CHANDRA AND SPITZER IMAGING OF THE INFRARED CLUSTER IN NGC 2071

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Received 2009 March 6; accepted 2009 June 16; published 2009 July 27

ABSTRACT

We present results of a sensitive Chandra X-ray observation and Spitzer mid-infrared (mid-IR) observations of the IR cluster lying north of the NGC 2071 reflection nebula in the Orion B molecular cloud. We focus on the dense cluster core known as NGC 2071-IR, which contains at least nine IR sources within a 40″ × 40′′ region. This region shows clear signs of active star formation including powerful molecular outflows, Herbig-Haro objects, and both OH and H2O masers. We use Spitzer Infrared Array Camera (IRAC) images to aid in X-ray source identification and to determine young stellar object (YSO) classes using mid-IR colors. Spitzer IRAC colors show that the luminous source IRS 1 is a class I protostar. IRS 1 is believed to be driving a powerful bipolar molecular outflow and may be an embedded B-type star or its progenitor. Its X-ray spectrum reveals a fluorescent Fe emission line at 6.4 keV, arising in cold material near the protostar. The line is present even in the absence of large flares, raising questions about the nature of the ionizing mechanism responsible for producing the 6.4 keV fluorescent line. Chandra also detects X-ray sources at or near the positions of IRS 2, IRS 3, IRS 4, and IRS 6 and a variable X-ray source coincident with the radio source VLA 1, located just 2′ north of IRS 1. No IR data are yet available to determine a YSO classification for VLA 1, but its high X-ray absorption shows that it is even more deeply embedded than IRS 1, suggesting that it could be an even younger, less-evolved protostar.

Key words: open clusters and associations: individual (NGC 2071) – stars: formation – stars: individual (IRS 1) – X-rays: stars

1. INTRODUCTION

The Lynds 1630 dark cloud (Lynds 1962) is located approximately 4′ north of the optical reflection nebula NGC 2071 in the Orion B molecular cloud (Maddalena et al. 1986). L1630 was recognized as a site of recent star formation by Strom et al. (1975), who identified a young stellar population with an estimated age of a few million years containing early B- and A-type stars, optically revealed H2 emission line stars (T Tauri stars), and several embedded infrared (IR) sources. An overview of star formation in the NGC 2071 region can be found in Gibb (2008).

The L1630 dark cloud was mapped at 2.2 μm by Strom et al. (1976) and 70 sources were detected down to a limiting magnitude \( K \approx 10.7 \) mag. About one-third of these lacked optical counterparts and they estimated an extinction \( A_v \approx 20 \) mag toward the cloud center. A more sensitive 2.2 μm survey of L1630 was undertaken by Lada et al. (1991) who identified 912 sources down to \( K \approx 13.0 \) mag, about half of which were associated with L1630 itself.

Using known MK spectral types and optical photometry for a large sample of non-variable B star members, the distance to this region was estimated to be 390 pc by Anthony-Twarog (1982). But, the near and far edges of the Orion OB1 association span a range of \( \approx 320 \) pc to 500 pc (Brown et al. 1994; Wilson et al. 2005). Using Spitzer Infrared Array Camera (IRAC) and MIPS data along with low-resolution optical spectra, Flaherty & Muzerolle (2008) determined a cluster age of 2 ± 1.5 Myr and concluded that 79% of the late-type cluster members in their sample have IR excesses. They found evidence for active accretion in all of the IR-excess objects.

The extended NGC 2071 cluster identified by Lada et al. (1991) covers an area of \( \approx 80 \) arcmin 2 and contains a dense subgroup known as NGC 2071-IR (Figures 1 and 2) which harbors at least nine IR sources in a 40″ × 40′′ core region (Walter et al. 1991; Walter et al. 1993, hereafter W93; Tamura et al. 2007, hereafter T07). The position of NGC 2071-IR within NGC 2071 is shown in Figure 2 of W93, and a wide-field perspective showing the location of this region within the Orion complex can be found in Figure 3 of Maddalena et al. (1986). Within NGC 2071-IR, the bright IR source IRS 1 is of particular interest. The nature of this object is unclear but previous studies have concluded it may be a young embedded B-type star (W93; Snell & Bally 1986). The NGC 2071-IR subgroup shows clear signs of active star formation including powerful bipolar molecular outflows (Bally 1982; Snell et al. 1984; Aspin et al. 1992; Eisloeffel 2000), Herbig-Haro objects (Zhao et al. 1999), and water masers near IRS 1 and IRS 3 (Torrelles et al. 1998 and IRS 2 (Sandell et al. 1985). An OH maser has been detected within \( \approx 20′′ \) of IRS 1 (Johansson et al. 1974; Pankonin et al. 1977; Sandell et al. 1985) but the maser position is not well enough known to determine if it is coincident with IRS 1. VLA maps in NH3 lines reveal what appears to be a large ring structure or edge-on disk surrounding NGC 2071-IR (Zhou et al. 1990).

More than one outflow may be present in NGC 2071-IR. Using H2 1–0 S(1) images, Eisloeffel (2000) identified at least three outflows. These include an east–west outflow that may be driven by IRS 1 (see also Aspin et al. 1992), and further support for such an outflow comes from high-velocity knots revealed in recent 3.6 cm VLA images (Carrasco-González et al. 2007). Eisloeffel
The X-ray source was identified with IRS 1, but was subject to detections at a position within 1 arcsec. Detailed driving sources remains somewhat uncertain due to the complex morphology of the region.

A previous X-ray observation of the NGC 2071 region with XMM-Newton detected a prominent X-ray source at a position within 1" of IRS 1 (Skinner et al. 2007, hereafter S07). The X-ray source was identified with IRS 1, but was subject to limitations on source identification in the crowded cluster core imposed by XMM-Newton’s ≈4′′ angular resolution. We present here the results of a higher angular resolution Chandra X-ray observation of NGC 2071-IR. Our main objectives were to confirm the previous X-ray detection of IRS 1 with improved positional accuracy and identify possible mechanisms for its X-ray emission. Although the X-ray emission of optically revealed OB stars has been extensively studied and is thought to arise in shocked winds, much less is known about X-ray sources such as IRS 1. We confirm that IRS 1 is indeed an X-ray source and discuss its X-ray properties along with several other X-ray detections in the NGC 2071-IR subgroup (IRS 2, IRS 3, IRS 4, and IRS 6). Chandra’s sharp angular resolution also reveals a new X-ray source associated with the radio continuum source VLA 1 lying 2′′ north of IRS 1. The VLA 1 X-ray source is seen through very high absorption equivalent to $N_H = 2 \times 10^{22} \text{ cm}^{-2}$. The X-ray source is seen through very high absorption equivalent to $N_H = 2 \times 10^{22} \text{ cm}^{-2}$.

The Chandra observation (ObsID 7417) began on 2007 November 6 at 19:40:19 TT and ended on November 7 at 15:18:03 TT. Pointing was centered near NGC 2071 IRS 1 at nominal pointing coordinates (J2000) R.A. = 05h47m04.994, decl. = +00°22′11.8′′. The exposure live time was 67,180 s. Exposures were obtained using the Advanced CCD Imaging Spectrometer (ACIS-I) imaging array in faint timed-event mode with 3.2 s frame times. ACIS-I has a combined field of view (FOV) of ≈16′′ × 16′′ consisting of four front-illuminated 1024 × 1024 pixel CCDs with a pixel size of 0.′′492. Approximately 90% of the encircled energy at 1.49 keV lies within 2′′ of the center pixel of an on-axis point source. Our discussion here focuses on ACIS-I, but the S2 and S3 CCDs in the ACIS-S array were also extended. More information on Chandra and its instrumentation can be found in the Chandra Proposer’s Observatory Guide (POG).

The Level 1 event file provided by the Chandra X-ray Center (CXC) was processed using CIAO version 3.49 using standard science threads. The CIAO processing applied calibration updates (CALDB version 2.26), selected good event patterns, and determined source centroid positions.

Additionally, we used the CIAO wavdetect tool to identify X-ray sources on the ACIS-I array. We ran wavdetect on full-resolution images using events in the 0.3–7 keV range to reduce the background. The wavdetect threshold was set at $s_{\text{thresh}} = 1.5 \times 10^{-3}$ and scale sizes of 1, 2, 4, 8, and 16 were used. We identified 207 X-ray sources on ACIS-I down to a threshold of 5 counts, including the sources of primary interest in this work located in the NGC 2071-IR core region listed in Table 1.

The unabsorbed X-ray luminosity upper limit for nondetections is $log L_X (0.3–7 \text{ keV}) \leq 28.7 \text{ erg s}^{-1}$. This upper limit from the Portable Interactive Multi-Mission Simulator (PIMMS)$^{10}$ assumes a 5 count on-axis detection threshold and an absorbed isothermal optically thin plasma spectrum similar to that observed for IRS 1 ($N_H = 2 \times 10^{22} \text{ cm}^{-2}$, $kT = 2 \text{ keV}$). At this upper limit, the observation was sensitive enough to detect low-mass T Tauri stars in Orion down to $\approx 0.1–0.2 M_\odot$, based on the known correlation between $L_X$ and stellar mass in T Tauri stars (Preibisch et al. 2005). The above upper limit should be considered as a representative value since the detection limit depends on many factors including the spectral properties of the source and extent to which the source is displaced off-axis.

At the sensitivity of our observation, we expect $\approx 1$ extragalactic background source in a region spanning $\approx 1.6$ arcmin$^2$, or $< 1$ extragalactic source in the $\approx 40'' \times 40''$ NGC 2071-IR region analyzed here. This estimate is based on hard-band (2–8 keV) number counts from the Chandra Deep Field (CDF) and other X-ray surveys (e.g., Brandt et al. 2001; Moretti et al. 2003) and an assumed power-law spectrum with a photon power-law index $\Gamma = 1.4$ for extragalactic sources. The above estimate should be considered as approximate because the accuracy of the log $N$–log $S$ distribution for extragalactic sources based on deep-field observations when applied to lower galactic latitude star-forming regions is not well known. Getman et al. (2005) concluded that CDF number counts overestimated the number of extragalactic sources in the deep Chandra COUP observation of the Orion Nebula Cluster by a factor of $\approx 3–4$.

CIAO psextract was used to extract source and background spectra for brighter sources, along with source-specific response matrix files (RMFs) and auxiliary response files (ARFs) used in spectral fitting. Light curves of brighter sources were also extracted using CIAO tools. We used the 3σ source ellipses from wavdetect to define the extraction regions and background was extracted from adjacent source-free regions. Background is negligible, contributing only 0.21 counts per pixel (0.3–7 keV) for the total exposure time, or less than one count in the regions used to extract source spectra and light curves. Spectral fitting and timing analysis were undertaken with the HEASOFT Xanadu$^{11}$ software package including XSPEC version 12.4.0. We also applied the Kolmogorov–Smirnov (KS) test (Press et al. 1992, p. 617) to unbinned photon arrival times to check for X-ray variability.

Since conventional spectral fitting is only practical for brighter sources, we used the quantile analysis approach of

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$^8$ See http://asc.harvard.edu/proposer/POG.

$^9$ Further information on Chandra Interactive Analysis of Observations (CIAO) software can be found at http://cxc.harvard.edu/ciao.

$^{10}$ Information on PIMMS can be found at http://asc.harvard.edu/ciao/ahelp/pimms.html.

$^{11}$ http://heasarc.gsfc.nasa.gov/docs/xanadu/xanadu.html
simulations based on a one-temperature (1T) APEC optically are defined such that one-fourth of the counts have energies that is akin to an X-ray color–color diagram.

This work). Quantile values (or functions thereof) are then over-

tuations $Q_x$ ($x = 25$, 50, $75, \cdots$) following Net Counts error indicates that the source is likely variable as indicated by a variability probability $P_{\text{var}} \geq 0.95$ determined from the KS statistic.

Notes.

$^a$ Chandra X-ray data are from CCD3 (ACIS chip 13) using events in the 0.3–7 keV range. Tabulated quantities are: source name, J2000.0 X-ray position (R.A., Decl.), net counts and net counts error from wavdetect (accumulated in a 67,180 s exposure, rounded to the nearest integer, background-subtracted and PSF-corrected), 25%, 50% (median), and 75% photon quartile energies $E_{25}$, $E_{50}$, and $E_{75}$, $K_s$ magnitude of near-IR 2MASS counterpart, and 2MASS (2M) or radio (VLA) candidate counterpart identification within a 2" search radius. The offset (in arcsec) between the X-ray and counterpart position is given in parentheses. A (v) following Net Counts error indicates that the source is likely variable as indicated by a variability probability $P_{\text{var}} \geq 0.95$ determined from the KS statistic.

$^b$ The name IRS 3 corresponds to the IR source identified by W93, which lies ≈2.3 northeast of the X-ray source.

$^c$ The IRS 3 $K_s$ magnitude is from W93.

$^d$ The closest 2MASS source (2M J05470473+0021497) lies at an offset of 2′′34 and $K_s = 12.88$. A Spitzer IRAC source is visible and the 4.5 μm IRAC position gives an offset of ≈0.42 from the Chandra position.

$^e$ The X-ray source is offset by 0′′27 from radio source VLA J054705.367+002150.51. VLA coordinates are from C. Carrasco-González (2009, private communication).

$^f$ Faint source not found by wavdetect. Net counts are measured within an extraction circle of radius 1″. Insufficient counts for variability analysis or calculation of reliable $E_{25}$ and $E_{75}$ values.

$^g$ A Spitzer IRAC source is visible and the 3.6 μm position gives an offset of ≈1″19 from the Chandra position.

Hong et al. (2004) to quantify source hardness. This technique has the advantage that it can be applied to sources that are too faint for spectral fitting. The quantile method uses sorted photon event energy lists to compute the median energy $E_{50\%}$ and the quartile energies $E_{25\%}$ and $E_{75\%}$. The quartile energies are defined such that one-fourth of the counts have energies below $E_{25\%}$, and three-fourths below $E_{75\%}$. The quartile fractions $Q_x$ are computed from quartile energies using $Q_x = (E_{x\%} - E_{25\%})/(E_{75\%} - E_{25\%})$, where $E_{25\%}$ and $E_{75\%}$ are the lower and upper energy bounds of the extracted events (0.3 and 7.0 keV in this work). Quantile values (or functions thereof) are then over-plotted on a grid of neutral hydrogen absorption column density ($N_H$) and plasma energy ($kT$) values generated from spectral simulations based on a one-temperature (1T) APEC optically thin thermal plasma model. This provides a graphical representation of the source hardness superimposed on a ($N_H$, $kT$) grid that is akin to an X-ray color–color diagram.

2.2. Spitzer Observations

We use IR observations of the NGC 2071-IR region obtained by the Spitzer Space Telescope to aid in X-ray source identification and to determine YSO classes using mid-IR colors. Spitzer’s IRAC mapped the NGC 2071-IR region as part of Spitzer Orion Survey (GTO program ID 043; Megeath et al. 2005b; Allen et al. 2007; Flaherty & Muzerolle 2008; S. T. Megeath et al. 2009, in preparation). Further information on IRAC can be found in Fazio et al. (2004). The IRAC data were obtained in four channels (3.6, 4.5, 5.8, and 8.0 μm) using the high dynamic range (HDR) mode, acquiring a short 0.6 s exposure plus a longer 12 s exposure at each pointing position. Four dithers were obtained at each position.

The reduction and analysis of the complete data set will be discussed in detail by S. T. Megeath et al. (2009, in preparation). In brief, individual basic calibrated data (BCD) frames were mosaicked with custom software to create separate mosaic images for the four IRAC channels. Point sources were identified using PhotVis version 1.10 (Gutermuth et al. 2004, 2008). Using the source positions determined from the mosaics, photometry was measured for each point source on the individual BCD images using the IDL module aper.pro (Landsman 1993). Magnitudes were measured in a circular aperture of radius $r = 2$ pixels centered on the source, using a background annulus of $r = 2–6$ pixels. A gain correction depending on pixel position was applied to each magnitude. The final magnitudes are the median magnitudes returned from the four dithers. Magnitudes of those sources in the NGC 2071-IR region discussed here are given in Table 2, along with magnitude zero points and aperture correction factors.

Spitzer MIPS data at longer wavelengths 24–160 μm are also available (Flaherty & Muzerolle 2008; S. T. Megeath et al. 2009, in preparation). Because the NGC 2071-IR region is confused and heavily saturated, we only provide here the MIPS 24 μm photometry for IRS 7. MIPS data were reduced using the procedure given in Megeath et al. (2009).

3. RESULTS

We focus here on the heavily reddened NGC 2071-IR subgroup shown in the Two Micron All Sky Survey (2MASS) 2.16 μm ($K_s$) image in Figure 1 and the Spitzer IRAC 3.6 μm (ch1) image in Figure 2. This region of high source density includes the IR sources IRS 1–8 and IRS 8a (W93; T07), as well as the radio source VLA 1 located near IRS 1. We summarize the IR and X-ray properties of each source on an individual basis below.

Figure 3 shows near-IR colors of IRS 1–8, all of which show some excess reddening. Figure 4 is an IRAC color–color diagram that provides one means of distinguishing between class I YSOs (protostars) and class II YSOs (classical T Tauri stars, or accreting star+disk systems). Figure 5 plots the IR SEDs of those sources in NGC 2071-IR for which reliable near-IR and
Figure 1. 2MASS $K_s$-band (2.16 $\mu$m) image of the region near IRS 1. Crosses mark positions of Chandra X-ray sources. Significant offsets between Chandra and 2MASS positions exist for IRS 3 (2.3) and IRS 6 (1.7). See Table 1 for positions. No X-ray emission was detected by Chandra at the 2MASS positions of IRS 5, IRS 7, and IRS 8. Log intensity scale. North is up and east is left.

Figure 2. Unsaturated Spitzer IRAC 3.6 $\mu$m (ch1) image of the region near IRS 1 (program 043). The image is a single 0.6 s frame. Crosses mark positions of Chandra X-ray sources. The positional offset between Chandra and IRAC for IRS 3 is only 0.042, in better agreement than obtained with 2MASS (Figure 1). The positional offset between Chandra and IRAC for the binary system IRS 6 is 1.2, again better than obtained with 2MASS (Figure 1). IRS 5, IRS 7, and IRS 8 were not detected by Chandra. Circled dots mark the 2MASS near-IR positions of IRS 5 and IRS 8 for clarity. Log intensity scale. Coordinates are J2000.

Table 2

| Object | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) | [8.0] (mag) |
|--------|-------------|-------------|-------------|-------------|
| IRS 1  | 8.359 ± 0.005 | 6.246 ± 0.005 | 4.576 ± 0.003 | 2.819 ± 0.001 |
| IRS 2  | 7.747 ± 0.046 | 6.382 ± 0.008 | 5.581 ± 0.005 | 4.717 ± 0.005 |
| IRS 3  | ... | 7.250 ± 0.015 | ... | ... |
| IRS 4  | 9.418 ± 0.035 | 8.263 ± 0.007 | 7.776 ± 0.005 | 6.678 ± 0.007 |
| IRS 5a | ... | ... | ... | ... |
| IRS 6  | 8.609 ± 0.023 | 8.052 ± 0.003 | 7.619 ± 0.003 | 6.966 ± 0.006 |
| IRS 7a | 8.546 ± 0.051 | 6.705 ± 0.003 | 5.776 ± 0.002 | 4.654 ± 0.002 |
| IRS 8a | ... | ... | ... | ... |

Notes.

* IRAC magnitudes were derived using a circular aperture of radius $r = 2$ pixels and a background annulus $r = 2 - 6$ pixels (pixel size $\approx 1''22$). The given magnitudes are background-subtracted and aperture-corrected. Aperture-correction factors are $1.213 (3.6 \mu$m), $1.234 (4.5 \mu$m), $1.379 (5.8 \mu$m), and $1.584 (8.0 \mu$m). Magnitude zero points ($Z_0$) for count rate units of DN s$^{-1}$ are 19.6642 (3.6 $\mu$m), 18.9276 (4.5 $\mu$m), 16.8468 (5.8 $\mu$m), and 17.3909 (8.0 $\mu$m), where [mag] = $-2.5 \log_{10}(\text{DN s}^{-1}) + Z_0$. Magnitude uncertainties are formal uncertainties (internal errors only). The actual uncertainties will in general be larger than the quoted values due to systematic effects such as zero-point uncertainties and other factors which can affect measurement accuracy such as bright nearby nebulosity.

* No photometry measured. IRS 5 is located between the nearby bright sources IRS 1 and IRS 2 and is not clearly visible in IRAC images.

* The MIPS 24 $\mu$m data for IRS 7 give a magnitude of 0.71 ± 0.03 mag.

* Source appears nebulous and is extended in NE/SW direction. Possibly a close pair. Photometry is uncertain and the lower limit is based on counts inside an $r = 2$ pixel extraction circle with no background subtraction, centered at J054704.28+002137.9.

Spitzer mid-IR data are available (IRS 1, IRS 2, IRS 4, IRS 6, IRS 7). Figure 6 shows the broadband Chandra ACIS-I image for the central region of NGC 2071-IR near IRS 1, and Figure 7 is a hard-band Chandra image zoomed in on IRS 1 and VLA 1. Figure 8 is a quantile diagram allowing the X-ray properties of Chandra detections to be compared.

Table 1 summarizes the properties of the X-ray sources detected by Chandra, and Spitzer IRAC photometry is given in Table 2. Chandra detected X-ray sources at or near the positions of IRS 1, 2, 4, 6, and VLA 1. The IR sources IRS 5, 7, 8, and 8a (offset $\approx 2''$ northeast of IRS 8) were undetected by Chandra. Table 3 summarizes X-ray spectral analysis results for the brighter detections.
IRS 1 was identified as a bright 10 μm source by Persson et al. (1981). It is also clearly visible in the 2MASS $K_s$ image (Figure 1) and in Spitzer IRAC images (Figure 2). A very bright source at or near the position of IRS 1 saturates the MIPS 24 μm images. IRS 1 is likely the dominant contributor to the mid/far-IR luminosity toward the NGC 2071-IR region, which was determined to be $L_{\text{tot}} = 520 L_\odot$ ($d = 390$ pc) by Butner et al. (1990). This luminosity suggests that IRS 1 may be an embedded early-type star, as discussed further in Section 5.1. But, its true nature is still somewhat of a mystery.

IRS 1 is clearly detected in all four IRAC channels and its SED rises sharply toward longer wavelengths over the 3.6–8.0 μm IRAC range (Figure 5). It is the brightest IR source in the NGC 2071-IR core region at 8.0 μm (Table 3). Spitzer’s angular resolution of FWHM $\approx 1\arcsec.7$ (3.6 μm) is unable to fully resolve VLA 1 located 2\arcsec.2 north of IRS 1. But, the IRAC images do show what appears to be faint emission extending northward of IRS 1, providing a clue that VLA 1 may be weakly contributing to the mid-IR flux measured inside the $r = 2\arcsec.4$ aperture centered on IRS 1. Higher angular resolution mid-IR observations will be needed to confirm that VLA 1 is indeed a mid-IR source.

The IRAC colors of IRS 1 are characteristic of a class I protostar (Figure 4). Adopting the YSO classification scheme of Gutermuth et al. (2008), class I sources are defined by $[4.5] - [5.8] > 1$, where brackets denote magnitudes at the enclosed wavelength (μm). IRS 1 has $[4.5] - [5.8] = 1.67$ (Table 3), so the class I criterion is satisfied. A similar conclusion is reached using the YSO classification schemes of Allen et al. (2004), Hartmann et al. (2005), and Megeath et al. (2005a).

Chandra detects an X-ray source that is offset by only 0\arcsec.42 from the near-IR position of IRS 1 (=2MASS 10$^{-17}$...10$^{-18}$ W cm$^{-2}$)}
J054704.77+002142.8. This offset is within Chandra positional uncertainties and we thus associate X-ray source CXO J054704.75+002142.9 with the IR source IRS 1. The IRAC 3.6 μm detection of IRS 1 has a centroid position J054704.76+002143.0, which is offset by only 0.018 from the Chandra X-ray position. This Chandra detection confirms that IRS 1 is an X-ray source, as suspected on the basis of the previous lower spatial resolution XMM-Newton observation (S07).

The X-ray light curve of IRS 1 (Figure 9) shows low-amplitude fluctuations about the mean at the ±2σ level but no large flares. The KS test gives a probability of constant count rate $P_{\text{const}} = 0.11$. Thus, low-level variability may be present but is not proven at high confidence levels.

IRS 1 is clearly detected in the hard-band ACIS-I image (Figure 7) but its emission is not as hard as that of VLA 1 or IRS 3 as gauged by median photon energy (Table 1). The X-ray spectrum of IRS 1 (Figure 10) is absorbed below 1 keV but the absorption is not as high as that of VLA 1. The ACIS-I spectrum of IRS 1 (Figure 11) shows an emission line from the Si XIII He-like triplet complex (1.839–1.865 keV), implying thermal emission. Maximum power for the Si XIII triplet is emitted at log $T_{\text{max}} = 7.0$ (K) so hot plasma is clearly detected. The spectrum also reveals a faint (7 counts) fluorescent emission line at $\approx 6.4$ keV from neutral or low-ionization stages of Fe (Figure 11), as anticipated from XMM-Newton spectra. This line forms in “cold” material in the vicinity of the star that is irradiated by the hard X-ray source and is discussed further in Section 5.3.

We attempted to fit the ACIS-I spectrum of IRS 1 with various emission models. All models included a fixed-width Gaussian line at 6.4 keV to reproduce the faint fluorescent Fe line. A simple 1T APEC solar-abundance optically thin plasma model underestimates the flux in the 1.7–1.9 keV range and is unacceptable in terms of $\chi^2$ statistics. This range includes the Si XIII He-like triplet lines at 1.839, 1.854, and 1.865 keV, which cannot be individually distinguished at the spectral resolution of ACIS-I. An acceptable 1T fit can be obtained by allowing Si to be overabundant by a factor of ~3 with respect to its solar value. The apparent Si overabundance could either be a real physical effect due to factors such as grain destruction (e.g., via grain–grain collisions in shocks) or an unphysical consequence of fitting the spectrum with an overly simplistic 1T model.

An acceptable solar-abundance fit can be obtained with a two-temperature (2T) APEC model that includes both a cool and hot plasma component (Table 3). Some further improvement in
the 2T fit can be obtained by allowing Si to be overabundant, but this is not required since the solar-abundance fit is already statistically acceptable ($\chi^2_{\text{red}} = 1.01$). Because of the heavy absorption below 1 keV, the temperature and emission measure of any cool component are quite uncertain. The 2T APEC model summarized in Table 3 uses a fixed temperature of 3.27 [1.43–12.0] keV, but the true temperature could be higher since the 90% confidence upper limit is not tightly constrained by the data. Using the conversion $N_H = 2.22 \times 10^{21} A_V \text{ cm}^{-2}$ (Gorenstein 1975), the solar-abundance 2T APEC model gives $A_V = 16$ [12–20] mag, where square brackets enclose the 90% confidence range. The slightly different conversion $N_H = 1.6 \times 10^{21} A_V \text{ cm}^{-2}$ (Vuong et al. 2003) yields $A_V = 22$ [16–28] mag. The standard conversions used above are reliable for low-extinction sources, but some studies have questioned their accuracy for deeply embedded YSOs (Winston et al. 2007).

The above APEC model assumes that the X-ray emission arises in an optically thin thermal plasma and is typically used to model coronal emission in magnetically active late-type stars. However, other emission processes might be operating in IRS 1. In particular, X-rays could be produced in shocks associated with its powerful outflow. Thus, we tried to fit the IRS 1 spectrum with an isothermal plane-parallel shock model (VPShock). The fit statistic for VPSHOCK ($\chi^2_{\text{red}} = 1.16$) is not quite as good as the 2T APEC model and the fit converges to shock temperatures $kT \approx 2–3$ keV (Table 3). Such shock temperatures are realistic but do require high-velocity flows, as discussed further in Section 5.2.1.

In summary, a 1T APEC thermal plasma model is able to reproduce the Chandra spectrum of IRS 1 provided that Si is allowed to be overabundant. An acceptable solar-abundance fit can be obtained with a 2T APEC model, but it does not tightly constrain the temperature or emission measure of the heavily absorbed cool component. This model requires hot plasma at $kT_2 \approx 3$ keV and an absorption column density equivalent to $A_V \approx 16–22$ mag.

### 3.2. VLA 1

VLA 1 is a compact 3.6 cm radio continuum source revealed in high-resolution VLA A-configuration images obtained by Carrasco-González et al. (2007). It was also marginally detected in previous 5 GHz VLA images shown in Snell & Bally (1986). The 3.6 cm radio source is located 2'2 north of IRS 1, which equates to a projected separation of $\approx 860$ AU at $d = 390$ pc. The Chandra X-ray position is in very good agreement with the radio position of VLA 1 (Table 1). Due to its close proximity...
to IRS 1, VLA 1 was not spatially resolved from IRS 1 by XMM-Newton. We are not aware of any published high-resolution IR images which show that VLA 1 is an IR source. But, Spitzer images (Figure 2) reveal faint northward extension from IRS 1 that may be due to VLA 1.

The KS test shows that the X-ray emission of VLA 1 is likely variable with $P_{\text{const}} = 0.02$, though the light curve shows no large amplitude flares (Figure 9). The ACIS-I spectrum is heavily absorbed with little or no X-ray emission detected below 2 keV. The spectrum can be acceptably fitted with a 1T APEC model at $kT = 2.2$ keV (Table 2). No significant Fe line emission is detected in the 6.4–6.7 keV range. The inferred absorption column density $\log N_H = 22.94$ gives an equivalent extinction $A_V = 39$ [22–69] mag using the Gorenstein (1975) conversion. Based on X-ray spectral fits, VLA 1 is more heavily absorbed than IRS 1 and Figure 8 indicates that it is the most heavily absorbed X-ray source in NGC 2071-IR. VLA 1 could thus be in an earlier evolutionary stage than IRS 1. Because of the high absorption, the intrinsic (unabsorbed) X-ray luminosity of VLA 1 is quite uncertain. But, the value inferred from the 1T APEC model (Table 2) is consistent with that of a ~solar-mass pre-main-sequence star or protostar, based on the known correlation between $L_X$ and stellar mass in low-mass YSOs (Preibisch et al. 2005; Telleschi et al. 2007a).

### 3.3. IRS 2

Previous studies have concluded that IRS 2 is likely a YSO (W93; T07) and Aspin et al. (1992) argued that it is driving a bipolar outflow. IRAC images show some indication that the source is extended. IRAC colors (Figure 4) indicate that IRS 2 is either a class I protostar or a heavily reddened class II object. However, some caution is warranted in interpreting IRAC colors. High-resolution 3.6 cm radio continuum observations reveal two closely spaced components A and B separated by $\approx 1'4$ with the brighter component A at radio position VLA

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**Figure 9.** Left: Chandra broadband (0.3–7 keV) ACIS-I light curve of IRS 1 binned at 5000 s intervals. The mean count rate is $2.02 \pm 0.69$ (±1σ) counts ks$^{-1}$. The KS test gives a probability of constant count rate $P_{\text{const}} = 0.11$, so variability is not demonstrated with high confidence. Right: Chandra broadband (0.3–7 keV) ACIS-I light curve of VLA 1 binned at 4500 s intervals. The mean count rate is $1.33 \pm 0.75$ (±1σ) counts ks$^{-1}$. The KS test gives $P_{\text{const}} = 0.02$, so variability is likely.

**Figure 10.** ACIS-I spectra of IRS 1, VLA 1, and IRS 6 binned to a minimum of 5 counts per bin.
J054705.36+002150.5 (C. Carrasco-González et al. 2009, private communication). Spitzer cannot resolve such a close pair and it is thus possible that the IRAC colors are the superposition of two sources.

Chandra detects a very faint X-ray source (4 net counts) at an offset of only 0′.27 from the brighter radio component A (Table 1). Because of the good positional coincidence with the radio source, this weak X-ray detection is likely real but is of marginal significance. There are too few counts to do any substantive X-ray analysis but the high median photon energy $E_{50} = 5.2$ keV suggests that this source is exceptionally hard or very heavily absorbed.

### 3.4. IRS 3

The IR source IRS 3 is about 1 mag fainter at K band and at 3.6 μm and 4.5 μm than IRS 1. Its K-band emission is highly polarized (W 93; T07). A 1.3 cm radio continuum source lies near IRS 3 (Torrelles et al. 1998), but the near-IR peak is offset slightly to the northeast relative to the VLA radio position (T07).

As Table 1 shows, the weak X-ray source detected by Chandra is in excellent positional agreement with the 1.3 cm radio source detected by Torrelles et al. (1998). The nearest 2MASS source lies 2′.3 from the X-ray peak. This offset is significant and supports the conclusion of T07 that the near-IR emission is nebulosity. The object detected with Chandra and the VLA is likely the star that illuminates the near-IR nebula. Spitzer IRAC images show an IR source near IRS 3 (Figure 2). The IRAC position as measured in the 4.5 μm (ch2) image is offset by only 0′.42 from Chandra. Thus, it appears that the self-luminous source is also detected by Spitzer. We do not have complete IRAC photometry for IRS 3 because it lies in the bright wings of IRS 1.

The KS test shows no significant X-ray variability. The distribution of event photon energies (Figure 12) shows clearly that this is a hard absorbed source, and the energy quantile plot (Figure 8) substantiates this. There were too few counts to analyze a binned spectrum but we did attempt to fit the unbinned spectrum with a 1T APEC thermal plasma model using C-statistics (Cash 1979). The absorption was held fixed at log $N_{H} = 22.79$ cm$^{-2}$, based on the estimated extinction $A_V = 28$ mag (W93). The fit converges to a high but uncertain temperature $kT \gtrsim 10$ keV, as also indicated by the quartile plot (Figure 8).

Visual inspection of the unbinned spectrum shows a weak buildup of counts near 6.4 keV, hinting that a weak fluorescent Fe line may be present. The IRS 3 event list reveals five events within the 6–7 keV range with event energies 6.11, 6.20, 6.42, 6.53, and 6.69 keV. The 6.42 and 6.53 keV events could be due to fluorescent Fe. We added a Gaussian line component to the 1T APEC model at a line energy of 6.4 keV, fixing the line width at FWHM = 120 eV, corresponding to the ACIS-I instrumental width at this energy (Chandra POG, Figure 6.8). With the Gaussian line included, the C-statistic $C = 133.1$ is slightly less than without the line ($C = 138.2$), and the fit gives log $N_{H} = 22.79$ cm$^{-2}$, $kT = 10$ keV, and an unabsorbed flux $F_X,\text{unabsorbed} (0.5–7.5 \text{ keV}) = 1.6 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$. This equates to log $L_X = 29.5$ erg s$^{-1}$ ($d = 390$ pc), which is typical of low-mass YSOs in Orion (Preibisch et al. 2005). Thus, the event list and spectral fits provide some marginal evidence for fluorescent Fe, but a deeper exposure would be needed to make a compelling case for a 6.4 keV line detection.

The high-resolution VLA 1.3 cm radio continuum images of IRS 3 obtained by Torrelles et al. (1998) show elongation in the ≈N–S direction, and elongated morphology is also visible in the more recent 3.6 cm VLA images of Carrasco-González et al. (2007). The extension was interpreted as a thermal radio jet, adding support to the belief that IRS 3 is driving an outflow (Section 1). The orientation of H$_2$O maser spots approximately perpendicular to the jet axis and maser velocity data led Torrelles et al. (1998) to conclude that the masers trace a compact rotating molecular disk surrounding a low-mass (~1 $M_\odot$) YSO. Such a disk viewed in a nearly edge-on geometry would act as a strong absorber of soft X-ray photons and would provide a natural explanation for the high $N_{H}$ (Figure 8) and lack of detected low-energy X-ray photons below ~2 keV in IRS 3 (Figure 12).

### 3.5. IRS 4

Tamura et al. (2007) concluded that IRS 4 is an IR cluster member because it is surrounded by a compact reflection nebula and is associated with faint H$_2$ emission. The faint X-ray source detected by Chandra is in good positional agreement with 2MASS and shows no significant variability. It has the lowest median and mean photon energy of the six X-ray sources detected in the cluster core. There are insufficient counts...
available for spectral analysis. About half of the detected photons have energies below 2 keV. Quantile analysis shows that this source has lower absorption than the other X-ray detections in NGC 2071-IR (Figure 8). Near-IR colors (Figure 3) are consistent with a star having intrinsic cTTS color but viewed through substantial reddening ($A_V \approx 13$ mag). IRAC colors (Figure 4) are consistent with a reddened class II YSO but the SED (Figure 5) is nearly flat in the IRAC bands and is more suggestive of a flat-spectrum source.

3.6. IRS 5

The near-IR morphology of this IR source changes with time and W93 concluded that the near-IR emission could be from a jet, a moving clump of shocked gas, or nebulosity. IRS 5 is located between the two nearby bright mid-IR sources IRS 1 and IRS 2. We were not able to identify a definite point source at the IRS 5 position in the IRAC images, and thus cannot provide any reliable IRAC photometry. No significant X-ray emission was detected so we find no evidence of a young star and our results are thus consistent with the nonstellar classification proposed by W93.

3.7. IRS 6

Near-IR observations have shown that IRS 6 is a binary with a 2'' separation (T07). We detect a variable X-ray source that is offset to the northwest of the 2MASS position by 1''68 at position angle PA = 315° (Table 1). This offset is significant and implies that the 2MASS near-IR source is not the same source detected in X-rays. Spitzer images show an IRAC source at an offset of 1''19 from the Chandra position. IRS 6 has similar near-IR and mid-IR colors to IRS 4, and both the near-IR and mid-IR colors of IRS 6 are consistent with a reddened class II object (cTTS).

The spectral fit of IRS 6 with a 1T APEC thermal model (Table 2) suggests a rather hot source with plasma temperature $kT = 3.85$ keV and moderate absorption $N_H \approx 10^{22}$ cm$^{-2}$. Similar values are inferred from the quantile plot (Figure 8), but both $kT$ and $N_H$ have rather large uncertainties due to the low number of X-ray counts. The absorption from the IRS 6 spectral fit (Table 2) gives an equivalent extinction $A_V = 5.6$ [$1.7$,--10.4], 90% conf.] mag (Gorenstein 1975 conversion), which is less than IRS 1 and VLA 1.

On the basis of its relatively high $kT$ and variability, we conclude that the X-ray source lying 1''68 from the 2MASS position is a magnetically active star. Because this system is a close near-IR pair, higher spatial resolution observations are needed to confirm the IR colors and more accurately determine the relative positions of the two near-IR sources and the X-ray source.

3.8. IRS 7

Tamura et al. (2007) argued on the basis of polarization angle that circumstellar material is present around IRS 7. IRAC colors support this conclusion, indicating either a class I protostar or a heavily reddened class II source (Figure 4). The object is visible in MIPS 24 μm images and the SED continues to rise out to 24 μm (Figure 5). Its [4.5] − [24] color is consistent with a protostar (Megeath et al. 2009). We detect no X-ray emission at or near IRS 7, so it is either intrinsically X-ray faint or its emission is reduced to undetectable levels by high absorption (e.g., a nearly edge-on disk or dense surrounding envelope).

3.9. IRS 8 and 8a

IRS 8 and 8a are two faint closely spaced IR sources separated by 1''6 in R.A. and 0''7 in decl., with IRS 8a lying northeast of IRS 8 (W93; T07). Both objects are >1.5 mag fainter at K than the other core sources (T07). The closest 2MASS positional match to IRS 8 has $K_s = 13.54$ (2MASS J054704.45+002138.8) and there are no other 2MASS sources within 5''. IRS 8 is associated with a near-IR nebula and was classified as a self-luminous object, probably an embedded star, by W93. IRS 8a is thought to be a shocked molecular hydrogen peak (W93).

The IRAC images reveal what appears to be extensive structure or nebulosity in the NE-SW direction near IRS 8. A faint emission peak is visible close to the IRS 8 position at 3.6 μm (Table 2) and the peak shifts slightly to the northeast in the 4.5 μm image, which is sensitive to shock emission. The close pair IRS 8/8a is not clearly resolved at IRAC’s resolution, but the slight shift of the 4.5 μm emission peak toward IRS 8a may be an indication that it is a stronger shock-excited source. Because of the nebulosity morphology in IRAC images, we were not able to obtain any reliable IRAC photometry. There is no X-ray emission at or near the 2MASS position of IRS 8 or at IRS 8a, and consequently no X-ray evidence of an embedded star.

4. COMPARISON WITH XMM-NEWTON RESULTS

The XMM-Newton EPIC CCD spectrum of IRS 1 analyzed by S07 was extracted using a nominal circular region of radius $R_c = 15''$ (68% encircled energy) centered on IRS 1. As the higher angular resolution Chandra image in Figure 6 shows, four X-ray sources were included in the XMM-Newton spectral extraction region, namely IRS 1, 2, 3, and VLA 1. Of these four, IRS 1 (144 counts) and VLA 1 (90 counts) are the brightest NGC 2071-IR core objects in the Chandra image. IRS 2 (4 counts) is very faint in ACIS-I and it is unlikely that it significantly affected the XMM-Newton spectrum. IRS 3 (18 counts) is also a faint hard Chandra source. Its absorbed flux $F_X (0.5–7.5$ keV) = $8 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ would have contributed ≈5% to the observed flux measured in the XMM-Newton pn spectrum.

Based on the above, it is clear that the XMM-Newton spectrum was dominated by emission from the close pair IRS 1 and VLA 1. The Chandra data show that VLA 1 has much higher X-ray absorption than IRS 1, which explains why fits of the XMM-Newton pn spectrum mysteriously required two spectral components with different $N_H$ values (S07).

The fluorescent Fe line at 6.4 keV was strongly detected in the XMM-Newton pn spectrum with an EPIC pn line flux $F_X (6.2–$ 6.6 keV) = $3.8 \pm (0.2) \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$ and an equivalent width (EW) measured relative to the underlying continuum $EW = 2.4$ keV (S07). The line flux measured in the Chandra ACIS-I spectrum (Table 3) is a factor of ~5 below the XMM-Newton value, but the Chandra EW ≥ 2.4 keV is consistent with the XMM-Newton value. The fluorescent Fe line is discussed further in Section 5.3.

5. DISCUSSION

5.1. Is IRS 1 a Young Embedded B-type Star?

The heavily reddened IRAC colors of IRS 1 and its rising SED in the IRAC bands, along with its bright (saturated) detection in MIPS 24 μm images, strongly suggest that it is a class I protostar. Based on its association with a radio continuum...
source and luminosity considerations, W93 concluded that IRS 1 is most likely a B0–B5 star. Under the assumption that the 6 cm radio continuum emission of IRS 1 arises in a photoionized compact H II region at a distance of 500 pc, Snell & Bally (1986) found that a single B2 star would be needed to produce sufficient Lyman continuum ionizing flux to account for the radio emission. Adjusting their distance downward to 390 pc (Anthony-Twarog 1982) would require a ~B3 star. However, we note that the volume emission measure of the radio continuum source computed from their 6 cm radio flux density $S_{\text{6 cm}} = 7.9$ mJy is 2 orders of magnitude below that typically found for optically thin compact H II regions (Equation (3) of Skinner et al. 1993). Thus, the radio continuum emission from IRS 1 could very well involve processes other than free–free emission from a compact H II region.

The more recent high-resolution 3.6 cm VLA A-configuration images of IRS 1 obtained by Carrasco-González et al. (2007) reveal a complex source morphology for IRS 1. A compact core is present along with fainter emission extending in the E–W direction. More interestingly, compact knots are seen expanding away from IRS 1 in an approximate E–W direction with high velocities of up to ~600 km s$^{-1}$, as determined from radio proper motions. These results, along with the positive radio spectral index, suggest that the radio emission includes a contribution from an extended ionized wind or jet. A possible analog is NGC 7538-IRS1, whose free–free emission is dominated by a highly collimated ionized jet (Sandell et al. 2009).

Using far-IR data obtained with the Kuiper Airborne Observatory (KAO), Butner et al. (1990) determined the total luminosity toward the NGC 2071-IR region to be $L_{\text{tot}} = 520 L_\odot$ ($d = 390$ pc). This is about 15% greater than the value determined by Harvey et al. (1979) when normalized to a common distance of 390 pc. Because of the rather large $\approx 30'\,$ KAO beam size, this total will include any contributions from other sources near IRS 1 and should thus be considered an upper limit for IRS 1 itself. If a single star, a value $L_{\text{tot}} = 520 L_\odot$ would correspond to a ZAMS star of mass $\sim 5 M_\odot$ (Siess et al. 2000) and ZAMS spectral type $\sim$B4 (Thompson 1984). But, if the $L_{\text{tot}}$ value is interpreted as an upper limit for IRS 1, a lower mass and later spectral type are possible. The above estimates are based on an assumed distance $d = 390$ pc. If IRS 1 lies at the far edge of the Orion OB1 association then a larger distance $d \sim 500$ pc is possible (Section 1). In that case, one infers a slightly higher mass of $\sim 6 M_\odot$ and ZAMS spectral type of $\sim$B3–B4.

The X-ray luminosity and temperature of IRS 1 are within the broad range observed in young B-type stars. The study of 20 early-type stars in the Chandra Orion Coup sample by Stelzer et al. (2005) included 12 B stars ranging in spectral type from B0.5 to B9. Their X-ray luminosities spanned a wide range from $L_X = 29.4–32.4$ erg s$^{-1}$, and a hot plasma component at typical temperatures $kT_{\text{hot}} \approx 1–3$ keV was present in all B stars. Different B stars with similar spectral types showed dramatic differences in $L_X$ and no support was found for earlier claims that $L_X$ correlates with $L_{\text{bol}}$ in OB stars. Using $L_{\text{bol}} = 520 L_\odot$ for IRS 1 and the range of $L_X$ values from the different models in Table 3, we obtain $\log (L_X/L_{\text{bol}}) = \sim -5.7 \pm 0.5$. This is consistent with values obtained for the COUP B-star sample, but some caution is needed in interpreting this ratio for IRS 1 since its $L_{\text{bol}}$ could be dominated by disk emission.

On the basis of the above comparisons, we conclude that a B-star classification for IRS 1 is plausible, but a mid-to-late B star is more likely than an early B star based on the luminosity determined by Butner et al. (1990). If IRS 1 is indeed an embedded intermediate-mass B star, it is tempting to speculate that it might be a Herbig Ae/Be star progenitor. Herbig Ae/Be stars are optically revealed intermediate-mass pre-main-sequence stars which in many cases show high-temperature X-ray plasma that is likely of magnetic origin. But, the question of whether their X-ray emission is intrinsic or instead due to coronal late-type companions remains open. For previous studies of X-ray emission from Herbig Ae/Be stars, the reader is referred to Damiani et al. (1994), Zinnecker & Preibisch (1994), Preibisch & Zinnecker (1996), Skinner & Yamauchi (1996), Skinner et al. (2004), Hamaguchi et al. (2005a), Stelzer et al. (2006, 2009), and Telleschi et al. (2007b).

5.2. X-ray Emission Processes in IRS 1

Given that the true nature of IRS 1 is not well known and that it may be an embedded B-type star, some further discussion of the origin of its X-ray emission is warranted. Very few massive embedded stars have been detected in X-rays and little is known about their X-ray emission during early evolutionary stages prior to becoming optically visible. We thus consider several possible emission mechanisms below.

5.2.1. Shocked Winds and Outflows

The hotter plasma clearly detected at $kT_{\text{hot}} \gtrsim 2$ keV is not consistent with the cool emission ($kT \ll 1$ keV) expected from wind shocks in OB stars formed by line-driven flow instabilities (Lucy & White 1980; Lucy 1982; Feldmeier et al. 1997; Owocki et al. 1988). However, if the wind is shocking onto another object or surrounding material, or is magnetically confined, then high-temperature plasma could be produced in a wind shock.

The predicted shock temperature for a strong adiabatic shock is $T_{\text{shock}} = 1.4 \times 10^5 \Delta v_{100}^2 K$, or $kT_{\text{shock}} = 0.012 \Delta v_{100}^2$ keV (Lamers & Cassinelli 1999, p. 360). Here, $\Delta v_{100}$ is the shock jump measured relative to the speed of the downstream flow, in units of 100 km s$^{-1}$. To achieve an X-ray temperature $kT_{\text{shock}} \sim 2$ keV, a value $\Delta v \sim 1300$ km s$^{-1}$ is required. Terminal wind speeds of B5–B9 stars are not well determined observationally, but values $v_{\infty} \sim 1200–1400$ km s$^{-1}$ are usually assumed (Cohen et al. 1997). To achieve the required velocity jump, the wind would have to be virtually stopped by dense surrounding material, e.g., either a disk, thick envelope, or close companion. The wind speed requirement could be reduced if the outflowing wind collides with a dense infalling envelope whose ram pressure exceeds that of the wind. In that case, the infalling envelope would overpower the wind, resulting in a non-stationary shock front (including both forward and reverse shocks) moving toward the star.

The above analysis can also be applied to jets and molecular outflows. High-velocity wings extending out to $\sim 70$ km s$^{-1}$ are visible in spectra of the 2.12 $\mu$m H$_2$ line toward NGC 2071-IR (Persson et al. 1981). If such an outflow shocks onto a stationary target, the maximum expected X-ray temperature is $kT_{\text{shock}} = 0.006$ keV, much too low to explain the hot X-ray plasma detected in IRS 1. As already noted (Section 5.1), high-velocity knots moving outward from IRS 1 at speeds up to $\sim 600$ km s$^{-1}$ have been detected with the VLA (Carrasco-González et al. 2007). If such a knot shocked onto a stationary object, the maximum shock temperature would be $kT_{\text{shock}} \sim 0.4$ keV, which is again too low to explain the higher temperature plasma in IRS 1. But, this process could contribute to any cooler heavily absorbed emission at $kT < 1$ keV.
5.2.2. Accretion Shocks

Since IRS 1 is a young class I object, it is expected to still be accreting. This is potentially relevant to the X-ray interpretation because X-rays can be produced in an accretion shock shock formed as infalling material impacts the (proto)star. The characteristic X-ray temperature for an accretion shock is \( kT_{\text{acc}} \approx 0.02 \frac{v_{100}^2}{L_{\odot}} \), where \( v_{100} \) is the infall speed in units of 100 km s\(^{-1}\) (Ulrich 1976).

Based on the above, it is apparent that very high infall speeds \( v \sim 1000 \) km s\(^{-1}\) would be needed to produce accretion shock temperatures \( kT_{\text{acc}} \sim 2 \) keV, comparable to the values observed for IRS 1. To achieve such infall speeds under free-fall conditions, a massive central object equivalent to a B0V star (\( M_\star \sim 18 M_\odot \), \( R_\star \sim 7 R_\odot \); Allen 1985) would be required. But, the total luminosity of IRS 1 (Section 3.1) falls well short of the value \( L_{\text{bol}} \sim 10^{44} L_\odot \) expected for a B0 ZAMS star. Thus, in the absence of any firm observational evidence for very high infall speeds toward IRS 1, it is very unlikely that the high-temperature X-ray emission arises in an accretion shock. Any cooler plasma (\( kT < 1 \) keV) that might be present could be accretion-related but, as already noted, the high absorption toward IRS 1 masks such cool emission.

5.2.3. Magnetic Activity

Plasma temperatures \( kT \gtrsim 2 \) keV as seen in IRS 1 are commonly found in magnetically active late-type stars, including T Tauri stars. The X-ray emission is accompanied by powerful magnetic reconnection flares, and is thought to arise in structures analogous to the solar corona. But, magnetic star+disk coupling undoubtedly leads to more complicated geometries in the case of TTS (reviewed by Feigelson & Montmerle 1999). Similarly, high plasma temperatures and large flares characteristic of magnetospheric processes have now been observed in low-mass class I protostars such as those in \( \rho \) Ophiuchus (Imanishi et al. 2001). X-ray luminosities in low-mass YSOs generally increase with stellar mass and luminosity, ranging from \( L_X \sim 10^{28} \text{ erg} \text{s}^{-1} \) for low masses \( M_\star \sim 0.1-0.2 M_\odot \) up to (and in some cases above) \( L_X \sim 10^{31} \text{ erg} \text{s}^{-1} \) for more massive TTS with \( M_\star \approx 2 M_\odot \) (Preibisch et al. 2005; Telleschi et al. 2007a).

The X-ray temperature and luminosity of IRS 1 inferred from the Chandra data are well within the above ranges for low-mass YSOs. It is thus possible that the X-rays observed toward IRS 1 arise in a low-mass YSO rather than a more massive object such as an embedded B-type star. The X-ray luminosity of IRS 1 could be accounted for by a TTS of mass \( \sim 1-2 M_\odot \). Even if IRS 1 is an embedded B-type star, a late-type TTS companion could dominate the X-ray emission. Late-type companions have been proposed as a means of explaining the wide range of \( L_X \) values observed for some mid-to-late B stars in Orion with weak winds (Stelzer et al. 2005).

5.2.4. Magnetically Confined Wind Shocks

If IRS 1 has an ionized wind and a sufficiently strong magnetic field, then the \( B \) field can confine the wind into two oppositely directed streams in each hemisphere which collide near the magnetic equator, forming a magnetically confined wind shock (MCWS). Such a shock can reach X-ray emitting temperatures. The MCWS mechanism has been used to explain high-temperature X-ray emission in magnetic Ap-Bp stars (Babel & Montmerle 1997a) and young magnetic O stars such as \( \theta^1 \) Ori C (Babel & Montmerle 1997b; Gagné et al. 2005).

The radio properties of IRS 1 do suggest it has an ionized wind or jet (Carrasco-González et al. 2007), but there are so far no reports of a magnetic field. Even so, an estimate of the field strength needed to confine the wind can be obtained by making reasonable approximations under the assumption that it is a mid-to-late B star.

The maximum X-ray temperature for a MCWS is given by the adiabatic shock equation (Section 5.2.1). We thus assume a terminal wind speed \( v_\infty \sim 1300 \) km s\(^{-1}\) for IRS 1 to achieve a shock temperature comparable to the observed value \( kT_{\text{shock}} \sim 2 \) keV. The degree to which the wind is confined by the magnetic field is expressed in terms of the confinement parameter \( \eta = B^2 R_\star^2 / M v_\infty \), where \( B \) is the equatorial magnetic field strength (ud-Doula & Owocki 2002). For values of \( \eta \sim 1 \) (critical confinement), the \( B \) field is able to confine the wind. For a B5V star (\( \eta \sim 3.8 R_\odot \); Allen 1985), the above relation with \( \eta = 1 \) becomes \( B_{100}^2 \sim 47 \eta M_6 \), where \( B_{100} \) is in units of 100 G and \( M_6 \) is in units of \( 10^{-6} M_\odot \) yr\(^{-1}\). The mass-loss rates of mid-to-late B stars are not well determined empirically, but \( B \sim 2 \) G for \( M = 10^{-11} M_\odot \) yr\(^{-1}\) (Cohen et al. 1997) and \( B \sim 70 \) G for \( M = 10^{-8} M_\odot \) yr\(^{-1}\). The latter \( M \) values are typical of intermediate mass Herbig Ae/Be stars (Skinner et al. 1993).

In summary, the MCWS mechanism is a potential means of explaining the high-temperature plasma in IRS 1. But, without a magnetic field detection and specific estimates of \( B \)-field strength and mass-loss parameters, any more definitive comparisons against MCWS model predictions cannot be made.

5.2.5. Summary of Emission Mechanisms

Based on the above discussion, we conclude that the high-temperature plasma at \( kT \sim 2 \) keV in IRS 1 is most likely due to either a high-speed wind (\( v_\infty \gtrsim 1200 \) km s\(^{-1}\)) shocking onto a dense target (e.g., a disk or dense surrounding envelope), or it originates in a low-mass magnetically active YSO companion. The wind-shock interpretation is plausible if IRS 1 is an embedded B-type star whose wind has already turned on, and the extended bright radio continuum emission detected with the VLA does point to an early-type star with a strong wind or jet. We cannot rule out a magnetically confined wind shock, but there are insufficient observational constraints on magnetic field strength and wind parameters to rigorously test MCWS models. Even if IRS 1 is an embedded B-type star (which seems likely), a lower mass YSO companion at close separation could still be responsible for some (or even all) of the observed X-ray emission. The X-ray luminosity determined from spectral models of IRS 1 is at the high end of the range observed for low-mass YSOs. If the X-ray emission is due entirely to a T Tauri-like companion, then the known correlation between \( L_X \) and stellar mass suggests a companion mass in excess of \( 1 M_\odot \).

5.3. Fluorescent Iron Emission in IRS 1

A fluorescent Fe line at 6.4 keV can be produced by photoionization when “cold” material containing neutral or weakly ionized iron is irradiated by a nearby hard X-ray continuum source. Photons with energies above 7.11 keV are needed to eject a K-shell electron. The K-shell vacancy is filled by another electron such as an L-shell electron, resulting in fluorescent Fe line emission at 6.4 keV. The line is in fact a doublet consisting of two closely spaced lines at 6.391 keV and 6.404 keV, but these cannot be distinguished at the energy resolution of the ACIS-I CCDs. The above photoionization
process is discussed in more detail by George & Fabian (1991) and Kallman et al. (2004). Analysis of the fluorescent Fe line can potentially provide information on the properties of the absorber and its location relative to the hard continuum source.

The fluorescent Fe line detected in IRS 1 is faint (Figure 11), consisting of seven events distributed in the 6.298–6.536 keV energy range, with a median energy 6.395 keV and mean energy 6.419 keV. Three of the seven photons arrived in the first half of the observation. A KS test applied to the arrival times of the seven events shows no significant variability and gives a probability of constant count rate $P_{\text{const}} = 0.35$. The line flux is $7.2 \pm 1.2 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$. This is about a factor of 5 less than measured during the 2005 March XMM-Newton observation (S07). The line equivalent width in the ACIS-I spectrum is uncertain because the continuum flux near 6.4 keV is very faint. But, our flux estimates give values EW $\geq 2.4$ keV, consistent with the previous XMM-Newton estimate (S07).

The detection of fluorescent Fe line emission in IRS 1 is a rare occurrence in YSOs, but certainly not unique. Tsujimoto et al. (2005) examined 1616 X-ray sources detected in the deep Chandra COUP observation of the Orion Nebula Cluster and identified seven sources with excess emission at 6.4 keV and line equivalent widths EW $\leq 0.27$ keV. All seven X-ray sources showed flare-like variability and high line-of-sight absorption $N_H \gtrsim 10^{22}$ cm$^{-2}$, as also seen in IRS 1. The broad fluorescent Fe line during a superhot flare in V1486 Ori (COUP source 331) was analyzed by Czesla & Schmitt (2007). The 6.4 keV line has also been detected in other YSOs including the class I objects YLW 16A (Imanishi et al. 2001) and Elias 29 (Giardino et al. 2007) in ρ Oph, and the class I source R CrA X$_E$ (= IRS 7B; Hamaguchi et al. 2005b).

The fluorescent Fe line detection in IRS 1 is interesting in three respects: (1) it was detected in the apparent absence of any large-amplitude flares (but low-level variability may be present), (2) there is no accompanying line at 6.7 keV from the highly ionized Fe xxv complex, and (3) the line has a very large equivalent width that is difficult to account for by illuminated disk models.

The absence of any detectable large flares in IRS 1 is unusual because the fluorescent Fe lines in almost all of the YSOs mentioned above occurred during flares. Analysis of the V1486 Ori data showed that its broad fluorescent Fe line appeared during the rise phase of a flare (Czesla & Schmitt 2007). An interesting exception is Elias 29, which showed a 6.4 keV line during a large flare. But the line persisted after the flare had decayed, remaining over a timescale much longer than the radiative lifetimes of fluorescent Fe transitions. Giardino et al. (2007) thus concluded that the X-ray flare was not directly responsible the post-flare 6.4 keV line. Instead, they proposed that the line was produced by collisional ionization from an unseen population of non-thermal electrons.

The 6.4 keV line in IRS 1 is similar to Elias 29 in the sense that it does not appear to be directly associated with a large flare. The line was present in both the XMM-Newton spectrum obtained in 2005 March and in the more recent Chandra spectrum, but no large flare was detected in either observation. If a large flare was involved, then it must have occurred prior to the start of the observations, or it escaped detection (as could occur if the flare occurred on the back side of IRS 1 and was occulted).

Unless large X-ray flares occurred and escaped detection, the existing data indicate that the 6.4 keV line in IRS 1 is persistent and does not correlate with large flares. In that case, some mechanism needs to be operating nearly continuously to ionize the absorbing material. At present, the ionizing source and the ionization mechanism are not known. The obvious candidate for the ionizing source is IRS 1 itself. But, in terms of hardness, its Chandra spectrum is rather benign, showing no large flares, no Fe xxv line and a weak continuum above $\sim 7$ keV. However, we cannot rule out the possibility of substantial hard emission ($kT \gtrsim 20$ keV) above the energy range accessible to Chandra and XMM-Newton. Nevertheless, the intriguing possibility does remain that the hard ionizing source is not IRS 1 and is not directly detected in our X-ray observations.

However, before discounting IRS 1 as the ionizing source, two factors should be noted. First, low-level variations appear to be present in the Chandra light curve of IRS 1 (Figure 9). These variations may be a signature of persistent low-level flaring. If that is the case, then quasi-continuous hard energy release by repeated small flares may play a role in photoionizing the absorber. Second, IRS 1 is thought to drive a powerful outflow and also shows evidence of a radio jet (Carrasco-González et al. 2007). If a population of non-thermal electrons is produced in the shocked jet (which may be magnetically collimated) they could play a role in collisional ionization of the absorber. Collisional ionization has been invoked as a means of explaining the 6.4 keV line in Elias 29 (Giardino et al. 2007) and in the active binary system II Peg (Osten et al. 2007). If a population of non-thermal particles is present, they may imprint a signature on the radio continuum emission. Thus, further radio observations of IRS 1 at lower frequencies where non-thermal emission can dominate over thermal (free–free) emission could be informative.

The large equivalent width EW $\geq 2.4$ keV of the IRS 1 fluorescent line is a noteworthy feature of its X-ray spectrum. This value is extreme for a YSO, exceeding even the maximum value EW $= 1.4$ keV observed for V1486 Ori during the rise phase of its superhot flare (Czesla & Schmitt 2007). These values conflict with theoretical models of centrally illuminated cold disks, which predict EW $\approx 0.1$–0.2 keV (George & Fabian 1991). The EW of the 6.4 keV line is proportional to the column density $N_H$ in the fluorescing material (Tsujimoto et al. 2005). If taken literally, the large EW of IRS 1 would imply a high absorber column density $N_H \gtrsim 10^{24}$ cm$^{-2}$ (S07). Since this value is much larger than the line-of-sight photoelectric absorption inferred from the X-ray spectrum (Table 3), one is led to the conclusion that the fluorescing material lies off the line-of-sight. But, the above conclusion rests on the assumption that the continuum measured in the X-ray spectrum has undergone negligible absorption. If the hard irradiating source is not IRS 1 itself and is occulted or very heavily absorbed, then some or all of the intrinsic hard continuum will be missing from the observed X-ray spectrum. In that case, the EW measurement would be based on a depressed continuum and thus overestimated, along with $N_H$.

In summary, our main conclusions with respect to the fluorescent Fe line in IRS 1 are (1) the line is present even in the absence of the Fe xxv line (6.67 keV) and any large flare detections, and evidently does not directly depend on large-amplitude X-ray flares for its existence, (2) the line flux is variable, showing a decrease between the XMM-Newton and Chandra observations taken 2.6 years apart, but no significant variability during the 67 ks Chandra observation, (3) the line EW is much larger than predicted by centrally illuminated disk models, suggesting either that the photoionization models do not accurately reflect the line formation process and that other mechanisms (e.g., collisional ionization) could play a role, or that the observed continuum is not the same as the intrinsic continuum of the photoionizing...
source (e.g., due to the effects of absorption or occultation), and (4) the hard ionizing source may have so far escaped X-ray detection.

6. CONCLUSIONS

The main conclusions of this study are the following.

1. Chandra’s excellent spatial resolution has resolved the NGC 2071-IR core region into six X-ray sources. X-ray emission was detected at or near the IR sources IRS 1, 2, 3, 4, and 6 and the radio source VLA 1. X-ray analysis shows that these sources are viewed through moderate-to-high absorption and have high/temperature X-ray emission ($kT \geq 2$ keV), consistent with their classification as embedded young stars. In some cases such as IRS 3, the X-ray position is significantly offset from the near-IR position, supporting the conclusion that the near-IR peak traces nebulosity or scattered light and not the star itself.

2. Spitzer IRAC detections of IRS 1, 2, 4, 6, and 7 provide the first reliable mid-IR colors for these objects. Using IRAC colors along with near-IR colors based on published JHK photometry and the sharply rising IR SED, we conclude that IRS 1 is a class I protostar. IRS 2 and IRS 7 are also likely class I protostars but could be heavily reddened class II objects. IRS 4 and IRS 6 have colors consistent with reddened class II objects. No reliable IRAC photometry or mid-IR colors were obtained for IRS 3, 5, 8, or 8a, but near-IR colors determined from existing JHK photometry show that these objects are heavily reddened.

3. Chandra provides the first X-ray detection of VLA 1, and its X-ray emission is likely variable. X-ray spectral models require a strong absorption component for VLA 1, equivalent to $A_V = 39$ mag. Thus, VLA 1 appears to be more heavily embedded than IRS 1 and it could thus be an even younger, less-evolved object. There are as yet no IR data for VLA 1 on which to base a YSO classification.

4. The existing data for IRS 1 are consistent with a mid-to-late B (proto)star classification. The X-ray spectral index of IRS 1 is heavily absorbed below 1 keV and clearly reveals high-temperature plasma at $kT \sim 2$–3 keV. Such plasma could originate either in a shocked high-velocity wind/jet or in a magnetically active low-mass YSO companion.

5. The most important finding of this study is that the fluorescent Fe line in IRS 1 is persistent and present even in the absence of large flares. Thus, an as yet unidentified quasi-continuous process that operates independently of large flares is needed to explain the K-shell ionization of cold proximate material that leads to the formation of fluorescent Fe. Both the Chandra and XMM-Newton light curves show signs of low-level variability, suggesting that short bursts of hard emission from persistent low-level flaring could play a role in ionizing the absorber. The large equivalent width $EW \geq 2.4$ keV of the 6.4 keV line is noteworthy because it is well in excess of values predicted by centrally illuminated disk models. Large 6.4 keV line equivalent widths have also been noted in other YSOs such as V1486 Ori. If interpreted literally, the large EW values imply either a very high absorption column density in the cold absorber, or perhaps processes other than photoionization (e.g., collisional ionization in shocks). However, some caution is needed in interpreting the large EW for IRS 1, since the absence of large flares raises the possibility that it is not the hard ionizing source. If the ionizing source is occulted by IRS 1 or buried behind heavy absorption, then the hard continuum measured in the IRS 1 spectrum may be less than the intrinsic continuum of the ionizing source (“missing continuum”), leading to an overestimate of the equivalent width.

S.S., K.F., and M.M. acknowledge Chandra support from SAO grant GO7-8008A. M.A. acknowledges support from a Swiss National Science Foundation Professorship (PP002-110504). We have utilized data products from the 2MASS, which is a joint project of the University of Massachusetts and IPAC/Caltech. This work is based in part on data obtained with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, CalTech, under a contract with NASA. We would like to thank C. Carrasco-González and G. Sandell for radio positions and J. Hong for information on quartile analysis computer codes.

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