X-RAY EMISSION FROM MASSIVE STARS IN OPEN CLUSTERS

M. F. Corcoran
USRA/LHEA, Goddard Space Flight Center, Greenbelt, MD 20771

RESUMEN

I present a review of studies of X-ray emission from massive O, B and WR stars in open clusters based mostly on data from the *ROSAT* X-ray observatory. Such open cluster studies can address the dependence of the X-ray emission from massive stars on stellar age and metallicity, on local environment, and explore questions of the generation of diffuse X-ray emission and cluster history and the influence of X-ray emission on the parent molecular cloud.

ABSTRACT

I present a review of studies of X-ray emission from massive O, B and WR stars in open clusters based mostly on data from the *ROSAT* X-ray observatory. Such open cluster studies can address the dependence of the X-ray emission from massive stars on stellar age and metallicity, on local environment, and explore questions of the generation of diffuse X-ray emission and cluster history and the influence of X-ray emission on the parent molecular cloud.

1. INTRODUCTION

In the mid-1960's spectra of hot massive OB stars in the rocket ultraviolet showed the presence of "superionized" line features (for example, strong O VI and N V in lines O stars, C IV in B stars). Since the formation temperature of these lines were of the order of 10^5 K, (at least a factor of 10 larger then the presumed ambient temperature of the stellar atmosphere) Cassinelli & Olson (1979) suggested an alternative source for the ionization: a X-ray emitting zone at the base of the wind (the so-called "base corona" model), in which X-ray ionization produced the superionization species by the Auger effect.

The first proof that OB stars were indeed X-ray sources was the detection of X-ray emission from the O stars in the Carina Nebula and Cyg OB2 associations with *EINSTEIN* (Seward et al. 1979, Harnden et al. 1979). Interestingly enough, the observed X-ray flux level agreed with "base corona" model. However, the shape of the observed X-ray spectrum from these sources was not quite right - there was a distinct excess of emission at low energies, which contradicted the "base corona" model, since low-energy X-rays from a source near the stellar photosphere would be almost entirely absorbed by the overlying stellar wind.

The absence of strong absorption in the stellar X-ray spectra was a puzzle, and suggested that a substantial fraction of X-ray emitting plasma existed in the stellar wind at large distances from the photosphere. But what produced this hot gas? Lucy and White (1980) recognized that radiatively-driven stellar winds were inherently unstable to Doppler perturbations and suggested that such instabilities could produce shock-heated gas throughout the stellar wind. More recent numerical models (Owocki, Castor and Rybicki 1988) suggested that strong reverse shocks would form in the radiatively-driven wind flow. Thus there was a plausible physical mechanism for producing X-ray emitting gas throughout the stellar wind.

Further observations with *EINSTEIN*, *ROSAT*, *BBXRT* and *ASCA* showed that:

- OB stars tend to follow $L_x/L_{bol} \approx 10^{-7}$ — but with large scatter (Chlebowski, Harnden & Sciortino 1989, Berghöfer et al. 1997). Also, this relationship does not seem to be followed by stars later than spectral type B1. The cause of this scatter and this break are currently unknown.
- There is not much variability in the observed X-ray emission (Berghöfer and Schmitt 1994a); but well-established exceptions do exist (for example ζ Ori, Berghöfer & Schmitt 1994b; ζ Pup, Berghöfer et al. 1996, and phase-locked colliding wind emission in some, though not all, massive binaries, Corcoran 1996).

- Studies of relatively high signal-to-noise X-ray spectra of nearby bright OB stars obtained with *ROSAT* and *ASCA* showed the presence of excess absorption beyond the interstellar medium (Hillier et al. 1993, Corcoran et al. 1993), which suggest that most of the X-ray emission is buried fairly close to the stellar photosphere.
- Other recent X-ray spectral observations (Corcoran et al. 1994) show peculiar, non-solar abundance values &/or optically thick emission regions.
- There seems to be a class of "superluminous" late B-type stars (Berghöfer et al. 1997).

More recent theoretical modeling (Feldmeier, Puls and Pauldrach 1997) suggests that the emission from individual shocks fall one/two orders of magnitude below the observed emission level; but mutual collisions of dense shells deep in wind could provide sufficient X-ray luminosity, though such emission should show significant variability. Thus "shock models" of the X-ray emission also have trouble describing all properties of the observed emission (though as the complex numerical 3-dimensional hydrodynamic problem becomes more tractable with increased computing power, perhaps some of these discrepancies may be resolved).

2. X-RAY EMISSION FROM STARS IN OPEN CLUSTERS AND ASSOCIATIONS

New X-ray telescopes are providing larger numbers of high signal-to-noise, (relatively) high spectral resolution observations of many classes of objects, including massive OB stars. These new observations are providing ever-higher-quality data with which to compare to models, and many questions which could not be addressed before can be raised:

- What is the dependence on age and metallicity?
- How does the X-ray emission depend on the local environment?
- What is the X-ray luminosity function for OB stars?
- How do OB stars generate large-scale diffuse X-ray gas?
- What influence does the point-source and diffuse X-ray emission have on the parent molecular cloud?

These questions can be addressed most efficiently by spatially-resolved, spectrally-resolved, deep X-ray observations of OB clusters and associations. Of the currently flying X-ray observatories, *ROSAT* is probably the best suited to making such observations, since it offers both spatial resolution and modest spectral information over a wide field of view.

ROSAT has studied numerous open clusters. Most of the observations of stellar clusters concentrate on studies of low mass PMS stars (eg. the Pleiades, Micela et al. 1996, Stauffer et al. 1994; the Hyades, Stern, Schmitt, & Kahabka 1995; IC 348, Preibisch, Zinnecker, & Herbig 1996; NGC 6490, Belloni & Tagliaferri, 1997; NGC 2516, Dachs & Hummel 1996). In the following we concentrate on deep *ROSAT* observations of 3 important OB associations: Cyg OB2, NGC 6231/Sco OB1, and Tr 14, 16 and Co 228 in the Carina nebula.

2.1. Sco OB1

Sco OB1 is at a distance 2 kpc, and has log(age) = 6.9 yr (Perry Hill, & Christodoulou 1991), making it moderately old. The association is centered around a compact open cluster NGC 6231, and is surrounded by an elliptical HII region with an extent of about $4^\circ \times 5^\circ$. Another notable feature is the "Elephant Trunk" dust lane which lies about 1° from NGC 6231. *ROSAT* observed Sco OB1 with the Position Sensitive Proportional Counter (PSPC) for about 13 ksec and also with the High Resolution Imager (HRI) for about 32 ksec. The PSPC provides arcminute-scale spatial resolution and some spectral resolution, while the HRI provide arcsecond-scale spatial resolution with no real energy resolution. Thus the HRI observations are useful for resolving the compact cluster NGC 6231 while the PSPC is useful for deriving fluxes. Because the sensitivity of the HRI is about a factor of three lower than that of the PSPC, the HRI and PSPC observations have about the same flux limit.

The HRI image of Sco OB1, centered on NGC 6231, is shown in figure 1. The HRI detected 35 sources in the field center; most (but not all) are associated with known massive star members.

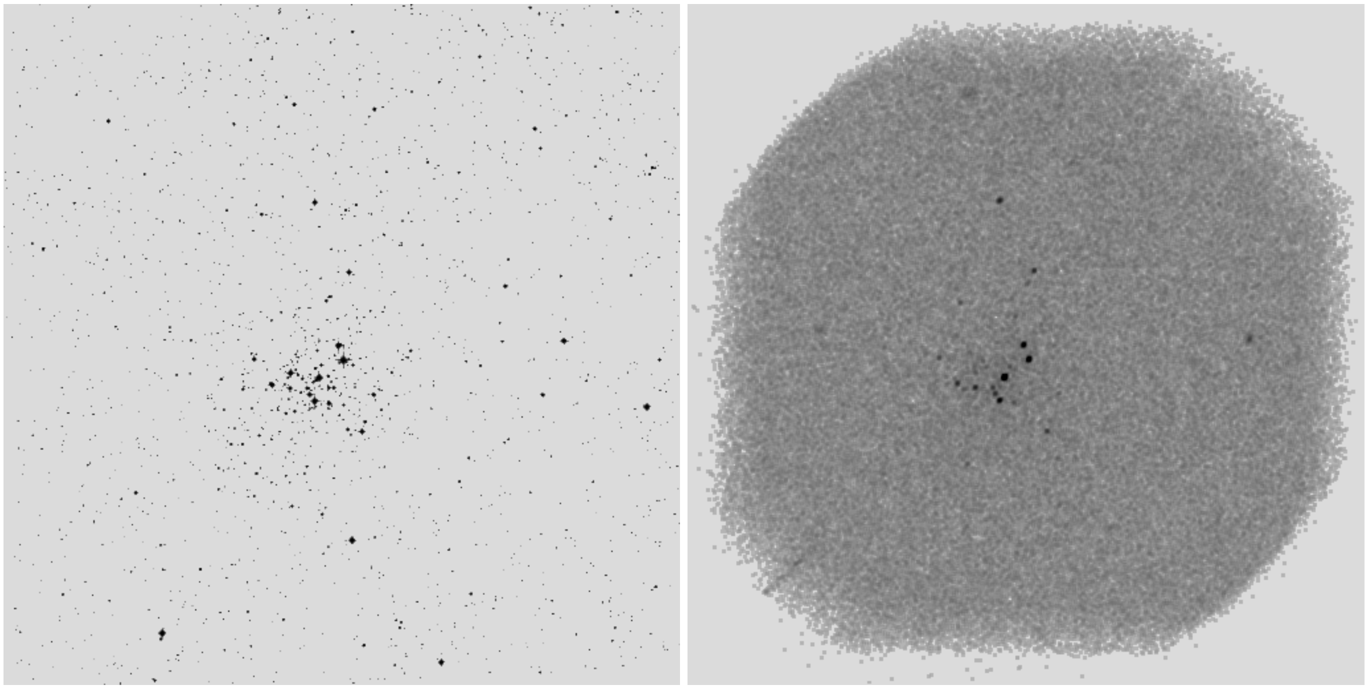

Fig. 1. Digitized Sky Survey image (left) and ROSAT HRI image of Sco OB1

2.2. Cyg OB2

Cyg OB2 lies at a distance of 1.7 kpc (Massey & Thompson 1991). It's marked by heavy, variable extinction (Johnson & Morgan 1953; Massey & Thompson 1991) and contains quite a few interesting massive stars. According to Massey and Thompson, Cyg OB2 #12 may be the visually brightest and most heavily reddened star known Cyg OB2 #7 is a very young, very massive O3 star. The star Cyg OB2 #9 is an O5 supergiant which is a peculiar variable radio source, changing irregularly from a non-thermal to thermal radio spectrum. Another interesting source in the field (not thought to be physically associated with Cyg OB2) is Cyg X-3, the only known WR + NS system. This region was one of the first *EINSTEIN* observations; the *EINSTEIN* HRI detected about 5 cluster members as X-ray sources (Harnden et al. 1979).

ROSAT observed Cyg OB2 with the PSPC for 20 ksec and the HRI for 73 ksec. Figure 2 shows the HRI field. The *EINSTEIN* sources are all readily apparent in the *ROSAT* image, along with about 15 other sources not seen by *EINSTEIN*. Cyg X-3 is visible in the observation as an extremely bright source to the south of the field center.

2.3. The Carina Nebula

The Carina Nebula contains the distinct associations Tr 14, Tr 16 and Collinder 228. These clusters lie at a distance of about 2.6 kpc (Massey & Johnson 1993), though there is thought to be a real difference in their distances. This region of the Galaxy is home to some of the youngest and most massive stars known, including six O3 stars as well as the supermassive evolved star η Car. Optical nebulosity is also prevalent in the region. Optical photometry and spectrophotometry in the region has been carried out by Feinstein (1969), Walborn (1971, 1973), Levato & Malaroda (1982) & Morrell Garcia, & Levato (1988). This region was one of the first *EINSTEIN* observations and resulted in the detection of point-source emission from the hot stars in the region, diffuse emission associated with the optical nebulosity, and peculiar emission from η Car.

ROSAT observed the Carina Nebula (with the pointing centered on η Car) for 30 ksec with the PSPC and 50 ksec with the HRI. The field of view is at least 1° in diameter so that Tr 14, 16 and Co 228 are all sampled. Preliminary analyses of these data have appeared Corcoran et al. (1995).

Figure 3 shows the HRI image of the Carinae Nebula. The extended source in the middle of the field is η Car, while the source just to the north of η Car is the O3 star HDE303308. Tr 14 is the extended bright emission

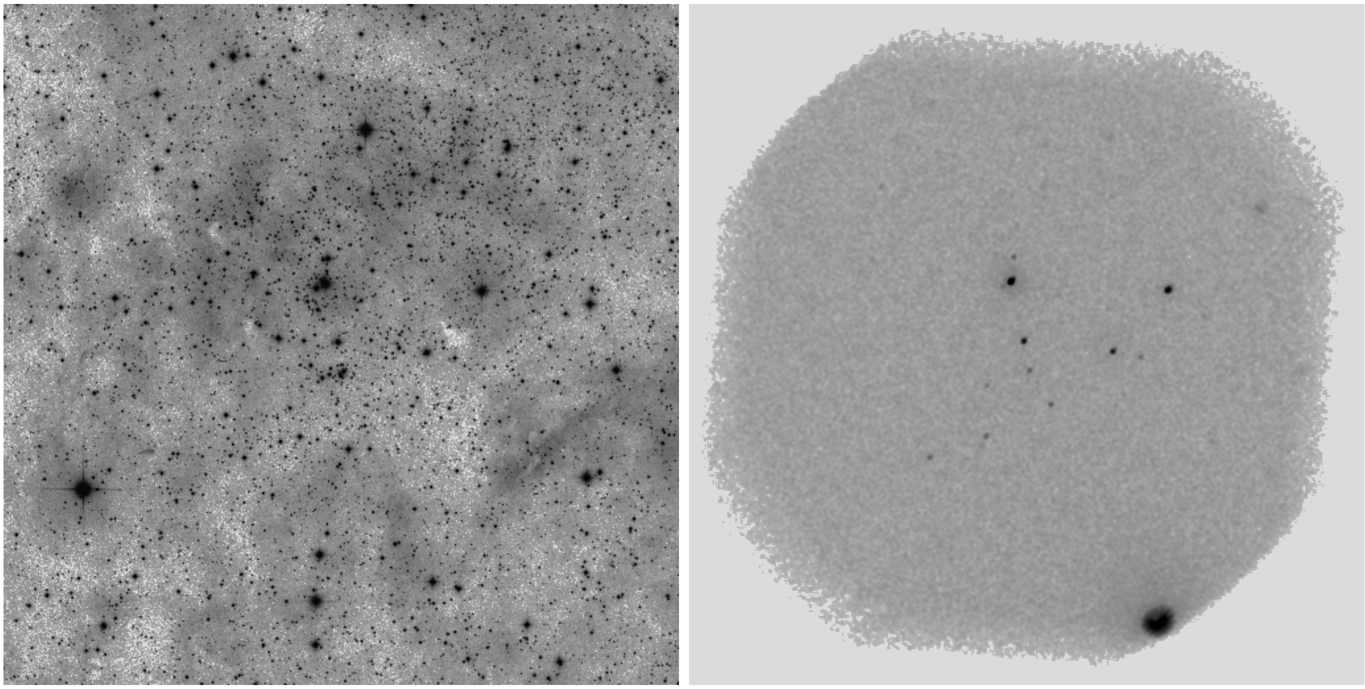

Fig. 2. Digitized Sky Survey image (left) and ROSAT HRI image of Cyg OB2

to the northwest of η Car; it's dominated by emission from HD 93129A & B which are barely resolvable at the HRI resolution. The "extended" emission could be real diffuse emission or unresolved emission from the other point sources in Tr 14, or a combination of both. The bright source to the east of Tr 14 is HD 93250, another O3 star. The source to the west of η Car is WR 25, an anomalously X-ray bright Wolf-Rayet star. Obvious diffuse emission is visible throughout the field; the diffuse emission just to the west of WR 25 is fainter than the surrounding emission due to the presence of an optical dust lane.

2.4. Comparison of the X-ray Stars in Sco OB1, Cyg OB2, and the Carina Nebula

Figure 4 shows the derived X-ray fluxes for the brightest member stars in all the observed clusters. η Car is the brightest X-ray object seen in any of the associations, primarily due to the contribution of bright extended emission which surrounds the star. The WR star WR 79 in Sco OB1 is anomalously faint, with the smallest L_x/L_{bol} ratio for any of the observed stars. On the other hand, WR 25 in the Carina Nebula is anomalously bright with a very high L_x/L_{bol}. We also find a large spread in the L_x/L_{bol} ratio, with $10^{-8} < L_x/L_{bol} < 10^{-6}$ in general, at least for the bright detections. Another interesting point is that the members of Sco OB1 seem to exhibit the smallest spread in L_x/L_{bol}, while Cyg OB2 seems to exhibit the largest.

3. CONCLUSIONS

Our studies of the X-ray emission from Sco OB1, Cyg OB2 and the Carina Nebula clusters suggest that $L_x/L_{bol} \approx 10^{-7}$ is a reasonable description of the gross X-ray properties of the the bright population of massive stars, but there is a real scatter in the observed ratio. We find some evidence that the scatter is different for different clusters, implying that the scatter may be intrinsic to the environment in which the stars form, or due to stellar metallicity or stellar age. There seems to be a significant population of sub-luminous stars as well (notably WR 79 in Sco OB1)

Most of the point sources are OB stars earlier than B1 or so; we did not detect substantial populations of X-ray bright late B stars or PMS stars. However, in the Carina nebula, we did find 2 rather X-ray bright sources associated with relatively bolometrically faint Be stars, suggesting that indeed some Be stars are anomalously bright in X-rays. The association of the X-ray sources and the Be stars needs to be confirmed with followup

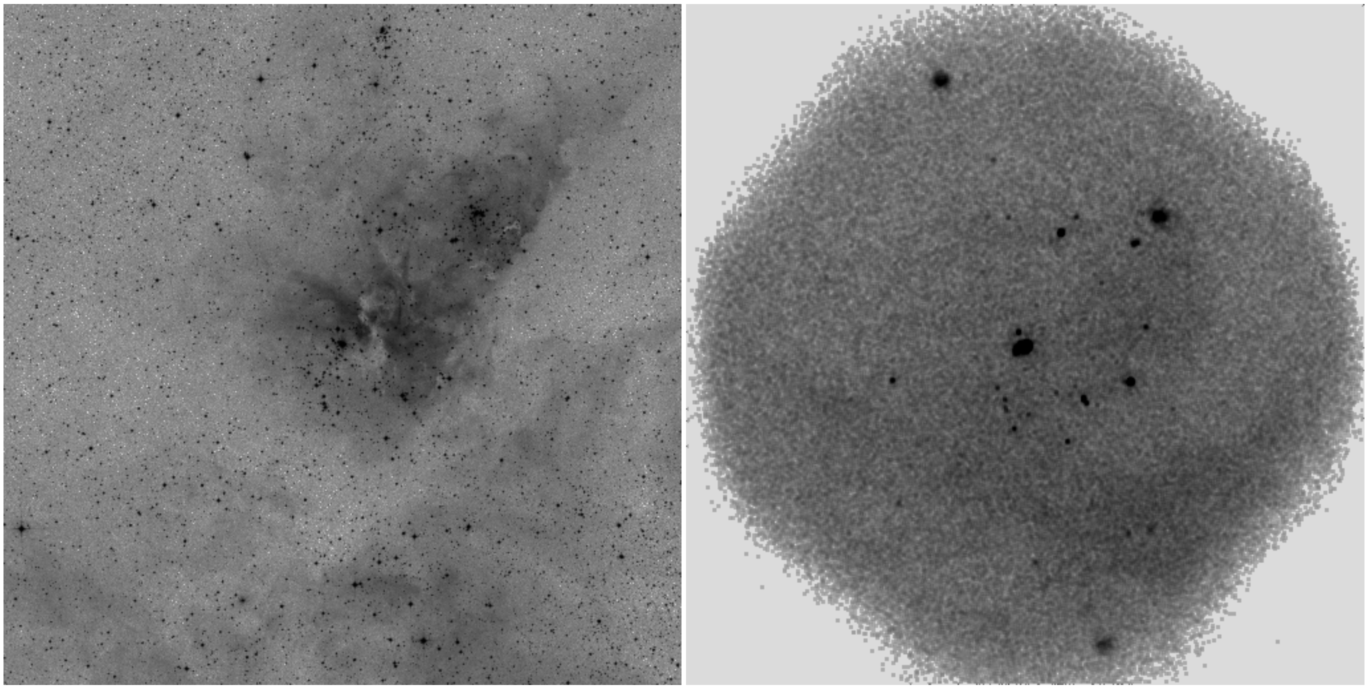

Fig. 3. Digitized Sky Survey image (left) and ROSAT HRI image of the Carina Nebula Field

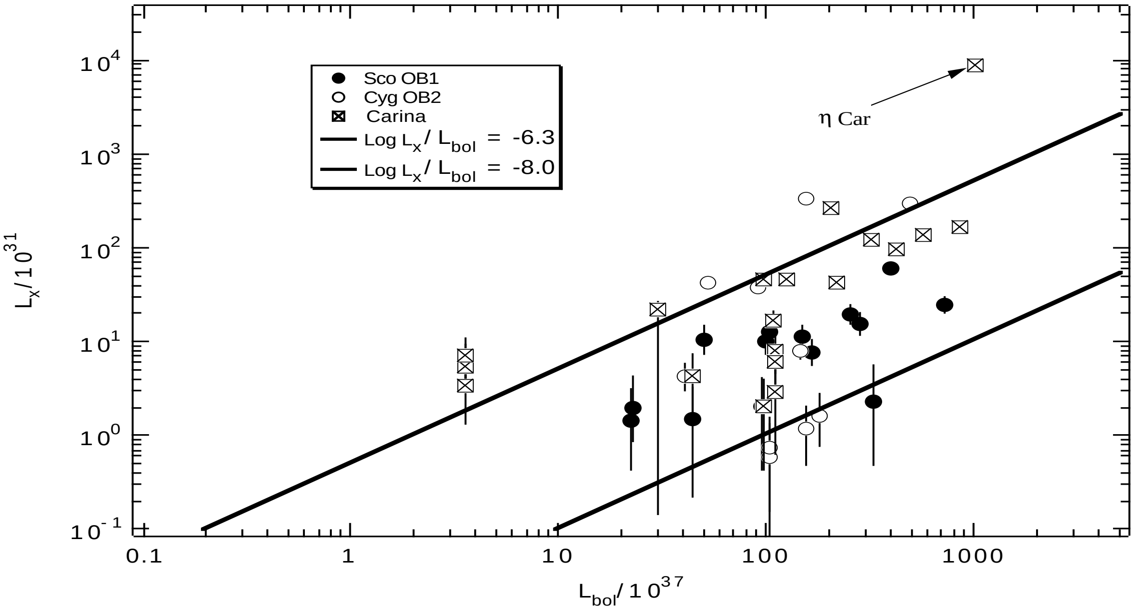

Fig. 4. Comparison of the X-ray luminosities for bright stars in the Sco OB1, Cyg OB2 and Carina Nebula fields.

observations, but if true suggests that some unknown mechanism (tied to rotation?) produces excess X-ray emission in these stars.

We also found differences in the amount of diffuse emission in the regions. The Carina nebula associations are clearly associated with diffuse X-ray emission while neither Sco OB1 nor Cyg OB2 show signs of strong diffuse X-ray emission. This may be related to age of the association or the intrinsic character of the ISM near the associations; it may also be due to the density of very massive stars in the region, if the diffuse X-ray emission is produced primarily via wind-ISM interaction (Chlebowski et al. 1984).

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