HARD X-RAYS AND FLUORESCENT IRON EMISSION FROM THE EMBEDDED INFRARED CLUSTER IN NGC 2071

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ABSTRACT

We present first results of XMM-Newton X-ray observations of the infrared cluster lying near the NGC 2071 reflection nebula in the Orion B region. This cluster is of interest because it is one of the closest regions known to harbor embedded high-mass stars. We report the discovery of hard X-ray emission from the dense central NGC 2071-IR subgroup, which contains at least three high-mass young stellar objects (NGC 2071 IRS 1, IRS 2, and IRS 3). A prominent X-ray source is detected within 1″ of the infrared source IRS 1, which is thought to drive a powerful bipolar molecular outflow. The X-ray spectrum of this source is quite unusual compared to the optically thin plasma spectra normally observed in young stellar objects (YSOs). The spectrum is characterized by a hard broadband continuum plus an exceptionally broad emission line at ≈6.4 keV from neutral or near-neutral iron. The fluorescent Fe line likely originates in cold material near the embedded star (i.e., a disk or envelope) that is irradiated by the hard, heavily absorbed X-ray source.

Subject headings: open clusters and associations: individual (NGC 2071) — stars: formation — X-rays: stars

1. INTRODUCTION

A high-mass star can arise on the main sequence completely enshrouded in dust and inaccessible to optical studies. Thus, the ability to penetrate high extinction is crucial to exploring the earliest stages of high-mass star formation. Infrared, radio, and millimeter observations have traditionally been used and provide important information on physical conditions in circumstellar disks and envelopes or in ionized winds or H II regions around the massive young star. X-ray observations can also penetrate high extinction and provide a different perspective that probes high-energy processes, including magnetic activity originating close to the stellar surface, mass loss, as traced by shocked winds, jets, or outflows, and hot diffuse gas that pervades some young clusters containing massive young OB stars with powerful winds.

One of the closest regions known to contain young high-mass stars is the infrared cluster near the optical reflection nebula NGC 2071 in the Orion B region (Lynds 1630 dark cloud) at a distance of ≈400 pc (Anthony-Twarog 1982; Brown et al. 1994). Near-infrared observations by Lada et al. (1991) revealed more than 100 K-band sources in a 100 arcmin2 region down to $K \approx 14$ mag. This extended cluster surrounds a dense central subgroup known as NGC 2071-IR, which contains at least 10 near-IR sources in a $\approx1' \times 1'$ region (Walther et al. 1993, hereafter Wa93). Of particular interest in the NGC 2071-IR subgroup are IRS 1, IRS 2, and IRS 3. These sources are surrounded by compact H II regions (Snell & Bally 1986), and H2O and OH masers lie in proximity. More detailed information on NGC 2071-IR and properties of the infrared sources can be found in Aspin et al. (1992) and Wa93, and references therein. The presence of strong ionizing UV radiation and maser emission strongly suggests that these objects are young embedded early-type stars. Such objects are exceedingly rare at distances less than 500 pc, and the NGC 2071 cluster thus plays a key role in observational studies of high-mass star formation.

We report here on first results of a pointed X-ray observation of NGC 2071 obtained with XMM-Newton. This observation is centered on the NGC 2071-IR subgroup and provides broader energy coverage and improved spectral information compared to two previous Röntgensatellit (ROSAT) HRI exposures (rh202521/22), which captured the IR subgroup $\approx8'' \times 10''$ off-axis. Our objectives were to (1) obtain an X-ray census of the NGC 2071 cluster and (2) search for X-ray emission from the massive embedded stars, whose X-ray properties are largely unknown. We report the detection of hard emission lying within 1″ of NGC 2071 IRS 1 and discuss its very unusual X-ray spectrum, which is dominated by strong fluorescent Fe line emission.

2. XMM-NEWTON OBSERVATIONS

The XMM-Newton observation began on 2005 March 30 at 15:20 UT and ended on March 31 at 03:53 UT. Pointing was centered on NGC 2071 IRS 1 (Wa93). The European Photon Imaging Camera (EPIC) provided CCD imaging spectroscopy from the pn camera (Strüder et al. 2001) and two nearly identical MOS cameras (MOS1 and MOS2; Turner et al. 2001). The medium optical blocking filter was used. The EPIC cameras provide energy coverage over $E \approx 0.2$–15 keV with energy resolution $E/\Delta E \approx 20$–50. The MOS cameras provide the best on-axis angular resolution, with FWHM $\approx 4.3''$ at 1.5 keV.

Data were reduced using the XMM-Newton Science Analysis System (SAS version 6.1). Event files generated by XMM-Newton standard processing were time-filtered to remove the first $\approx15$ ks of data, which were affected by high background radiation. This yielded 29.9 ks of usable pn exposure and 30.1 ks of usable...
| Source Number | R.A. (J2000.0) | Decl. (J2000.0) | Rate (counts s⁻¹) | E (keV) | Flux (ergs cm⁻² s⁻¹) | Identification | K_0 (mag) | Offset (arcsec) |
|---------------|---------------|----------------|------------------|---------|---------------------|----------------|-----------|---------------|
| 1             | 05 44 44.10   | +00 18 02.6    | 1.49E–02         | 1.66    | 8.18E–14            | 2MA J054644.08+001803 | 10.2      | 0.6           |
| 2             | 05 44 44.91   | +00 24 51.3    | 5.69E–04         | 2.33    | 1.03E–14            | ...            | ...       | ...           |
| 3             | 05 44 45.84   | +00 17 00.3    | 1.87E–03         | 2.34    | 1.46E–14            | ...            | ...       | ...           |
| 4             | 05 44 51.51   | +00 19 20.9    | 1.34E–02         | 1.68    | 6.18E–14            | 2MA J054651.48+001921 | 11.8      | 0.6           |
| 5            | 05 44 51.80   | +00 19 39.4    | 1.46E–03         | 1.89    | 1.99E–14            | 2MA J054651.85+001938 | 11.6      | 1.1           |
| 6            | 05 44 52.51   | +00 19 59.2    | 6.02E–04         | 1.80    | 1.64E–14            | ...            | ...       | ...           |
| 7            | 05 44 53.47   | +00 26 32.3    | 8.70E–04         | 2.62    | 4.81E–15            | ...            | ...       | ...           |
| 8            | 05 45 06.56   | +00 20 52.5    | 1.07E–02         | 1.97    | 4.81E–15            | ...            | ...       | ...           |
| 9            | 05 45 58.46   | +00 22 35.3    | 4.98E–04         | 1.93    | 6.80E–15            | 2MA J054658.37+002236 | 14.1      | 1.7           |
| 10           | 05 46 58.71   | +00 29 00.2    | 3.04E–03         | 2.04    | 1.02E–14            | 2MA J054658.59+002029 | 12.2      | 1.8           |
| 11           | 05 46 59.03   | +00 24 57.8    | 1.44E–03         | 3.27    | 1.74E–14            | 2MA J054659.03+002457 | 12.4      | 0.1           |
| 12           | 05 47 03.38   | +00 23 25.3    | 1.98E–02         | 2.29    | 1.39E–13            | 2MA J054703.31+002323 | 10.4      | 1.0           |
| 13           | 05 47 04.78   | +00 21 43.5    | 8.77E–03         | 4.62    | 1.29E–13            | IRS 1; 2MA J054704.78+002142 | 11.2      | 0.7           |
| 14           | 05 47 05.00   | +00 18 32.0    | 1.76E–02         | 1.88    | 8.92E–14            | 2MA J054704.94+001831 | 10.4      | 0.9           |
| 15           | 05 47 05.21   | +00 23 08.4    | 4.02E–03         | 2.64    | 7.01E–14            | ...            | ...       | 0.3           |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Data are from the XMM-Newton observation on 2005 March 30–31 and include sources within a 10′ × 10′ region centered on NGC 2071 IRS 1. All quantities are computed using events in the 0.5–7.5 keV range. Usable exposure times are 29,886 s for pn and 30,114 s per MOS. Data are from EPIC pn unless otherwise noted. The count rate is based on events extracted within a circular region of radius 15″ (68% EEF) centered on the source and is background subtracted. A smaller source region of radius ≈10″ was used for sources 5, 16, and 21 due to source crowding. The absorbed flux (0.5–7.5 keV) is based on spectral fits using an absorbed solar-abundance 1T or 2T optically thin plasma model (APEC) in XSPEC, except as noted for faint sources. (E) is the mean photon energy. Candidate identifications lie within 2″ of the X-ray position and are based (in order of preference) on searches of the 2MASS (2MA), HST GSC v2.2, and USNO B1 electronic databases. The 2MASS K_s magnitude is given for sources with 2MASS identifications. The quoted offset is the positional offset between the X-ray and 2MASS or USNO positions.

* Absorbed flux (0.5–7.5 keV) is from PIMMS, based on the quoted count rate and an assumed Raymond-Smith model with N_H = 10^{22} cm⁻² and plasma temperature kT = 2 keV.
* Based on MOS2 events. Second source lies nearby.
* Based on MOS2 events. Source lies near pn CCD gap.
* Based on MOS2 events. Source not detected in pn.
* MOS images show a faint source located 1″ north of source 16.
* The star HDE 290861 is offset 0.8″ from the X-ray position.
* IR source 29 in Walther et al. (1993) is offset by 2.4″ from the X-ray position.

exposure per MOS. Source detection was accomplished with the SAS task edetect_chain on images filtered in different bands. These results were compared with the source list provided from the XMM-Newton pipeline processing, and images were visually checked for missed or spurious detections. The properties of sources detected in the central cluster region (Table 1) are based on events in the 0.5–7.5 keV range.

Spectra and light curves were extracted from circular regions of radius R_e = 15″ centered on individual sources, corresponding to ≈68% enclosed energy at 1.5 keV. Smaller regions were used for a few closely spaced sources to avoid region overlap. Background files were extracted from circular source-free regions near the source. The SAS tasks rmfgen and arfgen were used to generate source-specific response matrix files (RMFs) and auxiliary response files (ARFs) for spectral analysis. The data were analyzed using the XANADU software package, including XSPEC version 12.3.0.

3. X-RAY OVERVIEW OF NGC 2071

Figure 1 shows a broadband 0.5–7 keV EPIC pn image of the central ≈10′ × 10′ cluster region surrounding the NGC 2071-IR

1 The XANADU X-ray analysis software package is developed and maintained by NASA’s High Energy Astrophysics Science Archive Research Center (HEASARC). See http://heasarc.gsfc.nasa.gov/docs/xanadu/xanadu.html for further information.
subgroup. Analysis of both the pn and MOS images resulted in 33 X-ray detections in this central region, as summarized in Table 1. Possible counterparts were found for 23 of these 33 sources (70%) within a search radius of 2” using the Two Micron All Sky Survey (2MASS), Hubble Space Telescope (HST) GSC v2.2, and USNO B1 electronic databases. Of the 23 sources in Table 1 with identifications, 22 have 2MASS counterparts, and their $K_s$ magnitudes are in the range $K_s = 6.3-14.1$. The X-ray positions in Table 1 have been registered against 2MASS, and the mean positional offset between the X-ray sources and their assigned counterparts is only 0.8”. A view of the harder X-ray sources in the cluster is seen in the 4–7 keV image (Fig. 2). The most prominent hard-band detections are a source lying within 1” of IRS 1 (source 13 = XMM J054704.78+002143; Figs. 2 and 3), a source associated with 2MASS J054705.25+002253 (source 16), a close X-ray pair lying near the position of IRAS 05445+0016 (sources 20 and 21; Fig. 4), and variable X-rays (Fig. 5) from the emission-line star LkHα 308 (source 19). These hard sources are discussed further below.

Sufficient counts were present in 21 sources to obtain fits of the X-ray spectra with either one-temperature (1T) or two-temperature (2T) APEC optically thin plasma models. The absorbed fluxes for these objects based on spectral fits are given in

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**Fig. 1.**—Broadband XMM-Newton EPIC pn X-ray image of the $\approx 10' \times 10'$ central region in NGC 2071 (0.5–7 keV; 29.9 ks usable exposure; rebinned to a pixel size of 4.4”; log scale; J2000.0 coordinates). Numbered X-ray sources correspond to Table 1. Boxes enclose X-ray sources with identified counterparts, and circled sources lack counterparts.

**Fig. 2.**—Same as Fig. 1, but restricted to the hard 4–7 keV band.

**Fig. 3.**—Zoomed EPIC MOS1+2 X-ray image of the central NGC 2071-IR subgroup (0.5–7 keV; rebinned to a pixel size of 4.4”; log scale; J2000.0). Plus signs show IR positions of IRS 1–8 (Wa93), and the cross is the centroid of the X-ray source associated with IRS 1.

**Fig. 4.**—EPIC MOS1+2 image (0.5–7 keV) of the close pair sources 20 (south) and 21 (north). Positions of 2MASS sources are marked with plus signs. Source 21 is possibly associated with the B star HDE 290861 (or its close companion), which lies at an offset of 0.8” from the X-ray peak. The position of IRAS 05445+0016 (cross) has a 95% uncertainty ellipse of $47'' \times 7''$ (semimajor × semiminor axes) with the ellipse major axis at PA = 89°.

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Table 1, and fluxes for fainter sources were estimated using \textit{PIMMS}.\textsuperscript{2} Two-temperature models gave acceptable fits of 10 of the brightest sources, excluding source 13, which is discussed in detail below (§ 4). These 10 sources (source numbers 1, 4, 8, 12, 14, 18, 19, 20, 21, and 29) gave a median hydrogen column density log \(N_{\text{H}}\) = 22.0 cm\(^{-2}\) and median plasma temperatures \(kT_1 = 0.74\) keV and \(kT_2 = 2.8\) keV. The means are nearly identical to the medians.

3.1. The NGC 2071-IR Region

Figure 3 shows the summed MOS1+2 image of the NGC 2071-IR region known to contain embedded massive young stars. An unusual X-ray source (source 13) is nearly coincident with IRS 1. Its offset from the VLA position of IRS 1 (Torrelles et al. 1998) and the near-IR source 2MASS J054704.78+002142 is only 0.7\(\text{''}\). Thus, an association of this X-ray source with IRS 1 is likely. A search of the HEASARC galaxies database\textsuperscript{3} revealed no known galaxies or active galactic nuclei (AGNs) within 20\(\text{''}\) of the IRS 1 position, so the probability of a chance association between this X-ray source and a distant background object is small. The cataloged VLA 20 cm radio source NVSS J054705.01+002147.2 lies 5.1\(\text{''}\) northeast of the X-ray peak and is most probably associated with IRS 5, which is offset by only 0.7\(\text{''}\) from the VLA source.

The X-ray source located within 1\(\text{''}\) of IRS 1 has 262 net pn counts (0.5–7.5 keV; \(R_e = 15\)\(\text{''}\)), and its mean photon energy \(\langle E\rangle = 4.62\) keV is the highest of any source in Table 1. Not only is it visible in the 4–7 keV hard-band image (Fig. 2), it is also seen in images restricted to the higher 8–12 keV range. No large-amplitude flarelike variability is seen in the X-ray light curve of this source (Fig. 6), but fluctuations at the \(\approx 2\sigma\) level are present. A \(\chi^2\) test using the pn light curve gives a probability of constant count rate \(P_{\text{const}} = 0.13\) (\(\chi^2/\text{dof} = 19.8/14\); bin size = 2000 s), so no significant variability can be claimed. Fainter X-ray emission is visible in Figure 3 extending to the northeast of IRS 1 that may be associated with IRS 2 (\(\delta = 11.4\)\(\text{''}\)), IRS 3 (\(\delta = 5.6\)\(\text{''}\)), or IRS 5 (\(\delta = 6.2\)\(\text{''}\)), where the offsets \(\delta\) are relative to IRS 1. In addition, faint emission is present near the position of HH 437 (Zhao et al. 1999), which lies \(\approx 15\text{''}\) northeast of IRS 1. Higher angular resolution images will be needed to make unambiguous identifications for this fainter emission.

3.2. The IRAS 05445+0016 Region

The luminous far-IR source IRAS 05445+0016 is located \(\approx 4\text{''}\) south of IRS 1, but with rather large \(\text{IRAS}\) position uncertainties (Fig. 4). This region is of interest because of reported maser detections in the vicinity (e.g., source Onsala 59 in Harju et al. 1998). The \textit{IRAS} source was listed as a candidate pre-main-sequence object by Clark (1991). Additional far-IR scans of NGC 2071 at 50 \(\mu\)m and 100 \(\mu\)m were obtained with the Kuiper Airborne Observatory by Butner et al. (1990).

A close pair of 2MASS sources separated by \(\approx 15\)\(\text{''}\) lies on either side of the \textit{IRAS} position (Fig. 4), and both were detected by \textit{XMM-Newton} (sources 20 and 21). Both sources are visible in the hard-band image (Fig. 2). The southern source (source 20 = XMM J054707.66+001740) has the highest mean count rate of all sources in Table 1. Its X-ray emission is clearly variable, as discerned by a slow decay in the pn light curve during the observation. Its pn spectrum shows a hard component including emission from the Fe K complex (\(\approx 6.7\) keV). We were able to obtain a good spectral fit with an absorbed two-temperature optically thin APEC plasma model with an absorption column density log \(N_{\text{H}}\) = 21.8 cm\(^{-2}\), plasma temperature components at \(kT_1 = 0.87\) keV and \(kT_2 = 3.1\) keV, and \(\chi^2/\text{dof} = 94.8/97\). The combination of X-ray variability and a high-temperature component (\(T_2 \approx 36\) MK) are characteristic of magnetic activity. The northerly source (source 21 = XMM J054707.93+001755) is offset by only 0.8\(\text{''}\) from the B-type star HDE 290861 (V1380 Ori), a known eclipsing binary system with a component separation of 0.59\(\text{''}\) at a position angle (PA) \(\approx 217\) (Prieur et al. 2001). Higher spatial resolution observations will be needed to determine whether the X-rays come from the B star itself or the companion.

3.3. LkH\(\alpha\) 308

The second brightest X-ray detection in Table 1 is LkH\(\alpha\) 308 (source 19 = XMM J054707.29+001932). This \(V = 15.6\) mag emission-line star was identified as a probable \(T\) Tauri star by Herbig & Kuhi (1963), and H\(\alpha\) emission was confirmed by Wiramihardja et al. (1989). It was discovered to be a relatively bright infrared source by Strom et al. (1976), and 2MASS data give \(K_s = 8.3\) mag. LkH\(\alpha\) 308 is an X-ray variable, as discerned

\textsuperscript{2} Further information on the Portable Interactive Multi-Mission Simulator (PIMMS) can be found at http://heasarc.gsfc.nasa.gov/docs/software/tools/pimms.html.

\textsuperscript{3} See http://heasarc.gsfc.nasa.gov/cgi-bin/W3Browse/w3browse.pl.
from its pn light curve, which shows a slow rise and fall in count rate by a factor of ~2 during the observation (Fig. 5). The pn spectrum reveals a faint Fe K emission line, and spectral fits with an absorbed two-temperature optically thin plasma model require a hot component at $kT_2 \approx 3.5–5$ keV, as commonly seen in magnetically active T Tauri stars.

4. X-RAY SPECTRUM OF IRS 1

The X-ray spectrum of the source that we associate with NGC 2071 IRS 1 is unusual compared to the optically thin plasma spectra typically seen in young stellar objects. As Figure 7 shows, the spectrum is characterized by a nearly flat broadband continuum that is heavily absorbed below $\approx 1$ keV and a strong broad emission line from neutral or near-neutral iron near 6.4 keV. The fluorescent Fe line dominates the spectrum, and its intensity and width are exceptional for a young stellar object.

The spectrum in Figure 7 was extracted using a circular region of radius $R_e = 15''$ and may include contributions from the nearby sources IRS 2, IRS 3, and IRS 5, which lie at offsets of 5.6''–11.4'' from IRS 1. However, we were able to recover a nearly identical spectrum including the strong fluorescent Fe line when using a smaller extraction region of radius $R_e = 4''$. The positions of IRS 2, IRS 3, and IRS 5 lie outside this smaller circle, and even though there could be some point-spread function (PSF) overlap, these results suggest that IRS 1 (or an as yet unresolved source within a few arcseconds of IRS 1) is the dominant X-ray contributor.

We attempted to fit the spectrum using a conventional optically thin plasma model with a single absorption component plus a Gaussian line near 6.4 keV. This model ran away to unphysically high temperatures even when multiple temperature components were allowed. However, we were able to fit the spectrum with either (1) an absorbed power-law continuum with a photon power-law index $\alpha_{ph} = +0.55$ plus a Gaussian line centered at $E_{line} = 6.48$ keV ($\chi^2/dof = 14.3/14$) or (2) a two-component optically thin plasma model with a cool, moderately absorbed component and a hot, heavily absorbed component plus a Gaussian line centered at $E_{line} = 6.43$ keV ($\chi^2/dof = 10.7/11$). Fit results are summarized in Table 2.

Table 2: XMM-Newton Spectral Fits for IRS 1

| Parameter | Model A | Model B |
|-----------|---------|---------|
| Emission | thermal + line | power law + line |
| $N_{H1}$ (10$^{22}$ cm$^{-2}$) | 3.8 [2.2–10.0] | 1.0 [0.19–2.3] |
| $kT_1$ (keV) | 0.75 [0.20–1.0] | ... |
| norm$_1$ (10$^{-5}$) | 2.1 [0.4–... | 0.04 [0.02–0.06] |
| $N_{H2}$ (10$^{21}$ cm$^{-2}$) | 1.6 [0.48–3.0] | ... |
| $kT_2$ (keV) | 10.5 [5.8–... | ... |
| norm$_2$ (10$^{-4}$) | 1.4 [0.76–2.3] | ... |
| $\alpha_{ph}$ | ... | 0.55 [0.26–0.85] |
| $E_{line}$ (keV) | 6.43 [6.37–6.53] | 6.48 [6.42–6.54] |
| $\sigma_{line}$ | 0.14 [0.06–0.26] | 0.21 [0.14–0.28] |
| norm$_{line}$ (10$^{-6}$) | 4.5 [2.9–6.5] | 5.5 [4.2–6.9] |
| $\chi^2$/dof | 10.7/11 | 14.3/14 |
| $\chi^2$/dof | 0.97 | 1.02 |
| $F_X$ (10$^{-13}$ ergs cm$^{-2}$ s$^{-1}$) | 1.28 (7.93) | 1.27 (1.39) |
| $F_{X,1}$ (10$^{-11}$ ergs cm$^{-2}$ s$^{-1}$) | 0.13 (4.99) | ... |
| $L_X$ (10$^{31}$ ergs s$^{-1}$) | 3.86 (4.03) | 3.56 (3.56) |
| $L_{X,1}$ (10$^{31}$ ergs s$^{-1}$) | 1.5 | 0.27 |
| $L_{X,2}$ (10$^{31}$ ergs s$^{-1}$) | 0.95 | ... |

Notes.—Based on XSPEC (version 12.3.0) fits of the background-subtracted EPIC pn spectrum, binned to a minimum of 15 counts per bin using 29.9 ks of low-background exposure. Thermal emission was modeled with a solar abundance (Anders & Grevesse 1989) APEC optically thin plasma model in XSPEC. The tabulated parameters are absorption column density ($N_H$), photon energy ($E_X$), plasma energy ($kT_X$), and centroid energy ($E_{line}$), and line width ($\sigma_{line} = FHWM/2.35$). Solar abundances are referenced to Anders & Grevesse (1989). Square brackets enclose 90% confidence intervals, and an ellipsis means that the algorithm used to compute confidence intervals did not converge. The total X-ray flux ($F_X$) and flux of the low-absorption component ($F_{X,1}$) are the absorbed values in the 0.5–7.5 keV range, followed in parentheses by unabsorbed values. The continuum-subtracted fluorescent Fe line flux ($F_{X,2}$) is measured in the 6.2–6.6 keV range. The unabsorbed total luminosity $L_X$ (0.5–7.5 keV) and cool-component luminosity $L_{X,1}$ (0.5–7.5 keV) assume a distance of 400 pc.

* $N_{H1}$, $kT_1$, $N_{H2}$, $kT_2$, $\alpha_{ph}$.
* $N_{H1}$, PL + GAUSS.
* $N_{H1}$, PL + GAUSS.

For thermal APEC models, the norm is related to the emission measure (EM) by $EM = 4\times10^{45}d_{\text{mag}}^2$, where $d_{\text{mag}}$ is the stellar distance in centimeters.

Both the power-law and thermal fits are formally acceptable, but the thermal model provides a better fit of the shape of the spectrum at lower energies between 1 and 2 keV and is easier to justify on physical grounds. Also, the X-ray absorption log $N_{H1} = 22.0$ cm$^{-2}$ determined from the power-law model corresponds to a visual extinction $A_V = 4.5$ mag (Gorenstein 1975), which is much less than the range $A_V \approx 28–51$ mag expected toward IRS 1 if it is an embedded B0–B5 star (War93). The thermal model yields a higher absorption that is consistent with the range expected for IRS 1. However, we do consider the possibility of power-law models further in § 5. High (but physically realistic) X-ray temperatures are required by the two-component thermal model to reproduce the broadband continuum (Table 2). The absorption inferred for the hot component at $kT_2 = 10.8$ keV is log $N_{H2} = 23.2$ cm$^{-2}$. This $N_{H2}$ implies an equivalent visual extinction $A_V \approx 70$ mag (Gorenstein 1975). Thus, the high-temperature source is heavily obscured. The absorption associated with the cooler component at $kT_1 = 0.7$ keV is log $N_{H1} = 22.6$ cm$^{-2}$, or $A_V \approx 17$ mag. The strong Fe line accounts for $\approx 30\%$ of the observed (absorbed) flux in the 0.5–7.5 keV range. The Gaussian line width deduced from the thermal model, $\sigma_{line} = 140$ eV, gives FHWM = 330 eV. The line is quite likely resolved, since the pn intrinsic energy resolution is FHWM $\approx 160$ eV at 6.5 keV.
4.1. The Fluorescent Fe Line

The physical picture needed to explain the fluorescent Fe emission requires the presence of neutral or near-neutral material in proximity to the X-ray source. This material is irradiated by the hard source, which is quite likely the embedded high-mass star. The origin of the line broadening is clearly of interest. Velocity broadening of a single line cannot fully account for the line width without invoking unrealistically high velocities. Some of the broadening could be due to multiple closely spaced Fe lines that are not spectrally distinguishable at the pn energy resolution. In this regard, inspection of the unfolded spectral model shows that a fainter Fe line may contribute to some of the flux near 6.7 keV, but this line, if present, is masked by the broad wings of the 6.43 keV fluorescent line.

If the broad fluorescent line width is a column density effect, then the inferred column density is large. The line equivalent width (EW) is related to the column density of cold fluorescent material in the optically thin slab approximation by EW \approx 2.3N_{24} \text{ keV} (Kallman 1995), where \( N_{24} \) is the column density of the cold matter in units of \( 10^{24} \text{ cm}^{-2} \). In the present case, our pn spectrum measurements give \( EW \approx 2.4 \text{ keV, so } N_{\text{H,cold}} \approx 10^{24.9} \text{ cm}^{-2} \). The lower signal-to-noise ratio MOS spectra give a somewhat smaller value: \( EW \approx 1.4 \text{ keV, or } N_{\text{H,cold}} \approx 10^{23.8} \text{ cm}^{-2} \). The value determined from the pn spectrum is at the upper limit where Kallman’s approximation breaks down, but if the 6.43 keV feature is a blend, then the inferred value of \( N_{\text{H,cold}} \) is only an upper limit.

The above approximation indicates that the absorption column of the cold material is about an order of magnitude greater than the absorption inferred for the hard thermal X-ray component (Table 2). The material responsible for the absorption of the hard X-rays cannot fully account for \( N_{\text{H,cold}} \) (see also eq. [4] of Tsujimoto et al. 2005). Thus, the cold fluorescent material may not lie directly on the line of sight. One possibility is that the fluorescent line originates in the dense ridge of molecular gas orthogonal to the outflow axis, which may be a rotating disk (Bally 1982; Seth et al. 2002).

Fluorescent Fe line analysis similar to that above has been undertaken on YSOs in other high-mass star forming regions. Of particular relevance is the Chandra study of the Sgr B2 giant molecular cloud by Takagi et al. (2002), who reported high-temperature plasma and strong 6.4 keV line emission for some luminous X-ray sources. Specifically, they obtained \( kT \approx 10 \text{ keV} \) and a fluorescent Fe line equivalent width \( EW \approx 630 \text{ eV} (180-1100; 90\% \text{ confidence}) \) for Sgr B2 source 10 (C XO J174720.2–282305). Takagi et al. note that this X-ray source lies near an ultracompact H ii region and may correspond to a massive YSO. The X-ray temperature reported for Sgr B2 source 10 is similar to what we infer for the hot component of NGC 2071 IRS 1, but the fluorescent line equivalent width and derived value of \( N_{\text{H,cold}} \) are \( \approx 3-4 \) times larger for IRS 1.

5. DISCUSSION

The unusual X-ray spectrum of the source near the massive young star IRS 1 warrants further discussion. The presence of cool and hot plasma components apparently seen through different absorption columns suggests that more than one source or X-ray emission process contributes to the spectrum. We consider possible emission processes below.

5.1. Similarities with Jet-Driving T Tauri Stars

The need to invoke two thermal X-ray components at different absorption columns to fit X-ray spectra has also recently been seen in some accreting low-mass pre-main-sequence stars, such as the T Tauri star DG Tau A (Güdel et al. 2005). High-resolution Chandra images reveal a two-component X-ray source consisting of a relatively hard strongly absorbed point source at the stellar position and softer less absorbed X-ray emission extending along a bipolar jet several arcseconds from the star. The jet is also seen in the optical. Spectral extractions centered on the star capture emission from both components, resulting in a double-absorption spectrum. Some of the softer emission is due to the shocked jet, while the harder pointlike emission at the position of DG Tau A is undoubtedly of magnetic origin.

It is conceivable that a similar phenomenon could be responsible for the double-absorption X-ray spectrum detected here for IRS 1. It is unavoidable that our spectral extraction captures a rather large region around the X-ray source and could sample shocked wind or outflow emission that is offset by several arcseconds from the central source. At \( d = 400 \text{ pc, the XMM-Newton PSF (FWHM } \approx 4.3'' \text{) corresponds to FWHM } \approx 1700 \text{ AU, and our nominal source extraction radius } R_e = 15'' \text{ corresponds to a radius of } 6000 \text{ AU (0.03 pc). The velocity of the bipolar molecular outflow (} \approx 70 \text{ km s}^{-1}; \text{ Bally 1982} \text{) is too low to produce shock-heated plasma at the temperatures inferred from the X-ray spectral fits. However, a higher velocity stellar wind or jet could suffice. The presence of a compact H ii region and luminosity considerations suggest that IRS 1 may be an embedded } B0-B5 \text{ star (Wa93), which could indeed have already developed a strong wind. Also, IRS 3 lies within our } R_e = 15'' \text{ extraction region, and it is known to have a radio jet (Torrelles et al. 1998).}

Simple shock-heating models (Krolik & Raymond 1985; Raga et al. 2002) give a predicted shock temperature \( T_s \approx 1.5 \times 10^5 \text{ (v}_s/100 \text{ km s}^{-1})^2 \text{ K, where } v_s \text{ is the shock speed relative to the upstream flow. In order to reach X-ray temperatures comparable to that of the cool X-ray component } T_i \approx 8.7 \times 10^6 \text{ [2.3–11.6] MK (Table 2), shock speeds } v_s \approx 760 \text{ [390–880] km s}^{-1} \text{ would be required. These are fast shocks, but perhaps within reason if IRS 1 is an embedded early B-type star. The above shock speed is only about half the terminal wind speed of a B3 V star and about one-third that of a B0 V star (Table 4 of Cassinelli et al. 1994).}

5.2. Comments on X-Rays from Wind Shocks

X-rays from radiation-driven wind shocks in early-type stars are predicted on theoretical grounds (Lucy 1982; Lucy & White 1980). The expected X-ray temperatures are \( < 1 \text{ keV} \), so this process could at best account only for the cooler plasma seen in the two-component spectrum. However, the moderately high X-ray absorption, plasma temperature, and required shock speed for the cool X-ray component noted above stretch the limits of what the radiative wind shock model can accommodate.

A more interesting possibility is that the hot plasma is shock related. The impact of a high-velocity wind or jetlike outflow from IRS 1 on a close companion or other obstruction could produce high-temperature X-ray plasma in a colliding-wind shock. The colliding-wind picture is usually invoked to explain high-temperature X-ray emission in massive close binaries, such as WR + O systems (e.g., Skinner et al. 2001), but in the present case, the high-speed wind of the embedded star might actually be shocking on dense surrounding material. Interestingly, Seth et al. (2002) have suggested that the walls of the cavity surrounding IRS 1 might be the interface between outflowing and infalling material. A similar picture, in which a high-velocity stellar wind is shocking on dense surrounding clumps, has been discussed by Kitamura et al. (1990).

The maximum colliding wind shock temperature in the adiabatic case is \( kT_{cw} \approx 1.95(v_{\perp,s}/1000 \text{ km s}^{-1})^2 \text{ keV, where } v_{\perp,s} \text{ is the velocity component normal to the shock interface (Luo} \text{ et al. 2002); this is about } 7 \times 10^6 \text{ K for } v_s = 760 \text{ km s}^{-1} \text{ (Table 2).}

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et al. 1990). Thus, a B0 V star with a terminal wind speed $v_{\infty} \approx 2500$ km s$^{-1}$ could in principle produce very hot X-ray plasma at $kT_{ew} \approx 12$ keV, similar to the value $kT_1 \approx 11$ keV inferred for the hot component in the X-ray spectrum (Table 2). The colliding-wind model, if relevant, would of course need to account for the X-ray luminosity (Table 2). The X-ray luminosity predicted for a colliding-wind system is a sensitive function of mass-loss parameters and orbital separation (Luo et al. 1990). In the absence of such information for IRS 1, a meaningful comparison with theory cannot be made, and the colliding-wind scenario thus remains quite speculative.

5.3. Magnetic Processes in Massive Young Stars?

The hard X-ray continuum detected in IRS 1 extends up to at least 8 keV. Such hard emission represents an extreme case for wind-generated shocks, but is not uncommon for X-ray emission from magnetic reconnection processes that are observed in low-mass pre-main-sequence stars (T Tauri stars) and even some low-mass protostars (Imanishi et al. 2001). Some additional support for magnetic behavior in massive young stellar objects comes from the Chandra detection of the high-mass embedded object Mon R2 IRS 2 (Kohno et al. 2002). The X-ray absorption, temperature, and X-ray luminosity reported for Mon R2 IRS 2 are strikingly similar to the values we determine for the hot component of NGC 2071 IRS 1. However, the fluorescent Fe line was not seen in Mon R2 IRS 2. More importantly, the X-ray emission of Mon R2 IRS 2 was found to be variable on timescales of a few $10^4$ s, as was that of at least two other embedded high-mass YSOs in Mon R2. The presence of such short-term variability in combination with very hot plasma is a strong argument in favor of magnetic processes.

Because of the close similarities in X-ray spectral properties between NGC 2071 IRS 1 and Mon R2 IRS 2 (apart from the lack of fluorescent Fe in the latter) it is quite possible that their high-temperature X-ray emission arises from similar processes. If the emission is indeed of magnetic origin, then the key questions are whether the emission is due to as yet undetected late-type companions or the massive YSOs themselves. If the emission is intrinsic to the embedded high-mass objects, then the theoretical challenge will be to determine whether the fields are internally generated (and by what mechanism) or instead primordial.

5.4. X-Rays from Inverse Compton Scattering

In conclusion, we comment briefly on the possibility that the X-ray continuum emission of the hard source near IRS 1 is nonthermal. As we have noted, the spectrum can be fitted with an absorbed power-law continuum plus a Gaussian Fe line (model B in Table 2), but the inferred absorption is much less than expected toward IRS 1. The production of nonthermal X-rays from OB star winds has been considered by Chen & White (1991). In their model, hard X-rays above 2 keV can be produced by inverse Compton scattering of stellar UV photons by relativistic electrons accelerated in wind shocks near the star.

To explore the nonthermal possibility further, we fitted the pn X-ray spectrum with a model consisting of an absorbed cool thermal component and an absorbed power-law component plus a Gaussian line. The cool thermal component is intended to model any soft radiative wind shock emission, and the power-law component models nonthermal emission from inverse Compton scattering. Different absorption columns were allowed for the thermal and power-law components. This model gives a statistically acceptable fit of the spectrum ($\chi^2$/dof = 11.3/11), with a cool thermal plasma temperature $kT_1 \approx 0.2$ keV and a photon power-law index $\alpha_{ph} = +0.6$. However, the fit converges to a very large emission measure for the cool thermal component, which leads to a high unabsorbed luminosity $L_X \sim 10^{34}$ ergs s$^{-1}$. The inferred presence of a very soft thermal component with extremely high emission measure viewed under high absorption, log $N_{H1} \approx 22.9$ cm$^{-2}$, is likely a result of fitting the data with an inappropriate model, and the fit results seem unphysical. We thus do not favor such a hybrid thermal + nonthermal emission model based on the existing data, but the model would be worth reconsidering if higher quality spectra are obtained.

6. SUMMARY AND OUTLOOK

We have presented results of the first X-ray observation centered on the core region of the infrared cluster in NGC 2071. The most important (and unanticipated) result of this study is the unusual X-ray spectrum of the source detected within 1" of the massive young stellar object IRS 1. The small positional offset and strong X-ray absorption inferred from thermal spectral models make an association of this X-ray source with IRS 1 likely.

The high X-ray temperature implied by thermal models is characteristic of magnetic processes and raises the intriguing possibility that magnetic fields play an important role in X-ray production in young high-mass stars. Kohno et al. (2002) were led to a similar conclusion based on Chandra observations of massive young stars in Mon R2. However, the role played by any as yet unresolved close companions in the X-ray emission process is unknown.

A higher resolution Chandra observation of NGC 2071-IR now pending will answer several key questions regarding the origin of the unusual X-ray emission. Specifically, Chandra’s arcsecond resolution will place tighter constraints on the position of the X-ray peak relative to IRS 1 and will determine if nearby objects such as IRS 2, IRS 3, or IRS 5 contribute to the X-ray emission. The longer Chandra exposure will also provide a more definitive test for variability on short timescales, a key discriminator between magnetic and shock processes.

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