because of the small number of X-ray detected late B-type stars with $L_x \leq 10^{29}$ erg s^{-1}, X-ray emitting late main-sequence stars which can exhibit X-ray luminosities of $L_x \leq 10^{29}$ can be disregarded in that context (cf. Schmitt 1996, Schmitt, Fleming & Giampapa 1995).

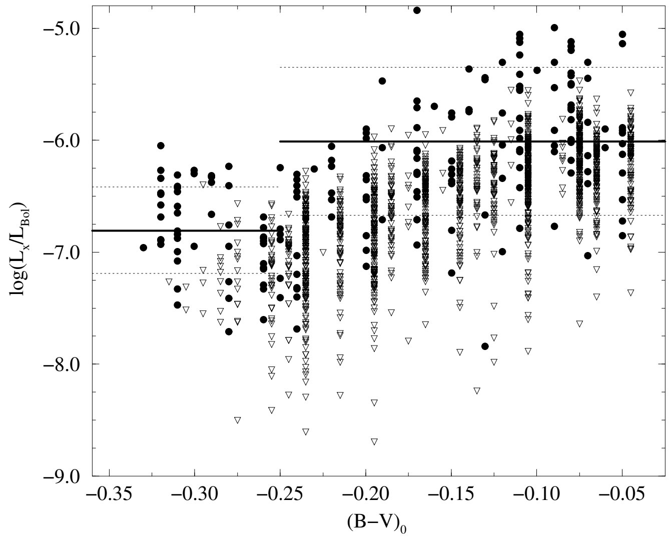

Fig. 5. Ratios between X-ray and bolometric luminosity for OB-type stars of luminosity classes III–V plotted versus intrinsic color $(B-V)_0$; for stars of spectral types O–B1.5 the solid line and the dashed lines show the mean values and standard deviations as given in Table 1.

For those RASS detected late B-type stars which are known to have visual companions and can be resolved with the ROSAT HRI (spatial resolution $\approx 5''$) we started a follow-up program with the HRI (cf. Berghöfer & Schmitt 1994e). First results show that know visual companions can be disregarded for the discussion of the X-ray detected late B-type stars. Note that in the spectral range B7–B9 ≈77% of the RASS detected stars are known spectroscopic binaries.

As in the case of data obtained with the *Einstein Observatory*, the L_x/L_{Bol}-ratios of stars of luminosity class III–V and earlier than B1.5 show a large scatter around the mean value. The formal fit results suggest that a direct relation between L_x and L_{Bol} does not exist, however, the standard deviation from the mean value is of the order of the estimated error for the calculated L_x/L_{Bol}-values.

5.3. Bright giants (II) - supergiants (I)

In Fig. 6 we show the L_x/L_{Bol}-ratios for the OB supergiants and bright giants (luminosity class I and II) as a function of color index $(B-V)_0$. Among the stars with $(B-V)_0 > -0.2$ (later than B1) only two stars have been found in the RASS data. However, in both cases, β Ori (B8Ia) and κ Cru (B5Ia), the detection is questionable. β Ori also has been observed with the PSPC during the ROSAT pointing program. The pointing centered on

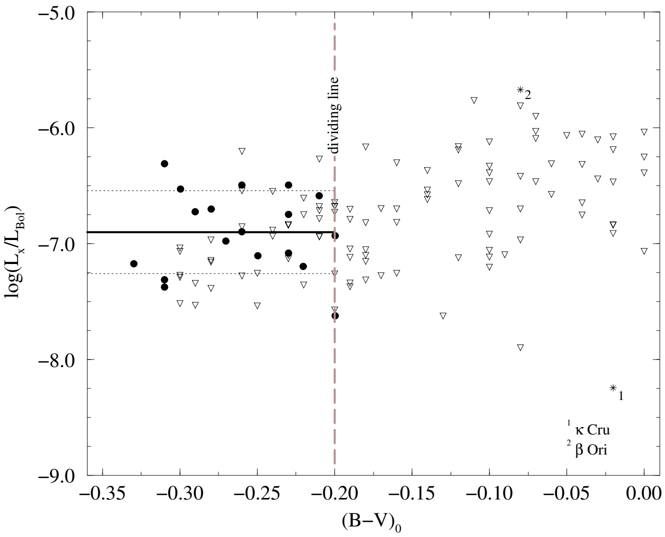

Fig. 6. Same as in Fig. 5 for OB-type stars of luminosity classes I and II ($\overline{L_x/L_{Bol}} = -6.92$, $1\sigma = 0.36$).

this star clearly demonstrates that the X-ray emission originates from a much fainter, nearby companion star (V=15.4) and not from the late B-type supergiant itself.

A recently obtained HRI observation of κ Cru definitely excludes the B5 supergiant as the source of the observed X-ray emission in the RASS. Note that κ Cru was one of our weakest detections in our sample and is based on 7 photons detected in 174 sec exposure time at a distance of $50''$ to the optical position of κ Cru. The nearest X-ray source in the HRI observation is located at a distance of more than $2'$ from κ Cru.

Apart from these two cases, all detections among the OB-type stars of luminosity classes I and II end at spectral type B1. This observation is in accordance with the observed terminal velocities v_∞. For early B supergiants v_∞ dramatically drops from more than 1000 km/s to typical values below 500 km/s (Cassinelli & Abbott 1981, Prinja, Barlow & Howarth 1990). Such low wind velocities are presumably not sufficient to produce sufficiently strong shocks and hence X-ray emission. Therefore, (at least for supergiants and bright giants) a dividing line for the existence of early-type star X-ray emission can be placed at spectral type B1.

For the supergiants in the spectral range O–B1 which represent a very homogenous sample of stars, the scatter of the observed L_x/L_{Bol}-ratios is in accordance with the error of the individual data points. It is thus clear that, e.g., intrinsic absorption of the X-ray emission in the stellar winds or the existence of a spectroscopic O-type star binary system can only influence the L_x/L_{Bol}-ratios by less than a factor of 2. Therefore, a further investigation of this point with our data does not appear very promising.

6. Discussion and conclusions

In this section we want to summarize our findings and discuss them in the context of some open issues regarding the X-ray properties of OB-type stars. Our analysis confirms that all O-type stars as well as early B-type stars are soft X-ray emitters. The RASS upper limits among these spectral types in our sample of program stars are obviously caused by a large distance combined with a large interstellar absorption column density towards these stars. In the case of the later B-type stars (B2-B9) the detection rate drops to $\lesssim 10\%$.

The comparison of X-ray count rates observed during RASS and ROSAT pointed observations shows for a number of late B-type stars variations in X-ray flux whereas among the early spectral types X-ray variability is not common on that time scale, thus, indicating a fundamental difference in the X-ray properties of detected late B-type stars compared to the earlier spectral types. This is further supported by the fact that we could not detected significant variability in X-ray flux for the early spectral types by comparing count rates observed during the *Einstein Observatory* mission, RASS, and the ROSAT pointing program. For most of the stars the count rate ratios between *Einstein* and RASS observations are directly related to the effective areas of the IPC and the PSPC. In summary, our comparisons between *Einstein Observatory*, RASS, and ROSAT pointed observations confirm our own time variability studies for OB-type star X-ray emission (Berghöfer & Schmitt 1994a, 1994b, 1994c, 1995) on the basis of a larger sample of stars. The higher level of variability for the X-ray emission of later B-type stars gives further support for the standard hypothesis of X-ray emitting late-type star companions in the case of detected later B-type stars, because late-type stars tend to be variable in X-ray flux (as in the case for our Sun).

Concerning the X-ray luminosities of the detected sample stars we find a significant difference for stars with $L_{Bol} > 10^{38}$erg s^{-1} and $L_{Bol} < 10^{38}$erg s^{-1}. In the case of the O-type stars we confirm the "canonical" relation between X-ray and total luminosity of $L_x/L_{Bol} \approx 10^{-7}$. Additionally, we demonstrate that this relation extends among the early B-type stars down to a spectral type B1–B1.5 ($L_{Bol} \approx 10^{38}$erg s^{-1}), thus, confirming on a much larger sample of stars the results of Cassinelli *et al.* (1994) who derived for a smaller number of B-type stars the X-ray properties from ROSAT pointed observations. Note that compared to the respective *Einstein Observatory* data, the scatter in L_x/L_{Bol}-ratios is significantly reduced and does compare to the respective errors.

In the case of the most massive OB-type stars (luminosity class I–II) the detection of X-ray emission ends at spectral type B1 which defines a dividing line and can be explained by the drop in wind velocity observed at this spectral type.

For luminosity classes III–V we also identified B-type stars with X-ray sources on the other side of the dividing line at spectral type B1. These stars show on average larger L_x/L_{Bol}-ratios than the earlier spectral types, but a direct relation between L_x and L_{Bol} does not exist. These detections in the RASS are not only limited to the here discussed late B stars, they does extend among the A stars, which also should be devoid of any X-ray emission up to spectral type A7 (Schmitt 1996). If we compare the observed X-ray luminosities of the detected B-type stars (later than B2) of luminosity classes III–V with the upper limits derived for the supergiants and bright giants (LC I–II), it is evident that the larger distances result in larger upper limits in X-ray luminosity and hence only non-detections among the LC I–II stars.

A small number of these detections are Algol-type systems typically showing $L_x/L_{Bol} \approx 10^{-5}$. However, note that a large number of later B-type stars (B2-B9) shows upper limits well below $L_x/L_{Bol} = 10^{-7}$ which provides further support for the findings of Cassinelli & Cohen (1994) that stars in this spectral range might have an intrinsic L_x/L_{Bol} below 10^{-8}.

Neither a wind emission mechanism (as in the case of O and early B-type stars) nor a solar-like, coronal X-ray production can explain the X-ray emission in the case of the detected later B-type stars which range up to $\approx 10^{31}$ erg s^{-1} and, therefore, in the case of the standard hypothesis (that the X-ray emission originates from a nearby companion) require an extremely young and active late-type star (e.g., a T Tauri star). The X-ray survey of all late-type main-sequence stars in the solar neighborhood by Schmitt (1996) and Schmitt *et al.* (1995) demonstrates that the X-ray output of main sequence stars of spectral type F, G, K, and M is too low to explain the observed X-ray luminosities. On the basis of the moderately resolved RASS observations we cannot decide whether the X-ray emission in fact originates from the respective late B-type star or can be attributed to an unresolved companion. However, Berghöfer and Schmitt (1994e) demonstrated that known visual companions can be disregarded in that context.

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