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Infrared and X-ray Emission in High Mass Star Forming Regions

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Abstract We present a correlated study of IR and X-ray emission in massive star formation regions using X-ray *Chandra* data and ground-based near, and mid-IR observations in order to understand the mechanisms of X-ray emission associated to high massive protostellar objects. Mon R2, and the complex giant molecular clouds W3 and NGC 6334 are the regions here analyzed.

Key words: SM: HII regions – stars: formation – X-rays: stars – infrared: general

1 INTRODUCTION

One of the most exciting results of the *ASCA* satellite was the discovery of hard X-ray emission from several high mass star-forming regions (HMSFRs) such as Orion (Yamauchi & Koyama 1993), NGC 6334 (Sekimoto et al. 2000), and W3 (Hofner & Churchwell 1997). While the X-ray emission of low-mass pre-main-sequence stars is primarily thought to be caused by magnetic activity near the stellar surface or in the star-disk environment (Feigelson & Montmerle 1999), little is known about X-ray emission from very young stars or protostars of high mass.

The *Chandra* X-Ray Observatory with its high angular resolution (better than 1 arcsec on axis) and the accurate astrometry in the 0.5 to 10 keV band allow now to make cross-correlated studies between the hard X-ray emission found in giant molecular clouds and the infrared and radio emission. This is important in order to investigate in detail the origin of the X-ray emission (Hofner et al. 2002). For instance, Garmire et al. (2000) report X-ray emission from the luminous infrared source *n* in the Orion hot core, demonstrating that highly embedded massive protostars can be detected using the *Chandra* X-Ray Observatory.

Chandra with its Advanced CCD Imaging Spectrometer (ACIS) observed in General Observer and Guaranteed Time programs, a number of HMSFRs including i.e. Orion, Mon R2, M17, RCW49, W51A, W3 Main, W3(OH), NGC 6334, Trumpler 14 in Carina, NGC 3603 (see Townsley et al. 2004, Townsley et al. 2005). Hundreds of X-ray point sources were found in HMSFRs. In addition hard diffuse X-ray emission was found in several Galactic high-mass star-forming regions of which a list is reported by Townsley et al. 2004. Recently Ezoe et al. (2004) report a diffuse X-ray emission associated with the complex HII region NGC 6334. Such a phenomenon is interpreted in terms of shocks produced by fast stellar winds from the young massive stars.

In this paper, we report the results of a search of X-ray emission from very embedded high mass protostellar objects in a sample of HMSFRs (Mon R2, W3, and NGC6334) observed with *Chandra*/ACIS. This study uses the comparison with the high spatial resolution infrared images. In Section 2 each region is discussed separately and for the identified high mass young stars we derive the ratio $L_{\rm x}/L_{\rm bol}$. Finally the conclusions are given in Section 3.

2 X-RAY AND IR EMISSION FROM HMSFRS

2.1 Monoceros R2

Monoceros R2 (MonR2) is one of the closest massive star forming regions to the sun (D=830±50 pc, Racine 1968). The central region is characterized by the presence of a shell-like complex infrared nebula

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Table 1 Bolometric and observed X-ray luminosities of the high mass protostars identified in the HMSFRs

Source	$L_{\rm bol}$ ($L_{\rm sun}$)	$L_{\rm X}$ (erg s^{-1})	$\log(L_{\rm X}/L_{\rm bol})$	α (IR)	Ref.
Mon R2					
IRS1SW	3.4×10^3	10^{31}	–6.11	2.7	1
IRS2	7.8×10^3	6.3×10^{30}	–6.68	3.0	1
IRS3NE	1.2×10^4	10^{30}	–7.66	2.0	1
W3 Main					
IRS 3a	2.5×10^5	3.0×10^{30}	–8.50	3.2	2
IRS 5	1.2×10^5	5.0×10^{30}	–7.96	3.3	2
NGC 6334I					
Irs1E	$3.3\ 10^3$	$6.2\ 10^{30}$	–6.30	3.8	3

References: X-Ray luminosities (1) Kohno et al. (2002); (2) Hofner et al. (2002); (3) this work.

with inside at least three very bright embedded IR sources associated with sub-millimeter and far-infrared dust cores (IRS 1–3) (Henning et al. 1992). A compact H II region inside the IR shell (Massi et al. 1985) and the presence of H_2O and OH masers (Smits et al. 1998) indicate that these IR sources are young massive protostars.

Kohno et al. (2002) detected 154 X-ray sources with the ACIS-I array in the central region ($3.2' \times 3.2'$) of Mon R2. Using the deep near-IR images of Carpenter et al. (1997), they identify about 85% of the X-ray sources with infrared counterparts, including the three high mass protostars. Figure 1 (*Left panel*) shows the position of these objects over the Ks image taken with 2MASS, while in Figure 1 (*Right panel*) is reported their spectral energy distribution (SED) derived from the near-IR photometry of Carpenter et al. (1997), the 10 and 20 μm flux densities of Hackwell et al. (1982), and the millimeter observations of Hennig et al. (1992).

Integrating the SED we have derived the bolometric luminosities. These are given in Table 1 together with the observed X-ray luminosities and the infrared spectral index computed between 2.2 and 10 μm, (α (IR)= dlog($\lambda F(\lambda)$)/dlog(λ))

2.2 W3 Main

W3 is a giant molecular cloud complex located in the Perseus arm at a distance of $\sim$ 2.3 kpc. This cloud contains at least two centers of massive star formation W3 Main and W3 (OH) located 13 arcmin SE of the Main. W3 Main is characterized by a cluster of compact and ultracompact HII (UCHII) regions of different sizes.

In the core of the cloud, Hofner et al. 2002 detected several point like X-ray sources with energy greater than 2.5 keV. Two of these sources are coincident with the massive young stars IRS 2 and IRS 2a of spectral types O5–O6 and O5–B1 (Tieftrunk et al. 1997) that are responsible for the ionization of the shell-type compact H II region W3A. In addition X-ray emission was detected associated with the ZAMS O6 star Irs3a and IRS4, exciting the ultracompact HII W3 B and C respectively, and in the massive protostar candidate W3 IRS 5. Figure 2 illustrates the X-ray–infrared identification of these sources, while Figure 3 report the SED obtained from the near-IR observations of Wynn-Williams et al. (1972) and the mid-IR photometry of Persi et al. (2002).

The infrared spectral index α(IR), and the ratio log $L_{\rm x}/L_{\rm bol}$ have been derived for the very red objects IRS 3a and IRS 5 and reported in Table 1. The SED of W3 IRS5 has been fitted with a spherically symmetric dust envelope model (solid line in Figure 3). The visual extinction derived for this source is A_V = 90. These observations confirms that very young massive stars are emitters of relatively hard X-rays and that they can be detected with *Chandra* even in a high-density environment.

2.3 NGC 6334

The giant molecular cloud NGC 6334 lies at a distance of 1.74 kpc from the Sun (Neckel 1978), parallel to and located in the Carina-Sagittarius spiral arm. At least five active centers of high mass star formation were found in far-IR by McBreen et al. (1979). They were labelled by using Roman numerals I–V. Each center, contains compact and ultracompact HII regions (A–F) detected at 6cm with the VLA by Rodriguez et al.

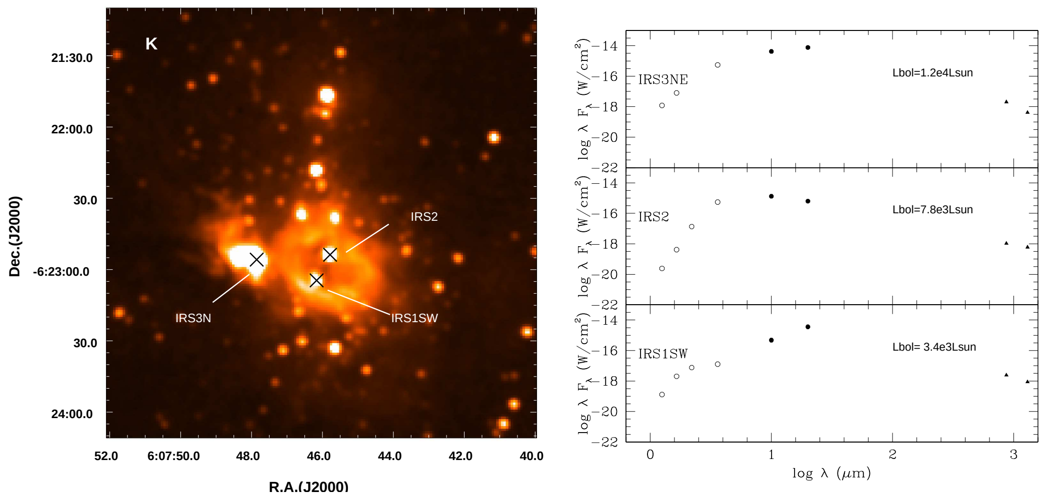

Fig. 1 *Left panel*: 2MASS Ks image of the central part of Mon R2. The crosses indicate the positions of the three *Chandra* X-ray sources identified with high mass stars. *Right panel*: Spectral energy distribution of the three high mass young stellar objects with X-ray emission.

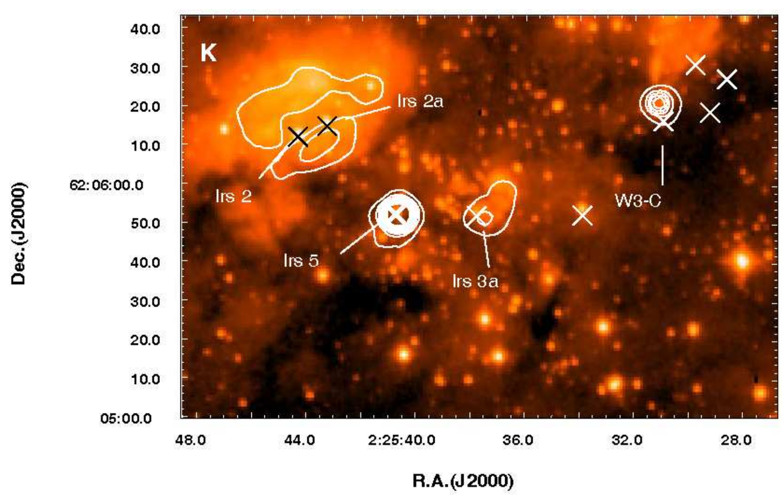

Fig. 2 2.2 μm image of W3 Main. The contours represent the 12.5 μm observations of Persi et al. 2002, while the crosses indicate the positions of the *Chandra* X-ray sources detected by Hofner et al. 2002.

(1982). The different sizes and morphologies of the radio sources suggest different evolutionary stages in the complex HMSFR. Infrared studies of NGC 6334 were carried out by different authors, and a review of the observation is recently presented by Persi et al. (2005).

Hard X-ray emission (E ≥2 keV) was detected by ASCA in the five FIR cores of the giant cloud (Sekimoto et al. 2000), but because of the low spatial resolution of the satellite it was not possible to identify properly the X-ray sources. In addition, diffuse hard X-ray emission was discovered in NGC 6334 by Ezoe et al. (2004) using *Chandra* observations. According to the authors, this emission can be explained in terms of strong shocks of stellar winds from young OB stars present in the region.

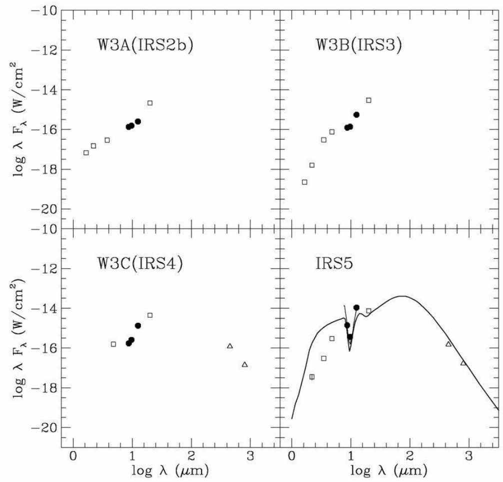

Fig. 3 SED of the high mass young stellar objects (HMYSOs) with X-ray emission observed in W3 Main.

In order to study the nature of the X-ray sources in NGC 6334, we have compared the public *Chandra* ACIS-I array imaging with the high spatial resolution near-IR images reported by Persi et al. (2005). We discuss here the results relative to NGC 6334 I and NGC 6334 IV. The details of the data analysis of the *Chandra* observations will be given in a further paper.

2.3.1 NGC 6334I

NGC 6334 I is characterized by the presence of the UCHII F in the south, the extended shell-shaped HII region E in the middle, and in the northern part by the millimeter and sub-millimeter peak I(N). We detect a total of 35 point-like X-ray sources above the detection limit of 7 counts in a field of 196×218 sq arcsec. Most of the sources emit predominantly between 2.5 and 8 keV and about 48% have been associated with near-IR sources. The locations of the X-Ray sources with near-IR counterparts are shown in Figure 4.

Particularly interesting is the identification of two X-Ray sources with the YSOs Irs1E and Irs1SE found by Persi et al. (1996) (see Figure 5 left panel). IRS1E is the exciting source of the UCHII F and has a very steep infrared energy distribution as shown in Figure 5 (right panel). The derived bolometric luminosity indicates the presence of a ZAMS B2-type star. The parameters of this source are reported in Table 1.

2.3.2 NGC 6334IV

NGC 6334 IV shows two extended low emissivity lobes detected in radio continuum by Rodriguez et al. (1988). Subarcsec JHK images obtained by Persi et al. (2000), detected a small number of luminous (O–B2) YSOs located in the densest part of the cloud that is at the center of a giant bipolar structure seen in the radio and infrared bands.

In this region we have found 150 X-ray *Chandra* sources of which only 24 sources identified with IR band (see Figure 6). None of the high massive young stars observed in the densest part of the cloud has been detected in X-ray, and most of the X-ray sources have no near-IR excess. Only three X-ray sources located to the east of the bipolar structure have near IR excess. This result is very different from the other HMSFRs in which massive protostellar objects show hard X-ray emission.

3 DISCUSSION AND CONCLUSIONS

The correlated IR-X-ray observations of HMSRs show that very young massive stars are emitters of relatively hard X-rays and that they can be detected with *Chandra* even in a high-density environment. It is interesting to ask whether the mechanism that produces the X-ray emission in high mass young stellar objects is identical to those discussed for more evolved massive stars. Berghöfer et al. (1997) found a relationship between X-ray and total luminosity of $L_\mathrm{X}/L_\mathrm{bol} \approx 10^{-7}$ for MS OB-type stars. In Figure 7 we plot the X-ray luminosities versus bolometric luminosities for the HMYSOs of Table 1. Although the uncertainty in the determination of L_X and L_bol is high, the wide scattering of our sources with respect to the canonical relationship found by Berghöfer et al.(1997) suggests that the X-ray mechanisms are different.

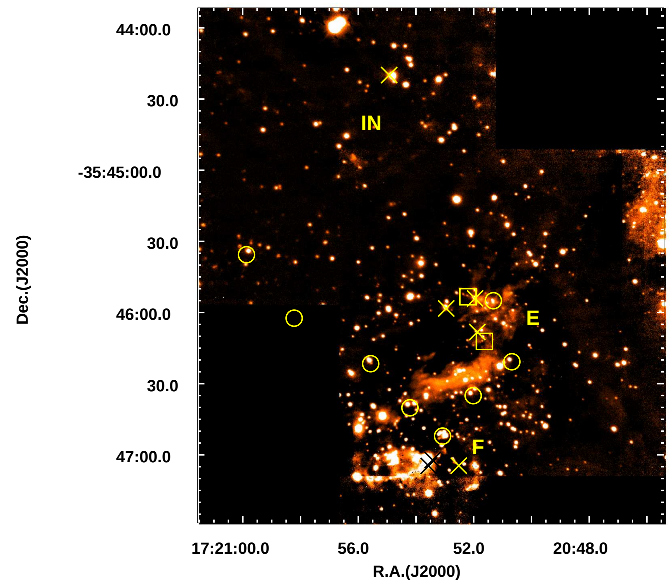

Fig. 4 2.2 μm image of NGC 6334 I (196 × 218 sq arcsec). X-ray sources associated with YSOs are marked with crosses, while the open circles indicate X-ray sources with no near-IR excess.

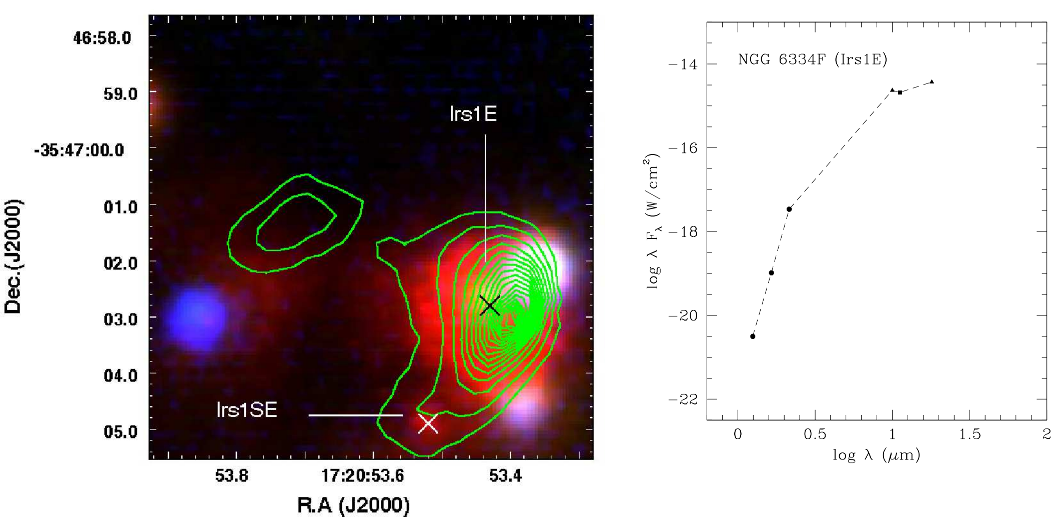

Fig. 5 *Left panel*: Composite $JHKs$ (J=blue, H=green, and Ks=red) image of NGC 6334F. The contours represent the 18μm emission of De Buizer et al. (2002), and the crosses are the positions of the two *Chandra* sources. *Right panel*: Spectral energy distribution of the high mass young stellar object Irs1E.

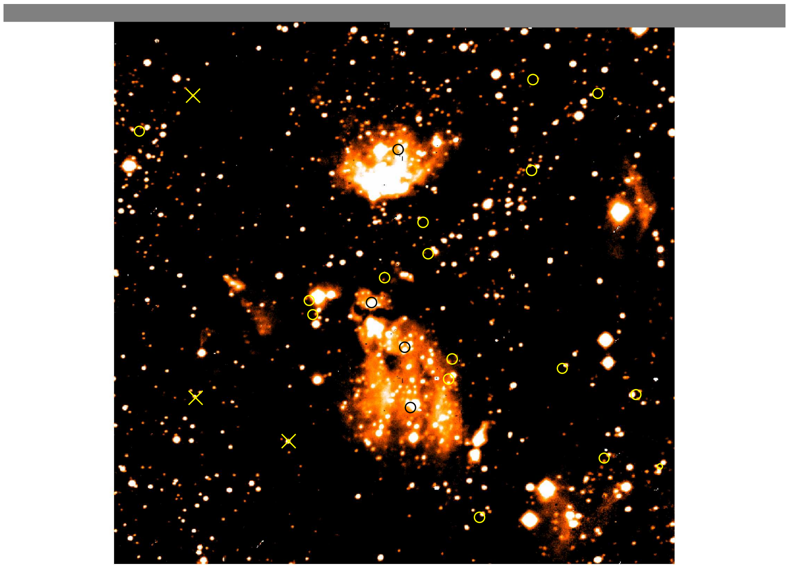

Fig. 6 2.2 μm image of NGC 6334 IV (230 $\times$ 230 sq arcsec). North is to the top, east to the left. X-ray sources associated with YSOs are marked with crosses, while the open circles indicate X-ray sources without near-IR excess.

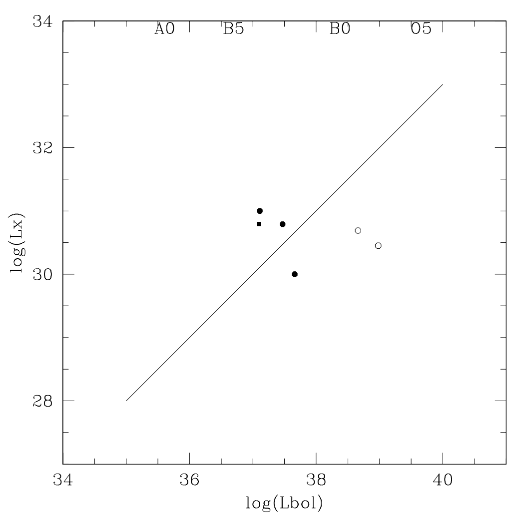

Fig. 7 $L_{\rm X}$ versus $L_{\rm bol}$ of the high massive young stellar objects of Table 1. The solid line shows $L_{\rm X}/L_{\rm bol} = 10^{-7}$.

Models for X-ray emission from single O-type stars have been summarized by Feigelson et al. (2002), from a hot corona at the base of the stellar wind (e.g., Cassinelli & Swank 1983) to wind instabilities (e.g., Lucy 1982). Feigelson & Montmerle (1999) and Feigelson et al. (2002) consider the possibility that young massive stars produce X-ray emission via violent magnetic reconnection events, similar to their low-mass counterparts. Magnetic activity such as that of low-mass stars has been also assumed by Kohno et al. (2002) to explain the X-ray emission in young massive stars in Mon R2.

At present, only a small number of high mass star forming regions have been analyzed, so we have a poor statistics of HMYSOs with X-ray emission to define an appropriate model. In the next future, thanks to the public release of the *Chandra* data and of the high sensitivity IR images from the Spitzer satellite, it will be possible to increase the statistics of HMSFRs.

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