THE DISCOVERY OF DIFFUSE X-RAY EMISSION IN NGC 2024, ONE OF THE NEAREST
MASSIVE STAR-FORMING REGIONS
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Received 2006 June 12; accepted 2006 August 4; published 2006 September 8

ABSTRACT
We analyzed deep 75 ks Chandra ACIS-I data of NGC 2024 with the aim of searching for diffuse X-ray emission in this most nearby (415 pc) of massive star-forming regions. After removing point sources, extended emission was detected in the central circular region with a radius of 0.5 pc, and it is spatially associated with this young massive stellar cluster. Its X-ray spectrum exhibits a very hard continuum ($kT > 8$ keV) and shows signs of having a He-like Fe Kα line with a $0.5$–$7$ keV absorption-corrected luminosity of $2 \times 10^{31}$ ergs s$^{-1}$. Undetected faint point sources, estimated from the luminosity function of the detected sources, contribute less than 10% to this emission. Hence, the emission is truly diffuse in nature. Because of the proximity of NGC 2024 and the long exposure, this discovery is one of the strongest pieces of evidence in support of the existence of diffuse X-ray emission in massive star-forming regions.

Subject headings: H II regions — ISM: individual (NGC 2024) — stars: early-type — stars: formation — stars: winds, outflows

1. INTRODUCTION
Increasing evidence of diffuse X-ray emission has been found in massive star-forming regions (MSFRs), using the Chandra X-Ray Observatory, such as the Rosette Nebula (at a distance of $D = 1.4$ kpc; Townsley et al. 2003), M17 ($D = 1.6$ kpc; Townsley et al. 2003), RCW 38 ($D = 1.6$ kpc; Wolk et al. 2002), NGC 6334 ($D = 1.7$ kpc; Ezoe et al. 2006), RCW 49 ($D = 1.9$–$7.9$ kpc; Townsley et al. 2005), W51A ($D = 5.5$–$7.5$ kpc; Townsley et al. 2005), NGC 3603 ($D = 7$ kpc; Moffat et al. 2002), the Arches cluster ($D = 8.5$ kpc; Yusef-Zadeh et al. 2002), and the Quintuplet cluster ($D = 8.5$ kpc; Wang et al. 2002). Townsley et al. (2003) explained the diffuse soft X-ray emission found in M17 in the context of strong shocks by fast stellar winds from young massive stars (Dyson & de Vries 1972; Castor et al. 1975; Weaver et al. 1977). Recent results on NGC 6334 by Ezoe et al. (2006) indicate that the spectra of the diffuse emission varies from place to place; those in tenuous molecular cloud regions are soft and thermal, with temperatures of several keV, while those in dense cores exhibit harder continua with a photon index of $\Gamma \sim 1$. They also have shown that these thermal and nonthermal spectra of the diffuse X-ray emission in MSFRs, found as a mixture in the NGC 6334 case, may be generally explained by the stellar-wind shock model. In spite of this observational progress, even with Chandra, there remains an uncertainty as to how much undetected faint point sources contribute to the emission, because these MSFRs are relatively distant ($>1.4$ kpc).

In order to unambiguously examine the diffuse X-ray emission in MSFRs, we analyzed the archival Chandra data of NGC 2024. This region, known as the Flame Nebula, is one of the nearest MSFRs ($D = 415$ pc; Anthony-Twarog 1982), located in the Orion Nebula. It is an H II region that is considered to be illuminated by the O8 V–B2 V star IRS 2b (Bik et al. 2003). In the vicinity of IRS 2b, there is one early B star candidate associated with the ultracompact H II region G206.543$-$16.347 and the infrared source IRS 2 (Lenorzer et al. 2004), and there are seven compact dust condensations, named FIR 1–7, that are possibly massive protostars (Megez et al. 1988). In addition, $\sim 300$ low-mass ($\approx 2$ $M_\odot$) young stars have been found by near-infrared observations (Lada 1991). The estimated age of NGC 2024 ranges from 0.3 Myr (Meyer 1996) to several megayears (Comerons et al. 1996). A previous analysis of the same Chandra data on point sources has been published by Skinner et al. (2003). In this Letter, we focus on the search for diffuse X-ray emission in this representative MSFR.

2. OBSERVATION
Chandra observed NGC 2024 on 2001 August 8–9 using ACIS-I for 21.9 hr. We started with the level 1 event files in the same way as Skinner et al. (2003). The analysis software versions utilized for the standard data reduction are different; we used CIAO (Chandra Interactive Analysis of Observations) version 2.3 and the calibration database version 2.18. These new software versions allowed us to correct the data for the effect of the charge transfer inefficiency; this was not possible in Skinner et al. (2003). No background flares were seen during the observation, and the average count rate for the six ACIS chips was 9.1 counts s$^{-1}$. We then excluded $>1.2$ times the average rate. This procedure excluded 2% of the exposure time. After these data screenings, the nominal exposure has become 75.3 ks.

We searched the data for diffuse X-ray emission, following the analysis method of Ezoe et al. (2006). We first created adaptively smoothed X-ray images in two energy bands, as shown in Figures 1a and 1b (Plate 1). We see a sign of extended emission associated with the massive star IRS 2b and its surrounding area. The extended emission in 0.5–2 keV is strong in the northwest direction of IRS 2b, while that in 2–7 keV is elongated in the northwest-southeast direction. We then used the wavdetect program to identify sources using images in three energy bands (0.5–2, 2–8, and 0.5–8 keV) independently, in order not to miss very soft or strongly absorbed sources. The significance criterion and wavelet scales were set at 1 $\times$ $10^{-6}$ and 1–16 pixels, respectively, in multiples of $\sqrt{2}$. In the ACIS-I field of view, 301 sources were detected. Among them,
Fig. 2.—(a) ACIS spectrum of the C1 region compared with that summed over 176 point sources. (b) C1 spectrum fitted with a power-law plus narrow Gaussian model. (c) Same as panel b, but for a single-temperature plasma model absorbed by two different column densities (dashed and dash-dotted lines). (d) Same as panel c, but including the escaped photons from the summed point sources (red lines).

28 sources are newly identified (i.e., they are not listed in Skinner et al. 2003) due to our three-band searching method.

We excluded all the detected point sources by creating a point-source mask using the “Chandra Ray Tracer” (ChaRT). For each source, we defined a radius that included ~98% of photons at the Al Kα-line energy (1.497 keV). Then we excluded all these regions by applying the mask to the raw ACIS-I image, and created images of the residual emission using the CIAO tools dmfilth and csmooth. Figures 1c and 1d show images of the extended emission thus obtained. In order to evaluate the significance of this emission, we defined a circular region named C1 (the largest circle in Fig. 1d) with a radius of 4′ = 0.5 pc. The total area of region C1 is 43/39 arcmin² or 0.62/0.52 pc² before/after excluding the area around point sources. The 0.5–7 keV count rate of region C1 is 0.142 ± 0.001 counts s⁻¹, while that of the same region in blank-sky data is 0.084 ± 0.001 counts s⁻¹. The errors are 1 σ statistical ones. Hence, its residual count rate is 0.057 ± 0.001 counts s⁻¹ or 4270 ± 110 counts. It is thus clear that a highly significant extended emission is present in the central region of NGC 2024.

3. EXTENDED X-RAY EMISSION

In the presence of significant excess emission, we immediately considered the possibility of diffuse emission. To know its basic properties, we compared its background-subtracted spectrum in Figure 2a with that summed over 176 point sources detected within region C1. The weighted ARF (ancillary response function) and RMF (response matrix function) were calculated using the CIAO programs mkwarf and mkwrmf, respectively. The apply_acisabs script was utilized when creating ARF files, to correct them for the decrease in the ACIS quantum efficiency. The background spectra were extracted from the same regions in the blank-sky data for individual regions. From Figure 2a, we can see important features of the extended emission. First, it is about 1 order of magnitude fainter than the summed point sources. Second, the extended emission shows a harder continuum in the 1–7 keV range. Third, a hint of an emission line is seen in 6–7 keV.

To know the basic parameters of the extended emission, we then conducted spectral fitting. We employed a simple power-law model with an interstellar absorption and a narrow Gaussian. Hereafter all quoted errors in the spectral fitting refer to 90% confidence levels unless otherwise noted. The result is shown in Figure 2b, and Table 1 lists the obtained parameters. The fit

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5 See http://cxc.harvard.edu/chart/threads/index.html.
was not acceptable with $\chi^2/d\nu \sim 1.5$ because of the excess around 0.5–1 keV. The line-center energy indicates a He-like Fe Kα line from thermal plasma. Therefore, we consider an alternative “leaky absorber” condition; a single emission component reaches us via two (or more) paths with different absorptions. This situation is possible in an MSFR like NGC 2024, where the density of the molecular cloud varies from place to place. Hence, we fitted the spectrum by a sum of two thermal components with independent absorptions, but with their temperatures and abundances together. The result is shown in Figure 2c and Table 1. As a thin thermal plasma model, we utilized the APEC (astrophysical plasma emission code) model. Then the fitting result went from $\chi^2/d\nu \sim 1.5$ to 1.3, with 99.7% confidence according to an $F$-test, which is a significant improvement. The soft excess is represented by the mildly absorbed high-temperature emission. The best-fit temperature is high, 11 keV, consistent with the small photon index of 1 in the power-law model. The 0.5–7 keV flux obtained from the leaky absorption model is 1.1 $\times$ 10^{-12} ergs s^{-1} cm^{-2}.

For comparison, we quantified the summed point-source spectrum. In the same manner as the extended emission, the source spectrum, the background, and the ARF and RMF files were obtained. The fit for a single thermal emission model with one absorption was not acceptable with $\chi^2/d\nu \sim 7$ because this model cannot represent both the soft excess below $\sim$2 keV (which is similar to that in the extended emission case) and also various emission lines. Hence, we used the leaky absorption model with free Ne, Mg, Si, S, Ar, Ca, and Fe abundances, in order to represent the data better. We obtained results as shown in Table 2 and Figure 3. The best-fit temperature of 4.4 keV is consistent with typical values of young low-mass stars (e.g., Imanishi et al. 2001) and significantly lower than that of the extended emission.

In spite of these spectral analyses, we must evaluate the effect of photons escaping from the summed point sources because the point sources are far brighter than the extended emission. In the same way as Ezoe et al. (2006), we took into account the summed point-source spectrum by multiplying the best-fit model for the summed point sources by the energy-dependent escaping-fraction curve, estimated by ChaRT. We have found that this contributes $\sim$40% to the extended emission. After correcting for the escaping-photon effect, the 0.5–7 keV flux of the extended emission becomes 6.3 $\times$ 10^{-13} erg s^{-1} cm^{-2}, yielding an absorption-uncorrected luminosity of 1.3 $\times$ 10^{39} ergs s^{-1} or a surface brightness of 2 $\times$ 10^{-13} ergs s^{-1} pc^{-2} at an assumed distance of 415 pc.

We refitted the C1 spectrum by including the escaping-photon effect. The result is shown in Figure 2d and Table 1. The fitting result was again acceptable. Also, the escaping-photon effect has relatively little effect on the fitting parameters, except the normalization.

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### TABLE 1

| Model | $N_{HI}$ | $N_{H}$ | $\Gamma$ or $kT$ | $Z^i$ | Norm.$^1$ | Norm.$^2$ | $E_x^i$ | Norm.$_{abs}^a$ | $F_x$ | $L_x^i$ | $\chi^2$/dof |
|-------|---------|--------|-----------------|------|---------|---------|--------|--------------|------|-------|---------|
| po+ga | 1.3 $^{+0.5}_{-0.4}$ | ... | 0.94 $^{+0.32}_{-0.24}$ | ... | 1.2 $^{+0.16}_{-0.15}$ | ... | 6.7 $^{+0.21}_{-0.18}$ | 6.3 $^{+1.6}_{-1.5}$ | 1.1 | 2.9 | 99.2/65 |
| leaky abs.1 | 0.62(2.1) | 4.0 $^{+1.4}_{-1.3}$ | 11 $^{+6.5}_{-3.5}$ | 1.3 $^{+1.6}_{-1.5}$ | 2.2 $^{+1.5}_{-1.5}$ | 2.5 $^{+2.0}_{-1.6}$ | 9.2 $^{+2.7}_{-2.6}$ | ... | ... | 1.1 | 4.0 | 85.9/64 |
| leaky abs.2 | 0.21(2.1) | 3.3 $^{+0.7}_{-0.6}$ | 11 $^{+7.6}_{-7.6}$ | 2.5(1.0) | 0.73 $^{+2.0}_{-1.6}$ | 4.4 $^{+1.6}_{-1.8}$ | 4.6 $^{+1.5}_{-1.6}$ | ... | ... | 0.63 | 2.2 | 84.2/64 |

* From top to bottom, these fitting models represent the power-law plus narrow Gaussian model and the leaky absorption model without and with the escaping-photon effect, respectively.

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### TABLE 2

| Parameter | Leaky Absorption Model |
|-----------|------------------------|
| $N_{HI}$ | 0.55 $\pm$ 0.09 |
| $N_{H}$ | 2.7 $^{+0.3}_{-0.2}$ |
| $kT$ | 4.4 $^{+0.1}_{-0.1}$ |
| $Z_0$ | 2.9(1.2) |
| $Z_{HI}$ | 1.1 $\pm$ 0.8 |
| $Z_{Fe}$ | 0.06(0.32) |
| $Z_{Mg}$ | 0.93 $^{+0.3}_{-0.2}$ |
| $Z_{Si}$ | 1.2 $^{+0.3}_{-0.2}$ |
| $Z_{Ar}$ | 0.59(1.2) |
| $Z_{Ca}$ | 0.23 $^{+0.05}_{-0.05}$ |
| Norm.$^1$ | 17 $^{+5}_{-5}$ |
| Norm.$^2$ | 130 $\pm$ 10 |
| $F_x$ | 9.5 |
| $L_x^i$ | 43 |
| $\chi^2$/dof | 292/157 |

* See http://cxc.harvard.edu/atomdb/.

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FIG. 3.—Summed point-source spectrum in the C1 region, fitted with the leaky absorption model (dashed and dash-dotted lines).
malizations. All the parameters are consistent with the previous ones that did not include this effect, within 90% confidence levels. The absorption-corrected X-ray luminosity is $2 \times 10^{30}$ ergs s$^{-1}$.

In addition, we also conducted the same spectral analysis on the C2 region (see, e.g., the soft X-ray clump in Fig. 1c). The photon index and temperature obtained are similar to those of the C1 region within errors, except for the lower absorption column density ($0.1 \times 10^{22}$ cm$^{-2}$ when fitted with the leaky absorption model, including the escaping-photon effect). No sign of emission lines was seen. Hence, the spectral hardness of the extended emission is considered to be common within the whole region, and the offset peak in the soft-band map is simply a consequence of a slightly reduced absorption.

4. LUMINOSITY FUNCTION

Based on the surface brightness of the extended emission, we estimated the contribution from unresolved faint point sources to this emission, in order to know whether it can be explained by faint sources that are individually undetectable. We utilized the luminosity function of the detected point sources, as in Ezoe et al. (2006). We also utilized the X-ray surface brightness of the extended emission after subtracting the escape photons from the point sources, obtained in § 3.

Figure 4 shows the luminosity function of the 176 point sources in region C1. We derived the absorption-corrected 0.5–7 keV luminosity $L$. The X-ray flux of each point source is obtained by spectral fitting for a bright source ($\geq 30$ net counts or counts after subtracting the background), while by using a count-to-flux conversion factor derived from the summed point sources, a value of $1.6 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ (net counts per second)$^{-1}$ is obtained for a fainter source.

The source number density increases toward lower luminosities and saturates below 10 net counts, corresponding to the completeness limit of this observation. We estimated the limit from source number histograms as a function of the logarithm of net counts, and we regarded the maximum of the histogram as the completeness limit of this observation. We estimated the limit from the source number histograms as a function of the logarithm of net counts, and we regarded the maximum of the histogram as the completeness limit of this observation. We estimated the limit from the source number histograms as a function of the logarithm of net counts, and we regarded the maximum of the histogram as the completeness limit of this observation. We estimated the limit from the source number histograms as a function of the logarithm of net counts, and we regarded the maximum of the histogram as the completeness limit of this observation. We estimated the limit from the source number histograms as a function of the logarithm of net counts, and we regarded the maximum of the histogram as the completeness limit of this observation. We estimated the limit from the source number histograms as a function of the logarithm of net counts, and we regarded the maximum of the histogram as the completeness limit of this observation.

The solid line in Figure 4 indicates the necessary point-source number, in order to explain the extended emission by point sources. The point-source number is clearly short, supporting the notion that the extended emission is truly diffuse. Furthermore, even when we extrapolate the luminosity function toward a lower limit of 0 ergs s$^{-1}$, using a linear function fitted in log-log space from the completeness limit to $10^{30}$ ergs s$^{-1}$, the estimated contribution of unresolved sources is at most $\sim 10\%$ of the extended emission. Based on these results, the extended emission of NGC 2024 can be considered diffuse in nature.

5. DISCUSSION

We have found diffuse X-ray emission in NGC 2024. Because of the proximity of NGC 2024 and the long exposure time, this discovery itself is one of the strongest pieces of evidence in support of the existence of diffuse emission in MSFRs among the previous Chandra results. Also, this result provides us with new observational evidence that, even in an MSFR in which only late O to early B stars exist, diffuse X-ray emission can be observed if the sensitivity is high enough. The spectral analysis suggests that diffuse emission is dominated by thermal emission. At the same time, since the continuum ($kT > 8$ keV) of diffuse emission is harder than the typical spectra of young stars, a part of the emission may come from a nonthermal origin. In NGC 6334, the soft thermal regions and the hard, possibly nonthermal, regions can be spatially distinguished (Ezoe et al. 2006). In NGC 2024, the soft and hard regions may be cospatial and, hence, may be observed as a mixture of both thermal and nonthermal emission.

We now discuss whether the thermal or nonthermal interpretation is feasible in terms of energetics. First, if we assume that the whole diffuse emission is thermal, the total plasma energy $U$ will be $\sim 10^{57}\eta^{0.5}$ ergs s$^{-1}$, where $\eta$ is the filling factor, from the equation (3) in Ezoe et al. (2006). Using the X-ray luminosity $L_x$ and $U$, the plasma cooling time is estimated to be $UL_x^{-1} \sim 10^7\eta^{0.5}$ yr, which is far longer than the age of NGC 2024, from 0.3 Myr (Meyer 1996) to several megayears (Comeron et al. 1996). Although the sound crossing time in a 10 keV plasma across the region of 0.5 pc in size is $\sim 10^5$ yr and hence short, the plasma with an estimated pressure of $5 \times 10^{7}\eta^{-0.5}$ K cm$^{-3}$, calculated from equation (5) in Ezoe et al. (2006), may be confined by the dense H ii region known to exist around the molecular cloud dark lane (Fig. 1c) (Subrahmanyan et al. 1997) and also by the strong magnetic field within the molecular cloud (Crutcher et al. 1999). Then, by dividing the total energy by the assumed age of NGC 2024 (0.3 Myr), the average energy input is estimated to be $10^{48}$ ergs s$^{-1}$.

Second, we consider the nonthermal possibility. The flat continuum ($T \sim 1$ or $kT > 8$ keV) of the emission strongly suggests bremsstrahlung emission by 10 keV to several MeV electrons, rather than synchrotron or inverse Compton emission (Ezoe et al. 2006). Since the Coulomb loss overpowers the bremsstrahlung emission, if we assume that the diffuse emission is totally nonthermal, the necessary kinematic energy to be supplied is at least $\sim 10^6$ times larger than the observed X-ray luminosity, $\sim 2 \times 10^{36}$ ergs s$^{-1}$.

One of the most plausible energy sources for the diffuse emission is the shocks generated by fast stellar winds ($\sim 2000$ km s$^{-1}$) from young massive stars. The huge kinetic energy of the stellar winds can be easily converted via the strong shocks, among dense molecular clouds and H ii regions, into the thermal...
(and nonthermal) energy of particles in the surrounding gases. This explanation has been proposed for M17 (Townsley et al. 2003) and NGC 6334 (Ezoe et al. 2006). In NGC 2024, at least one late O to early B star, IRS 2b (O8 V–B2 V), one early B star candidate, IRS 2, and seven possibly massive protostars reside. As shown in Figure 1, these massive stars are spatially associated with the diffuse emission. A typical kinematic luminosity of the stellar wind is $\sim 10^{33} - 10^{35}$ ergs s$^{-1}$ per one B2 V–O8 V star (Howarth & Prinja 1989; Prinja et al. 1990; Panagia 1973). Therefore, the necessary energy supply of the thermal interpretation is explained if there is at least one massive star with a strong wind, comparable to or stronger than those of a typical B0.5 V star. The nonthermal interpretation is also possible if we consider all nine sources as massive stars having strong winds. Wind-wind collisions may effectively increase the energy of a shock. Hence, the stellar-wind scenario is possible from the viewpoint of energetics.

Y. E. is financially supported by the Japan Society for the Promotion of Science.

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Fig. 1.—Adaptively smoothed X-ray images of NGC 2024 taken with the Chandra ACIS-I. Panels $a$ and $b$ correspond to 0.5–2 and 2–7 keV band images before applying the point-source mask, respectively, while panels $c$ and $d$ are point-source–excluded contours in 0.5–2 and 2–7 keV bands overlaid on the optical Digitized Sky Survey image. J2000 coordinates are shown. All the images are corrected for the exposure and vignetting, but the background is not subtracted. Boxes show the ACIS-I fields of view, while the large circles (C1 and C2) are regions utilized in our spectral analysis. The small circles are the positions of IRS 2b, IRS2, and FIR 1–7. Because IRS 2 is located just 5'' southeast of IRS2b, these two circles overlap. The color intensity is plotted logarithmically from $5 \times 10^{-10}$ to $5 \times 10^{-9}$ counts s$^{-1}$ pixel$^{-1}$ cm$^{-2}$ in panel $a$ and from $7 \times 10^{-10}$ to $7 \times 10^{-9}$ in panel $b$. Also, the contours are plotted logarithmically from $7.5 \times 10^{-10}$ to $1.0 \times 10^{-9}$ counts s$^{-1}$ pixel$^{-1}$ cm$^{-2}$ in panel $c$ and from $1.3 \times 10^{-9}$ to $4.0 \times 10^{-9}$ in panel $d$. 

PLATE 1