General X-ray properties of hot, massive stars

Yaël Nazé[1*]

[1] GAPHE, Dépt AGO, ULg, Allée du 6 Août 17, Bât B5C, B4000-Liège, Belgium

Abstract: The recent X-ray observatories have not yet provided a large survey comparable (in sky coverage) to that based upon the *ROSAT* All-Sky Survey (RASS). However, two limited surveys exist : the 2XMM catalog for *XMM-Newton* (294 OB stars detected) and the Carina large-scale survey from *Chandra* (129 OB stars detected). Medium-resolution (CCD) spectra were analyzed and led to new results on the relationship between the X-ray luminosity and the bolometric luminosity, as well as on the typical properties (plasma temperature, variability) of these objects. This contribution thus presents the results of the first high-sensitivity investigation of the overall high-energy properties of a sizeable sample of hot stars.

1 Introduction

The X-ray emission of massive stars was serendipitously discovered 30 years ago in Cygnus OB2, Orion and Carina nebulae (Harnden et al. 1979, Ku & Chanan 1979, Seward et al. 1979). Very soon, a proportionality between the X-ray and optical/bolometric luminosities was detected (Harnden et al. 1979, Pallavicini et al. 1981). It is now called the 'canonical' relation ($L_X \sim 10^{-7} \times L_{BOL}$).

At first, such a relationship could appear surprising, as the X-ray emission of low-mass objects is rather related to rotation and/or age. However, for massive stars, most phenomena are linked to the presence of stellar winds, and the X-ray emission makes no exception. A short summary of the argument is: the winds are line-driven, thus depend on the stellar bolometric emission; this driving process is unstable, creating shocks throughout the wind; these shocks generate hot plasma, hence X-ray emission. Owocki & Cohen (1999) formally showed that the X-ray luminosity "naturally" scales with the wind density parameter $\dot{M}/v_\infty$. It then scales with the bolometric luminosity if there is "a delicate balance between X-ray emission and absorption" and "a special form for the radial distribution of wind shocks[1]" (for details see Owocki & Cohen 1999).

Observationally, the first global investigation of the $L_X - L_{BOL}$ relation was reported by Berghöfer et al. (1997). Cross-correlating the *ROSAT* All-Sky Survey (RASS) with the Yale bright star catalog, Berghöfer et al. (1997) found 216 detections of O and B stars, down to fluxes of $10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, with a decreasing detection rate as one goes to later types (all O-stars earlier than O7 were detected whereas the fraction is only 6.5% for B2 stars). Using the RASS count rates and hardness ratios together with the interstellar column densities derived from the optical Yale photometry,

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[1]The X-ray filling factor should follow r^{-s} with s equal to 0.25–0.4. Note however that recent fitting of X-ray lines by embedded wind-shock models rather yields $s = 0$ (Cohen et al. 2006).

Berghöfer et al. (1997) evaluated the temperatures and unabsorbed X-ray luminosities for each star. The $L_X \sim 10^{-7} \times L_{BOL}$ relation was confirmed down to bolometric luminosities of 10^{38} erg s^{-1} (i.e. spectral types B1–1.5), but a large scatter (0.4 dex) was found around this relation. In addition, when comparing RASS and pointed observations, Berghöfer et al. (1997) detected no variations of the count rates of massive stars — note that this excludes only large variations, since the errors on the RASS count rates are quite large.

2 The $L_X - L_{BOL}$ relation revisited

2.1 Observations of clusters or associations

In the last decade, no further global X-ray survey was made, but the *XMM-Newton* and *Chandra* observatories have performed several sensitive observations of clusters and associations, some of these containing enough massive stars for a (limited) statistical study. In general, the $L_X \sim 10^{-7} \times L_{BOL}$ relation was once more confirmed. However, the scatter around the relation differs from that of the RASS study: when the properties of the massive star population were well known (i.e. deep photometric observations and spectral monitoring were available to assess both multiplicity and stellar parameters), the scatter was reduced to 0.1–0.2 dex (see the cases of NGC 6231, Sana et al. 2006; or Carina, Antokhin et al. 2008 or Nazé et al. 2010). The scatter remained large only when the stellar properties were known approximately (e.g. Westerlund 2, Nazé et al. 2008, or Cygnus OB2, Albacete Colombo et al. 2007). One could wonder where this difference in scatter comes from. Indeed, when comparing the two "philosophies" of these studies, clear differences appear (see Table 1) but it is unclear which one really explains the scatter problem.

It is important to note that, not considering the scatter, comparing recent studies with each other is not an easy task, as the effects of heterogeneous treatments can be surprisingly large. Indeed, the absolute value of $\log(L_X/L_{BOL})$ is always close to –7, but varies from one study to another. A good example is provided by the Carina studies: *XMM-Newton* data yielded $\log(L_X/L_{BOL}) = -6.58$ (Antokhin et al. 2008) whereas *Chandra* data led to $\log(L_X/L_{BOL}) = -7.26$ (Nazé et al. 2010). Crowding, as the cluster is seen with different spatial resolutions, does not seem to be the cause, nor the spectral fitting itself (similar models used); the main differences rather lie in the R_V, gas-to-dust ratio $N_H/E(B-V)$, and BCs (which are used to evaluate L_{BOL}). As a proof, using R_V of 3.1 rather than 4.0 yields $\log(L_X/L_{BOL}) = -6.99$ for the *Chandra* study, i.e. a reduction of the difference with the *XMM* study from 0.7 dex to 0.4 dex (Nazé et al. 2010).

2.2 The 2XMM survey

To really assess the origin of the scatter difference and search for potential cluster-to-cluster differences, one should combine both approaches. This has been made possible thanks to the 2XMM survey. With 220 000 X-ray sources, it is the largest X-ray catalog available at the present time. It consists of 4117 *XMM-Newton* archival datasets processed homogeneously by the SSC (Watson et al. 2009). Indeed, it is not an all-sky survey — it covers only 1% of the sky, biased to extragalactic fields — but it is still very useful for large, statistical studies. In the context of $L_X - L_{BOL}$ studies, it combines a high sensitivity (enabling detailed spectral/timing studies), an homogeneous treatment (single facility, single reduction of the data, single R_V,...), and a large sample (heterogeneous population like in RASS). The 2XMM catalog was cross-correlated with a recent catalog of O and B stars (Reed catalog, version of 2009 made available by the author) which includes the latest monitoring hence provides an up-to-date knowledge of the stellar properties: 294 O and B stars were detected in the X-ray range, down to fluxes of 10^{-14} erg cm^{-2} s^{-1}, and 128 sources display enough counts for a

Table 1: Comparison between RASS and *XMM/Chandra* studies of the $L_X - L_{BOL}$ relation.

RASS	*XMM/Chandra*
Survey (i.e. full sky)	A single cluster or association at a time
$\rightarrow$ heterogeneous population (field+clusters)	$\rightarrow$ homogeneous population
$\rightarrow$ large sample, many spectral types	$\rightarrow$ small sample, not all spectral types
$\rightarrow$ short exp. times	$\rightarrow$ deep exposure
Homogeneous treatment	Heterogeneous treatment
$\rightarrow$ single instrument and reduction software	$\rightarrow$ several instruments and reduction softwares
$\rightarrow$ single R_V, BC,...	$\rightarrow$ different R_V, BC,... for each cluster/ass.
Sp. types & photom. from general catalog	Sp. types & photom. from specific monitoring
L_X from count rates and HRs	L_X from detailed spectral fitting
Only ISM absorption	ISM + "wind" absorption

detailed spectral study (Nazé 2009). The distribution by subtype of the detected O-type stars closely follows that of the full Reed catalog: no bias is therefore detected. For B-type stars, however, there is a clear lack of detections of the late-type objects compared to early-type ones, and of giant stars compared with supergiants and main sequence objects. The former was already reported by Berghöfer et al. (1997), but the latter remains unexplained as such (but could be an artifact from the spectral type-luminosity class sampling). Variability was investigated at two levels: during exposures (provided there were enough counts) and between exposure (when several were available). Considering a 1% significance level, less than 1/10 of the O and B stars show variability during one exposure (and in the rare cases where it is detected, the lightcurves are compatible with PMS-like flares) but up to 70% of the stars display variability between exposures, with no obvious difference between O and B stars or single and binaries. It must be noted that, due to the high sensitivity of *XMM-Newton*, the changes reported here were well below the RASS detection threshold. While some variations are expected from the embedded-wind shock model, they should be rather stochastic, without long-term trends, and of very small amplitude. The detected variations therefore remain to be fully explained.

The spectral fitting was made using a model with two absorptions (one fixed to the interstellar value, the other let free to vary in order to represent a potential "wind" absorption) and a sum of optically-thin thermal plasma emissions (usually two, one only when the signal-to-noise was low). This is consistent with the models used in the cluster/associations studies mentioned above. An additional absorption (of the order of $\sim 0.4 \times 10^{21}$ cm^{-2}) is definitely needed to fit the spectra of O-type stars, while B-type stars rather show no absorption beyond the interstellar component. Concerning plasma temperatures, the dominant component always lies higher than 1 keV for B-type stars but amounts to only 0.2 or 0.6 keV for O-type stars, thereby confirming cluster studies (e.g. Sana et al. 2006). It is important to note, however, that the second thermal component often appears at ~ 2 keV for O-type stars. This is not expected in the embedded-wind shock model, which predicts only soft X-ray emission. The origin of such a hard component must therefore be investigated: does it come from magnetic phenomena, from colliding wind emission (assuming therefore that most of these "single" stars actually are binaries), or from an entirely different direction? The question remains open.

Finally, the estimation of the $F_X/F_{BOL} = L_X/L_{BOL}$ ratios for the O-type stars shows a rather high dispersion, actually very similar to that of the RASS. It therefore seems that the observed scatter is not an artifact from the treatment itself (e.g. conversion of count rates vs. detailed spectral fitting) but is rather intrinsic to the massive star population. Considering subsamples of the 2XMM data indeed show hints of intercluster differences, but these differences are below or about the dispersion itself, hence not formally significant. Further investigation is needed to see which physical parameter,

beyond the bolometric luminosity, influences the X-ray emission. Studies of stars with different metallicities, in the Magellanic Clouds for example, would be invaluable in this context.

3   Additional information

Beyond the $L_X - L_{BOL}$ studies, the *XMM* and *Chandra* data yielded several additional results. One of them is a revision of our view on binaries. A decade ago, it was common wisdom to consider that a massive binary implies the presence of two winds which must collide and therefore leads to an enhanced (and harder) X-ray emission. The equality "binary$\Longleftrightarrow$X-ray overluminosity" is still quite popular, as exemplified by some recent papers (e.g. Crowther et al. 2010). However, the sensitive observations of *XMM* and *Chandra*, together with a better knowledge of the stellar population, have forced us to revise what now appears as an "urban legend"[2] (Oskinova 2005, Sana et al. 2006, Nazé 2009, Nazé et al. 2010). In NGC 6231, only two binary systems appear (slightly) overluminous (HD 152248 and CPD −41°7742, Sana et al. 2006), while in Carina, only one binary system is overluminous (HD 93403, Nazé et al. 2010). Binaries and single objects indeed appear mixed, i.e. at similar positions or $\log(L_X/L_{BOL})$ ratios, in $L_X - L_{BOL}$ diagrams. It must be noted, however, that these ratios are systematically larger for binaries whatever the energy band considered, but the difference is always below the dispersion of each sample (single or binary) around the $L_X - L_{BOL}$ relation (Nazé et al. 2010), e.g. $\log(L_X(0.5 - 10.keV)/L_{BOL}) = -7.26 \pm 0.21$ and -7.16 ± 0.21 for single stars and binaries in Carina, respectively. This implies that it is quasi-impossible to detect binarity by looking at the L_X/L_{BOL} ratio alone, since only few multiple systems show X-ray bright wind-wind emission. Detailed MHD modelling, as well as more observations of O+OB binaries (in order to study the influence of a single parameter, e.g. period, for otherwise similar stellar systems), should help pinpoint the cause of this rarity (effect of radiative braking, lack of ram pressure balance?).

In addition, it is also interesting to sample the O- to B-stars transition. Whatever the parameter envisaged (e.g. L_X/L_{BOL} ratio, medium-to-soft X-ray flux ratio), the earliest B-type stars always show properties close to those of the latest O-type stars. There thus seems to be a smooth transition from O- to B- stars, with a decreasing influence of the X-ray production by the embedded wind-shock process and another process growing in influence towards later B types (Nazé et al. 2010).

Finally, two additional parameters could be investigated thanks to the spectral fits: the average plasma temperature $< kT >= \sum kT \times norm_i / \sum norm_i$ and the medium-to-soft flux ratio $HR = F_X^{unabs}(1 - 2.5keV)/F_X^{unabs}(0.5 - 1keV)$. The average temperature is indeed well below 1 keV for O-type stars, except for a few peculiar systems. In a graph of L_X/L_{BOL} ratio vs. average temperature (e.g. Fig. 1), the "normal" O-type stars display low temperatures and L_X/L_{BOL} ratios and colliding wind binaries as well as objects with magnetically confined winds are expected to display both high temperatures and ratios. However, there appears to be a number of objects showing low temperatures but high ratios or high temperatures and low ratios: their nature is unknown, and both observational as well as theoretical follow-up studies are needed to understand them.

Considering the medium-to-soft flux ratio, it increases with average plasma temperature, as could reasonably well be expected, but there are also shallow increasing trends of this ratio with larger L_X/L_{BOL} (Fig. 1) or larger bolometric luminosities. These trends, which must be confirmed, could be related to two different effects, not mutually exclusive. One is that the plasma temperature could increase with bolometric luminosity (as possibly observed in the line ratio trends found by Walborn et al. 2009), another is that, at constant plasma temperature, the medium-to-flux ratio can change if the "additional absorption" varies (indeed, the L_X in the L_X/L_{BOL} ratio has been corrected only for

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[2]For O+O systems at least, since evolved systems such as WR+O do appear overluminous, the question of the actual level of the intrinsic X-ray emission of (evolved) WRs stars being still debated.
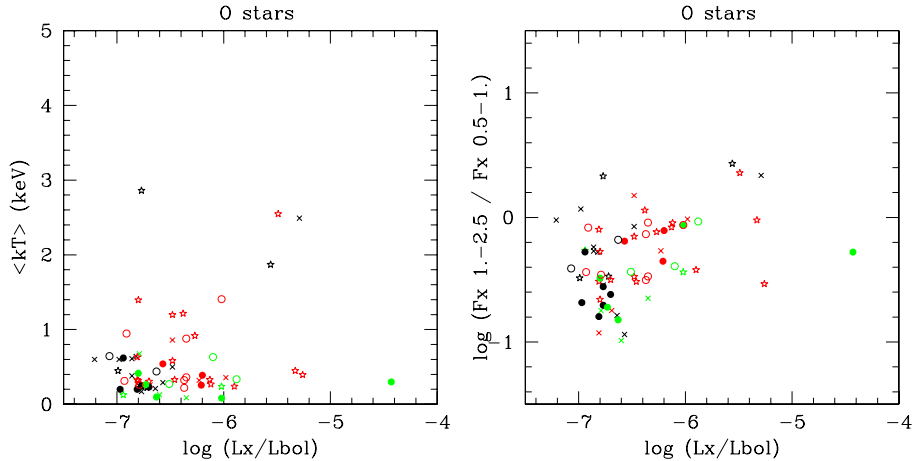
Figure 1: Average temperature (left) or medium-to-soft flux ratio (right) plotted against the L_X/L_{BOL} ratio. Crosses (resp. filled dots) correspond to single (resp. binary) stars showing no variation, stars (resp. open circles) to variable single (resp. binary) stars; black, red and green colors correspond to 1T, 2T and 3T spectral fits, respectively.

the interstellar absorption and, if the wind absorption is larger for larger bolometric luminosities, this could explain the observed shallow trend — note however that no obvious trend, not even a shallow one, of "wind" absorption vs. bolometric luminosity was detected in Carina (Nazé et al. 2010).

4 Conclusions

In the last decade, sensitive X-ray observations have led to several unexpected results. The scatter found in the RASS for the $L_X - L_{BOL}$ relation is not an effect from the poor X-ray data available back then, but a real phenomenon: cluster-to-cluster differences should exist. The X-ray variability of O and B stars is rare on short timescales but rather common on long timescales, though still unexplained. The spectral fits reveal a generally soft character of the X-ray emission of O-type stars, but a faint, hard component does exist in many cases — again of unknown origin. Finally, X-ray bright binaries are quite rare, though X-ray overluminosities are still a valid "binarity criterion" at the present time.

Acknowledgements

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Discussion

A. Willis: You mentioned that the O-binaries do not often show enhanced L_X/L_{Bol}, as would be expected with CWB X-ray emission. Was there any evidence for these binaries of harder X-ray emission than for single O-stars?

Y. Nazé: No, the binaries showing no "peculiar" L_X/L_{Bol} do not show any significantly higher $< kT >$ ... Binaries in general have slightly higher average temperatures (cf. Carina analysis in Naz et al. 2010), but the dispersion is high for both single and binaries, and therefore binaries really lie amongst the "single" objects in terms of luminosity and temperature.

H. Zinnecker: I have a question on the X-ray emission of B-stars. People have suggested that their rather hard spectrum ($\approx 2\,\mathrm{keV}$) may be associated with T Tauri (low-mass) companions which are known to have coronal temperatures of 1-2 keV.
Have you followed this discussion and what is the current status? As an aside, would X-ray observations be sensitive enough to detect T Tauri companions to O-stars?

Y. Nazé:

1. Concerning B-type stars: hard emission, together with the reduced detection rate and an X-ray luminosity close to that of PMS stars, have indeed been seen as hints/evidence that the X-ray emission did not come from the B stars themselves. This is still considered as a good possibility — see, e.g., NGC 6231 (Sana et al. 2006) and Carina (Evans et al. 2011).

2. Concerning O-type stars: it is possible in principle if considering the late O-type stars and the most intense flares of PMS stars (otherwise, the X-ray luminosity of O stars is too high to detect the faint one from a PMS star).
   Additional note: some flares and PMS-like characteristics have been detected for some late O or early B stars (e.g. σ Ori E). These objects have been confirmed as magnetic, so that it is the same underlying phenomenon but truly linked to the massive stars.

N. Evans: In response to the question about whether X-ray sources associated with B-type stars could be due to T Tauri companions:

- it is not surprising that we do not identify (in general) T Tauri companions to O stars since the O-star X-ray luminosity is stronger than that of T Tauri stars;

- starting from the assumption that X-rays from B stars are from T Tauri companions, we (Evans 2011) derive a fraction of low mass companions (mid F through K-type stars) for B stars later than B3 in Trumpler 16.