INVESTIGATION OF DIFFUSE HARD X-RAY EMISSION FROM THE MASSIVE STAR-FORMING REGION NGC 6334

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Received 2005 May 15; accepted 2005 October 25

ABSTRACT

Chandra ACIS-I data of the molecular cloud and H ii region complex NGC 6334 were analyzed. The hard X-ray clumps detected with ASCA (Sekimoto and coworkers) were resolved into 792 point sources. After removing the point sources, an extended X-ray emission component was detected over a 5 × 9 pc² region, with the 0.5–8 keV absorption-corrected luminosity of 2 × 10³³ ergs s⁻¹. The contribution from faint point sources to this extended emission was estimated as at most ~20%, suggesting that most of the emission is diffuse in nature. The X-ray spectrum of the diffuse emission was observed to vary from place to place. In tenuous molecular cloud regions with hydrogen column density of (0.5–1) × 10²² cm⁻², the spectrum can be represented by a thermal plasma model with temperatures of several keV. The spectrum in dense cloud cores exhibits harder continuum, together with higher absorption of more than ~3 × 10²³ cm⁻². In some of such highly obscured regions, the spectra show extremely hard continua equivalent to a photon index of ~1, and favors a nonthermal interpretation. These results are discussed in the context of thermal and nonthermal emission, both powered by fast stellar winds from embedded young early-type stars through shock transitions.

Subject headings: H ii regions — ISM: individual (NGC 6334) — stars: early-type — stars: formation — stars: winds, outflows

1. INTRODUCTION

X-rays provide a powerful diagnostic tool of massive star-forming regions (MSFRs). X-ray photons penetrate dense gas and dust cores more deeply than optical and even near-infrared lights. Not only serving as a probe, the X-ray emission itself provides evidence that some unexpected energetic processes are operating in MSFRs. Therefore, since the surprising discovery of X-ray emission from the Orion Nebula (Giacconi et al. 1974), X-ray photons penetrate dense gas forming regions (MSFRs). Therefore, since the surprising discovery of X-ray emission from the Orion Nebula (Giacconi et al. 1974), vigorous X-ray studies on MSFRs have been made with Einstein, ROSAT (Röntgensatellit), and ASCA (Advanced Satellite for Cosmology and Astrophysics). In particular, the hard X-ray (>2 keV) imaging spectroscopy with ASCA has for the first time revealed several clumps in MFSRs, each showing a high temperature (3–10 keV) and a high luminosity (10³⁴–10³⁵ ergs s⁻¹) (e.g., Yamauchi et al. 1996; Hofner & Churchwell 1997; Nakano et al. 2000; Sekimoto et al. 2000). Thanks to its superb angular resolution, these X-ray clumps in MSFRs have been resolved into hundreds of stars with the Chandra X-Ray Observatory (e.g., Garmire et al. 2000; Feigelson et al. 2002, 2003; Hofner et al. 2002; Kohno et al. 2002; Nakajima et al. 2003).

Besides individual stars at various evolutionary stages, Chandra first enabled a detailed examination of diffuse X-ray emission in MSFRs. Theoretically, such a phenomenon had long been expected both around individual OB stars (Dyson & de Vries 1972; Castor et al. 1975; Weaver et al. 1977) and in MSFRs (Chevalier & Clegg 1985). The reported detections of extended soft X-rays (≤1 keV) associated with MSFRs before Chandra (e.g., the Carina Nebula [Seward & Chlebowski 1982] and the 30 Doradus Nebula in the Large Magellanic Cloud [Wang 1999]) were consistent with these predictions. However, even in Galactic MSFRs, it has remained difficult to date to quantify whether the extended X-ray emission really exists, because MSFRs are usually too complex to be resolved by the past X-ray telescopes.

With Chandra, Townsley et al. (2003) indeed reported detections of diffuse soft X-ray emission in two nearby MSFRs, M17 (at a distance of D = 1.6 kpc from the Sun) and the Rosette Nebula (D = 1.4 kpc). They concluded that at least the emission in M17 is diffuse, and explained the phenomenon in terms of stellar-wind shock model (Dyson & de Vries 1972; Castor et al. 1975; Weaver et al. 1977). Its spectrum was very soft, represented by a two-temperature plasma model (kT = 0.13 ± 0.6 keV). Another Chandra result is the possible detection of diffuse hard X-ray emission from RCW 38 (D = 1.7 kpc; Wolk et al. 2002), which could be of nonthermal origin because a part of the emission show hard continua with a photon index of 1.3–1.6. Similar phenomena may have also been detected from more distant galactic MSFRs, including the Arches Cluster (Wang et al. 2002; Yusef-Zadeh et al. 2002), the Quintuplet Cluster (Wang et al. 2002) near the Galactic center, and NGC 3603 at D = 7 kpc (Moffat et al. 2002), although their larger distances make it difficult to remove, even with Chandra, contributions from unresolved point sources.

Thus, the search for diffuse X-ray emission from MSFRs is becoming a new topic explored with Chandra. In the present paper, we describe the analysis of Chandra data on NGC 6334 and report on the discovery of diffuse hard X-ray emission from this representative MSFR.

2. PREVIOUS X-RAY RESULTS ON NGC 6334

NGC 6334 is a nearby (D = 1.7 kpc, yielding a plate scale of 1" = 0.01 pc; Neckel 1978) MSFR, with the bolometric luminosity reaching $L_{bol} \sim 4 \times 10^{39}$ ergs s⁻¹ (Loughran et al. 1986), which is one of the highest of this class. As shown in Figure 1, it...
contains several star-forming sites defined in wide wavelength ranges. Although designations of these sites depend on the observing wavelength, we here follow two commonly used ones; the far-infrared (FIR) cores named I(N), I, II, III, IV, and V (Fig. 1a); and the radio sources named A, C, D, E, and F (Fig. 1b). Not all of these are detected in both wavelength ranges (see Table 4 in Kraemer et al. 1999 for nomenclature). Each site is known to be powered by one or more massive stars, either zero-age main-sequence (ZAMS) stars or protostars (e.g., Rodriguez et al. 1982; Harvey and Gatley 1983; Straw et al. 1989). These sites coincide with the dense molecular clouds (Fig. 1c), the densest part of which appears as the central dark lane in the near-infrared (NIR) map (Fig. 1d). The central FIR core (III) has no radio masers or outflows that indicate early stages of stellar evolution, but it hosts H II regions. Core I (N) has no H II region but does have masers and an outflow, so this core is regarded as one of the youngest massive star-forming sites.

In X-rays, NGC 6334 was first detected with the Einstein satellite as 2E1717.1-3548 (Harris et al. 1990), which coincides in position with FIR core III. With ASCA, Matsuzaki (1999), Matsuzaki et al. (1999), and Sekimoto et al. (2000) found hard X-ray clumps associated with the FIR and radio sources; five FIR cores (I, II, III, IV, and V) were visible in the 2–10 keV band. The region-integrated spectrum exhibits a temperature of 9 keV, which is the highest among the MSFRs observed with ASCA. The X-rays are absorbed by a large absorption column density ($N_H \sim 1 \times 10^{22} \text{ cm}^{-2}$), suggesting that the emission originates from embedded young massive stars. The region-integrated 0.5–10 keV X-ray luminosity, $6 \times 10^{33} \text{ ergs s}^{-1}$, makes NGC 6334 one of the most X-ray–luminous MSFRs ever observed with ASCA. Thus, NGC 6334 is without doubt an attractive target to search for diffuse hard X-rays, and if detected, to investigate their properties and emission mechanism.

3. OBSERVATION AND DATA REDUCTION

We conducted two 40 ks observations of NGC 6334 with Chandra, on 2002 August 31 and 2002 September 2. In order to cover the whole nebula, we placed the aim point at the J2000.0 coordinates of ($17^h20^m53^s45, -35\degree47\prime19\farcs33$) and ($17^h20^m00^s44, -35\degree56\prime22\farcs26$) in the August and September observations, respectively. Hereafter we call the former the “north field” and the latter the “south field,” according to their declinations. The two fields of view partially overlap (see Fig. 1d). The Advanced CCD Imaging Spectrometer (ACIS-I0, I1, I2, I3, S2, and S3) was utilized. In this paper, we analyze only the data from the four ACIS-I chips, because the point-spread function (PSF) of the telescope becomes significantly broader at the positions of the ACIS-S chips.
We started data reduction with level 1 event files provided by the Chandra X-Ray Center and followed the standard data reduction procedures using the CIAO (Chandra Interactive Analysis of Observations) software package version 2.3 and the calibration database (caldb) version 2.18. We corrected pulse heights for the charge transfer inefficiency (CTI) and removed the ACIS pixel randomization to improve image quality. No background flares occurred in the north-field observation, while nearly half the south-field exposure was affected by them. We then conducted flare filtering by excluding those portions where the 0.5–8 keV count rate was >1.2 times the quiescent average of the south-field observation (~4 × 10⁻⁷ count s⁻¹ pixel⁻¹). We have thus obtained 39.4 and 19.4 ks exposure times for the north and south observations, respectively.

Using these data sets, we created X-ray images in the 0.5–2 and 2–8 keV bands, as shown in Figure 2. We observe a number of point sources and also indication of extended structures. However, it is not clear at this stage whether they really represent diffuse emission or simply a sum of point sources that cannot be resolved even with Chandra. Therefore, before analyzing the data for suggested extended emission, we conduct point-source analysis in the next section.

4. POINT-SOURCE ANALYSIS

The wavdetect program was utilized to detect point sources (Freeman et al. 2002). We used images in three 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 as 1; 1–16 pixels in multiples of \sqrt{2}, respectively. As a result, we have detected 449 and 390 sources in the north and south fields, respectively. Among them, 42 sources in the north field have counterparts in the south field within the position-dependent angular resolution, approximately defined in Feigelson et al. (2002). Excluding these overlaps, the total source number becomes 792.

We extracted events of the individual point sources using regions given by the wavdetect program. The background was extracted around each source, excluding other point sources, and then scaled to the on-source area. The scaled background counts amount to ~1%–8% of the raw source counts near the aim point and ~20%–40% for sources at 8'. After subtracting the background, the detected sources exhibit net signal counts (hereafter net counts) of ~2–300. Although faint sources of less than ≤5 net counts have low significance (≤2 σ), we here take them as possible point sources, in order not to include their counts into the potentially extended emission. We then produced source-number histograms as a function of the logarithm of net counts, in six separate annular regions (0–2, 2–4, 4–6, 6–8, 8–10 and >10 arcminutes from the aim point) in each ACIS-I field. Reflecting a roughly power-law-like source intensity distribution (see § 5.3 for details), the source number first increases toward lower counts, reaches a maximum, and then decreases due to the sensitivity limit. We regard this maximum of the histogram as representing the completeness limit of the point-source detection.

In both observations, the completeness limit estimated in this way monotonically increases with the angular distance from ~10 to ~30 net counts, due to the PSF broadening. When utilizing a typical count-to-flux conversion factor of ~2 × 10⁻¹⁴ erg s⁻¹ cm⁻² (net counts s⁻¹)⁻¹ obtained from spectral fitting of the 163 bright (>30 net counts) sources, 10 net counts corresponds to the 0.5–8 keV X-ray flux of ~0.5 × 10⁻¹⁴ and ~1 × 10⁻¹⁴ erg s⁻¹ cm⁻², in the north and south fields, respectively. At an assumed distance of 1.7 kpc, these fluxes translate to ~2 × 10⁻¹⁰ and ~4 × 10⁻¹⁰ ergs s⁻¹ cm⁻².

Detailed point-source analyses will be presented elsewhere (Y. Ezoe et al. 2006, in preparation).

We have so far utilized signal extraction regions specified by the wavdetect routine. Although these regions are optimum for the source detection, they are usually too small to thoroughly remove photons from the point source. Accordingly, we defined new circular regions around individual sources, based on the “Chandra Ray Tracer” (ChaRT). Specifically, we calculated the encircled-photon fraction as a function of energy and separation angle from

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5 See http://cxc.harvard.edu/chart/threads/index.html.
the aim point (0, 1, 2, 3, 5, 7, 10, and 15 arcminutes). For each source, we looked up the results, using interpolation if necessary, and chose a radius to include $\sim$98% of photons at the Al Kα-line energy (1.497 keV). Figure 3 shows point-source mask patterns, obtained by summing up these larger regions around the individual point sources. In this procedure, 8% and 7% of the whole ACIS-I area have been excluded from the north and south field, respectively.

5. ANALYSIS OF EXTENDED X-RAY EMISSION

5.1. Images

We applied the point-source masks (Fig. 3) to the raw ACIS images to remove point sources, and then created images of the residual emission using the CIAO tools dmfilth and csmooth. The former fills holes in the image with values interpolated from surrounding regions, and the latter adaptively smooths the filled image. We utilized default parameters (kernel sizes and significances) in the csmooth routine. We corrected these images for the vignetting and exposure times. Figure 4 shows the images of the residual emission in two energy bands obtained in this way. To retain the best positional resolution available, we here show the two images separately instead of merging them together. In addition, the energy range is restricted to below 7 keV, to avoid the strong instrumental Ni Kα line in the ACIS background.

As is clear from the procedure, the images shown in Figure 4 are thought to represent the apparently extended emission noticed in Figure 2, although they must be examined carefully against possible contribution from fainter (and hence individually undetectable) point sources. The overlapping region appears in somewhat different ways between the north and south field images. This is due to the position-dependent angular resolution, as described in § 4.

5.2. Spectrum

5.2.1. Region Definition

In order to analyze the spectrum of the extended emission, we define in Figure 4 a rectangle of $\sim$10′ × 18′, elongated along the linearly aligned cores, and call it the “extended emission region,” or EER for short. Using the equilateral line from the two aim points, we further subdivide this EER into two trapezoids. When analyzing the northeastern and southwestern trapezoids, we use only the north- and south-field observation data, respectively. This ensures that the overlapping region is always placed within $\sim$8′ of either of the two aim points.

Because NGC 6334 is located on the Galactic plane, it is contaminated by the diffuse emission along the Galactic ridge (e.g., Kaneda et al. 1997; Valinia & Marshall 1998; Ebisawa et al. 2001). In order to remove this unwanted component, we need to subtract the local background rather than those from blank skies. We have therefore chosen two square background regions where the extended emission is relatively weak (see Fig. 4). Hereafter we call them collectively the “background region,” or BR for short, and utilize the events summed over them as our background. The total area of the EER is 2.80/2.55 × 10⁶ pixel² before/after excluding the areas around point sources. These areas correspond to 191/174 arcmin², or 47/43 pc² in 1.7 kpc. Thus, the excluded area is $\sim$10%. Similarly, those of the BR are 1.57/1.50 × 10⁶ pixel².

We then extracted spectra from the EER. The weighted ARF (ancillary response file) and RMF (response matrix file) files were calculated using the CIAO programs mkwarf and mkwrmf, respectively, which take account of position-dependent detector responses such as vignetting and exposure times. The applyciao script was utilized when creating ARF files, to correct them for the recent decrease in the ACIS quantum efficiency. We thus obtained two sets of spectra, ARF, and RMF files corresponding to the two observations, and then added them together considering the difference in their exposure times. In this way, we have acquired the combined spectrum of the EER. We similarly derived a background spectrum from the BR. Below, we utilize them after normalizing to the detector area (pixel²), excluding the removed point sources. Since the effective area (cm²) and also the instrumental background varies from place to place within ACIS-I, we must consider the positional difference of the sky and non-X-ray backgrounds between the EER and BR. In the next section, we hence examine the excess emission considering these uncertainties.
5.2.2. Excess Emission

Figure 5a compares the spectrum of the EER with that derived from the BR, both normalized to the same detector area. The former is higher than the latter by a factor of 2 in the 2–5 keV range, while they agree in energies below 0.7 keV and above 7 keV, where the instrumental background is dominant. The 0.5–7 keV raw counts of the EER and BR spectra are 22,500 ± 150 and 14,600 ± 160, respectively, yielding the excess counts of 7900 ± 220. Thus, the excess emission is statistically quite significant.

To further confirm the significance of the extended emission, we investigated the systematic uncertainties in the background. First, we compared the 5–10 keV count rates of two blank-sky spectra, extracted from the EER and BR locations of a blank-sky observation available to us, and examined the instrumental background for any position dependence. We found a negligible (~1%) difference between the two detector regions. Second, to examine how much the vignetting effect affects the amount of the sky background (Galactic ridge emission and cosmic X-ray background), we compared effective areas of the EER and BR specified by their response files. The BR area was found to be smaller than the EER area by ~5% at <5 keV, and by ~15% at 7 keV; the resultant increase of the sky background is only 4% of the extended emission. Thus, the excess counts in the EER can be concluded to be significant even considering systematic errors.
5.2.3. Comparison with Summed Point Sources

In order to characterize the spectrum of the background-subtracted EER emission, we compare it in Figure 5b with the ACIS spectrum summed over the 548 point sources detected within the EER. This figure immediately reveals several important features of the extended emission. First, it is nearly half as luminous as the emission summed over all the detected point sources. Second, the extended emission exhibits a harder spectral continuum in the 2–7 keV range. Third, no significant emission line is observed in the EER spectrum, in contrast to the point-source spectrum, which shows several emission lines from elements such as S, Ar, and Fe. (Incidentally, the simultaneous presence of these lines is not surprising, since we have added sources with various temperatures.) In order to better visualize this, we show the ratio of the two spectra in Figure 5c. By fitting the spectral ratios with a linear function of energy, given as \((A_0 + A_1 \times \text{energy})\), we obtained \(A_0 = 0.38 \pm 0.03\) and \(A_1 = 0.043 \pm 0.012\), where errors are 1σ. The two spectra significantly differ from each other.

5.2.4. Flux and Luminosity

We conducted spectral fitting to the EER spectrum, to quantify its basic properties such as the X-ray flux and luminosity. We here employed a simple power-law model with an interstellar absorption. Here and hereafter all quoted errors in the spectral fitting refer to 90% confidence levels unless otherwise stated. Table 1 lists the obtained parameters, and Figure 6a shows the fitting results. The fit was not acceptable with \(\chi^2/\nu \sim 2\) because of an excess around 2–3 keV, although it contributes only \(\sim 5\%\) in the 0.5–7 keV flux. The 0.5–8 keV flux implied by the best-fit model is \(5.6 \times 10^{-12}\) ergs s\(^{-1}\) cm\(^{-2}\) before removing the absorption, and the absorption-corrected 0.5–8 keV luminosity reaches \(2 \times 10^{33}\) ergs s\(^{-1}\).

For comparison, we quantified the summed point-source spectrum in terms of a power-law model. In addition, three Gaussians
were utilized to reproduce the H-like Si K\(\beta\) (line 1), He-like Ar K\(\alpha\) (line 2), and a complex of neutral and He-like Fe K\(\alpha\) (line 3) lines, seen in the spectrum. We obtained results as shown in Table 2 and Figure 6b; the relatively hard continuum (\(\Gamma \sim 1.2\)) is considered to arise from a superposition of plasma emission absorbed with different column densities.

We also consider to what extent the EER spectrum is contaminated by photons that escaped from the summed point sources. We then multiplied the above model for the summed point sources by the escape-fraction curve estimated by the ChaRT program and refitted the EER spectrum considering this contribution. This has little changed the results, except an \(~10\%\) decrease of the EER flux. Thus, the contamination of the detected point sources is small.

### 5.3. Luminosity Function

The Chandra data of NGC 6334 thus reveal an apparently extended hard X-ray emission, which remains significant after removing the detected point sources. Although this emission could be truly diffuse, it could alternatively be formed by a collection of faint point sources that are individually undetectable. In order to examine this issue, we utilize the luminosity function of the detected point sources. Here we define it by a cumulative column number density (pc\(^{-2}\)) of those sources of which the absorption-uncorrected 0.5–8 keV luminosity is higher than a specified value, \(L\) (ergs s\(^{-1}\)).

**Figure 7** shows the luminosity function of the 548 point sources in the EER; we derived the \(L\) of the bright sources (\(\geq\)30 net counts) by spectral fitting. We fitted each spectrum with a plasma emission code called APEC (Astrophysical Plasma Emission Code)\(^6\) or a power-law model, whichever gave a better fit to the data. Details will be presented in Y. Ezoe et al. (2006, in preparation). For the other faint sources (\(<\)30 net counts), we utilized the count-to-flux conversion factor derived from the summed point sources (Fig. 6b); \(\sim2\times10^{-11}\) ergs s\(^{-1}\) cm\(^2\) s\(^{-1}\) (net counts s\(^{-1}\))\(^{-1}\).

In Figure 7 the source number density increases toward lower luminosities and saturates below \(~10\) net counts, corresponding to the completeness limit estimated in § 4. Specifically, the completeness limit becomes about 30 net counts per 40 ks, or 5 \(\times\) 10\(^{20}\) ergs s\(^{-1}\), in terms of absorption-uncorrected 0.5–8 keV luminosity. Then, in order to complement the luminosity function below this limit, we have incorporated Chandra results on the Orion Nebula Cluster (ONC) by Feigelson et al. (2002), which also utilize an absorption-uncorrected luminosity function. This is a representative and very nearby (\(D = 450\) pc) MSFR, and the

\(^6\) See http://hea-www.harvard.edu/APEC.
compared with that of ONC (\(g\) forming cores in 47.1 pc\(^2\), while ONC has 1 in 4.9 pc\(^2\). Thus, the molecular cloud envelopes; the EER contains around seven star-

and NGC 6334 are lower luminosities, because typical column densities in ONC considering this, we scaled that of ONC by a factor of 1.3 toward luminosity functions after correcting for the absorption. Con-

stidering this, we scaled that of ONC by a factor of 1.3 toward luminosity functions after correcting for the absorption. Consequently, we used the ONC result to scale the luminosity function of ONC by a factor of 0.3, so that it coincides with that of NGC 6334 at the luminosity of the completeness limit. This scaling factor, \(<1\), is consistent with the fact that the EER contains not only star-forming cores but also molecular cloud envelopes; the EER contains around seven star-forming cores in 47.1 pc\(^2\), while ONC has 1 in 4.9 pc\(^2\). Thus, the stellar density must be higher in ONC. After these shifts, the two luminosity functions coincide with each other very well within Poisson errors in luminosities above \(5 \times 10^{30}\) ergs \(s^{-1}\). This re-confirms that the X-ray source population is similar between these two objects, and that the estimation of the completeness limit is reliable.

We estimated the expected flux of unresolved sources by in-

tegrating the rescaled ONC luminosity function, from the complete-

ness limit down to the end, \(~10^{28}\) ergs \(s^{-1}\). From this we subtracted the number of point sources actually detected in our observations at luminosities below the completeness limit. Then, the estimated unresolved sources turned out to be 2500 in number, and \(~0.5 \times 10^{31}\) ergs \(s^{-1}\) pc\(^{-2}\) in surface brightness. This is only 12\% of the value needed to account for the surface brightness of the extended emission. We further extrapolated the function into 0 ergs \(s^{-1}\) assuming a slope of 0.4, taken from that of ONC in the \(10^{27}–10^{30}\) ergs \(s^{-1}\) range; we found that it reaches at most \(~20\%\) and hence still falls short of the extended emission.

In order to estimate the expected flux from the background extra-

galactic sources, we utilized the source density from Giacconi et al. (2001). We converted the flux into the luminosity and the surface number density of sources into their column density, both assuming that all of them are at the distance of NGC 6334. The flux estimated in this way is negligible (3\% in \(10^{27}–10^{28}\) ergs \(s^{-1}\)). Furthermore, the strong concentration of the extended emission on the EER cannot be explained by background objects.

In conclusion, a large part (\(\geq 80\%\)) of the extended emission is suggested to be truly diffuse in nature. The spectral difference between the diffuse emission and the point sources (\(\S 5.2.3\), Fig. 5c) independently supports this conclusion.

6. REGION-BY-REGION SPECTRAL ANALYSIS

Although the apparently flat continuum of the EER, represen-
ted by a power-law index of 0.9, is suggestive of nonthermal emission, such a flat continuum could alternatively be produced by a superposition of thermal components with different absorptions. Accordingly, in this section, we divide the EER into finer regions and study the spectrum and X-ray absorption as a function of the position.

6.1. Region Selection

To conduct the spatially resolved spectroscopy, we have repro-
duced in Figure 8 the two-band images of Figure 4, but utilizing this time logarithmic contour representations. The contours are separated by a factor of 1.1 and 1.2 in the background-inclusive brightness in the soft- and hard-band images, respect-
ively, while the lowest contour represents \(~1\) times the average BR value in both bands. In reference to these two-band images, let us define characteristic regions, particularly bright clumps, to be utilized in the subsequent analysis.

Figure 8a, namely, the soft X-ray image of the north field, re-

veals several bright clumps coincident with the FIR cores or the condensations of massive stars. Referring to this contour map, we then define three circular regions, named C2, C3, and AXJ, with C standing for “FIR core” and AXJ the known X-ray source AX J1720.4–3544, which is identified with a B0.5e star by Matsuzaki (1999). The C3 region is less clear than the other two, but it is chosen so as to include the known massive ZAMS star (O8) at its center.

In the hard X-ray image of the north field (Fig. 8b), these three regions become less clear. On the other hand, a bright clump emerges at the position of FIR cores I(N) and I. Accordingly, a new region C1 is defined, together with two more subregions in it, C1N and C1S to represent the two independent FIR cores therein. Also, significant emission can be seen to the west of FIR core II, coincident with a molecular cloud dark lane and a condensation of embedded stars. Hence, we define another region, named the C2W region. After all, we have defined seven regions in the north field (C1, C1N, C1S, C2, C2W, C3, and AXJ).

Similarly, using Figure 8c, which is the soft X-ray image of the south field, we select two bright soft X-ray regions, C4E and C5N, toward the east and north directions of the core IV and V, respectively. In the hard X-ray map (Fig. 8d), a bright clump stands out.
at FIR core IV and its north position, which are covered by regions named C4 and CB, respectively. A larger region, C4B, is employed to sum up C4 and CB. Thus, in the south field, we have defined five regions (C4E, C5N, C4, CB, and C4B). After all, the EER has been subdivided into 12 representative regions.

6.2. Color-Color Diagram

To grasp the spectral properties of the 12 regions, we arranged them in Figure 9 on a color-color diagram. We divide the 0.5–7 keV band into three finer bands (S, M, and H, at 0.5–2.0, 2.0–3.5, and 3.5–7 keV, respectively), and created two hardness ratio maps by calculating \( HR_1 = M/S \) and \( HR_2 = H/M \). \( HR_1 \) is expected to mainly reflect a difference in an absorption column density, while \( HR_2 \) is more sensitive to the intrinsic continuum hardness. The data points can be clearly subdivided into two groups: (1) “soft” regions with \( HR_1 \leq 1 \) and \( HR_2 \leq 1 \), including AXJ, C2, C3, C4E, and C5N; and (2) “hard” regions with \( HR_1 \geq 1 \) and \( HR_2 \geq 1 \), including C1, C1N, C1S, C2W, C4, CB, and C4B.

For comparison, the green points in Figure 9 show the hardness ratios of the summed point sources in the individual regions. The green data are again divided into the two groups; the point sources in the soft regions exhibit smaller values of \( HR_1 \) than those in the hard ones. The \( HR_2 \) values are also different.
between the two groups, especially in CB and C4B, although these two are contaminated by the bright background active galactic nucleus (AGN; NGC 6334 B). Importantly, most of these summed point sources have similar or even higher values of HR1 than the diffuse emission in the same region, suggesting that the latter suffers less absorption.

6.3. Spectral Fitting for Summed Point Sources

Before analyzing the diffuse emission spectra, we analyze spectra of the summed point sources with two aims in mind. One is to estimate their absorption column densities, which serve as a measure of absorption affecting the diffuse emissions. The other is to utilize their spectral shapes to estimate the effects of those photons that escape from the point sources into the diffuse emission.

In the same way as in § 5.2.3, we prepared the spectrum of the summed point sources in each region and fitted it with simple models. The spectra in eight out of the 12 regions have been represented successfully by a single-temperature thin-thermal model. The C2W and C3 region required an additional narrow Gaussian and a second thermal plasma model of a rather low temperature, respectively. For the remaining two regions (CB and C4B), which we then conducted model fitting to the diffuse emission spectrum in each region. In the same way as in the EER analysis (§ 5.2.4), the escape photons from the summed point sources were taken into account by adding their best-fit models, after multiplying with the third-order polynomial function. Unlike the EER case as a whole, this effect is significant (~20%–30% of the diffuse emission in 0.5–7 keV) in a few regions (AXJ, C3, and CB) hosting very bright X-ray sources (≥1000 net counts).

6.4. Spectral Fitting of the Diffuse Emission

We estimated the absorption number density in the region may still take multiple values. The derived temperatures are moderately high, i.e., several keV, in agreement with the typical X-ray temperature of YSOs. Therefore, the detected point sources can be mostly understood as YSOs suffering from region-dependent absorptions.

6.4.1. Soft Regions

We fitted the spectra of the five soft regions with a single-temperature plus power-law model, respectively. For the remaining two regions (CB and C4B), which involve the bright AGN (NGC 6334 B), a power-law model and a single temperature plus power law model, respectively, gave acceptable fits. All 12 spectra have been successfully reproduced in this way, yielding the results in Figure 10.

The obtained absorption number density differs clearly between the soft and hard regions, confirming the inference from the color-color diagram. Specifically, the soft regions have column densities of (0.5–1) × 10^{22} cm^{-2}, while the hard ones have (2–10) × 10^{22} cm^{-2}. These values are consistent (within a factor of ~3) with those values estimated in other wavelength ranges, such as the radio CO line (Kraemer et al. 1999) and NIR extinctions (Straw et al. 1989). Furthermore, every spectrum except those from three regions (C3, CB, and C4B) has been successfully reproduced by a single-temperature plasma model absorbed by a single column density. This ensures that each of the 12 regions has a well-defined value of N_H. The derived temperatures are moderately high, i.e., several keV, in agreement with the typical X-ray temperature of YSOs. Therefore, the detected point sources can be mostly understood as YSOs suffering from region-dependent absorptions.

6.4.2. Hard Regions

In the same way, we fitted all seven hard-region spectra with a single-temperature model. Because photon statistics in the soft X-ray band are rather limited and the HR1 in the color-color diagram (Fig. 9) are similar between the diffuse emission and the
Fig. 11.—Diffuse emission spectra in the five soft regions, fitted with a model consisting of a thermal plasma emission (dashed line), and the escape photons from the excluded point sources (dash-dotted line). See Table 3 for the obtained parameters.
summed point sources, we fixed the absorption column densities at those of the summed point sources [(3.5–8.8) × 10^22 cm^{-2}; see the first line in Table 4], except in the C4B region, in which we left N_H free to vary. The abundance was fixed at 0.3 solar, except in C1 and C1S, for which it was left free to reproduce a sign of Fe-K line emission.

The results of this analysis are shown in Figure 12 and Table 4. All the fits have been acceptable, although that of C4B fit is marginal (χ^2/ν ~ 1.4) because of the data excess in 1–2 keV. As already suggested by the color-color diagram, the diffuse continua in the hard regions are generally flatter than those in the soft regions. Nevertheless, the C1, C1N, C1S, and C2W spectra could still be regarded as dominated by thin thermal emission, because the obtained temperatures (5–10 keV) are not unusual among cosmic hot plasmas, and the C1 spectra (and possibly C1S spectra too) shows the emission feature attributable to Fe-K lines.

Among the four spectra (C1, C1N, C1S, and C2W) with reasonable temperatures, those of C1N, C1S, and C2W show reasonable abundances (solar or subsolar). However, the C1 spectrum requires a very high (>1.9 solar) abundance, because of the strong Fe K line. If the spectrum is fitted by a phenomenological model consisting of a power-law continuum and a Gaussian, the line-center energy is obtained as 6.7±0.2 keV, with the intrinsic line width of 180 (<830) eV and an equivalent width as huge as 1.5 keV. The center energy implies a highly ionized Fe-K line. Then, if we naturally interpret the C1N spectrum as thermal emission, the large equivalent width may be due to a high local abundance. On the other hand, as suggested in the Galactic ridge X-ray emission (Masai et al. 2002), the hard continuum of C1N and also the Fe K line may partially be quasi-thermal, i.e., arising from Coulomb collisions of accelerated (nonthermal) electrons with thermal ions. This quasi-thermal component can create an apparently thermal spectrum of several keV and increase the equivalent width of the ionized Fe K line. Hence, we cannot reject this nonthermal possibility for the C1N spectrum.

The remaining three spectra (C4, CB, and C4B) lack emission lines and exhibit very flat continua, requiring kT > 10 keV if adopting thermal interpretation. Such flat continua could be better interpreted as nonthermal emission rather than thermal signals. Accordingly, we refitted them by a power-law model, and actually obtained an comparable or even better fits as shown in Figure 13. (See Table 5 for the obtained parameters.) Furthermore, the data excess in the 1–2 keV range, which was observed in the thermal fit to the C4B spectrum, has disappeared because of a decrease in N_H. The obtained power-law indices are extremely small (0–1) with 90% confidence upper limits of 1–1.4.

Although the “soft excess” of the C4B fit in Figure 12 has been removed by the power-law modeling, it could alternatively be a result of “leaky absorber” condition; a single thermal emission component reaches us via two (or more) paths with different absorptions. This is particularly likely to be the case with diffuse emission. We hence fitted the C4B spectrum by a sum of two thermal components with independent absorptions (see Table 6 for the obtained parameters) but with their temperatures tied together. The higher absorption was fixed at the 90% upper limit value of the summed point sources (4.0 × 10^{22} cm^{-2}). Then, the soft excess has been explained away by the less absorbed (<1 × 10^{22} cm^{-2}) component. However, the common temperature has still remained unrealistically high (>30 keV). When the higher absorption is left free to vary, the temperature decreased to 4 keV, but the higher absorption increases to 1.1 × 10^{23} cm^{-2}, which is 3 times higher.
than the upper limit absorption obtained from the summed point sources in the same region. Thus, the leaky-absorber assumption does not relax the extreme requirements (a high temperature and a high absorption) for the thermal interpretation.

Finally, we fitted the C4B spectrum by a sum of a power law and a thermal model, modified by separate absorptions. The results are basically the same as the leaky-absorber model. The power-law component still showed a small photon index (1.2) and a strong absorption ($5 \times 10^{22}$ cm$^{-2}$) to reproduce the hard continuum, while the plasma model with a low temperature of $kT \sim 0.3$ keV and a lower absorption ($2 \times 10^{22}$ cm$^{-2}$) to explain the soft excess. Hence, the most favored interpretation of the C4B spectrum is still the single-power-law model.

7. DISCUSSION

7.1. Emission Mechanism and Energy Supply

We detected extended hard X-ray emission from this representative MSFR and found that it is likely to be dominated by truly diffuse emission, rather than formed mainly by unresolved faint
Taking it for granted that the emission is of a diffuse nature, we showed that it may well be a mixture of thermal and nonthermal components. Below we examine the two possible emission mechanisms and estimate the necessary energy supply.

7.1.1. Nonthermal Interpretation

We have found flat continua in some parts of the diffuse emission of NGC 6334 (C4, CB, and C4B regions). The best example is the C4B spectrum, which has a photon index of $\Gamma = 0.39^{+0.66}_{-0.63}$ with a $0.5-8$ keV luminosity of $4 \times 10^{32}$ ergs s$^{-1}$. As mentioned in § 6.4.2, such flat spectra are more reasonably interpreted as nonthermal emission than thermal signals. Taking this for granted, there can be three candidate emission mechanisms; bremsstrahlung from nonthermal (>10 keV) electrons, inverse Compton scattered emission from hundreds-of-MeV electrons, and synchrotron emission from multi-TeV electrons.

Among the three candidates, we can easily rule out the synchrotron emission on the basis of the observed flat X-ray spectra. In fact, synchrotron scattered emission from hundreds-of-MeV electrons, and synchrotron emission from multi-TeV electrons.

Fig. 13.—Same as Fig. 12, but for (a–c) the C4, CB and C4B spectra fitted with a power-law model and (d) the same C4B spectra fitted with a leaky absorber model. See Tables 5 and 6 for the obtained parameters.

| Model          | Parameter | Value     |
|----------------|-----------|-----------|
| Absorption     | $N_H$     | 4.0 (fixed) |
| Power law      | $\Gamma$  | $1.0^{+0.44}_{-0.47}$ |
| Normalization  | $F_X$     | 2.2 |
|                | $L_X$     | 1.2 |
| $\chi^2/\nu$   |           | 9.7/12 |

Note.—Notations and symbols are the same as for Table 1, except that the normalization is in $10^{-3}$ photons cm$^{-2}$ ergs s$^{-1}$, $F_X$ is in $10^{-15}$ cm$^{-2}$ s$^{-1}$, and $L_X$ is in $10^{32}$ ergs s$^{-1}$.
a population of energetic electrons has the same spectral slope as their synchrotron spectrum.

The remaining possibility is thus the bremsstrahlung emission by mildly energetic electrons. Unlike the former two mechanisms, the electron energy only has to exceed \( \sim 10 \) keV, which is the highest photon energy observed. In an environment with a high matter density reaching \( 10^3-10^4 \) cm\(^{-3} \) like in these two cases, the bremsstrahlung loss overwhelms the synchrotron and inverse Compton losses up to electron energies of \( \sim 10 \) MeV, and the spectrum of energetic electrons will become flatter than the initially injected spectrum because lower energy electrons lose energy more quickly than the more energetic ones via the Coulomb loss. This makes a contrast to the synchrotron and inverse Compton mechanisms, in which the energy loss always steepen the electron spectrum. Such electrons will emit bremsstrahlung with a photon index \( \Gamma = 1 \), as is expected for a monoenergetic case. Actually, Uchiyama (2002) successfully explained a flat (\( \Gamma \sim 1 \)) photon spectrum observed from hard X-ray clumps toward the SNR \( \gamma \) Cygni in terms of this process invoking tens-of-MeV electrons. In our case, the observed flat spectra may be explained in the same manner, and hence the bremsstrahlung emission is the most favorable, at least from the viewpoint of spectral shapes.

Although the bremsstrahlung interpretation is feasible from several important aspects, one issue remains; in this energy range, the emitting volume \( V \) and the electron density \( n_e \) are required as \( 10^3-10^4 \) cm\(^{-3} \) and \( 10^3-10^4 \) ergs s\(^{-1} \), respectively. In an environment with a high matter density reaching \( 10^3-10^4 \) cm\(^{-3} \), the bremsstrahlung emission is possible only if a kinetic luminosity of more than \( 10^{36} \) ergs s\(^{-1} \) is supplied to the hard X-ray clump at the C4B region. This is examined in \( \S \) 7.2.1.

### 7.1.2. Thermal Interpretation

Since some parts (particularly the soft regions) of the EER are thought to be emitting optically thin thermal X-rays, we may also examine whether the thermal interpretation is physically feasible. The bolometric luminosity \( L_X \) of a thin-thermal plasma of a temperature \( T \) is expressed, in terms of the electron density \( n_e \) and the emitting volume \( V \), as

\[
L_X = \Lambda(T)EM = \Lambda(T)n_e^2 V \eta
\]

where \( \Lambda \), \( EM \), and \( \eta \) denote the cooling function, the volume emission measure, and a filling factor of the emitting plasma (\( \leq 1 \)), respectively.

From the observations, we here assume \( kT = 5 \) keV, \( L_X = 5 \times 10^{31} \) ergs s\(^{-1} \), and \( \eta = (4\pi/3)r^3 (r = 0.5 \text{ pc}) \). Also, we approximate the cooling function of a low-density plasma of a solar metallicity as \( 1.0 \times 10^{-23}(kT)^{0.5} \) ergs s\(^{-1} \) cm\(^{-3} \) s\(^{-1} \), which is valid for \( kT > 3 \) keV (Raymond et al. 1976; McKee & Cowie 1977). Then, equation (1) is solved for \( n_e \) as

\[
n_e = 0.4\eta^{-1/2} \text{ cm} \left( \frac{L_X}{5 \times 10^{31} \text{ ergs s}^{-1}} \right)^{1/2} \left( \frac{r}{0.5 \text{ pc}} \right)^{-3/2}.
\]

The total plasma energy \( U \) of a single soft region, the plasma pressure \( p \), and the radiative cooling timescale \( t_{cool} \) are then derived as

\[
U = 3n_e kTV = 1 \times 10^{39} \eta^{1/2} \text{ ergs}
\]

\[
\times \left( \frac{L_X}{5 \times 10^{31} \text{ ergs s}^{-1}} \right)^{1/2} \left( \frac{kT}{5 \text{ keV}} \right) \left( \frac{r}{0.5 \text{ pc}} \right)^{3/2}.
\]

\[
t_{cool} = U/L_X = 9 \times 10^{7} \eta^{1/2} \text{ yr}
\]

\[
\times \left( \frac{L_X}{5 \times 10^{31} \text{ ergs s}^{-1}} \right)^{-1/2} \left( \frac{kT}{5 \text{ keV}} \right) \left( \frac{r}{0.5 \text{ pc}} \right)^{3/2}.
\]

The cooling time as estimated above is far longer than the typical age of the massive star-forming regions (\( 10^5-10^6 \) yr) and sound crossing time (\( \sim 10^2 \) yr) in a 5 keV plasma across the region of \( \sim 0.5 \) pc in size. Therefore, the total energy \( U \) must be accumulated over the MSFR age if the plasma is confined, and over the sound crossing time otherwise. Although the thermal plasma pressure of equation (4) is higher than that of the surrounding molecular clouds (\( 10^5-10^6 \) K cm\(^{-3} \)), the plasma may be confined by the surrounding dense H \( \text{ii} \) region, where the pressure is thought to be higher (\( 10^6-10^7 \) K cm\(^{-3} \); Rodriguez et al. 1982). The magnetic pressure of the molecular cloud (on the order of \( 100 \mu \text{G} \); Sarma et al. 2000) may help the confinement. Then, the total energy of equation (3) can be understood as an average luminosity of \( 3 \times 10^{33-34} \) ergs s\(^{-1} \) over the typical age of \( 10^5-10^6 \) yr. If scaled it to the whole diffuse emission of NGC 6334, the necessary energy input becomes \( 1 \times 10^{35-36} \) ergs s\(^{-1} \), which is comparable to that required by the nonthermal interpretation. These values are in fact upper limits, and can be lowered as \( \propto \eta^{1/2} \) by assuming a lower filling factor.

### 7.2. Stellar Winds as the Energy Source

#### 7.2.1. Energetics

Then, what explains the huge luminosity of up to \( \sim 10^{36-37} \) ergs s\(^{-1} \) required by either the nonthermal or thermal picture? Since the diffuse emission is clearly localized to the massive star-forming sites, it must have a close connection to the formation of massive stars. Although there are many energetic phenomena (molecular outflows, jets, and H \( \text{ii} \) regions), the most plausible candidate is a fast stellar winds from massive OB stars; the stellar wind may collide with the ambient gas (e.g., dense H \( \text{ii} \) regions), producing shocked regions that may become the source of both thermal and nonthermal X-rays.

This interpretation has been proposed to explain the soft (\( kT \leq 1 \) keV) possible diffuse emission in M17 and Rosette Nebula (Townsley et al. 2003). Already in the \( \text{ASCA} \) era, Matsuizaki (1999) also suggested this possibility to explain the high-temperature spectra of the region-integrated emission from NGC 6334. Below, we reconsider this scenario on the basis of our new results, keeping in mind with the long-studied stellar-wind shock theory (Dyson & de Vries 1972; Castor et al. 1975; Weaver et al. 1977).

Observationally, seven of the 12 diffuse emission regions (AXJ, C1, C1N, C1S, C3, C4, and C4B) involve at least one OB star candidate (Matsuizaki 1999; Loughran et al. 1986; Straw et al. 1989; Persi et al. 2000). Although the other five regions (C2, C2W, C4E, CB and C5N) do not include any OB stars reported in the optical, IR or radio bands, this does not necessarily indicate a difficulty with the stellar wind scenario. Actually, the shocked region around each OB star is expected to be rather asymmetric, because of the strong pressure gradient across the dark lane. Then, the emission region may appear rather offset, or even detached, from the central star. Furthermore, some of these regions may host embedded OB stars or represent an interaction among winds from more than one massive stars.
These massive late O- or early B-type stars in individual cores are expected to emit thick and fast stellar winds, each supplying a kinematic luminosity of

\[ L_w = \frac{1}{2} M \dot{v}_w^2 = 1 \times 10^{35} \text{ ergs s}^{-1} \times \left( \frac{\dot{M}}{10^{-7} \ M_\odot \ \text{yr}^{-1}} \right) \left( \frac{\dot{v}_w}{2000 \ \text{km s}^{-1}} \right)^2, \]  

(6)

where \( \dot{M} \) and \( \dot{v}_w \) denote the mass loss rate and wind velocity, respectively. Thus, modest values of \( \dot{M} \) and \( \dot{v}_w \), used to normalize equation (6), would be sufficient to give \( 1 \times 10^{35} \) ergs s\(^{-1}\) per star.

Considering several massive stars, we can readily explain the energy input required by the thermal interpretation. On the other hand, when we consider the nonthermal emission arises from high-energy particles accelerated at the shock front, similar to those seen in some SNRs such as SN 1006 (Koyama et al. 1995) and G347.3−0.5 (Koyama et al. 1997), the situation will be more difficult. In this shock acceleration case, because of the conversion efficiency of the kinematic energy into sub-MeV electrons, the required energy (\( 1 \times 10^{36} \) ergs s\(^{-1}\) for C4B region) increases by at least an order of magnitude (Bykov et al. 2000). Hence, the nonthermal interpretation needs a cluster of OB stars or a faster or more massive wind or wind-wind collisions. The most plausible case will be the OB cluster and/or wind-wind collisions, because at least two late O to early B star candidates are detected within C4B region (Straw et al. 1989; Persi et al. 2000). Deep NIR to FIR observations with, e.g., Spitzer is necessary to the OB star population in this region.

7.2.2. Shock Temperature

The wind will experience a shock transition at a certain radius from the star, where the ram pressure of the wind becomes equal to the external pressure (e.g., of H II regions). The shell region between the shock and the contact discontinuity is then filled with shocked hot winds or a hot bubble and becomes the diffuse thermal X-ray source. The maximum temperature \( kT \), behind the shock is given by

\[ kT = \frac{3}{16} \mu n_H \dot{v}_w^2 = 5 \text{ keV} \left( \frac{\dot{v}_w}{2000 \ \text{km s}^{-1}} \right)^2, \]  

(7)

where \( n_H \) is the mass of a hydrogen atom and \( \mu = 0.62 \) is the mean molecular weight. The observed temperatures of the soft regions in NGC 6334, \( 1-10 \) keV, can be explained by wind velocities in the range of \( 1000-3000 \) km s\(^{-1}\), as usually seen in OB stars (Prinja 1990). The actual temperature behind the shock may be considerably lower than that in equation (7), due to thermal conduction from the shocked hot wind to the surrounding cold material (Weaver et al. 1977). However, in the high stellar density environment of star-forming cores, the wind-wind shock may be realized and can increase the shock temperature.

7.2.3. Wind Confinement

We can estimate the size of the expanding hot wind bubble \( R_b \) or the distance from the central OB star to the contact discontinuity by assuming that the wind energy is equal to the displaced energy of the cold gas. This can be described as

\[ \frac{1}{2} \dot{M} \dot{v}_w^2 t = \left( \frac{4}{3} \pi R_b^3 \right) \frac{3}{2} p_s, \]  

(8)

where \( t \) is the time since the wind started blowing and \( p_s \) is the thermal pressure of the surrounding material (Chevalier 1999). Assuming an H II region with a temperature of \( 10,000 \) K and a density of \( 10^3 \) cm\(^{-3}\) as the surrounding material, and the age of a young massive star as 0.1 Myr, we obtain

\[ R_b = 1 \ \text{pc} \left( \frac{\dot{M}}{10^{-7} \ M_\odot \ \text{yr}^{-1}} \right)^{1/3} \times \left( \frac{\dot{v}_w}{2000 \ \text{km s}^{-1}} \right)^{2/3} \left( \frac{p_s}{10^7 \ \text{K cm}^{-3}} \right)^{-1/3} \left( \frac{t}{10^5 \ \text{yr}} \right)^{1/3}. \]  

(9)

This estimation is in a good agreement with the observed size of the 12 diffuse emission regions. The whole diffuse emission region of NGC 6334 (\( \sim 5 \times 9 \) pc\(^2\)) can be explained by a superposition (seven or more) of this bubble. If the stellar wind and its confinement are the origin of the observed diffuse X-ray emission, we expect the emission properties to depend on the confining pressure \( p_s \). Assuming in equation (9) that \( \dot{M} \), \( \dot{v}_w \), and \( t \) are unchanged, we expect \( R_b \propto p_s^{-1/3} \), and hence \( n_e \propto \dot{M} t R_b^3 \propto p_s \), where \( n_e \) is the density of the X-ray-emitting plasma. Since the X-ray volume emissivity scale as \( n_e^2 \propto p_s^2 \), we expect the absorption-corrected surface brightness to scale as

\[ S_X^c \propto n_e^2 R_b \propto p_s^2 p_s^{-1/3} \propto p_s^{5/3}. \]  

(10)

Since the absorption column density \( N_{H} \) is an integrated line-of-sight hydrogen density, we may very roughly assume \( p_s \propto N_{H} \). This yields

\[ S_X^c \propto N_{H}^{5/3}. \]  

(11)

Indeed, as shown in Figure 14a, the observed surface brightness of the 12 regions shows a strong positive correlation to the value of \( N_{H} \), and the dependence is consistent with equation (11). This agreement holds even if excluding the hard regions of NGC 6334, which is considered to be dominated by the nonthermal emission. Although the lack of data points in the large absorption and low surface brightness region could be a selection effect, that in the small absorption and large surface brightness region is free from such artifacts.

We similarly compared the absorption with the temperature in Figure 14b. This is equal to compare their continua hardness. Again we observe a positive correlation between the two quantities. Presumably, in dense environments, the stellar-wind shock becomes stronger. Consequently, the nonthermal emission may be dominant, or the shock temperature increases.

Thus, our Chandra result on NGC 6334 provides support to the view that the strong stellar winds from young OB stars, confined by dense surrounding gas, give rise to the diffuse hard X-ray emission.

7.3. Possible Contribution to the Galactic Ridge X-Ray Emission

Finally, we can roughly estimate the contribution of the diffuse emission in Galactic MSFRs. We here utilize the X-ray luminosity-to-mass ratio, in order to estimate the contribution, following Sekimoto et al. (2000). The total mass of the giant molecular clouds, the birth places of massive stars, in our Galaxy, is estimated as \((1-3) \times 10^9 \ M_\odot \) from CO observations (Bronfman et al.
1988; Combes 1991). The mass of NGC 6334 is estimated as $1.6 \times 10^5 M_\odot$ (Dickel et al. 1977). The mass to X-ray luminosity ratio of the diffuse emission becomes $1 \times 10^{28}$ erg s$^{-1}$ M$_\odot^{-1}$. If we take the mass of giant molecular clouds in our Galaxy as $2 \times 10^9 M_\odot$, we obtain total X-ray luminosity of $2 \times 10^{33}$ erg s$^{-1}$. This is $\sim$10% of the hard tail of Galactic ridge X-ray emission ($\sim 2 \times 10^{38}$ ergs s$^{-1}$ in 2–10 keV; Valinia & Marshall 1998). Hence, a certain part of the Galactic ridge emission can be explained by diffuse emission in MSFRs.

8. CONCLUSION

In this paper we have investigated the newly suggested phenomenon of diffuse X-ray emission associated with the massive star formation in NGC 6334 using the Chandra data. We have arrived at the following conclusions:

1. After removing point sources, the extended X-ray emission is detected with a high significance, exhibiting a 0.5–8 keV luminosity of $2 \times 10^{33}$ ergs s$^{-1}$. It is distributed over $\sim 5 \times 9$ pc$^2$ and becomes bright in the vicinity of massive star-forming cores known in the optical, infrared, or radio wavelength ranges. The luminosity function within the extended emission suggests that most of the emission is diffuse in nature.

2. The diffuse emission outside the dense molecular cloud cores of NGC 6334 shows thermal spectra, with the temperature in the range of 1–10 keV. In the molecular cloud cores of NGC 6334, the emission exhibits very hard continua (photon indices of $\sim 1$) with significant absorption, which favors the nonthermal interpretation over the thermal scenario.

3. The observed luminosity, temperature, possibly nonthermal emission, and angular extent of the emission are discussed in terms of shocks that may be produced when fast stellar winds from embedded young massive stars are confined by the thick materials surrounding them.

The authors acknowledge technical advice from Tai Oshima, Kensuke Imahishi, and Masahiro Tsujimoto on the ACIS analysis. They also thank Yasunobu Uchiyama and Takao Nakagawa for useful discussions and comments. Y. E. is financially supported by the Japan Society for the Promotion of Science.

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