X-RAY EMISSION FROM YOUNG STARS IN THE MASSIVE STAR-FORMING REGION IRAS 20126+4104

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ABSTRACT

We present a 40 ks Chandra observation of the IRAS 20126+4104 core region. In the inner 6′ two X-ray sources were detected, which are coincident with the radio jet source I20S and the variable radio source I20Var. No X-ray emission was detected from the nearby massive protostar I20N. The spectra of both detected sources are hard and highly absorbed, with no emission below 3 keV. For I20S, the measured 0.5–8 keV count rate was 4.3 counts ks$^{-1}$. The X-ray spectrum was fitted with an absorbed 1T APEC model with an energy of $kT = 10$ keV and an absorbing column of $N_H = 1.2 \times 10^{23}$ cm$^{-2}$. An unabsorbed X-ray luminosity of about $1.4 \times 10^{32}$ erg s$^{-1}$ was estimated. The spectrum shows broad line emission between 6.4 and 6.7 keV, indicative of emission from both neutral and highly ionized iron. The X-ray light curve indicates that I20S is marginally variable; however, no flare emission was observed. The variable radio source I20Var was detected with a count rate of 0.9 counts ks$^{-1}$ but there was no evidence of X-ray variability. The best-fit spectral model is a 1T APEC model with an absorbing hydrogen column of $N_H = 1.1 \times 10^{23}$ cm$^{-2}$ and a plasma energy of $kT = 6.0$ keV. The unabsorbed X-ray luminosity is about $3 \times 10^{31}$ erg s$^{-1}$.

Key words: stars: pre-main sequence – stars: protostars – stars: winds, outflows – X-rays: general – X-rays: individual (IRAS 20126+4104) – X-rays: stars

1. INTRODUCTION

Massive protostars are still embedded in their natal molecular material, and due to the high extinction are traditionally observed in the radio/millimeter and infrared wavelength bands. X-rays with energy >2 keV can also penetrate dense molecular cloud cores, and recent observations have shown that X-ray emission can be detected from regions of massive star formation (e.g., Hofner & Churchwell 1997; Hofner et al. 2002; Feigelson et al. 2005; Getman et al. 2006). In particular, the arcsecond resolution imaging capability of the Chandra X-ray Observatory has allowed for the detection of young, and hence embedded, massive stars in a number of the nearest massive star-forming regions (e.g., Townsley et al. 2011). Here, we present the results of Chandra observations of the IRAS 20126+4104 region, which contains a massive protostar, i.e., a massive star that is still in the process of assembling most of its final mass through accretion from its envelope. A small number of low-mass “class 0” type protostars have been detected in X-rays (e.g., Tsuboi et al. 2001) and the observations presented in this paper were carried out to search for X-ray emission from similar, but more massive objects.

The IRAS 20126+4104 region of massive star formation has been studied extensively in the last few years. It is relatively nearby (1.7 kpc), has a FIR luminosity of about $10^4 L_\odot$, and shows classic signs of massive star formation: dense and hot molecular gas (e.g., Cesaroni et al. 1997); maser emission from the H$_2$O, OH, CH$_3$OH, and NH$_3$ molecules (e.g., Trinidad et al. 2005; Edris et al. 2005; Kurtz et al. 2004; Zhang et al. 1999); and a massive molecular flow (e.g., Su et al. 2007; Shepherd et al. 2000). The radio continuum emission in IRAS 20126+4104 is very weak (Hofner & Churchwell 1997), which demonstrates the early evolutionary state of the region. In the central core, a disk/jet system was observed and the dynamics of the disk indicated a protostar of mass $\approx 7 M_\odot$, which is thought to be accreting mass through the disk (e.g., Cesaroni et al. 1999, 2005). Infrared observations support this picture, but also show that the inner 0.1 pc of the IRAS 20126+4104 region hosts a complex environment with multiple stars and different flow components (e.g., Shridaran et al. 2005; De Buizer 2007).

Hofner et al. (2007) studied the radio continuum emission in the IRAS 20126+4104 core and found three compact sources: I20N1, I20N2, and I20S, located about 1′′ to the south. Figure 1 shows the 3.6 cm continuum map of this region. These authors discuss the possible origin of the radio continuum sources, and while the detailed nature of the radio continuum sources is still under debate, they favor a model for I20N1 and N2 where the ionization is shock-induced by the outflow from the putative massive protostar, located about 0.3 to the southeast of I20N1. For I20S, on the other hand, the radio continuum data are consistent with direct photoionization of jet material from an early B-type star.

Several models have been proposed to explain X-ray emission from early-type stars: shocks in line-driven winds in the outer atmosphere of the star (e.g., Lucy & White 1980), magnetically confined stellar winds (Gagné et al. 2005), collisions of strong winds in close binary systems (e.g., Pittard & Parkin 2010), and binary-induced magnetic reconnection events (Schulz et al. 2008). For massive stars in very early evolutionary states we also need to consider X-ray emission from accretion events (e.g., Günther et al. 2007), as well as interaction of outflows/jets with the surrounding medium (e.g., Güdel et al. 2005; Pravdo et al. 2004). In this paper, we present Chandra observations of IRAS 20126+4104 with the goal to search for and investigate these X-ray emission processes from massive protostars.

In Section 2 of this paper, we describe the Chandra observations and data reduction methods. Section 3 presents the observational results, which are further discussed in Section 4. We summarize the paper in Section 5.
shown in contours (Hofner et al. 2007). Contour levels are seen Weisskopf et al. (1996), Weisskopf et al. (2002), and Garmire et al. (2003). The nominal pointing position for the ACIS array the positional accuracy of our X-ray data.

The IRAS 20126+4104 region of massive star formation was observed with the Advanced CCD Imaging Spectrometer (ACIS) on board the Chandra X-Ray Observatory on 2003 March 17. The energy range of ACIS is 0.1–10 keV and the total exposure time was 39.35 ks. For details on the instrument see Weisskopf et al. (1996), Weisskopf et al. (2002), and Garmire et al. (2003). The nominal pointing position for the ACIS array was R.A. (J2000) = 20°14′30″27, decl. (J2000) = +41°13′42″1. The observations were taken in the standard “Timed Event, Very Faint” telemetry mode. The roll angle of the spacecraft during the observations was 58°19, and the focal plane temperature was −119.6 °C. Although six CCD chips (I0–I3, S2, S3) were active during the observations, no useful data were obtained from the spectroscopic array and we report here only data from the imaging array, ACIS-I. The imaging array consists of four abutted 1024 × 1024 pixel CCDs (pixel size 0′′.492) covering an angular region of about 17′ × 17′. Data reduction was performed using the CIAO software package version 3.3.01 provided by the Chandra X-Ray Center, starting from level 2 reprocessed data (processing version DS 7.6.8). This version of the data processing pipeline provides an improved aspect solution and correction of effects due to the increase of the charge transfer inefficiency (Townesley et al. 2000). ASCA grades 0, 2, 3, 4, 6 were selected and the data were gain-corrected and filtered for bad CCD pixels and times of bad aspect. The energy range was restricted to 0.5–8 keV, where the point-spread function was of good quality. Exposure maps were created and applied to the data in the standard fashion. No background flares were detected during the observations, and the average background emission, as measured in a source-free region in the ACIS-I chips, was 2.3 × 10−7 count s−1 pixel−1.

To check the astrometric accuracy of the Chandra data, the positions of 17 bright X-ray sources located near the center of the ACIS array were compared with their counterparts in the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) catalog. Although the initial astrometry was already very good, with a maximum individual deviation of < 0′′.4 in either coordinate, a small systematic offset of 0′′.2 toward the west and 0′′.1 toward the south was detected. After correction of the Chandra source positions, the root-mean-square offset in R.A. and decl. between Chandra and 2MASS was about 0′′.1. We take this value as an indication of the astrometric accuracy of our data.

3. RESULTS AND ANALYSIS

3.1. Source Detection

Sources were identified in the ACIS-I field of view using WAVDETECT, a wavelet-based source detection program that works well to detect closely spaced sources (Freeman et al. 2002). We used a “threshold significance” of 10−6 and wavelet scale sizes from 1 to 16 pixels incremented by a factor √2. These values provided good sensitivity to faint sources (e.g., <100 counts). To more reliably identify weak sources with emission only in the soft (0.5–2 keV) or hard (2–8 keV) X-ray energy ranges, WAVDETECT was run for each range separately as well as for the full energy range (0.5–8 keV). All sources found by WAVDETECT were inspected visually. We found that spurious detections occurred below seven counts, often having the appearance of linear stripes and edge effects. These sources were removed from our list of detected sources.

Sources with at least seven counts within the source detection region identified by WAVDETECT were considered to be real detections.

The total number of sources detected was 150; this included sources that were only detected in soft or hard X-rays as well as those that were detected in the full energy range. The brightest detected X-ray source had a total of 340 counts and was identified with a foreground main-sequence K05 spectral-type star. The second brightest source (167 counts) corresponds to the radio source I20S. Approximately 80% of the sources had less than 50 counts. In this paper, we focus on the two X-ray sources detected in the central 6′′ of the IRAS 20126+4104 region. The entire data set of the X-ray cluster in IRAS 20126+4104 will be presented in a subsequent paper.

A gray-scale image of the X-ray emission detected in the central 6′′ is shown in Figure 2. The peak positions of the 3.6 cm radio continuum sources from Hofner et al. (2007) are shown as crosses. Two sources are clearly detected by Chandra. The bright X-ray source CXO J201426.0+411331.7 with 167 counts within 2–8 keV, or a count rate of 4.3 counts ks−1, is coincident with the peak position of the ionized radio jet source I20S. The X-ray emission from I20S is consistent with a point source, and its J2000 coordinates are R.A. (J2000) = 20°14′26″03, decl. (J2000) = +41°13′31″7. Due to the highly accurate astrometry (∼0′′.1) of both radio and X-ray data, there can be little doubt that the X-ray emission is associated with the radio jet source I20S. There is no indication of X-ray emission from the massive protostellar candidate I20N, which is located about 1″ to the north.

The second X-ray source detected in the inner 6′′, CXO J201426.2+411327.9, has a total of 33 counts (count rate of 0.9 counts ks−1) and, as with I20S, is only detected in the hard energy range. The emission is point like, and its position is

Figure 1. Radio continuum emission at 3 cm toward IRAS 20126+4104 is shown in contours (Hofner et al. 2007). Contour levels are −3, 3, 4, 5, 6, 7, 10, 13, 16 × 8μJy beam−1. The size of the synthesized beam is shown in the lower left corner. The cross marks the position of the X-ray source CXO J201426.0+411331.7 associated with I20S. The size of the cross is three times the positional accuracy of our X-ray data.

http://www.ipac.caltech.edu/2mass/
Figure 2. 0.5–8 keV X-ray emission in the IRAS 20126 core region is shown in gray scale overlaid on the 3 mm continuum emission from Cesaroni et al. (1999). The red crosses show the peak positions of the 3.6 cm continuum sources from Hofner et al. (2007), with the size of the crosses six times the astrometric error of the Very Large Array observations.

R.A. (J2000) = 20h14m26.25, decl. (J2000) = +41° 13′ 27.9″. This source is coincident with the variable radio source I20Var (Hofner et al. 2007).

3.2. Timing Analysis

Timing analysis was performed to determine whether either source displayed X-ray variability using the XRONOS software package. For I20S and I20Var, the count rate versus time (i.e., X-ray light curve) was determined by measuring counts in 2000 s temporal bins within angular regions defined by WAVDETECT. The background from a nearby, source-free region was then subtracted to obtain the final light curve. Analysis of the light curves was done using the LCSTATS program in the XRONOS package. Due to the low number of counts in our observation, the $\chi^2$ method was used to determine source variability. Light curves for I20S and I20Var are shown in Figure 3.

The X-ray emission from I20S (Figure 3, upper panel) was found to be marginally variable, with a $\chi^2$ probability for constancy of $1.1 \times 10^{-5}$. The variation of the X-ray flux in this source appears to be smooth on a timescale of a few times $10^4$ s, and it did not exhibit any flare-like behavior. For I20Var (Figure 3, lower panel), the $\chi^2$ probability for constancy was 0.4, indicating no variation of its X-ray flux was detected. I20Var has shown strong variability in 3.6 cm radio continuum observation, where it exhibited a flux density increase of a factor of 40 within two observations taken between 1998 and 2000 (Hofner et al. 2007). Since the 3.6 cm and X-ray observations were not simultaneous, it is possible that the X-ray emission was simply quiescent at the time of the observations. In the I20Var light curve, the last bin shows a sudden rise to more than three times the average count rate, which might indicate the onset of an X-ray flare. Nearby X-ray sources on the ACIS-I chip do not show any similar behavior; hence it is unlikely that this is an instrumental effect.

3.3. Spectroscopy

The 0.5–8 keV spectra of I20S and I20Var are shown in Figure 4. Both sources are highly absorbed with no X-ray counts detected below 3 keV. Model fitting of the I20S and I20Var spectra was performed using the XSPEC software package.

In order to fit the X-ray spectrum of I20S, we tried a variety of models including optically thin, one- (1T) and two-temperature (2T) thermal models (APEC) and mixed thermal and non-thermal models with fixed solar abundance of 0.2. All models were also run allowing the abundance to vary. None of these models fit the data well; however all models imply similar absorption columns of about $10^{23}$ cm$^{-2}$, as well as the presence of a hot plasma with $kT \geq 6$ keV.

In Figure 4 (upper panel), we show an overlay of our best-fit model, which consists of an absorbed 1T APEC model plus three Gaussians. The best-fit model parameters are an absorbing column of $N_H = 1.2^{+0.3}_{-0.2} \times 10^{23}$ cm$^{-2}$, a plasma temperature of $kT = 10^{25.5}$ keV, and an abundance of 1.2 solar. Two of the three Gaussian lines were added to represent energies of 3.9 and 4.9 keV, which are likely due to Ca xix. Whether in fact these lines are actually present in the data cannot be stated with any certainty.

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5 http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/xanadu/xronos
6 http://heasarc.gsfc.nasa.gov/docs/software/lheasoft/xanadu/xspec
7 APEC code v1.3.1, http://hea-www.harvard.edu/APEC
The X-ray spectrum of I20Var is shown in Figure 4 (lower panel). The low count rate precludes a detailed spectral analysis. A 1T APEC model with a fixed abundance (0.2 solar) was fitted to the X-ray data. Our best fit has an absorbing hydrogen column of $N_{H} = 1.1 \times 10^{23}$ cm$^{-2}$ and a plasma energy of $kT = 6.0$ keV. We estimate that $N_{H}$ is accurate within about a factor of two, but the plasma temperature is less well constrained: reasonable fits were possible with any energy larger than about 2.3 keV. The observed 0.5–8 keV flux of I20Var is $2.7 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, corresponding to an unabsorbed luminosity of approximately $3 \times 10^{33}$ erg s$^{-1}$.

4. DISCUSSION

4.1. I20N

We first turn to the non-detection of X-rays from the position of the massive protostar I20N. As has been pointed out by Skinner et al. (2007), very few massive embedded stars have been detected in X-rays and little is known about their X-ray emission during early evolutionary stages. Among the candidates for massive protostars which have been detected are the well-known sources HH80-81 (GGD27-X, Pravdo et al. 2009), S106-IRS4 (Giardino et al. 2004), NGC2071-IRS1, IRS3 (Skinner et al. 2009), and several sources in the MonR2 region (Kohno et al. 2002). These sources show relatively hard spectra with energies in the range of 2–8 keV, observed through column densities $10^{22}$–$10^{23}$ cm$^{-2}$ and unabsorbed X-ray luminosities of $10^{30}$–$10^{31}$ erg s$^{-1}$. Translating our detection limit of seven counts to physical parameters is model dependent: for an optically thin thermal spectrum with an energy of 3.5 keV and absorption column of $N_{H} = 10^{22}$ cm$^{-2}$, our detection limit corresponds to an X-ray luminosity of about $1 \times 10^{30}$ erg s$^{-1}$ in the 0.5–8 keV energy band. As the column density increases, much more luminous sources would be required for detection, e.g., $L_{X} = 7 \times 10^{30}$ erg s$^{-1}$ for $N_{H} = 10^{23}$ cm$^{-2}$ and $L_{X} = 2 \times 10^{32}$ erg s$^{-1}$ for $N_{H} = 10^{24}$ cm$^{-2}$. I20N is located near the column density maximum in the IRAS 20126+4104 core region, where Cesaroni et al. (1999) estimate $N_{H} \approx 10^{25}$ cm$^{-2}$. Thus, at present, the non-detection of I20N in X-rays is consistent with the X-ray properties of known massive protostellar candidates if the hypothetical X-ray source in I20N suffers the full extent of the absorption through the column density of $10^{25}$ cm$^{-2}$.

4.2. I20S

This source is located about 1″ south of I20N near the edge of the dense central core. No compact emission in any molecular transition or dust continuum has been reported at this position; the only detection so far is at 3.6 cm (Hofner et al. 2007). At this wavelength, the source shows a smooth elongated structure of axis ratio $\approx 5$ oriented in the direction of the large-scale flow (Figure 1), which has been interpreted by Hofner et al. (2007) as either a photoionized jet or shock ionization due to outflowing matter.

The detailed evolutionary state of I20S is difficult to assess. Most existing models for jets are based on collimated disk winds (e.g., Pudritz et al. 2007); hence the presence of a radio jet inside the dense molecular cloud core suggests that an accretion disk might exist around the central object in I20S. However, the absence of any detectable, compact, high-density tracer suggests that the total mass of such a putative disk and the accretion rate would be substantially lower than in I20N. If the
radio continuum emission from I20S is due to ionizing photons beamed into the solid angle of the jet, the required UV photon flux corresponds to a zero-age main-sequence spectral type B1 (Hofner et al. 2007). This spectral type is likely an upper limit since a high-velocity jet might produce a significant fraction of the ionizing radiation. Accretion onto the stellar surface of such an object even at free-fall velocities would result in a spectrum with $F \ll 2$ keV (Günther et al. 2007), i.e., much softer than is observed.

One scenario which can produce plasmas with energies of several keV is strong shocks, which can occur when the outflowing matter in the jet is stopped by the surrounding dense gas in the molecular core (e.g., Raga et al. 2002). As discussed above, the energy of the X-ray emitting plasma of I20S is poorly determined, but it is likely larger than 5 keV. Shock speeds $>2000$ km s$^{-1}$ are required to produce a plasma of this energy. Terminal wind speeds of early B stars can be of this magnitude (e.g., Cassinelli et al. 1994), and proper motions within the HH80-81 jet as large as 1400 km s$^{-1}$ have been detected (Marti et al. 1995), so this scenario is a distinct possibility. The radio morphology of I20 is reminiscent of the jet in the classical T Tauri star DG Tau which is also known to be an X-ray emitter (Güdel et al. 2005, 2008). However, the X-ray emission from I20S arises from a much hotter plasma, suffering much higher extinction, and is more luminous than DG Tau, so that I20S might be an upscaled version of DG Tau.

For lower mass stars, hard X-rays are produced mostly by magnetic reconnection events which heat the plasma to high temperatures (e.g., Feigelson & Montmerle 1999), and similar processes have recently been detected for massive stars (Schulz et al. 2006). This type of emission usually occurs in X-ray outbursts with a typical flare profile in the light curve. While there is evidence for marginal variability of the X-ray flux from I20S, no flare-type variability is seen. This type of flux variation is more likely related either to the rotation of the star or to orbital modulation in a binary. For the former case, a possible production mechanism for hard X-ray emission would be the magnetically confined wind model (Gagné et al. 2005), and for the latter case, the colliding binary wind model (e.g., Pittard & Parkin 2010).

We now turn to a discussion of the emission line at 6.4 keV. This line is due to weakly ionized iron indicating the presence of relatively cold gas. Following the theory outlined in Tsujimoto et al. (2005), if the fluorescent matter is along the line of sight to I20S, an order-of-magnitude estimate for the equivalent width (EW) of the 6.4 keV line is $EW \approx \frac{N_H}{10^{22}}$ cm$^{-2}$, where $N_H$ is the equivalent hydrogen column in the fluorescent material. The absorption column measured from model fitting the I20S X-ray spectrum is $N_H = 1.1 \times 10^{23}$ cm$^{-2}$. Based on the IRAM Plateau de Bure 1.3 mm observations ($\theta_{\text{syn}} = 0.6$) of Cesaroni et al. (1999) and the formulas of Mezger et al. (1990) with an assumed dust temperature of 100 K, we estimate a column density of $N_H = 3 \times 10^{23}$ cm$^{-2}$ at the position of I20S. Considering the uncertainties (angular resolution, dust properties, and assumed temperature), this value is consistent with the absorption derived from the X-ray spectrum. Thus, the expected EW of the 6.4 keV iron line is on the order of a few times 10 eV, whereas much larger values for EW are necessary to explain the excess in the spectrum near 6.4 keV, suggesting a much higher column density for the fluorescent matter. As noted above, I20S is located near the edge of the dense molecular core, which contains the massive protostar I20N. A likely scenario is therefore that the 6.4 keV line arises from reflection of X-ray emission from I20S at the edge of the dense molecular core. However, the low count rate of the I20S spectrum precludes a more detailed analysis, and more sensitive observations are needed to study the putative 6.4 keV line.

4.3. I20Var

This source was first detected by Hofner et al. (2007) at radio wavelengths, where it showed strong variability on timescales of 20 days or longer. The emission characteristics of I20Var are consistent with gyro-synchrotron emission from a low-mass, pre-main-sequence star, which infrared emission is made undetectable by an overlaying column of about $N_H = 10^{23}$ cm$^{-2}$. Our X-ray data imply the same amount of absorption from fitting the low-energy cutoff.

With the exception of a possible flare onset at the end of these observations, the emission from I20Var appears mostly quiescent (Figure 3, bottom) rather than flare like. The luminosity of quiescent X-ray emission from low-mass pre-main-sequence stars is generally found to be smaller than a few times $10^{30}$ erg s$^{-1}$ (e.g., Imanishi et al. 2001), whereas I20Var has an unabsorbed X-ray luminosity of approximately $3 \times 10^{31}$ erg s$^{-1}$. This suggests that I20Var is either a low-mass star with unusually high quiescent X-ray emission, or that it is an intermediate-mass star.

5. SUMMARY

In this paper, we described Chandra observations of the IRAS 20126+4104 core region. The massive protostar I20N was not detected in our observations. If the X-ray luminosity of this source is similar to the massive protostars detected so far, then the non-detection indicates that the X-ray emission suffers the full extent of the absorption toward I20N, which is thought to be dominated by an edge-on accretion disk. X-ray emission was detected from the radio jet source I20S. The source was marginally variable, but showed no evidence of X-ray flares. The emission has a hard and strongly absorbed spectrum, showing a broad line between 6.4 and 6.7 keV. The line is consistent with a superposition of emission from both weakly and highly ionized iron. Also, X-ray emission from the variable radio source I20Var was detected. The X-ray emission from this source was constant during the observations, with a larger X-ray luminosity than would be expected from a low-mass pre-main-sequence star. Together with detection limits from 2MASS, this suggests that I20Var is possibly an intermediate-mass star.

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