

# An X-ray and Infrared Survey of the Lynds 1228 Cloud Core

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## ABSTRACT

The nearby Lynds 1228 (L1228) dark cloud at a distance of 200 pc is known to harbor several young stars including the driving sources of the giant HH 199 and HH 200 Herbig-Haro outflows. L1228 has been previously studied at optical, infrared, and radio wavelengths but not in X-rays. We present results of a sensitive 37 ks Chandra ACIS-I X-ray observation of the L1228 core region. Chandra detected 60 X-ray sources, most of which are faint ( $>40$  counts) and non-variable. Infrared counterparts were identified for 53 of the 60 X-ray sources using archival data from 2MASS, Spitzer, and WISE. Object classes were assigned using mid-IR colors for those objects with complete photometry, most of which were found to have colors consistent with extragalactic background sources. Seven young stellar object (YSO) candidates were identified including the class I protostar HH 200-IRS which was detected as a faint hard X-ray source. No X-ray emission was detected from the luminous protostar HH 199-IRS. We summarize the X-ray and infrared properties of the detected sources and provide IR spectral energy distribution modeling of high-interest objects including the protostars driving the HH outflows.

*Subject headings:* ISM: clouds (L1228) — ISM: Herbig-Haro objects — stars: formation — X-rays: stars

## 1. Introduction

Lynds 1228 (hereafter L1228; centered at J2000 RA = 20.97h, Dec. = +77.32°) is one of the closest dark clouds in the catalog of Lynds (1962). It is part of the Cepheus Flare region

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which in its entirety comprises one of the nearest giant molecular clouds. The Cepheus Flare consists of as many as eight different dark cloud complexes widely distributed over  $\sim 100$  deg<sup>2</sup> (Kun 1998; Kiss et al. 2006). The main cloud complex lies at  $d = 300 \pm 30$  pc but L1228 is in the foreground at  $d = 200_{-20}^{+100}$  pc (Kun 1998; Kun, Kiss, & Balog 2008). The total mass of L1228 is estimated to be  $M_{cloud} \sim 230 M_{\odot}$  which is intermediate within the range  $\sim 40 - 1500 M_{\odot}$  for the other cloud complexes in the Cepheus Flare (Kirk et al. 2009).

Star-formation has occurred in several of the clouds as evidenced by the discovery of a number of low-mass young stellar objects (YSOs) in various surveys, as summarized below. But several dense cores are also present which appear starless and may eventually form low-mass stars (Kun 1998). Star-formation in some of the clouds may have been triggered by a supernova which exploded  $\sim 40,000$  years ago whose vestige is an expanding hot bubble known as the Cepheus Flare Shell (Grenier et al. 1989; Olano, Meschin, & Niemela 2006). L1228 is of particular interest since its projected position lies just inside the current radius of this expanding shell (Fig. 1 of Kirk et al. 2009). As such, it emerges as a likely candidate for recent star-formation.

An objective prism survey of L1228 was undertaken by Ogura & Sato (1990) to identify candidate pre-main sequence (PMS) stars. Their survey identified 69 H $\alpha$  emission stars of which nine clustered near the central part of L1228. Using optical spectroscopy and photometry in combination with Two-Micron All-Sky Survey (2MASS) near-IR and *Spitzer* Space Telescope IRAC and MIPS-24  $\mu$ m data, Kun et al. (2009) identified 13 PMS stars in L1228 with extinctions in the range  $A_V = 0.0 - 5.9$  mag (median  $A_V \approx 3$  mag) and ages spanning 1 - 10 Myr with a median of  $\sim 3$  My. The *Spitzer* Gould Belt Survey (Kirk et al. 2009) included L1228 in which 23 YSO candidates were identified. Further analysis of JHK photometry combined with *Spitzer* IRAC and MIPS 24 $\mu$ m/70 $\mu$ m data by Chapman & Mundy (2009) identified seven YSOs in the L1228 core region. The YSOs identified so far are predominantly class II objects (e.g. Fig. 8 of Kirk et al. 2009), also known as classical T Tauri stars (cTTS). These objects are low-mass PMS stars still surrounded by accretion disks. However, at least two young class I protostars are also present, HH 199-IRS and HH 200-IRS. High-mass stars such as the young OB stars found in Orion are not currently present and the Cepheus Flare complex thus more closely resembles regions such as Taurus where low-mass stars are the rule.

The studies cited above have focused on optical and IR identification of candidate YSOs. X-ray observations are also useful for this purpose since low-mass YSOs typically show elevated levels of X-ray emission relative to their main sequence counterparts. L1228 has not previously been observed in a pointed X-ray observation but it was part of the *ROSAT* All-Sky Survey (RASS) coverage region in Cepheus studied by Tachihara et al.

(2005). They identified 16 weak-lined T Tauri stars (wTTS) in Cepheus but none lie in L1228. We present here the results of a more sensitive X-ray observation of the L1228 cloud core with *Chandra*. Our goals are to obtain the first census of X-ray sources in the cloud core and identify potential X-ray emitting YSOs. Because of the proximity of L1228 and its relatively low extinction, the observation provides high sensitivity and is capable of detecting X-ray emitting T Tauri stars down to the low end of the stellar mass limit (Sec. 2). We also analyze IR data from 2MASS, *Spitzer*, and the Wide-field Infrared Survey Explorer (*WISE*) in order to identify counterparts to X-ray sources, distinguish between YSOs and extragalactic contaminants, and determine basic YSO properties. The study goes beyond previous work by including new X-ray data and by incorporating all previous *Spitzer* archive data as well as new *WISE* mid-IR data.

## 2. Observations and Data Reduction

### 2.1. Chandra

The *Chandra* observation is summarized in Table 1. The exposure was obtained using the ACIS-I (Advanced CCD Imaging Spectrometer) imaging array in faint timed-event mode. ACIS-I has a combined field of view (FoV) of  $\approx 16.9' \times 16.9'$  consisting of four front-illuminated  $1024 \times 1024$  pixel CCDs with a pixel size of  $0.492''$ . Approximately 90% of the encircled energy at 1.49 keV lies within  $\approx 1''$  of the central pixel of an on-axis point source. More information on *Chandra* and its instrumentation can be found in the *Chandra* Proposer’s Observatory Guide (POG)<sup>4</sup>.

The Level 1 events file provided by the *Chandra* X-ray Center (CXC) was processed using CIAO version 4.4<sup>5</sup> standard science threads. The CIAO processing script *chandra\_repro* applied recent calibration updates. We used the CIAO *wavdetect* tool to identify X-ray sources on the ACIS-I array along with their centroid positions and  $3\sigma$  position error ellipses. *Wavdetect* was executed on full-resolution images using events in the 0.3 - 7 keV range to reduce the background. Wavelet radii as set by the *scales* input parameter were 1, 2, 4, 8, and 16 pixels. Background was very low, amounting to 0.0104 counts per pixel (0.3 - 7 keV) integrated over the full 36.8 ks exposure. A nominal on-axis source extraction region of radius  $r = 1''$  contains only  $\approx 0.14$  background counts (0.3 - 7 keV). We retained only

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<sup>4</sup>See <http://asc.harvard.edu/proposer/POG>

<sup>5</sup>Further information on *Chandra* Interactive Analysis of Observations (CIAO) software can be found at <http://asc.harvard.edu/ciao>.

those X-ray sources found by *wavdetect* having  $\geq 5$  net counts in our final source list. This threshold corresponds to an unabsorbed X-ray luminosity detection limit  $L_x \approx 10^{28.05}$  ergs  $s^{-1}$  (0.3 - 7 keV) at  $d = 200$  pc, assuming a generic T Tauri star thermal X-ray spectrum with plasma temperature  $kT = 3$  keV and hydrogen absorption column density  $N_H = 10^{21.8}$   $cm^{-2}$  ( $A_V \approx 3$  mag). This extinction is typical for the cloud as a whole (Kun et al. 2009) but  $A_V$  is higher toward the most obscured central regions (Kiss et al. 2006; Chapman & Mundy 2009; Kirk et al. 2009). Using the known correlations between  $L_x$  and stellar mass ( $M_*$ ) for TTS as determined from deep *Chandra* survey of the Orion Nebula Cluster (Preibisch et al. 2005), and from the *XMM-Newton* survey of the Taurus Molecular Cloud (Telleschi et al. 2007), the above  $L_x$  limit corresponds to a TTS of mass  $M_* \lesssim 0.1 M_\odot$ . The CIAO tool *specextract* was used to extract X-ray spectra of selected bright sources and spectral fitting was carried out with HEASOFT XSPEC software vers. 12.4.0<sup>6</sup>. Source variability probabilities were computed using the CIAO tool *glvary* which is based on the Gregory-Loredo (GL) algorithm (Gregory & Loredo 1992, 1996).

## 2.2. Infrared Archive Data (2MASS, Spitzer, WISE)

We have used existing IR archive data to identify potential IR counterparts to X-ray sources, obtain IR photometry of high-interest sources, and determine object classes in those cases where good-quality multi-band photometry are available.

*2MASS*: We obtained near-IR positions and magnitudes from the 2MASS All-Sky Catalog (Skrutskie et al. 2006). 2MASS provides photometry at J (1.25  $\mu m$ ), H (1.65  $\mu m$ ), and  $K_s$  (2.17  $\mu m$ ). The spatial resolution of  $\approx 1.''2$  is comparable to that of *Chandra* and to *Spitzer* at 3.6  $\mu m$ .

*Spitzer*: The Spitzer Space Telescope (Werner et al. 2004) observed the L1228 region multiple times with the Infrared Array Camera (IRAC; Fazio et al. 2004) and the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004). IRAC provides data in four channels: I1 (3.6  $\mu m$ ), I2 (4.5  $\mu m$ ), I3 (5.8  $\mu m$ ), and I4 (8.0  $\mu m$ ). The IRAC native pixel size is  $1.''2$  with spatial resolution FWHM  $\approx 1.''6 - 2.''0$ . MIPS has three channels: MIPS-24 (24  $\mu m$ ), MIPS-70 (70  $\mu m$ ), and MIPS-160 (160  $\mu m$ ) with respective spatial resolutions FWHM  $\approx 6''$ ,  $18''$ , and  $40''$ . Further information on these instruments can be found in the respective *Instrument Handbooks*<sup>7</sup>. We have reprocessed all *Spitzer* IRAC and MIPS-24 archive data

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<sup>6</sup><http://heasarc.gsfc.nasa.gov/docs/xanadu/xanadu.html>

<sup>7</sup><http://irsa.ipac.caltech.edu/data/SPITZER/docs/>

(Table 2) intersecting the *Chandra* FoV to generate deep-coverage image mosaics. Since MIPS-70 and MIPS-160 band data are not available for all the MIPS Astronomical Observation Requests (AORs) we have only reprocessed the MIPS-24 data. However, MIPS-70 photometry are available for some sources such as HH 199-IRS and HH 200-IRS from the Cores-to-Disks (c2d) *Spitzer* Legacy program (Evans et al. 2003). We reprocessed the AORs starting from the IRAC pipeline-corrected Basic Calibrated Data (BCD) files or, for MIPS photometry observations, the enhanced BCD (eBCD) files. For MIPS scan maps we started from the BCD files since eBCD files are not available. We used MOPEX (Makovoz & Marleau 2005) to calculate overlap corrections and to create exposure-time-weighted mosaics with a substantial reduction in instrumental artifacts. Exposure time weighting is necessary since the total integration time varies as a function of position on the sky. The pixel size for our mosaics was the same as the pipeline mosaics, 0."6 for IRAC and 2."45 for MIPS-24. The *Spitzer* mosaics cover the full ACIS-I FoV except for the NE and SW corners where 2MASS and *WISE* provide coverage. We used the IDL *aper.pro* routine to perform aperture photometry at the IR peak positions of sources of interest. For the IRAC mosaics we used an aperture radius  $r = 3."$ 6 and a background annulus of  $r = 3."$ 6 - 8."4. Aperture corrections in the four IRAC channels (1.124, 1.127, 1.143, & 1.234 respectively) and IRAC zero-point magnitudes (280.9, 179.7, 115.0, and 64.13 Jy, respectively) were taken from the *IRAC Instrument Handbook*. Point-response function (PRF) fitting of MIPS-24 sources was carried out with MOPEX. In those cases where PRF fitting was not successful we obtained MIPS-24 aperture photometry using an aperture of radius  $r = 7"$ , an annulus of  $r = 7"$  - 13", and an aperture correction of 2.05 as per the *MIPS Instrument Handbook*.

*WISE*: We searched for mid-IR counterparts of X-ray sources using the 14 March 2012 release of the *WISE* All-Sky Catalog (Wright et al. 2010). *WISE* completed an all-sky survey during its cryogenic mission phase from January to August 2010. *WISE* provides photometry in four bands: W1 (3.4  $\mu\text{m}$ ), W2 (4.6  $\mu\text{m}$ ), W3 (12  $\mu\text{m}$ ), and W4 (22  $\mu\text{m}$ ). Time variability can also be assessed based on comparison of fluxes in each band for a given source obtained at different times during the mission. *WISE* sensitivity is somewhat less than obtained in our mosaiced *Spitzer* images of L1228 and *WISE* spatial resolution is modest with FWHM values of 6.1", 6.4", 6.5", and 12.0" in the W1, W2, W3, W4 bands. *WISE* images and associated data in all four bands (e.g. instrumental profile-fit photometry) were downloaded from the archive for analysis.

### 3. X-ray Results

#### 3.1. Source Identification

*Chandra* detected 60 X-ray sources on ACIS-I with  $\geq 5$  net counts. Their positions on the ACIS-I detector are plotted in Figure 1 and source properties are summarized in Table 3. Most of the X-ray sources are faint and only eight sources have  $> 50$  net counts. The mean number of counts is 25 and the median is 13 counts. None of the X-ray sources are listed in the less sensitive RASS compilation of Tachihara et al. (2005). We found potential IR counterparts for 53 of the 60 sources (Table 4). In almost all cases the offsets between the X-ray and IR positions are  $< 2''$ . As Table 4 shows, larger offsets of  $2.''0 - 3.''6$  are present for some sources (CXO sources 2, 5, 14, 16, 58, 60). These sources lie off-axis and have large X-ray position error ellipses due to broadening of the point-spread-function (PSF), so their IR counterpart identifications given in Table 4 are more uncertain. WISE coverage spans the entire ACIS-I field-of-view and potential WISE counterparts were found for 30 sources. Four WISE sources have variability flag values  $varflg \geq 6$  in one or more bands indicating likely IR variability (CXO 26, 27, 30, 53). Figure 2 is an overlay of the X-ray source positions on a WISE W1-band image. The mosaiced *Spitzer* images are more sensitive than WISE and *Spitzer* counterparts were found for all but ten X-ray sources, seven of which lie outside the *Spitzer* coverage area (Table 4). IR photometry for each source are summarized in Table 5.

Interestingly, the brightest IR source in the field IRAS 20582+7724 = HH 199-IRS was not detected by *Chandra*. It is a class I protostar that is believed to power the HH 199 outflow (Bally et al. 1995). Its IR properties are discussed further in Section 5. The hardest X-ray source as gauged by its mean photon energy  $\bar{E} = 5.1$  keV is CXO source 26 (J205706.72+773656.1). This mean energy is well above the average value  $\bar{E} = 2.8$  keV for the sample (Fig. 3). The X-ray position of CXO source 26 as determined by *wavdetect* is offset by only  $0.''06$  from the radio source L1228 VLA 4 (Reipurth et al. 2004) which is identified with the IR source HH 200-IRS that is thought to power the HH 200 outflow. As discussed further in Section 5, a second IR source is located  $5.''7$  northeast of HH-200 IRS but is well outside the X-ray position error ellipse and is thus ruled out as the X-ray source. We thus associate this faint hard X-ray source with HH 200-IRS, a known class I protostar (Chapman & Mundy 2009). Other previously known YSOs detected by *Chandra* are CXO sources 30, 36, and 53 and their properties are discussed further in Section 4.

### 3.2. X-ray Variability

X-ray variability is a common feature of YSOs but only four L1228 sources (CXO 8, 10, 31, 50) show a high probability of variability  $P_{var} \geq 0.9$ . They are all relatively X-ray bright with  $>50$  net counts (Fig. 3). This suggests that variability could be present in some fainter sources but went undetected because of low count rates. The X-ray light curves of the variable sources are shown in Figure 4. In all cases the variability is rather low-level with count rates changing by factors of  $\sim 2 - 3$ . No large-amplitude X-ray flares were detected.

### 3.3. X-ray Spectra

The analysis of X-ray spectra can potentially provide useful information on the line-of-sight neutral hydrogen absorption column density ( $N_H$ ) toward the source and characteristic plasma temperatures (kT) for thermal sources, or photon power-law indices ( $\Gamma$ ) for nonthermal sources such as active galactic nuclei (AGN). In our experience, at least  $\sim 50$  counts are needed to justify rudimentary spectral analysis and we have thus extracted spectra for the eight sources with  $>50$  counts. We attempted to fit the spectra with an absorbed isothermal (1T) thermal plasma model (the *apec* model in XSPEC) and also with an absorbed power-law (PL) model for those sources which were classified as galaxies or AGNs based on their IR properties (Sec. 4). In all but two cases the simple 1T model gave statistically acceptable results with realistic plasma temperatures of  $kT \approx 0.8 - 6$  keV. The two exceptions (CXO 10 and 50) are discussed below. The spectral fit results are summarized in Table 6.

The median of the  $N_H$  values for the eight sources in Table 6 is  $N_{H,med} = 5.25 \times 10^{21}$   $\text{cm}^{-2}$ , where we have used the average of the two slightly different  $N_H$  values for those sources fitted with both a thermal and a power-law model. Using the conversion  $N_H = 2.2 \times 10^{21} A_V$   $\text{cm}^{-2}$  of Gorenstein (1975), the median value is  $A_{V,med} = 2.4$  mag. The conversion  $N_H = 1.6 \times 10^{21} A_V$   $\text{cm}^{-2}$  of Vuong et al. (2003) gives  $A_{V,med} = 3.3$  mag. Although the sample is small, the latter value  $A_{V,med} = 3.3$  based on the Vuong et al. conversion is nearly identical to the median  $A_{V,med} = 3.1$  obtained in the optical study of Kun et al. (2009).

The 1T model did not give an acceptable spectral fit for CXO source 10 but a two-temperature (2T) model was acceptable. It is the brightest X-ray source in the sample and is variable. It is classified as a star in the *HST* GSC (Table 3). Its X-ray variability is a sign of magnetic activity and if it is a YSO then it is likely a weak-lined T Tauri star (Sec. 4.5). Multi-temperature thermal plasma models are often required to fit the spectra of X-ray bright T Tauri stars where higher signal-to-noise ratio more tightly constrains the shape of the spectrum. Thus, the need for a 2T model in the case of CXO 10 is not unusual and may

simply reflect the higher quality of its spectrum.

CXO source 50 is also noteworthy. It is the second brightest X-ray source and is classified as a AGN based on its *Spitzer* and *WISE* infrared properties (Sec. 4). But its X-ray emission is likely variable ( $P_{var} = 0.98$ ) and X-ray variability is more commonly associated with magnetically-active YSOs in star-forming regions. Both 1T and 2T thermal models require a high plasma temperature component  $kT \gtrsim 20$  keV. Such a high temperature is well above the typical range  $kT \sim 1 - 6$  keV for YSOs but is not impossible for a flaring magnetically-active YSO. If the IR classification as a AGN is indeed correct, then the X-ray emission would more likely be nonthermal with a power-law spectrum. We thus fitted the spectrum with an absorbed power-law model and the fit is acceptable with a  $\chi^2$  value nearly identical to that of the thermal model (Table 6). We thus cannot distinguish between a hot thermal plasma spectrum and a power-law spectrum on the basis of fit statistics for CXO source 50.

## 4. YSO Identification

### 4.1. Methods

We have used multi-wavelength IR data to identify those X-ray sources that are potential YSOs. Object classifications based on IR analysis are given in Table 3. We have used IR color cuts (where color refers to the magnitude difference in two different bands) and color-magnitude constraints to identify candidate YSOs in the presence of contaminants such as star-forming galaxies with enhanced PAH emission, AGNs, and shock emission knots. Several different color analysis methods have been discussed in the literature and we have adopted that of Gutermuth et al. (2008) for *Spitzer* data and Koenig et al. (2012) for WISE data. Similar IR analysis for the Taurus-Auriga region based on these methods was presented by Rebull et al. (2010, 2011). We have restricted our IR color analysis to those objects for which IR photometry is available in all four IRAC bands or all four WISE bands (or both). In our sample, 41 objects have 4-band photometry from IRAC or WISE (or both), and 10 of these also have 2MASS JHK<sub>s</sub> photometry (Table 5).

The color space methods implement cuts based on the photometric properties of previously identified extragalactic sources, shock emission features, and YSOs. It should be emphasized that classification schemes based on IR color diagrams are statistical in nature and are not 100% reliable. Such schemes are tuned to finding IR-bright YSOs. Contamination from AGNs becomes significant for fainter IR sources and the contamination rate increases as the objects become fainter. The schemes of Gutermuth et al. (2008) and Koenig et al. (2012) thus also apply magnitude cuts to identify potential faint extragalactic sources.

For example, the Gutermuth et al. criteria require  $[I2] > 13.5$  mag along with other color constraints before an object is classified as a broad-line AGN. Even so, low-mass embedded YSOs can occupy these IR-faint regimes. Closely-spaced sources can also affect color analysis results, especially for lower resolution MIPS and WISE data. We have inspected the IR images of all *Chandra* sources and those with more than one IR source within the *Chandra* position error ellipse are noted in Table 4.

IR color analysis is capable of distinguishing between heavily-reddened class I protostars with infalling envelopes and class II objects (i.e. cTTS with accretion disks). Class III objects (weak-lined T Tauri stars) have little or no infrared excess and are generally not identifiable on the basis of IR colors, as demonstrated below (e.g. CXO source 36). Once a YSO candidate has been identified, its status as a class I, II, or III object can also be discerned by fitting the IR spectral energy distribution (SED) to determine the IR spectral index  $\alpha = d \log(\lambda F_\lambda) / d \log \lambda$  where  $F_\lambda$  is the flux density at wavelength  $\lambda$ . In the approach of Haisch et al. (2001),  $\alpha$  is evaluated in the  $\approx 2 - 10 \mu\text{m}$  range. Class I sources have  $\alpha > 0.3$ , flat spectrum sources have  $-0.3 \leq \alpha < 0.3$ , class II sources have  $-1.6 \leq \alpha < -0.3$ , and class III sources have  $\alpha < -1.6$ . We have computed spectral indices for those sources suspected of being YSOs for comparison with classes assigned on the basis of IR colors.

## 4.2. Extragalactic Contaminants

Because of the modest extinction toward L1228 (median  $A_V \approx 3$  mag) and its location above the galactic plane ( $b = +20.2^\circ$ ), the X-ray sample is expected to contain a substantial number of extragalactic sources. Indeed, of the 41 X-ray sources with 4-band IRAC or *WISE* mid-IR photometry suitable for color space analysis, 28 are classified as AGNs or star-forming galaxies. This yields an estimated extragalactic source fraction of 28/41 (68%). There are undoubtedly other as yet unidentified extragalactic sources in the sample since twelve sources with IR counterparts lacked sufficient photometry for color-based classification and seven X-ray sources have no counterparts. We also note here that nine X-ray sources having complete 4-band IR photometry did not pass any of the color-based criteria for classification as AGN, PAH-emission star-forming galaxy, shock emission knot, or YSO. Optical catalog searches show that four of these are stars (CXO 10, 29, 36, 45; see Table 3) but the other five objects remain unclassified (CXO 18, 28, 46, 49, 60).

All eight of the brightest X-ray sources with  $>50$  counts have 4-band mid-IR photometry and five of them are classified as extragalactic on the basis of their IR properties (CXO 8, 31, 38, 50, 55). We compare the above with the number of bright extragalactic X-ray sources ( $>50$  counts) predicted on the basis of source count data in the *Chandra* Deep Field-North

(CDF-N) Survey as analyzed by Brandt et al. (2001). They show that the number of X-ray sources  $N$  per square degree with an *absorbed* hard-band (2 - 8 keV) flux greater than a specified lower limit  $F_{x,hard}$  is  $N(>F_{x,hard}) = 2820(F_{x,hard}/10^{-15} \text{ ergs cm}^{-2} \text{ s}^{-1})^{-1.0\pm 0.3} \text{ deg}^{-2}$ . To apply this result, we need to know what value of  $F_{x,hard}$  is required to accumulate at least 50 counts (0.3 - 7 keV) from a generic extragalactic source toward L1228 in a 36,779 s exposure. Note here that we require  $>50$  counts in the *broad* 0.3 - 7 keV band in order to make comparisons with the L1228 net counts measurements in Table 3. Following Brandt et al. we assume a power-law X-ray spectrum with a photon power-law index  $\Gamma = 1.4$  for the generic extragalactic source. We also assume a median absorption column density toward L1228 of  $N_{\text{H}} = 5 \times 10^{21} \text{ cm}^{-2}$  (Sec. 3.1). Under these spectral assumptions, the PIMMS<sup>8</sup> simulator predicts an absorbed flux  $F_{x,hard} = 1.54 \times 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1}$ . This value of  $F_{x,hard}$  will yield 50 broad-band counts (0.3 - 7 keV) and 27 hard-band counts (2 - 8 keV) in 36,779 s. Substituting this value of  $F_{x,hard}$  into the above expression for source counts and scaling the result to the ACIS-I FoV ( $0.07834 \text{ deg}^2$ ) gives  $N(>F_{x,hard}) = 14$  (6 - 33) where the range in parentheses reflects the uncertainties in the CDF-N source count power-law fit index. Thus, the hard-band CDF-N data predict at least six extragalactic sources in the L1228 FoV with  $>50$  broad-band counts and we have identified five candidates. This small difference is not problematic since we have assumed a constant  $N_{\text{H}}$  toward L1228 but the absorption is in fact higher toward the center of the cloud (Kun et al. 2009; Chapman & Mundy 2009). In addition, some field-to-field variation in X-ray source counts is anticipated (Cowie et al. 2002).

### 4.3. YSO Candidates

We have identified seven YSO candidates in the X-ray sample (CXO sources 14, 16, 26, 30, 36, 53, 56). All of these except CXO 36 were classified as YSOs on the basis of color analysis using 4-band IRAC or *WISE* mid-IR photometry. Representative color-color diagrams for these objects are shown in Figure 5. CXO source 36 was unclassified on the basis of its IR colors but is designated a likely YSO by virtue of its association with H $\alpha$  emission star number 38 (OSHA 38) in the list of Ogura & Sato (1990). Our SED fits (Sec. 4.3) indicate that it has little if any IR excess so it is probably a class III object (wTTS).

Four of the YSOs are known from previous studies (CXO sources 26, 30, 36, and 53). CXO 26 is associated with the class I protostar HH 200 IRS (Chapman and Mundy 2009).

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<sup>8</sup>For more information on the Portable Interactive Multi-Mission Simulator (PIMMS) see <http://cxc.harvard.edu/ciao/ahelp/pimms.html>.

CXO 30 was identified as a class II YSO (cTTS) by Chapman and Mundy (2009) and our analysis confirms this. CXO 36 is an H $\alpha$  emission-line star as noted above. CXO 53 is associated with the emission-line star OSHA 42 (Kun et al. 2009), a class II object which has the strongest H $\alpha$  emission of the stars identified in the survey of Ogura & Sato (1990).

In addition to the above four previously-known YSOs, CXO sources 14, 16, and 56 are classified as possible YSOs on the basis of IR color analysis. The YSO classifications of CXO 14 and 16 are questionable as discussed further below, but the classification of CXO 56 as a class II YSO on the basis of both *Spitzer* and *WISE* colors is relatively secure. The IR counterpart of CXO 56 is offset by only 0."48 from the X-ray position, making its association with the X-ray source highly probable.

Both CXO 14 and 16 are faint in X-rays and the latter object lies near the north edge of the ACIS-I detector (Fig. 1) where sensitivity is degraded and the PSF is broadened. The *Spitzer* and *WISE* counterparts in Table 4 are offset from the X-ray position of CXO 14 by 3.1" and 3.6" respectively. Similarly, the *Spitzer* counterpart of CXO 16 is offset by 3.6" from its X-ray position. Even though these offsets are larger than for most of the other sources, the IR counterparts do lie within the *Chandra*  $3\sigma$  position error ellipses. The *Spitzer* source located 3.1" SE of CXO 14 is resolved. This *Spitzer* source has IR colors consistent with a class I YSO but its corresponding *WISE* colors give a PAH-rich star-forming galaxy classification. Because of the above issues with mid-IR position offsets and IR color-class ambiguities, the classification of CXO sources 14 and 16 as YSOs will require further confirmation. Tighter constraints on their X-ray positions could be achieved by placing them more nearly on-axis where the *Chandra* PSF is sharpest and would provide a more reliable assessment of whether the *Spitzer* and *WISE* sources in Table 4 are legitimate counterparts.

#### 4.4. YSO Properties

Four of the six objects identified as YSOs on the basis of IR colors have 2MASS near-IR photometry in addition to *Spitzer* or *WISE* photometry in at least four bands. Also, more recent near-IR photometry is available for CXO sources 26 and 30 from Chapman & Mundy (2009). We have modeled the IR SEDs of these sources using the online modeling tool of Robitaille et al. (2007). The modeling results are summarized in Table 7. The fitting tool provides detailed information for several different models listed in order of increasing  $\chi^2$  fit statistics. Substantial differences can be present for the value of any fitted parameter between different models. In Table 7 we give the median value of each parameter based on the five models with the lowest  $\chi^2$  values. The most noteworthy result from the fits is

the very high extinction toward the class I protostar HH 200-IRS (CXO 26). Such high absorption would absorb most soft X-ray photons and may thus be largely responsible for the low number of counts and high mean photon energy detected by *Chandra*.

We have also fitted the IR SED of CXO 36 since it is a H $\alpha$  emission star, even though it was not classified as a YSO on the basis of its IR colors. The best-fit model gives no indication of a significant disk and the mass of any remnant disk must be very low ( $M_{disk} \lesssim 10^{-8} M_{\odot}$ ). A pure stellar photosphere Kurucz model with  $T \sim 3750$  K provides a good fit. The presence of H $\alpha$  emission without a significant disk is indicative of a class III YSO (wTTS). This classification is further supported by its SED power-law index  $\alpha = -2.5 \pm 0.1$ .

#### 4.5. Other Interesting Sources

*Bright Variable X-ray Sources (CXO 8, 10, 31, 50)*: As already noted in Section 3.2, four of the brightest X-ray sources have a high probability of variability  $P_{var} \geq 0.9$ . Three of these are classified as AGNs or galaxies on the basis of their IR colors (CXO sources 8, 31, 50). No counterparts were found for these three sources in a search of several galactic and extragalactic databases including the *HST* GSC v. 2.3.2, *Hipparcos*, and USNO B1 catalogs. Nevertheless, since X-ray variability is a common trait of YSOs in star-forming regions, deep follow-up observations and time-monitoring of these three sources would be worthwhile in order to confirm that they are indeed extragalactic in nature. The fourth variable X-ray source (CXO 10) is the brightest X-ray detection and was unclassified on the basis of IR colors but has an optical counterpart in the *HST* GSC (Table 3). Its IR spectral index is  $\alpha = -2.45 \pm 0.1$  which would only be consistent with a class III object if it is a YSO.

*CXO 27*: This faint hard X-ray source was classified as a AGN on the basis of both IRAC and *WISE* colors. It lies just 19" south of HH 200-IRS (Fig. 7). Its IR emission may be variable in the WISE W1 band ( $varflg = 91nn$ ). Because of its possible IR variability and projected position close to other known YSOs, follow-up observations of CXO 27 would be useful to determine if it is a YSO masquerading as a AGN. If it is a YSO then its IRAC spectral index  $\alpha = +1.0$  [+0.1 - +1.9; 90% conf. range] would be consistent with either a class I or flat-spectrum source.

*CXO 29*: The bright X-ray source CXO 29 was unclassified by IR colors and it also has an optical counterpart in the *HST* GSC classified as a star (Table 3). Its IR spectral index  $\alpha = -2.24 \pm 0.13$  would imply a class III object if it is a YSO.

## 5. Herbig-Haro Energy Sources

### 5.1. HH 199-IRS

HH 199-IRS (= IRAS 20582+7724 = 2MASS J205712.94+773543.7) is the brightest infrared source in the L1228 cloud core and is believed to power the giant HH 199 molecular outflow (Bally et al. 1995; Devine et al. 2009). This object was not detected by *Chandra* nor were any of the optical emission knots in its outflow identified by Devine et al. (2009). Nevertheless, because of its IR brightness and key role as a HH driving source we summarize its IR properties. The discussion below is restricted to 2MASS and WISE data since IRAC fluxes are affected by saturation.

Based on WISE colors (Fig. 5) it is classified as a class I protostar by the Koenig et al. (2012) criteria. A fit of its SED using 2MASS and WISE photometry gives a spectral index  $\alpha = +0.32 \pm 0.32$  (90% confidence errors). This again gives class I using the criteria of Haisch et al. (2001) but the uncertainties are large enough to allow a flat-spectrum source classification (i.e. borderline case between class I and class II). No significant IR variability was found by WISE (*varflag* = 2214) but it is worth noting that its outflow exhibits large changes in morphology over time and may be precessing (Bally et al. 1995; Devine et al. 2009).

We have modeled the IR SED of HH 199-IRS using 2MASS and WISE photometry (Table 5; Fig. 8). If the interstellar extinction is loosely constrained to be  $A_{V,ism} < 20$  mag, then the Robitaille et al. tool finds a good fit with a total extinction  $A_V = A_{V,ism} + A_{V,cs} = 14.7$  [14.5 - 16.1] mag, almost all of which is attributed to the interstellar component. The total system luminosity is  $L_{bol} = 7.0$  [2.7 - 9.6]  $L_\odot$  assuming a distance  $d = 200 \pm 20$  pc. These are the median values of the five best-fitting models followed in brackets by the range of values. The above luminosity is at least an order of magnitude greater than that of HH 200-IRS if both objects are at similar distances. The inferred disk mass is  $M_{disk} \approx 0.026$  [0.022 - 0.032]  $M_\odot$  with a disk accretion rate  $\dot{M}_{disk} = 2.6$  [1.5 - 7.2]  $\times 10^{-7} M_\odot \text{ yr}^{-1}$ . If we enforce a tighter constraint  $A_{V,ism} < 13$  mag based on the maximum L1228 core extinction determined by Kirk et al. (2009), then the modeling tool compensates by adding in additional circumstellar absorption but the resulting fit has larger residuals than the one summarized above. Thus, in terms of goodness-of-fit, the models which invoke relatively high interstellar extinction with low circumstellar extinction are favored.

## 5.2. HH 200-IRS

This source shows a nearly-flat IR SED in the 3 - 8  $\mu\text{m}$  range but it then rises steeply at longer wavelengths (Fig. 8). WISE colors are consistent with a class I source (Fig. 5). Although its IR emission is bright it is only faintly detected in X-rays. The X-ray emission is hard with all detected photons having energies  $E \geq 3.7$  keV. The extinction toward this class I source is high. The five best-fit SED models using the Robitaille et al. tool (Table 7) yield a median interstellar extinction  $A_{V,\text{ism}} = 5$  [3 - 13] mag but an additional large circumstellar extinction is also required. We examined several different models, all of which required  $A_{V,\text{cs}} > 32$  mag. This implies that the central protostar is heavily obscured by a surrounding envelope. Any soft photons ( $E < 2$  keV) emitted by the central source will thus be heavily absorbed and undetected. Because of the high absorption, the intrinsic X-ray properties of the central source are quite uncertain but the presence of sufficient hard emission to penetrate the dense circumstellar envelope is a strong clue that magnetic processes are involved in the X-ray production. Shocks created by impact of the outflow with surrounding material are expected to produce only soft emission ( $E \lesssim 1$  keV) which would be undetected unless viewed through lower absorption at large offsets from the star. We have checked for faint X-ray emission at the position of the optical emission knots in the HH 200-IRS outflow listed in Table 1 of Devine et al. (2009) and none was detected by *Chandra*.

A second IR source HH 200-IRSB (= 2MASS J205707.89+773659.7) lies 5."7 NE of HH 200-IRS. As Figure 6 shows, HH 200-IRSB is well outside the *Chandra* position error ellipse and is not detected in X-rays. Figure 7 is a *Spitzer* 3-color image of the region. This second source lies nearly on the HH 200 outflow axis, thus raising the question of whether it might actually be driving the giant HH outflow. This possibility cannot be totally ruled out but we believe that HH 200-IRS is more likely to be the driving source because of its elevated activity as evidenced by hard X-ray and radio emission (Reipurth et al. 2004).

Figure 8 compares the SEDs of HH 200-IRS and the close IR companion. The pair is resolved by 2MASS and IRAC but not by MIPS or WISE. Overall, the SEDs of the two sources look quite similar and both are likely in the protostellar stage. As Figure 8 shows, there is a discrepancy between the  $JHK_s$  fluxes of HH 200-IRS between 2MASS and the more recent values obtained by Chapman & Mundy (2009) using the KPNO 4m. The 4m fluxes are a factor of  $\sim 4$  lower than 2MASS at J band and a factor of  $\sim 2$  lower at H and  $K_s$ . This difference may be largely due to the better spatial resolution of the KPNO 4m but some IR variability may also be present. The *WISE* variability flag has values  $varflag = 6631$  where a value of 6 in both W1 and W2 bands means that the source is potentially variable with small amplitudes.

### 5.3. HH 199-IRS and HH 200-IRS in Comparison

Our SED models indicate that  $L_{bol}$  for HH 199-IRS is about ten times greater than HH 200-IRS, in agreement with other studies (Chapman & Mundy 2009; Kirk et al. 2009). The extinction toward the two protostars determined from SED fits is high and models require substantial circumstellar absorption in the case of HH 200-IRS. Faint X-ray emission was detected from HH 200-IRS but HH 199-IRS was undetected. Differences in the column density of X-ray absorbing gas toward the two protostars or their intrinsic X-ray properties could account for this. The high median photon energy of the events detected from HH 200-IRS is a clear sign that its intrinsic X-ray spectrum contains a hard component, undoubtedly of magnetic origin. X-ray flares in class I protostars can produce such hard emission and in some cases the protostar only becomes detectable during an X-ray flare (Imanishi, Koyama, & Tsuboi 2001). If HH 200-IRS was in an active flare state during our *Chandra* observation then that could explain why it was detected as a hard source but HH 199-IRS was not. Variability is expected during an X-ray flare but we lack sufficient counts in HH 200-IRS to obtain a definitive test for X-ray variability, but IR variability is suspected as mentioned above.

## 6. The Nature of the L1228 Core X-ray Population

The *Chandra* observation reported here comprises the first deep X-ray census of the L1228 cloud core. The area observed by *Chandra* covers a relatively small  $0.28^\circ \times 0.28^\circ$  field-of-view and thus does not capture the entire L1228 cloud for which the region of highest extinction spans roughly  $1 \text{ deg}^2$  (Fig. 9 of Kun et al. 2009).

A large fraction of the 60 X-ray sources appear to be extragalactic which is not surprising given that L1228 lies well above the Galactic plane ( $b = +20.2^\circ$ ) and the cloud opacity is low (Lynds 1962). We have identified 7 known or suspected YSOs. This 12% YSO fraction should be interpreted as a lower limit. We lack sufficient information for 19 X-ray sources to assess their YSO status, either because no optical or IR counterpart was found or because IR/optical data were insufficient to assign an object class.

It is of some interest that very few class III sources (wTTS) have so far been identified in L1228, but some have been found in other dark clouds in the Cepheus Flare and in off-cloud regions (Tachihara et al. 2005; Kirk et al. 2009). Since wTTS have weak  $H\alpha$  emission by definition and lack significant IR excesses they can be overlooked in  $H\alpha$  and infrared surveys. Of the 23 YSO candidates in L1228 identified in the IR study of Kirk et al. (2009), only one is classified as a wTTS. That object (Kirk et al. nr. 136) lies outside the *Chandra*

FoV but was not reported as a RASS X-ray detection by Tachihara et al. (2005). Is the wTTS population in L1228 truly absent or simply not yet seen? Some of the X-ray sources in our sample which lack IR color classifications may be wTTS, two of which have already been mentioned (CXO 10 and 29). Follow-up observations to search for stellar counterparts and spectral signatures of youth such as Li will be needed to determine whether any of the unclassified X-ray sources are indeed wTTS.

Another point worth noting is that the X-ray luminosities of the L1228 YSO candidates are quite low. The seven YSO candidates have a median of 12 net counts with a range spanning 5 - 75 net counts. Assuming a generic TTS thermal X-ray spectrum with  $kT \sim 3$  keV and  $A_V \approx 3$  mag (Kun et al. 2009), this corresponds to unabsorbed luminosity  $\log L_x(0.3 - 7 \text{ keV}) = 28.43$  [28.05 - 29.23]  $\text{ergs s}^{-1}$  at the nominal L1228 distance of 200 pc. These values increase by 0.35 dex at the high end of the distance range ( $d = 300$  pc; Kun 1998) and by about 0.17 dex for the higher mean extinction  $A_V \approx 7$  mag obtained by Kirk et al. (2009). Based on the known correlations between  $L_x$  and  $M_*$  for TTS in Orion and Taurus, the above  $L_x$  range corresponds to lower mass TTS with  $M_* \lesssim 0.7 M_\odot$ . (Fig. 3 of Preibisch et al. 2005; Fig. 1 of Telleschi et al. 2007). Thus, if a similar  $L_x \propto M_*$  correlation holds for L1228, we are detecting a highly-dispersed low-mass population of PMS stars that apparently is deficient in the more X-ray luminous TTS with masses  $M_* \gtrsim 1 M_\odot$ . This conclusion would also apply to any of the unclassified X-ray sources that may turn out to be YSOs. They have 6 - 37 net counts or  $\log L_x = 28.13 - 28.92$   $\text{ergs s}^{-1}$  (at  $d = 200$  pc,  $A_V = 3$  mag,  $kT = 3$  keV).

Some additional support for the dearth of higher mass TTS comes from the optical study of L1228 by Kun et al. (2009). Of the 13 PMS stars they identified in L1228, only one was more massive than  $1 M_\odot$  and the median mass was  $0.5 M_\odot$ . One of the stars in their sample, the class II source OSHA 42, was the brightest X-ray source classified as a YSO in our sample. Kun et al. classify OSHA 42 as spectral type M0 with an estimated mass  $M_* = 0.6 M_\odot$  and  $L_{bol} = 0.49 L_\odot$ . The value we obtain for  $L_{bol}$  from IR SED modeling is nearly identical (Table 7). To the extent that  $L_x$  correlates with  $M_*$  in L1228, it thus seems likely that the remaining L1228 X-ray sources identified as TTS (class II or possible III) with fainter emission than OSHA 42 are lower mass objects.

## 7. Summary

The main results of our combined X-ray/infrared study of L1228 are summarized below.

1. *Chandra* has provided the first sensitive pointed X-ray observation of the Lynds 1228 cloud core. Previous optical, IR, and radio studies have shown that L1228 contains a modest population of low-mass PMS stars and the heavily-reddened protostars HH 199-IRS and HH 200-IRS. *Chandra* detected 60 X-ray sources, most of which are faint (<40 counts) and non-variable.
2. Using reprocessed *Spitzer* archive data, along with 2MASS near-IR data and recent WISE All-Sky Survey mid-IR data, IR counterparts were found for 53 sources. Source classification based on IR colors and magnitudes was undertaken on 41 of these for which photometry in at least four IRAC or WISE bands was available.
3. Seven *Chandra* sources are classified as YSOs, four of which were already known from previous studies. In addition, three X-ray sources have optical counterparts in the *HST* GSC or Tycho catalogs that are classified as stars but it remains to be determined whether they are PMS stars. We have classified 28 of the X-ray sources as extragalactic on the basis of their IR properties but additional extragalactic contaminants are likely present among the 19 X-ray sources which lack sufficient IR data to assign object classes. But some of the unclassified X-ray sources may be weak-lined T Tauri stars, which are conspicuously absent in previous YSO surveys of L1228. Evidence that some wTTS may be present comes from the X-ray detection of H $\alpha$  emission-line star OSHA 38 whose IR SED shows no evidence for a significant disk.
4. Disk properties were inferred for four of the YSOs having good-quality IR photometry using the SED modeling tool of Robitaille et al. (2007). Similar SED modeling was undertaken for the protostars HH 199-IRS and HH 200-IRS.
5. Faint hard X-ray emission was detected from HH 200 IRS, the suspected driving source of the HH 200 giant outflow. Its IR colors confirm that it is a class I protostar and there are hints that its IR emission is variable. A close IR companion located 5.''7 away also has a rising IR SED characteristic of a protostar but was undetected by *Chandra*. A very high circumstellar extinction is inferred for HH 200-IRS from SED modeling, which likely accounts for its hard X-ray emission. No X-ray emission was detected from HH 199-IRS but its IR colors and spectral index yield a class I protostar classification. Modeling of its IR SED shows that it is at least an order of magnitude more luminous than HH 200-IRS if it lies at the same distance.
6. The X-ray luminosities of the T Tauri stars in L1228 detected by *Chandra* are low:  $\log L_x \lesssim 29.7$  ergs s $^{-1}$ , assuming  $A_V$  and distances at the high end of the L1228 range. If a correlation between  $L_x$  and stellar mass exists among TTS in L1228 similar to that in Taurus and Orion, then the inferred masses of the X-ray detected TTS are  $M_* \lesssim$

$0.7 M_{\odot}$ . Although this result is based only on partial X-ray coverage of the L1228 dark cloud, it is nevertheless consistent with the broader picture that L1228 has formed only low-mass stars.

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Table 1. Chandra Observation of L1228

| Parameter                           |                     |
|-------------------------------------|---------------------|
| ObsId                               | 7425                |
| Start Date/Time (TT)                | 2007-07-22/20:33:39 |
| Stop Date/Time (TT)                 | 2007-07-23/07:13:40 |
| Instrument                          | ACIS-I              |
| Field-of-View (arcmin) <sup>a</sup> | 16.9 × 16.9         |
| Livetime (s)                        | 36,779              |
| Frame time (s)                      | 3.2                 |

<sup>a</sup>Nominal pointing position was at (J2000)  
R.A. =  $20^h 57^m 02.71s$ , Dec. =  $+77^\circ 35' 45.1''$ ,  
or  $(l,b) = (111.664^\circ, +20.226^\circ)$ .

Table 2. Spitzer Observations of L1228

| Instrument | Mode    | Program (PI) | AORKEY <sup>a</sup> | Frame time<br>(s) | Observation<br>date | Notes                               |
|------------|---------|--------------|---------------------|-------------------|---------------------|-------------------------------------|
| IRAC       | Map     | 104 (Soifer) | 6577664             | 12 <sup>b</sup>   | 2003-12-06          | First Look Survey (FLS)             |
| IRAC       | Map     | 139 (Evans)  | 5161216             | 12 <sup>b</sup>   | 2003-12-02          | Cores-to-Disks legacy program       |
| IRAC       | Map     | 3656 (Mundy) | 11400192            | 30                | 2004-12-15          |                                     |
| IRAC       | Map     | 3656 (Mundy) | 11391232            | 30                | 2004-11-27          |                                     |
| MIPS       | Scan    | 104 (Soifer) | 6577408             | 2.6               | 2003-12-08          | FLS; MIPS 24, 70, 160 $\mu\text{m}$ |
| MIPS       | Photom. | 139 (Evans)  | 5161472             | 2.6               | 2003-12-13          | very small footprint                |
| MIPS       | Photom. | 3656 (Mundy) | 11397632            | 9.96              | 2004-12-26          | MIPS 24 $\mu\text{m}$ only          |
| MIPS       | Photom. | 3656 (Mundy) | 11395072            | 9.96              | 2004-12-07          | MIPS 24 $\mu\text{m}$ only          |

<sup>a</sup>An AOR (Astronomical Observation Request) is the fundamental unit of Spitzer observing. An AORKEY is the unique 8-digit identifier for the AOR which can be used to retrieve these data from the Spitzer archive.

<sup>b</sup>Obtained in high dynamic range (HDR) mode, consisting of a short 0.6 s and long 12 s frame at each pointing.

Table 3. Chandra X-ray Sources in Lynds 1228<sup>a</sup>

| CXO<br>nr. | R.A.<br>(J2000) | Decl.<br>(J2000) | Net Counts<br>(cts) | $\bar{E}$<br>(keV) | $P_{var}$ | IR | IR Class       | Notes                  |
|------------|-----------------|------------------|---------------------|--------------------|-----------|----|----------------|------------------------|
| 1          | 20 54 38.03     | +77 39 13.03     | 11±4                | 2.66               | 0.46      | y  | ...            | 1,2                    |
| 2          | 20 54 39.93     | +77 40 00.51     | 9±4                 | 2.40               | 0.40      | y  | ...            | 1,2                    |
| 3          | 20 54 42.76     | +77 31 49.17     | 7±3                 | 1.81               | 0.83      | n  | ...            |                        |
| 4          | 20 54 45.42     | +77 29 35.74     | 13±4                | 2.70               | 0.38      | n  | ...            | 1                      |
| 5          | 20 54 46.34     | +77 36 58.24     | 12±4                | 3.65               | 0.47      | y  | ...            | 2,3                    |
| 6          | 20 54 51.05     | +77 33 11.31     | 11±3                | 2.65               | 0.60      | y  | agn            |                        |
| 7          | 20 55 00.39     | +77 40 37.38     | 27±6                | 3.12               | 0.55      | y  | agn            |                        |
| 8          | 20 55 06.20     | +77 30 03.59     | 57±8                | 2.38               | 0.96      | y  | agn            |                        |
| 9          | 20 55 14.38     | +77 34 03.69     | 18±5                | 2.42               | 0.36      | y  | agn            |                        |
| 10         | 20 55 27.94     | +77 35 22.62     | 135±12              | 1.29               | 0.99      | y  | none/star      | 4                      |
| 11         | 20 55 34.40     | +77 34 36.88     | 18±4                | 3.20               | 0.55      | y  | ...            | 2                      |
| 12         | 20 55 46.39     | +77 29 42.88     | 7±3                 | 3.54               | 0.44      | n  | ...            |                        |
| 13         | 20 55 50.22     | +77 30 32.87     | 20±5                | 2.54               | 0.48      | n  | ...            |                        |
| 14         | 20 56 00.44     | +77 41 05.33     | 8±3                 | 2.46               | 0.43      | y  | galaxy/yso?    | 3,8                    |
| 15         | 20 56 03.86     | +77 30 16.28     | 16±4                | 3.88               | 0.77      | y  | ...            | 2                      |
| 16         | 20 56 13.39     | +77 45 21.47     | 10±4                | 3.77               | 0.67      | y  | yso (cl. I/II) | 1,3                    |
| 17         | 20 56 15.06     | +77 30 40.38     | 7±3                 | 2.08               | 0.47      | y  | ...            | 2                      |
| 18         | 20 56 15.77     | +77 39 21.97     | 25±5                | 1.11               | 0.47      | y  | none           |                        |
| 19         | 20 56 16.58     | +77 29 21.25     | 22±5                | 2.52               | 0.35      | y  | ...            | 2                      |
| 20         | 20 56 17.15     | +77 40 27.23     | 7±3                 | 2.90               | 0.49      | y  | ...            | 2                      |
| 21         | 20 56 21.97     | +77 32 37.25     | 13±4                | 3.76               | 0.57      | y  | galaxy/agn     |                        |
| 22         | 20 56 26.19     | +77 28 44.39     | 10±3                | 2.33               | 0.62      | y  | ...            | 1,2                    |
| 23         | 20 56 27.47     | +77 42 52.57     | 21±5                | 3.23               | 0.50      | y  | agn            |                        |
| 24         | 20 56 40.29     | +77 34 20.29     | 27±5                | 3.92               | 0.83      | y  | galaxy/agn     |                        |
| 25         | 20 57 05.32     | +77 42 25.21     | 22±5                | 2.71               | 0.50      | y  | galaxy         |                        |
| 26         | 20 57 06.72     | +77 36 56.10     | 5±2                 | 5.10               | 0.34      | y  | yso (cl. I)    | HH200-IRS              |
| 27         | 20 57 08.23     | +77 36 37.76     | 10±3                | 3.57               | 0.33      | y  | agn            |                        |
| 28         | 20 57 09.55     | +77 32 42.98     | 10±3                | 3.64               | 0.60      | y  | none           |                        |
| 29         | 20 57 15.56     | +77 37 53.63     | 81±9                | 1.39               | 0.15      | y  | none/star      | 5                      |
| 30         | 20 57 16.88     | +77 36 58.33     | 12±3                | 2.35               | 0.47      | y  | yso (cl. II)   |                        |
| 31         | 20 57 26.69     | +77 28 50.90     | 57±8                | 2.63               | 0.99      | y  | galaxy/agn     |                        |
| 32         | 20 57 29.17     | +77 32 45.55     | 6±2                 | 4.48               | 0.33      | y  | agn            |                        |
| 33         | 20 57 32.51     | +77 29 04.68     | 8±3                 | 3.25               | 0.44      | y  | ...            | 2                      |
| 34         | 20 57 35.86     | +77 29 19.31     | 9±3                 | 2.86               | 0.44      | y  | galaxy/agn     |                        |
| 35         | 20 57 36.97     | +77 29 03.02     | 9±3                 | 1.99               | 0.47      | y  | agn            |                        |
| 36         | 20 57 38.62     | +77 34 12.32     | 25±5                | 1.40               | 0.47      | y  | none/yso       | 6; H $\alpha$ em. star |
| 37         | 20 57 38.82     | +77 33 34.92     | 40±6                | 3.58               | 0.40      | y  | galaxy/agn     |                        |
| 38         | 20 57 40.24     | +77 28 38.71     | 123±12              | 2.38               | 0.59      | y  | agn            |                        |
| 39         | 20 57 44.26     | +77 34 19.56     | 8±3                 | 3.99               | 0.48      | y  | agn            |                        |
| 40         | 20 57 52.30     | +77 37 30.13     | 8±3                 | 3.56               | 0.65      | y  | agn            |                        |
| 41         | 20 57 54.81     | +77 36 09.83     | 14±4                | 4.05               | 0.39      | y  | agn            |                        |
| 42         | 20 57 55.34     | +77 29 39.00     | 24±5                | 2.53               | 0.33      | y  | galaxy         |                        |
| 43         | 20 58 04.93     | +77 39 42.30     | 29±5                | 2.88               | 0.72      | y  | agn            |                        |
| 44         | 20 58 05.77     | +77 36 48.77     | 21±5                | 2.71               | 0.45      | y  | agn            |                        |
| 45         | 20 58 06.67     | +77 44 02.47     | 9±4                 | 1.70               | 0.65      | y  | none/star      | 1,7                    |
| 46         | 20 58 11.03     | +77 33 18.63     | 6±2                 | 3.29               | 0.53      | y  | none           |                        |
| 47         | 20 58 21.78     | +77 36 15.76     | 17±4                | 3.60               | 0.46      | y  | galaxy/agn     |                        |
| 48         | 20 58 25.18     | +77 27 05.70     | 10±4                | 3.06               | 0.38      | y  | agn            | 1                      |

Table 3—Continued

| CXO<br>nr. | R.A.<br>(J2000) | Decl.<br>(J2000) | Net Counts<br>(cts) | $\bar{E}$<br>(keV) | $P_{var}$ | IR | IR Class     | Notes                  |
|------------|-----------------|------------------|---------------------|--------------------|-----------|----|--------------|------------------------|
| 49         | 20 58 37.61     | +77 33 13.36     | 37±6                | 1.25               | 0.51      | y  | none         |                        |
| 50         | 20 58 38.98     | +77 37 38.94     | 127±11              | 2.54               | 0.98      | y  | agn          |                        |
| 51         | 20 58 39.79     | +77 31 11.28     | 10±4                | 1.79               | 0.34      | y  | ...          | 2                      |
| 52         | 20 58 40.84     | +77 38 20.07     | 11±3                | 2.40               | 0.55      | n  | ...          |                        |
| 53         | 20 58 46.78     | +77 40 25.47     | 75±9                | 1.96               | 0.09      | y  | yso (cl. II) | 9; H $\alpha$ em. star |
| 54         | 20 58 57.09     | +77 41 44.97     | 24±6                | 2.80               | 0.38      | n  | ...          |                        |
| 55         | 20 59 05.10     | +77 34 46.39     | 69±9                | 2.63               | 0.11      | y  | agn          |                        |
| 56         | 20 59 15.26     | +77 33 22.87     | 30±6                | 1.32               | 0.62      | y  | yso (cl. II) |                        |
| 57         | 20 59 15.51     | +77 34 55.20     | 6±3                 | 3.75               | 0.40      | y  | ...          | 2                      |
| 58         | 20 59 18.68     | +77 30 57.72     | 14±4                | 2.43               | 0.20      | y  | agn          | 1,3                    |
| 59         | 20 59 19.10     | +77 42 10.71     | 13±5                | 3.63               | 0.62      | n  | ...          |                        |
| 60         | 20 59 42.55     | +77 38 06.20     | 19±5                | 2.23               | 0.40      | y  | none         | 1                      |

<sup>a</sup>X-ray data are from ACIS-I using events in the 0.3 to 7 keV range. Tabulated quantities are: running source number; X-ray source position (R.A., Decl.) from *wavdetect* based on CXC events list with no additional astrometric refinement; net counts and net counts error obtained from *wavdetect* accumulated in a 36,799 s exposure, rounded to the nearest integer, background subtracted and PSF-corrected; mean photon energy  $\bar{E}$ ; X-ray variability probability  $P_{var}$  from *glvary*. A *y* or *n* in the IR column denotes whether a potential IR counterpart was found (see Table 4). IR Class is based on IR color analysis using the IRAC criteria of Gutermuth et al. (2008) and WISE criteria of Koenig et al. (2012).

Note. —

1. Source lies near edge of ACIS-I array and is heavily vignetted.
2. No IR class assigned due to incomplete IR photometry.
3. IR offset  $>2''$ . IR match questionable. See Table 4 for IR positions.
4. Optical counterpart *HST* GSC J205527.93+773522.1. Classified as stellar in the GSC.
5. Optical counterpart *HST* GSC J205715.70+773753.8. Classified as stellar in the GSC.
6. Optical counterpart is H $\alpha$  emission star nr. 38 in Ogura & Sato (1990).
7. Star. Tycho J205806.80+774402.44.
8. IR classification is ambiguous.
9. Optical counterpart is H $\alpha$  emission star nr. 42 in Ogura & Sato (1990).

Table 4. IR Counterparts to X-ray Sources in L1228

| CXO nr. | 2MASS                     | WISE                      | Spitzer                   | Notes  |
|---------|---------------------------|---------------------------|---------------------------|--------|
| 1       |                           |                           | J205437.98+773911.7 (1.3) | 3      |
| 2       |                           |                           | J205440.45+774002.7 (2.7) | 3,6    |
| 3       |                           |                           |                           | 1      |
| 4       |                           |                           |                           | 1      |
| 5       |                           |                           | J205447.00+773656.6 (2.7) | 2,6    |
| 6       |                           | J205451.29+773311.4 (0.8) |                           | 1      |
| 7       |                           | J205500.21+774037.2 (0.6) | J205500.28+774036.8 (0.7) |        |
| 8       |                           | J205505.85+773005.1 (1.9) |                           | 1      |
| 9       |                           | J205514.07+773405.0 (1.7) | J205514.19+773404.4 (0.9) | 2      |
| 10      | J205527.94+773522.3 (0.3) | J205527.89+773522.7 (0.2) | J205527.98+773522.7 (0.2) | 7      |
| 11      |                           |                           | J205534.17+773437.9 (1.2) | 7      |
| 12      |                           |                           |                           | 2      |
| 13      |                           |                           |                           | 2      |
| 14      | J205600.25+774105.4 (0.6) | J205559.46+774103.6 (3.6) | J205559.57+774103.9 (3.1) | 5,6,7  |
| 15      |                           |                           | J205603.94+773015.8 (0.6) | 4      |
| 16      |                           |                           | J205612.79+774518.4 (3.6) | 6      |
| 17      |                           |                           | J205614.93+773040.8 (0.6) |        |
| 18      | J205615.81+773922.5 (0.5) | J205615.73+773922.2 (0.3) | J205615.94+773921.9 (0.5) |        |
| 19      |                           |                           | J205616.45+772921.3 (0.4) | 4      |
| 20      |                           |                           | J205617.21+774028.1 (0.9) |        |
| 21      |                           | J205621.51+773237.5 (1.5) | J205622.03+773237.6 (0.4) | 7      |
| 22      |                           |                           | J205625.85+772843.4 (1.5) | 4      |
| 23      |                           | J205627.39+774253.1 (0.6) | J205627.29+774253.0 (0.7) |        |
| 24      |                           | J205640.35+773421.1 (0.8) | J205640.29+773420.1 (0.2) |        |
| 25      |                           |                           | J205705.49+774226.6 (1.5) | 7      |
| 26      | J205706.55+773655.9 (0.6) | J205707.16+773657.4 (1.9) | J205706.61+773656.0 (0.4) | 5,8,9  |
| 27      |                           | J205708.44+773637.7 (0.7) | J205708.23+773637.8 (0.0) | 9      |
| 28      |                           |                           | J205709.66+773242.8 (0.4) |        |
| 29      | J205715.60+773754.0 (0.4) | J205715.63+773753.8 (0.3) | J205715.53+773753.8 (0.2) |        |
| 30      | J205716.97+773658.6 (0.4) | J205716.98+773658.5 (0.4) | J205717.02+773658.4 (0.5) | 5,9,10 |
| 31      |                           | J205726.65+772851.4 (0.5) | J205726.58+772851.2 (0.5) |        |
| 32      |                           |                           | J205729.15+773245.4 (0.2) |        |
| 33      |                           |                           | J205732.72+772904.2 (0.8) |        |
| 34      |                           | J205735.43+772918.5 (1.6) | J205735.79+772919.4 (0.2) | 7      |
| 35      |                           | J205737.40+772902.3 (1.6) | J205737.15+772902.9 (0.6) |        |
| 36      | J205738.73+773412.5 (0.4) | J205738.71+773412.4 (0.3) | J205738.73+773412.3 (0.4) | 11     |
| 37      |                           | J205738.82+773335.1 (0.2) | J205738.79+773334.8 (0.2) |        |
| 38      |                           | J205740.44+772838.8 (0.7) | J205740.46+772838.9 (0.7) |        |
| 39      |                           |                           | J205744.35+773419.5 (0.3) |        |
| 40      |                           |                           | J205752.26+773730.2 (0.2) |        |
| 41      |                           |                           | J205754.83+773610.3 (0.5) |        |
| 42      |                           |                           | J205755.09+772938.1 (1.2) | 7      |
| 43      |                           |                           | J205804.99+773942.8 (0.5) |        |
| 44      |                           | J205805.86+773648.5 (0.4) | J205805.86+773648.8 (0.4) |        |
| 45      | J205806.81+774402.4 (0.5) | J205806.82+774402.3 (0.5) | J205806.83+774402.5 (0.5) | 3      |
| 46      |                           |                           | J205811.25+773318.8 (0.7) |        |
| 47      |                           | J205821.91+773616.0 (0.5) | J205821.70+773616.0 (0.4) |        |
| 48      |                           | J205825.16+772706.3 (0.6) | J205825.28+772705.7 (0.3) |        |
| 49      | J205837.68+773314.0 (0.7) | J205837.72+773313.7 (0.5) | J205837.62+773314.0 (0.6) |        |

Table 4—Continued

| CXO nr. | 2MASS                     | WISE                      | Spitzer                   | Notes  |
|---------|---------------------------|---------------------------|---------------------------|--------|
| 50      |                           | J205839.07+773739.0 (0.3) | J205839.00+773738.9 (0.1) |        |
| 51      |                           |                           | J205839.96+773111.4 (0.6) |        |
| 52      |                           |                           |                           | 2      |
| 53      | J205846.68+774025.6 (0.3) | J205846.71+774025.6 (0.3) | J205846.71+774026.0 (0.6) | 2,9,12 |
| 54      |                           |                           |                           | 1      |
| 55      |                           |                           | J205905.14+773447.5 (1.1) |        |
| 56      | J205915.41+773322.8 (0.5) | J205915.40+773322.8 (0.5) | J205915.37+773322.7 (0.4) |        |
| 57      |                           |                           | J205915.42+773455.2 (0.3) | 4,7    |
| 58      |                           | J205919.39+773056.7 (2.5) | J205919.28+773056.7 (2.2) | 6      |
| 59      |                           |                           |                           | 1      |
| 60      | J205942.32+773808.3 (2.2) | J205942.35+773808.1 (2.0) |                           | 1,6    |

Note. — The number in parentheses is the offset in arcseconds between the IR position and the X-ray position in Table 3.

1. Source lies outside *Spitzer* coverage area.
2. Source is off-edge in IRAC 1-4.
3. Source is off-edge in IRAC 1 & 3.
4. Source is off-edge in IRAC 2 & 4.
5. Source appears extended in IRAC images.
6. IR position is offset by  $> 2''$  from X-ray position. Match is questionable.
7. Multiple IR sources near X-ray position. Possible source confusion.
8. HH 200-IRS. Previously identified in Table 1 of Devine et al. (2009) and as source 5 in Table 4 of Chapman and Mundy (2009). The radio counterpart is L1228 VLA 4 in Table 2 of Reipurth et al. (2004). Source is extended in 2MASS, IRAC, and WISE images. Close IR companion (Fig. 6).
9. WISE emission is likely variable ( $varflg \geq 6$  in one or more bands).
10. Corresponds to source 9 in Table 4 of Chapman and Mundy (2009) and source 11 of Kirk et al. (2009).
11. Optical counterpart is source 38 (OSHA 38) of Ogura & Sato (1990).
12. Optical counterpart is source OSHA 42 in Table 1 of Kun et al. (2009) and source 42 of Ogura & Sato (1990).

Table 5. L1228 IR Photometry<sup>a</sup>

| CXO nr.           | J          | H          | K <sub>s</sub> | I1         | I2         | I3         | I4         | M1         | W1         | W2         | W3         | W4        |
|-------------------|------------|------------|----------------|------------|------------|------------|------------|------------|------------|------------|------------|-----------|
| 1                 |            |            |                | ...        | 17.58 0.27 | ...        | ...        | ...        |            |            |            |           |
| 2                 |            |            |                | ...        | 17.31 0.23 | ...        | 16.16 0.27 | ...        |            |            |            |           |
| 3                 |            |            |                | ...        | ...        | ...        | ...        | ...        |            |            |            |           |
| 4                 |            |            |                | ...        | ...        | ...        | ...        | ...        |            |            |            |           |
| 5                 |            |            |                | ...        | ...        | ...        | ...        | 9.90 0.19  |            |            |            |           |
| 6                 |            |            |                | ...        | ...        | ...        | ...        | ...        | 17.73 0.18 | 16.51 0.22 | 13.27 ...  | 9.57 ...  |
| 7                 |            |            |                | 15.98 0.06 | 15.73 0.12 | 15.17 0.09 | 14.40 0.11 | 10.89 0.13 | 16.51 0.07 | 15.88 0.12 | 13.12 ...  | 9.56 ...  |
| 8                 |            |            |                | ...        | ...        | ...        | ...        | ...        | 16.31 0.06 | 15.42 0.08 | 13.19 ...  | 9.35 ...  |
| 9                 |            |            |                | ...        | ...        | ...        | ...        | 9.13 0.15  | 15.57 0.04 | 14.91 0.06 | 12.24 0.23 | 9.12 0.35 |
| 10                | 13.88 0.03 | 13.26 0.03 | 13.07 0.05     | 12.78 0.05 | 12.76 0.06 | 12.70 0.05 | 12.64 0.05 | ...        | 12.85 0.02 | 12.65 0.02 | 12.27 0.24 | 9.30 ...  |
| 11                |            |            |                | ...        | 16.71 0.18 | ...        | 15.22 0.18 | ...        |            |            |            |           |
| 12                |            |            |                | ...        | ...        | ...        | ...        | ...        |            |            |            |           |
| 13                |            |            |                | ...        | ...        | ...        | ...        | >10.80     |            |            |            |           |
| 14                |            |            | >13.93         | 13.39 0.06 | 13.28 0.07 | 11.85 0.06 | 9.90 0.06  | ...        | 13.12 0.02 | 12.85 0.02 | 8.80 0.02  | 6.73 0.06 |
| 15                |            |            |                | 16.44 0.06 | ...        | 15.67 0.10 | ...        | ...        |            |            |            |           |
| 16                |            |            |                | 17.96 0.28 | 17.03 0.20 | 16.30 0.36 | 16.56 0.30 | >10.99     |            |            |            |           |
| 17                |            |            |                | 18.51 0.07 | ...        | ...        | ...        | >11.86     |            |            |            |           |
| 18                | 10.39 0.03 | 9.98 0.03  | 9.98 0.03      | 9.84 0.05  | 9.84 0.05  | 9.82 0.05  | 9.78 0.05  | 9.77 0.11  | 9.79 0.02  | 9.84 0.02  | 9.87 0.03  | 9.27 ...  |
| 19                |            |            |                | 17.88 0.06 | ...        | 16.37 0.21 | ...        | ...        |            |            |            |           |
| 20                |            |            |                | 17.45 0.22 | 17.03 0.20 | ...        | 15.95 0.21 | ...        |            |            |            |           |
| 21                |            |            |                | 17.59 0.06 | 17.26 0.23 | 17.04 0.28 | 16.61 0.33 | ...        | 17.54 0.15 | 17.13 ...  | 13.25 ...  | 9.65 ...  |
| 22                |            |            |                | >17.85     | ...        | ...        | ...        | ...        |            |            |            |           |
| 23                |            |            |                | 15.09 0.05 | 14.01 0.07 | 12.92 0.06 | 11.77 0.06 | 8.48 0.11  | 15.71 0.04 | 14.00 0.04 | 10.91 0.07 | 8.58 0.22 |
| 24                |            |            |                | 17.17 0.05 | 16.71 0.18 | 16.21 0.06 | 15.88 0.24 | ...        | 16.74 0.08 | 16.07 0.14 | 12.49 0.24 | 9.62 0.45 |
| 25                |            |            |                | 16.71 0.06 | 16.20 0.05 | 16.03 0.15 | 14.76 0.06 | 10.92 0.13 |            |            |            |           |
| 26 <sup>b,c</sup> | 14.76 0.09 | 13.56 0.08 | 12.71 0.05     | 11.37 0.06 | 10.57 0.06 | 9.76 0.06  | 8.85 0.05  | 3.38 0.11  | 11.75 0.02 | 10.63 0.02 | 7.42 0.01  | 3.43 0.01 |
| 27 <sup>c</sup>   |            |            |                | 16.45 0.13 | 15.17 0.10 | 13.87 0.08 | 13.32 0.08 | ...        | 16.84 0.09 | 14.69 0.05 | 12.26 0.20 | 7.58 0.08 |
| 28                |            |            |                | 18.16 0.06 | 17.30 0.06 | 17.42 0.13 | 17.18 0.26 | ...        |            |            |            |           |
| 29                | 12.14 0.02 | 11.48 0.03 | 11.10 0.02     | 10.66 0.05 | 10.60 0.06 | 10.51 0.06 | 10.46 0.05 | ...        | 10.86 0.02 | 10.56 0.02 | 10.24 0.04 | 8.74 0.22 |
| 30 <sup>c</sup>   | 13.51 0.03 | 11.98 0.03 | 11.00 0.02     | 9.96 0.05  | 9.24 0.05  | 8.76 0.05  | 8.04 0.05  | 4.91 0.11  | 10.03 0.02 | 9.14 0.02  | 7.09 0.01  | 4.72 0.02 |
| 31                |            |            |                | 16.47 0.05 | 16.04 0.06 | 15.57 0.06 | 15.26 0.12 | ...        | 16.91 0.09 | 16.43 0.19 | 12.15 0.18 | 9.74 0.53 |
| 32                |            |            |                | 16.21 0.05 | 15.62 0.05 | 14.92 0.11 | 13.79 0.06 | ...        |            |            |            |           |
| 33                |            |            |                | 17.59 0.06 | 16.65 0.07 | 16.20 0.07 | >15.39     | ...        |            |            |            |           |
| 34                |            |            |                | 16.65 0.05 | 16.33 0.06 | 16.00 0.06 | 14.71 0.16 | ...        | 17.12 0.11 | 16.56 0.21 | 12.26 0.20 | 9.11 ...  |
| 35                |            |            |                | 16.77 0.05 | 15.74 0.12 | 14.41 0.05 | 13.61 0.09 | 9.83 0.11  | 17.73 0.18 | 15.78 0.11 | 11.40 0.09 | 8.92 0.25 |
| 36                | 11.98 0.02 | 11.05 0.03 | 10.73 0.02     | 10.60 0.05 | 10.54 0.06 | 10.47 0.06 | 10.46 0.06 | 10.60 0.11 | 10.62 0.02 | 10.49 0.02 | 10.34 0.04 | 8.91 0.25 |
| 37                |            |            |                | 16.65 0.05 | 16.06 0.05 | 15.56 0.06 | 14.89 0.07 | 10.87 0.11 | 16.68 0.08 | 16.37 0.18 | 12.44 0.22 | 9.47 ...  |

Table 5—Continued

| CXO nr.          | J          | H          | K <sub>s</sub> | I1         | I2         | I3         | I4         | M1         | W1         | W2         | W3         | W4        |
|------------------|------------|------------|----------------|------------|------------|------------|------------|------------|------------|------------|------------|-----------|
| 38               |            |            |                | 16.38 0.05 | 15.65 0.12 | 14.64 0.06 | 13.72 0.10 | 10.50 0.12 | 16.74 0.08 | 15.54 0.10 | 12.04 0.16 | 9.43 0.41 |
| 39               |            |            |                | 17.36 0.06 | 16.42 0.06 | 15.75 0.06 | 14.21 0.06 | ... ..     |            |            |            |           |
| 40               |            |            |                | 18.20 0.06 | 17.54 0.06 | 16.56 0.08 | 16.00 0.09 | 12.03 0.18 |            |            |            |           |
| 41               |            |            |                | 17.38 0.05 | 16.59 0.06 | 16.23 0.19 | 15.24 0.07 | 11.52 0.14 |            |            |            |           |
| 42               |            |            |                | 16.78 0.15 | 16.25 0.16 | 15.86 0.16 | 14.38 0.12 | 10.40 0.11 |            |            |            |           |
| 43               |            |            |                | 17.02 0.05 | 16.45 0.06 | 16.08 0.06 | 15.83 0.22 | >10.77     |            |            |            |           |
| 44               |            |            |                | 16.99 0.05 | 16.19 0.05 | 15.47 0.06 | 14.26 0.06 | 10.54 0.11 | 17.09 0.10 | 15.70 0.10 | 11.70 0.12 | 9.35 ...  |
| 45               | 10.79 0.02 | 10.50 0.03 | 10.47 0.02     | ... ..     | 10.48 0.06 | ... ..     | 10.43 0.06 |            | 10.41 0.02 | 10.43 0.02 | 10.37 0.04 | 9.40 ...  |
| 46               |            |            |                | 16.39 0.13 | 16.01 0.13 | 15.76 0.15 | 15.68 0.20 |            |            |            |            |           |
| 47               |            |            |                | 16.75 0.05 | 15.78 0.12 | 14.89 0.11 | 13.88 0.09 | 10.72 0.12 | 16.90 0.09 | 16.01 0.13 | 12.00 0.16 | 9.53 0.45 |
| 48               |            |            |                | 16.34 0.05 | 16.07 0.06 | 15.71 0.06 | 14.88 0.18 |            | 16.71 0.08 | 17.16 0.35 | 12.57 0.25 | 9.68 ...  |
| 49               | 13.71 0.03 | 13.13 0.04 | 12.84 0.03     | 12.60 0.05 | 12.52 0.05 | 12.42 0.05 | 12.43 0.05 | 11.65 0.14 | 12.69 0.03 | 12.53 0.02 | 11.58 0.10 | 9.16 ...  |
| 50               |            |            |                | 16.29 0.05 | 15.40 0.05 | 14.52 0.06 | 13.44 0.06 |            | 16.58 0.07 | 15.12 0.07 | 11.32 0.09 | 8.99 0.28 |
| 51               |            |            |                | 18.24 0.06 | ... ..     | 16.95 0.08 | ... ..     | >12.45     |            |            |            |           |
| 52               |            |            |                | ... ..     | ... ..     | ... ..     | ... ..     | >13.87     |            |            |            |           |
| 53 <sup>c</sup>  | 11.51 0.02 | 10.36 0.03 | 9.70 0.02      | ... ..     | ... ..     | ... ..     | ... ..     | 4.52 0.11  | 8.75 0.02  | 8.09 0.02  | 6.50 0.01  | 4.45 0.02 |
| 54               |            |            |                | ... ..     | ... ..     | ... ..     | ... ..     | ... ..     |            |            |            |           |
| 55               |            |            |                | 17.65 0.06 | 16.96 0.09 | 16.40 0.08 | 15.06 0.23 | ... ..     |            |            |            |           |
| 56               | 11.90 0.02 | 10.95 0.03 | 10.55 0.02     | 10.25 0.05 | 9.92 0.05  | 9.60 0.05  | 8.84 0.05  | 6.35 0.11  | 10.29 0.02 | 9.95 0.02  | 7.95 0.02  | 6.20 0.04 |
| 57               |            |            |                | 18.21 0.29 | ... ..     | ... ..     | ... ..     | ... ..     |            |            |            |           |
| 58               |            |            |                | 15.83 0.11 | 15.70 0.12 | 15.20 0.12 | 14.44 0.14 | ... ..     | 15.84 0.05 | 15.33 0.08 | 11.87 0.14 | 9.09 ...  |
| 59               |            |            |                | ... ..     | ... ..     | ... ..     | ... ..     | ... ..     |            |            |            |           |
| 60               | 14.56 0.04 | 13.99 0.04 | 13.59 0.05     | ... ..     | ... ..     | ... ..     | ... ..     | ... ..     | 13.49 0.02 | 13.32 0.03 | 11.43 0.09 | 9.72 0.53 |
| 199 <sup>d</sup> | 13.02 0.03 | 10.61 0.03 | 9.17 0.03      | ... ..     | ... ..     | ... ..     | ... ..     | ... ..     | 7.89 0.02  | 6.55 0.02  | 3.88 0.01  | 1.38 0.01 |

<sup>a</sup>J,H,K<sub>s</sub> = 2MASS. I1 - I4 = IRAC bands 1-4. M1 = MIPS-24. W1 - W4 = WISE bands 1-4. Each column gives source magnitude followed by its uncertainty.

<sup>b</sup>There is disagreement between 2MASS JHK<sub>s</sub> photometry and that obtained with the KPNO 4m by Chapman & Mundy (2009).

<sup>c</sup>IR emission may be variable. WISE *varflag* ≥ 6 in one or more bands.

<sup>d</sup>HH 199-IRS. Not detected by Chandra.

Table 6. Spectral Fits of Lynds 1228 Bright X-ray Sources<sup>1</sup>

| CXO<br>nr.      | Model           | $N_{\text{H}}$<br>( $10^{22}$ cm <sup>-2</sup> ) | $kT_1$<br>(keV)    | $\Gamma$           | norm <sub>1</sub><br>( $10^{-5}$ ) | $\chi^2/\text{dof}$ | $F_x(0.3 - 7 \text{ keV})$<br>( $10^{-14}$ erg cm <sup>-2</sup> s <sup>-1</sup> ) |
|-----------------|-----------------|--|--------------------|--------------------|------------------------------------|---------------------|---|
| 8               | 1T              | 1.10 [0.25 - 3.04]                               | 2.20 [0.83 - 9.88] | ...                | 3.11 [1.52 - 11.9]                 | 7.39/8              | 1.94 (4.86)   |
| 8               | PL              | 1.05 [0.24 - 3.14]                               | ...                | 2.55 [1.49 - 4.35] | 1.63 [0.00 - 16.3]                 | 8.01/8              | 1.92 (7.59)   |
| 10              | 2T <sup>a</sup> | 0.16 [0.00 - 0.50]                               | 0.22 [0.14 - 0.51] | ...                | 1.97 [0.23 - ...]                  | 7.61/7              | 3.01 (6.57)   |
| 29              | 1T              | 0.69 [0.35 - 0.99]                               | 0.84 [0.56 - 1.05] | ...                | 1.92 [0.91 - 4.14]                 | 2.99/3              | 1.20 (6.17)   |
| 31              | 1T              | 0.70 [0.06 - 1.78]                               | 4.09 [1.54 - ...]  | ...                | 2.10 [1.21 - 4.28]                 | 2.82/4              | 2.13 (3.56)   |
| 31              | PL              | 0.66 [0.04 - 1.71]                               | ...                | 1.95 [1.02 - 3.12] | 0.77 [0.00 - 3.03]                 | 2.92/4              | 2.01 (3.95)   |
| 38              | 1T              | 0.32 [0.09 - 0.65]                               | 6.38 [3.20 - ...]  | ...                | 3.26 [2.55 - 4.31]                 | 11.2/11             | 4.35 (5.82)   |
| 38              | PL              | 0.42 [0.11 - 0.84]                               | ...                | 1.83 [1.23 - 2.58] | 1.23 [0.60 - 2.69]                 | 11.0/11             | 4.06 (6.69)   |
| 50 <sup>b</sup> | 1T              | 0.31 [0.12 - 0.69]                               | 20.4 [4.35 - ...]  | ...                | 3.80 [2.96 - 5.14]                 | 3.32/6              | 4.96 (6.25)   |
| 50 <sup>b</sup> | PL              | 0.35 [0.07 - 0.75]                               | ...                | 1.44 [0.97 - 1.99] | 0.92 [0.49 - 1.78]                 | 3.31/6              | 4.84 (6.47)   |
| 53              | 1T              | 0.20 [0.01 - 1.45]                               | 2.71 [0.49 - 4.79] | ...                | 1.73 [1.21 - 12.4]                 | 6.62/8              | 1.99 (2.76) <sup>c</sup>  |
| 53              | 1T              | {0.65} <sup>d</sup>                              | 1.60 [1.22 - 2.19] | ...                | 2.22 [1.63 - 2.85]                 | 8.58/9              | 1.59 (3.90)   |
| 55              | 1T              | 1.84 [0.40 - 3.79]                               | 2.91 [1.50 - ...]  | ...                | 4.25 [1.78 - 10.8]                 | 4.04/4              | 2.68 (6.84)   |
| 55              | PL              | 1.84 [0.26 - 5.65]                               | ...                | 2.23 [0.98 - 4.54] | 1.87 [0.00 - 53.7]                 | 5.09/4              | 2.56 (8.81)   |

<sup>1</sup>Based on XSPEC (vers. 12.7.1) fits of background-subtracted ACIS-I spectra binned to a minimum of 10 counts per bin, unless otherwise noted. The tabulated parameters are the CXO source number (Table 3); model type, where PL denotes a power-law model and 1T or 2T denotes the number of temperature components in the *apec* optically thin thermal plasma model; absorption column density ( $N_{\text{H}}$ ); plasma energy ( $kT_1$ ); photon power-law index ( $\Gamma$ ) where  $F_x \propto E^{-(\Gamma-1)}$ ; XSPEC component normalization (norm<sub>1</sub>);  $\chi^2$  statistic/degrees-of-freedom; and the absorbed X-ray flux followed in parentheses by the unabsorbed flux. For those sources classified as galaxies or AGNs on the basis of IR colors, results of a PL model are given in addition to thermal models. Solar abundances were assumed for *apec* models and are referenced to the values of Anders & Grevesse (1989). Square brackets enclose 90% confidence intervals and an ellipsis means that the algorithm used to compute confidence intervals did not converge.

<sup>a</sup>A 1T model fit is statistically unacceptable. The 2T model requires an additional hot plasma component at  $kT_2 = 1.43$  [1.22 - 1.95] keV and norm<sub>2</sub> = 1.33 [0.85 - 1.94]. The tabulated results are for the 2T model.

<sup>b</sup>The spectrum was binned to a minimum of 15 counts per bin. A 1T model requires a high but uncertain plasma temperature.

<sup>c</sup>Class II YSO (OSHA 42). At an assumed L1228 distance of 200 pc the unabsorbed flux gives an X-ray luminosity  $\log L_x(0.3 - 7 \text{ keV}) = 29.12$  ergs s<sup>-1</sup>.

<sup>d</sup> $N_{\text{H}}$  held fixed at the value corresponding to  $A_V = 3.42$  mag obtained by Kun et al. (2009). The unabsorbed flux gives  $\log L_x(0.3 - 7 \text{ keV}) = 29.27$  ergs s<sup>-1</sup> at  $d = 200$  pc.

Table 7. IR SED Model Fits of Lynds 1228 YSOs<sup>1</sup>

| CXO<br>nr.      | $A_{V,ism}$<br>(mag) | $A_{V,cs}$<br>(mag) | $M_{disk}$<br>( $M_{\odot}$ ) | $\dot{M}_{acc}$<br>( $M_{\odot} \text{ yr}^{-1}$ ) | dist.<br>(pc) | $L_{tot}$<br>( $L_{\odot}$ ) | $\alpha$ | IR class<br>( $\alpha$ ) | IR class<br>(colors) |
|-----------------|----------------------|---------------------|-------------------------------|--|---------------|------------------------------|----------|--------------------------|----------------------|
| 14 <sup>a</sup> | ...                  | ...                 | ...                           | ...  | ...           | ...                          | +1.38    | I                        | I                    |
| 16 <sup>a</sup> | ...                  | ...                 | ...                           | ...  | ...           | ...                          | +0.31    | I/flat                   | I/II                 |
| 26 <sup>b</sup> | 5.0                  | >32 <sup>b</sup>    | 1.1e-04                       | 2.0e-06 <sup>c</sup>                               | 191           | 0.66                         | -0.04    | flat                     | I                    |
| 30              | 8.9                  | <0.35 <sup>d</sup>  | 1.3e-03                       | 6.5e-07 <sup>c</sup>                               | 209           | 0.24                         | -0.56    | II                       | II                   |
| 53              | 3.4                  | 2.2                 | 7.9e-03                       | 3.8e-07  | 191           | 0.52                         | -0.98    | II                       | II                   |
| 56              | 1.9                  | ... <sup>c</sup>    | 1.3e-04                       | 3.5e-11 <sup>c</sup>                               | 200           | 0.23                         | -1.44    | II                       | II                   |

<sup>1</sup>Based on fits of  $JHK_s$  and *Spitzer* IRAC/MIPS-24 and WISE IR photometry using the Robitaille et al. (2007) modeling tool. The source number in the first column refers to Table 3. Tabulated parameters determined from the modeling tool are the interstellar and circumstellar extinctions, disk mass, mass accretion rates (sum of disk and envelope contributions), best-fit distance (constrained during fitting to lie within the range 180 - 220 pc), and total system luminosity  $L_{bol}$ . The quoted values are the median values of the five fitted models with the lowest  $\chi^2$  fit statistic, unless otherwise noted. The IR spectral index  $\alpha$  is based on power-law fits over the  $\approx 2 - 8 \mu\text{m}$  range where  $\alpha = d \log(\lambda F_{\lambda}) / d \log \lambda$ . The IR class is based on the spectral index criteria of Haisch et al. (2001) and that determined from mid-IR colors (see Fig. 5).

<sup>a</sup>No SED modeling performed due to lack of near-IR photometry.

<sup>b</sup>HH 200-IRS. The fit used more recent  $JHK_s$  photometry from Chapman & Mundy (2009) instead of 2MASS data. The  $A_{V,cs}$  limit is the lowest value obtained from the set of best-fit models.

<sup>c</sup>Parameter is not tightly constrained by IR SED models. Fitted values for different models span an order of magnitude.

<sup>d</sup>The  $A_{V,cs}$  limit is the largest value obtained from the set of best-fit models.

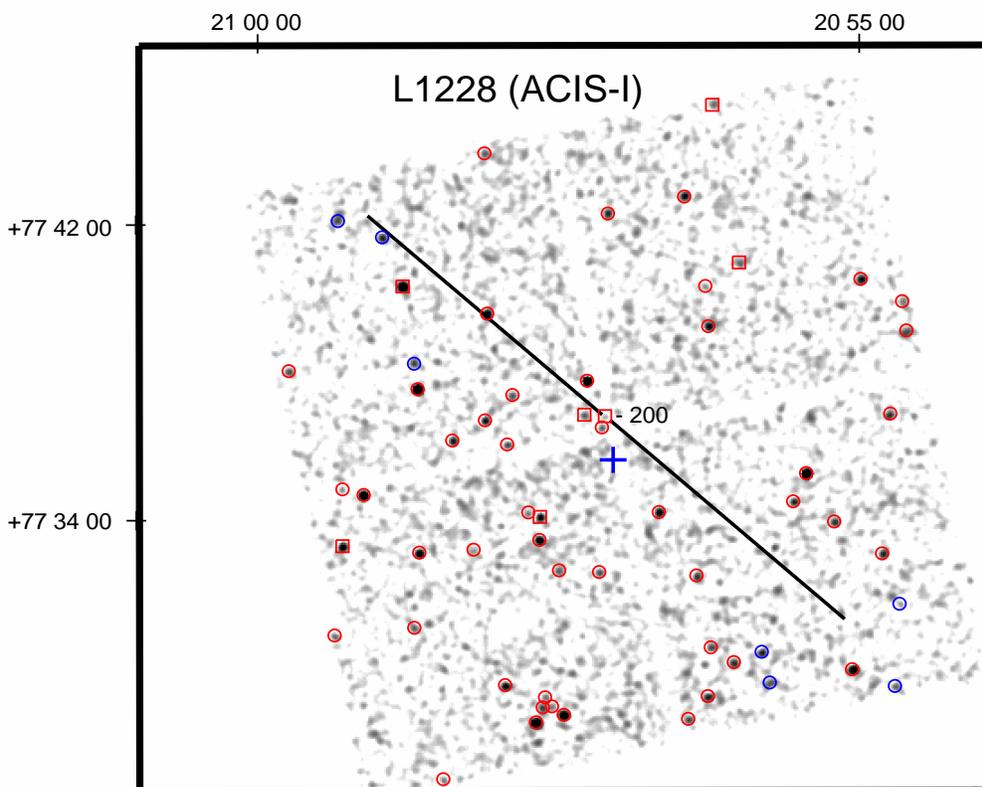


Fig. 1.— Positions of L1228 X-ray sources overlaid on the *Chandra* ACIS-I image (0.3 - 7 keV). The image has been Gaussian-smoothed with a 3-pixel kernel. The raw (unsmoothed) pixel size is  $0.''49$ . Objects marked in red have candidate IR counterparts (Table 4) and those in blue lack counterparts. Squares denote known or suspected YSOs (Table 3). The object labeled “200” is HH 200-IRS (CXO source nr. 26 in Table 3). The solid lines show the HH 200 bipolar outflow axes at P.A. =  $49^\circ/229^\circ$ , measured east from north (Devine et al. 2009). A cross (+) marks the nominal pointing position. Log intensity scale. J2000 coordinate overlay.

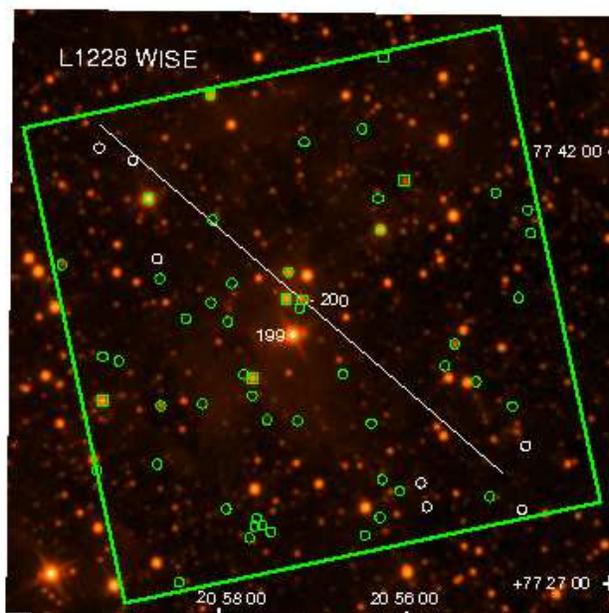


Fig. 2.— Positions of L1228 X-ray sources overlaid on a WISE W1 ( $3.4 \mu\text{m}$ ) image. Squares denote known or suspected YSOs. Objects marked in green have IR counterparts but only the brightest IR sources are visible in this image. Objects marked in white circles lack IR counterparts. The HH-driving sources HH 199-IRS (IRAS 20582+7724) and HH 200-IRS are marked. The solid lines show the HH 200 outflow axes at P.A. =  $49^\circ/229^\circ$ . The emission knots associated with HH 199 are directed generally eastward (to the left) but span a range of position angles P.A. =  $60^\circ - 100^\circ$  (Devine et al. 2009; see also Fig. 7). HH 199-IRS was not detected in X-rays. The *Chandra* ACIS-I detector footprint is shown as a  $16.9' \times 16.9'$  square. Log intensity scale. J2000 coordinates.

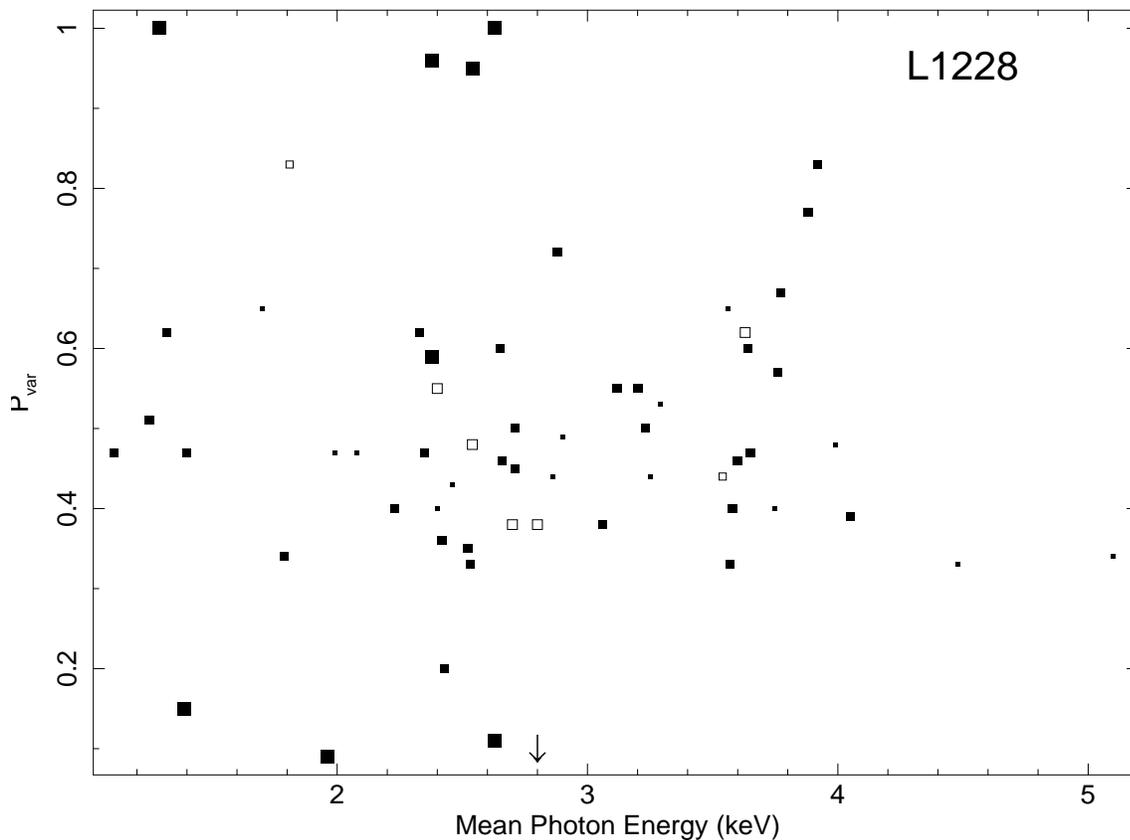


Fig. 3.— X-ray variability probability  $P_{var}$  versus mean photon energy for the X-ray sources detected in L1228. Symbol sizes reflect the number of X-ray counts: small <10 cts, medium 10 - 50 cts, large >50 cts. Filled symbols denote sources with IR counterparts and open symbols lack counterparts. The arrow at 2.8 keV marks the average value of the mean photon energy for the X-ray sample. The source with the highest mean energy at far right is HH 200-IRS. Those sources with  $P_{var} \geq 0.9$  all have >50 counts (CXO sources 8, 10, 31, 50).

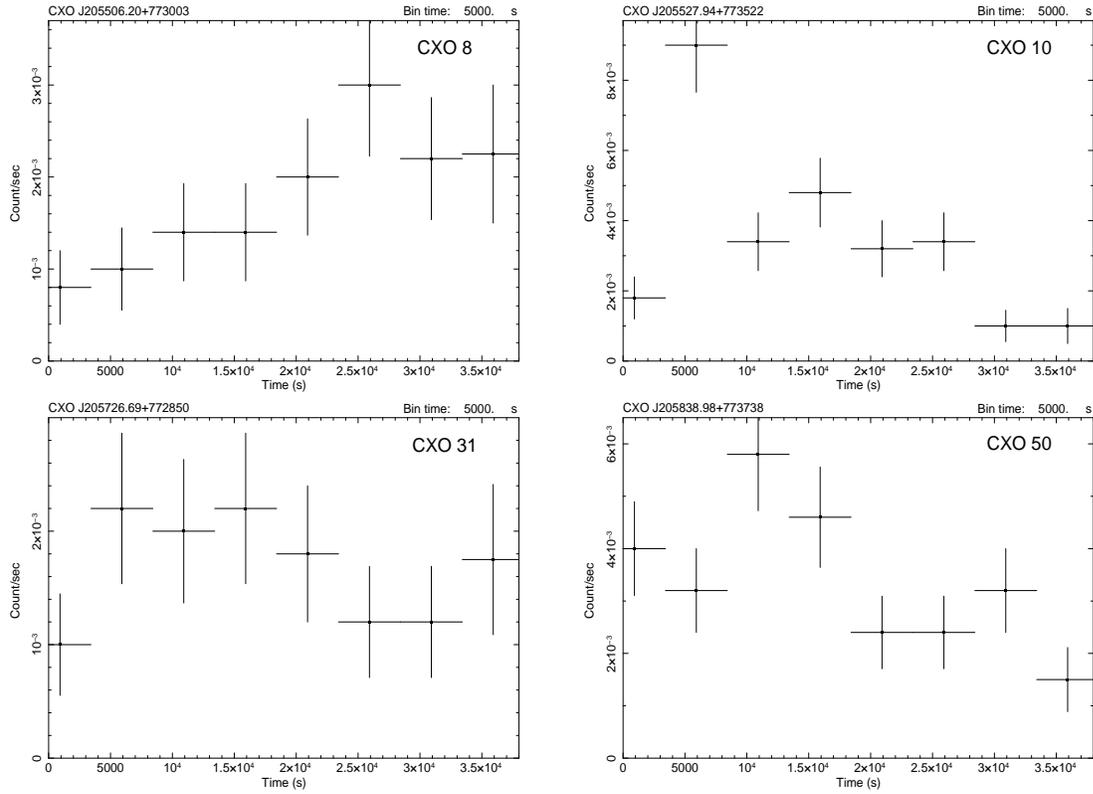


Fig. 4.— Chandra ACIS-I light curves (0.3 - 7 keV) of L1228 X-ray sources with high probability of variability  $P_{var} > 0.9$ , binned at 5000 s intervals.

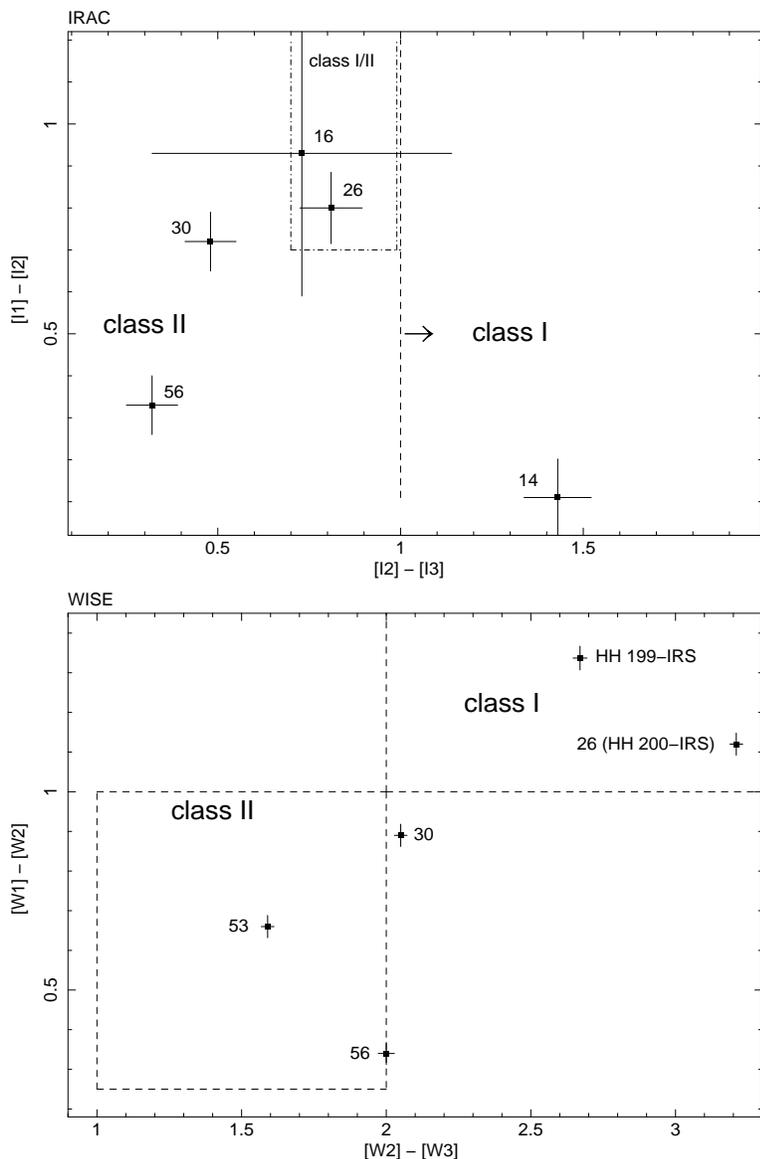


Fig. 5.— Representative color-color diagrams for *Spitzer* IRAC (top) and WISE (bottom) with colors of candidate YSOs shown. Source numbers correspond to Tables 3, 4, and 5. The IRAC color-cut regions are from Gutermuth et al. (2008) and WISE regions are from Koenig et al. (2012). In the IRAC diagram, sources 16 and 26 lie in a region that includes both class I and heavily-reddened class II sources. The WISE colors of HH 199-IRS are shown for comparison but it was not detected as an X-ray source.

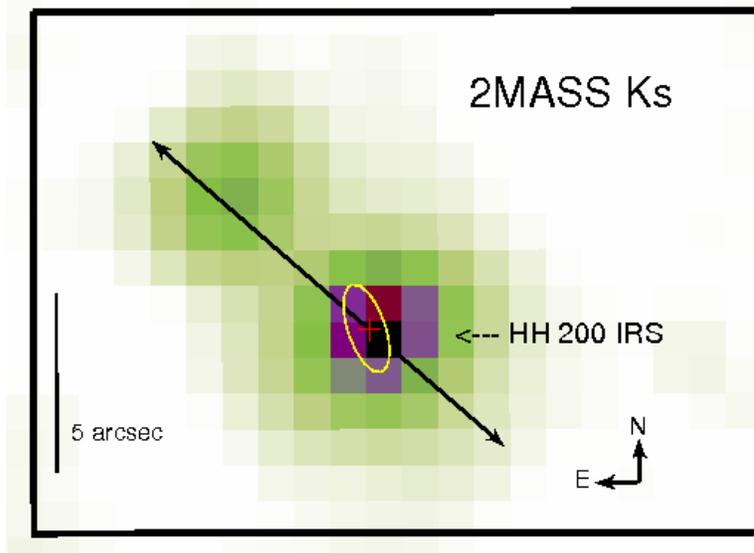


Fig. 6.— 2MASS  $K_s$  ( $2.159 \mu\text{m}$ ) image of HH 200-IRS = 2MASS J205706.55+773655.94. The cross marks the radio counterpart position of source VLA 4 = J205706.703+773656.07 (Reipurth et al. 2004). The X-ray position error ellipse for CXO source 26 (J205706.72+773656.1) is overlaid and has semi-axes  $1.''28 \times 0.''52$ . The ellipse is centered almost exactly on the VLA position. The arrows show the direction of the HH outflow axis at P.A. =  $49^\circ/229^\circ$  (Devine et al. 2009). The second fainter source located  $5.7''$  NE of HH 200-IRS is 2MASS J205707.89+773659.7 ( $J = 15.76$ ,  $H = 14.24$ ,  $K_s = 13.44$ ) and was not detected by *Chandra*.

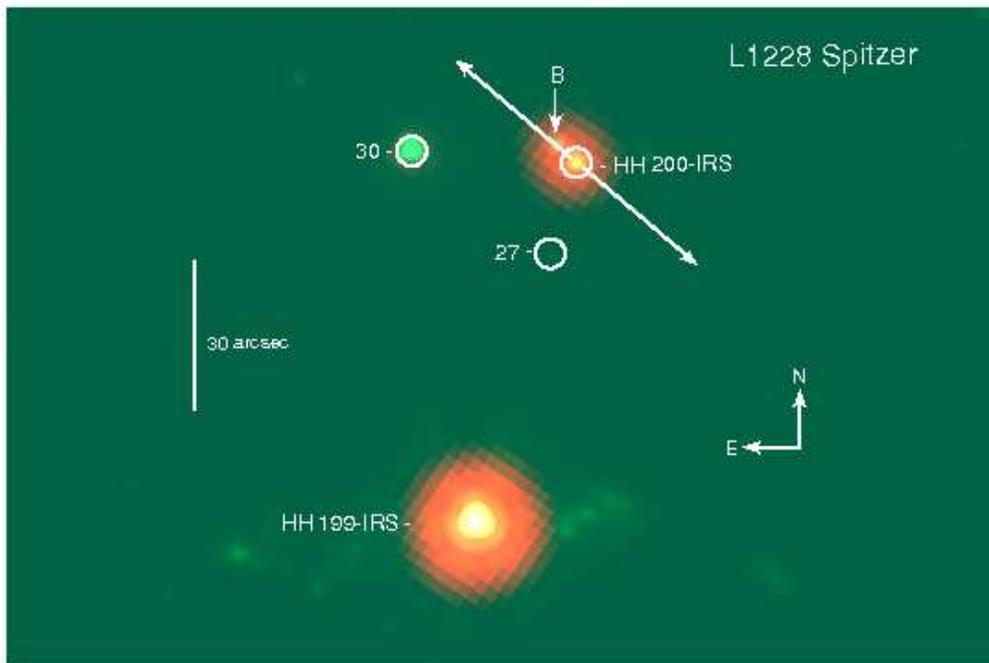


Fig. 7.— Gaussian-smoothed Spitzer RGB image of the region near HH 199-IRS and HH 200-IRS. R = MIPS-24 ( $24 \mu\text{m}$ ), G = I2 ( $4.5 \mu\text{m}$ ), B = I1 ( $3.6 \mu\text{m}$ ). The solid lines show the directions of the HH 200 bipolar outflow. Circles mark the positions of Chandra X-ray sources (HH 200-IRS = CXO nr. 26). The IR source marked B (= 2MASS J205707.89+773659.7) is located on the outflow axis  $5.7''$  NE of HH 200-IRS but was not detected by *Chandra*. HH 199-IRS was not detected by Chandra. Faint nebulosity associated with the HH 199 outflow is visible to the east and west of HH 199-IRS.

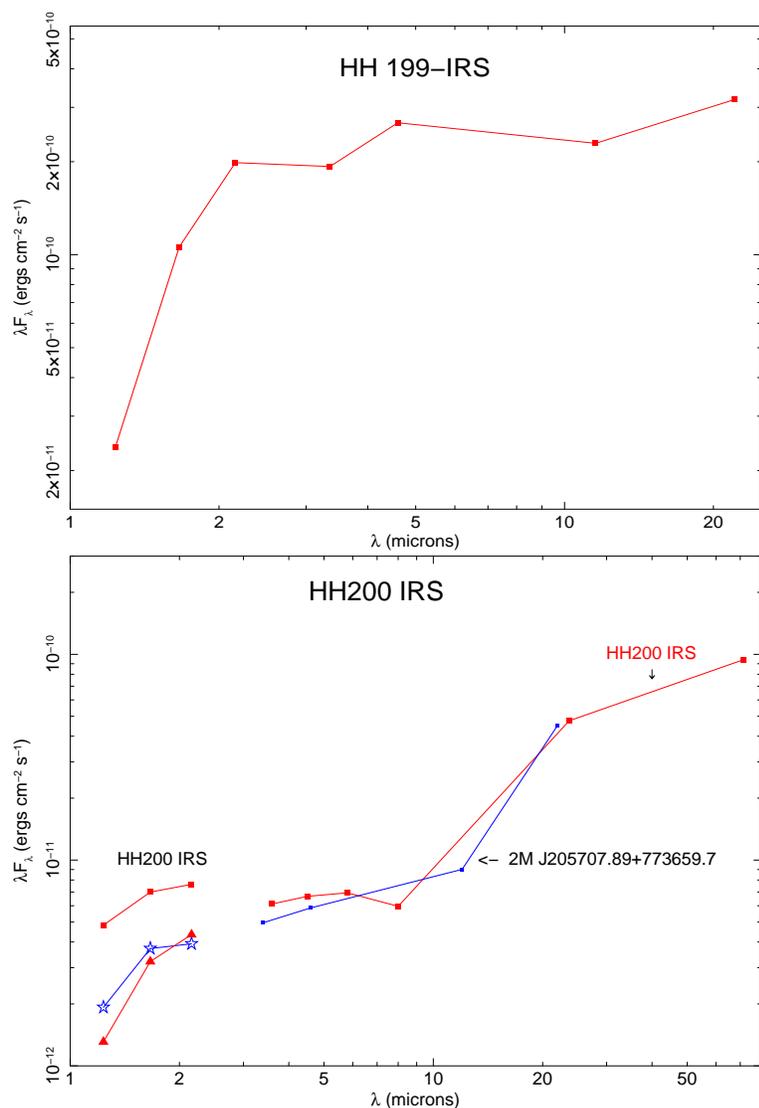


Fig. 8.— *Top:* IR SED of HH 199-IRS based on 2MASS and WISE photometry (Table 5). *Bottom:* IR SEDs of HH 200-IRS (red) and the close IR companion 2MASS J205707.89+773659.7 (blue) located  $5.''7$  northeast of HH 200-IRS. The  $JHK_s$  data for HH 200-IRS are from 2MASS (squares) and Chapman & Mundy 2009 (triangles). The MIPS-70  $\mu\text{m}$  data point is from c2d. The two sources are only partially resolved by MIPS at 24  $\mu\text{m}$  and are unresolved by MIPS at 70  $\mu\text{m}$ . The pair is not fully resolved by WISE.