AN X-RAY CENSUS OF YOUNG STARS IN THE CHAMELEON I NORTH CLOUD
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ABSTRACT

Sensitive X-ray imaging surveys provide a new and effective tool to establish the census of pre–main-sequence (PMS) stars in nearby young stellar clusters. We report here a deep Chandra X-Ray Observatory observation of PMS stars in the Chamaeleon I North cloud, achieving a limiting luminosity of \( \log L_x \approx 27 \text{ ergs s}^{-1} (0.5–8 \text{ keV band}) \) in a \( 0.8 \times 0.8 \text{ pc}^2 \) region. Of the \( 10^7 \) X-ray sources, 37 are associated with Galactic stars of which 27 are previously recognized cloud members. These include three PMS brown dwarfs; the protostellar brown dwarf ISO 192 has a particularly high level of magnetic activity. Follow-up optical photometry and spectroscopy establish that 9–10 of the Chandra sources are probably magnetically active background stars. Several previously proposed cloud members are also inferred to be interlopers because of the absence of X-ray emission at the level expected from the \( \log L_x - K \) correlation. No new X-ray–discovered stars were confidently found despite the high sensitivity. From these findings, we argue that the sample of 27 PMS cloud members in the Chandra field is uncontaminated and complete down to \( K = 12 \) or \( M \approx 0.1 \, M_\odot \). The initial mass function (IMF) derived from our sample is deficient in \( 0.1–0.3 \, M_\odot \) stars compared with the IMF of the rich Orion Nebula cluster and other Galactic populations. We cannot discriminate whether this is due to different star formation processes, mass segregation, or dynamical ejection of lower mass stars.

Subject headings: open clusters and associations: individual (Chamaeleon I) — stars: low-mass, brown dwarfs — stars: luminosity function, mass function — stars: pre–main-sequence — X-rays: stars

1. INTRODUCTION

After many decades of study of the stellar initial mass function (IMF), recent progress has been made in defining the population of substellar objects (Kroupa 2002). Brown dwarfs (BDs) are much more luminous and have hotter surfaces shortly after birth compared with their later cooler stages as L and T dwarfs. It has thus proved possible to count them in young pre–main-sequence (PMS) stellar clusters associated with nearby star formation regions (e.g., Luhman 2000; Hillenbrand & Carpenter 2000; Muench et al. 2002; Briceño et al. 2002; Preibisch et al. 2003; Comerón 2003; Wilking et al. 2004). A strong suggestion has emerged that the very young BD population is lower in lower density star formation regions (such as the Taurus-Auriga clouds) and higher density regions (such as the Orion Nebula). Such studies are important for understanding the efficiency of gravitational collapse at low masses, the uniformity of the IMF under different cloud conditions, and the possible ejection of lower mass objects from multiple systems or circumstellar disks.

X-ray astronomical surveys of young stellar clusters have proved to be an effective complement to optical and near-infrared (O/NIR) surveys in defining PMS stellar populations. X-ray emission is elevated \( 10^3–10^4 \) above old disk levels in virtually all stars \( 10^7 \) yr and younger, providing an easy discriminant between PMS cluster members and most Galactic field stars (Feigelson & Montmerle 1999). X-rays trace magnetic activity, primarily magnetic reconnection flaring, which is relatively insensitive to the presence or absence of circumstellar disks. X-ray samples are thus particularly effective in recovering young stars in which the disks have dissipated, often classified as weak-lined or post–T Tauri stars. This relieves the bias toward disky and accreting PMS stars that is often present in samples based on O/NIR surveys. An additional feature is a well-established empirical correlation between X-ray and photospheric brightness that links the X-ray luminosity function (XLF) with the \( K \)-band luminosity function (KLF). The astrophysical origin of this correlation is uncertain (Feigelson et al. 2003).

While previous generations of X-ray telescopes had insufficient sensitivity and resolution to reveal the bulk of lower mass members of young stellar clusters, the Chandra X-Ray Observatory can penetrate deeply into the PMS IMF. Intermediate-sensitivity Chandra studies had detected the majority of the stellar population and a modest fraction of the BD population in the \( \rho \text{ Oph} \), IC 348, \( \sigma \text{ Ori} \), and Orion Nebula young stellar clusters (Imanishi et al. 2001; Preibisch & Zinnecker 2002; Mokler & Stelzer 2002; Feigelson et al. 2002a). X-ray studies thus join the active O/NIR efforts to identify and characterize future BDs that are contemporaneous with the PMS protostellar and T Tauri population.

We report here an unusually deep observation of the northern core of the Cha I star-forming cloud obtained with Chandra. Cha I was the site of the first X-ray–discovered BD based on ROSAT imagery (Neuhauser & Comerón 1998), and a considerable number of candidate BDs have been reported using O/NIR photometric and spectroscopic techniques (Cambresy et al. 1998; Tamura et al. 1998; Oasa et al. 1999; Comerón et al. 2000, 2004; Gómez & Mardones 2003; López-Martí et al. 2004; Luhman 2004). Our Chandra observation is about 100 times more sensitive than the ROSAT observations because of a combination of a lower detector background, wider bandwidth, and longer exposure time. If the X-ray emission extends to substellar masses without change in the typical \( L_x/L_{\text{bol}} \) ratio, then we expect to detect many of the young BDs, as well as the entire T Tauri population.

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The Cha I cloud is particularly well suited to studies of young stellar populations. First, it is one of the nearest active star formation regions, at \( d \approx 160 \) pc.\(^3\) Second, it is relatively isolated from other star-forming clouds, so there is little confusion due to older PMS stars that have drifted into the field. Third, the stellar population is relatively rich, with a total population of 200–300 members. The population associated with the North cloud core has two additional advantages: the molecular material is confined to a small region, so many members are only lightly obscured, and the stellar cluster is sufficiently compact that several dozen members can be studied in a single X-ray image. This molecular core, 296.5–15.7, has \( 30 M_\odot \) of gas in a 0.4 pc (8") diameter region with peak column density \( \log N_H \approx 22.3 \text{ cm}^{-2} \) (Mizuno et al. 1999).

The stellar population of the Cha I North region has been surveyed at many spectral bands. The deepest of these surveys attain limits of \( R \approx 22, I \approx 20 \) (López-Martí et al. 2004), \( J = 18.1, H = 17.0, K = 16.2 \) (Oasa et al. 1999), \( L \approx 11 \) (Kenyon & Gómez 2001), \( \approx 2 \text{ mJy in the 5–8.5 \mu m band, } \approx 4 \text{ mJy in the 12–18 \mu m band (Persi et al. 2000), and } \approx 150 \text{ mJy at 1.3 mm (Reipurth et al. 1996). It has also been examined for faint H\alpha-emitting stars (Hartigan 1993; López-Martí et al. 2004) and for X-ray-emitting stars down to \( \log L_X \approx 29.0 \text{ ergs s}^{-1} \) in the soft \textit{ROSAT} 0.3–2.4 keV band (Feigelson et al. 1993).

2. CHANDRA OBSERVATIONS AND ANALYSIS

2.1. Data Reduction and Source Detection

A 16' \times 16' region of the Cha I North cloud was observed with the imaging array of the Advanced CCD Imaging Spectrometer (ACIS-I) detector on board the Chandra X-Ray Observatory. The satellite and instrument are described by Weisskopf et al. (2002). The detector aim point was set at \( (\alpha, \delta) = (11^h10^m0^s, -76^\circ35'00") \) (J2000.0). Figure 1 shows the field of view superposed on the molecular cloud; it subtends a 0.8 \times 0.8 pc\(^2\) region at the cloud. The observation took place on 2001 July 2.25–3.04 UT. With 1.3% of the exposure lost to CCD readout and 6 s lost to telemetry dropouts, the effective exposure was 66.3 ks.

The initial stages of data reduction are described in the Appendix of Townsley et al. (2003). Briefly, we start with the Level 1 events from the satellite telemetry, correct event energies for charge transfer inefficiency, and apply a variety of data selection operations such as \textit{ASCA} event grades. Several bright sources near the field center with clear stellar counterparts in the 2MASS catalog (sources 41, 45, 48, 54, 57, and 62 in Table 1) were used to align the field to the \textit{Hipparcos} reference frame. An offset of 0.15 was applied to the initial Chandra field position; the individual scatter of these alignment sources with respect to their 2MASS positions is \( \pm 0.08 \).

Candidate sources were located using a wavelet-based detection algorithm (Freeman et al. 2002). We applied a low threshold \( (P = 1 \times 10^{-5}) \) so that some spurious sources would be found that we exclude later. The image was visually examined for possible additional sources missed by the algorithm; no missing sources or close double sources were found. Events for each candidate source were extracted using the IDL- and CIAO-based script \textit{acis\_extract}.\(^4\) Here events were extracted in a small region around each source containing 95% of the enclosed energy derived from the point-spread function of the telescope at that position. A local background was defined from a nearby source-free region of each source and was scaled to the source extraction area.

Unreliable weak candidate sources were then removed. These include sources with less than 3.5 net (i.e., background subtracted) extracted counts, faint sources with median energies above 5 keV that are probably fluctuations in the background, faint sources with poorly concentrated events, and faint sources with event arrival times indicating contamination by cosmic-ray afterglows (i.e., several events appearing in a single pixel within 30 s). Near the field center (off-axis angle \( \theta < 5\)\(^\circ\)), source positions are simple centroids of the extracted events, while positions for sources far off-axis are obtained from a convolution of the point-spread function with the extracted event positions. The \textit{acis\_extract} script also provides position-dependent telescope-plus-detector effective area versus energy curves (\textit{ARF} files) and spectral resolution matrices (\textit{RMF} files) for all sources.

The resulting 107 Chandra sources are shown in Figure 2, and their observed properties are given in Table 1. It gives the running source number, source position, off-axis angle, background-subtracted extracted counts (rounded to the nearest count), and cross-reference to the earlier \textit{ROSAT} sources designated CHRX (Feigelson et al. 1993). Only 17 of the brightest sources were found with \textit{ROSAT}.\(^5\)

\(^3\) \textit{Hipparcos} studies show that dust appears in the Chamaeleon region around 150 pc (Knude & Hog 1998) and that the mean distance for seven stars in the cloud is 165\(^{+14}_{-12}\) pc (Bertout et al. 1999). We adopt a distance of 160 pc.

\(^4\) Description and code for \textit{acis\_extract} are available at http://www.astro.psu.edu/xray/docs/TARA/ac\_users\_guide.html.

\(^5\) The \textit{ASCA} satellite, with low spatial resolution but a wide spectral band similar to \textit{Chandra}'s, detected two sources in our ACIS field (Ueda et al. 2001): IAXG J110943-7629 (log \( L_X = 30.4 \text{ ergs s}^{-1}\)), which blends our sources 38, 39, 40, 42, and possibly 41, and IAXG J111011-7635 (log \( L_X = 30.8 \text{ ergs s}^{-1}\)), which blends sources 53, 56, and 61. These sources were earlier seen with the \textit{Einstein} satellite with similar blending problems (Feigelson & Kriss 1989).
### Table 1

**Chandra Sources and Counterparts in Cha I North**

| Source | R.A. | Decl. | $\theta$ | Counts | CHRX | Star | $\Delta$ |
|--------|------|-------|----------|--------|------|------|---------|
| 1       |      |       |          |        |      |      |         |
| 2       |      |       |          |        |      |      |         |
| 3       |      |       |          |        |      |      |         |
| 4       |      |       |          |        |      |      |         |
| 5       |      |       |          |        |      |      |         |
| 6       |      |       |          |        |      |      |         |
| 7       |      |       |          |        |      |      |         |
| 8       |      |       |          |        |      |      |         |
| 9       |      |       |          |        |      |      |         |
| 10      |      |       |          |        |      |      |         |
| 11      |      |       |          |        |      |      |         |
| 12      |      |       |          |        |      |      |         |
| 13      |      |       |          |        |      |      |         |
| 14      |      |       |          |        |      |      |         |
| 15      |      |       |          |        |      |      |         |
| 16      |      |       |          |        |      |      |         |
| 17      |      |       |          |        |      |      |         |
| 18      |      |       |          |        |      |      |         |
| 19      |      |       |          |        |      |      |         |
| 20      |      |       |          |        |      |      |         |
| 21      |      |       |          |        |      |      |         |
| 22      |      |       |          |        |      |      |         |
| 23      |      |       |          |        |      |      |         |
| 24      |      |       |          |        |      |      |         |
| 25      |      |       |          |        |      |      |         |
| 26      |      |       |          |        |      |      |         |
| 27      |      |       |          |        |      |      |         |
| 28      |      |       |          |        |      |      |         |
| 29      |      |       |          |        |      |      |         |
| 30      |      |       |          |        |      |      |         |
| 31      |      |       |          |        |      |      |         |
| 32      |      |       |          |        |      |      |         |
| 33      |      |       |          |        |      |      |         |
| 34      |      |       |          |        |      |      |         |
| 35      |      |       |          |        |      |      |         |
| 36      |      |       |          |        |      |      |         |
| 37      |      |       |          |        |      |      |         |
| 38      |      |       |          |        |      |      |         |
| 39      |      |       |          |        |      |      |         |
| 40      |      |       |          |        |      |      |         |
| 41      |      |       |          |        |      |      |         |
| 42      |      |       |          |        |      |      |         |
| 43      |      |       |          |        |      |      |         |
| 44      |      |       |          |        |      |      |         |
| 45      |      |       |          |        |      |      |         |
| 46      |      |       |          |        |      |      |         |
| 47      |      |       |          |        |      |      |         |
| 48      |      |       |          |        |      |      |         |
| 49      |      |       |          |        |      |      |         |
| 50      |      |       |          |        |      |      |         |
| 51      |      |       |          |        |      |      |         |
| 52      |      |       |          |        |      |      |         |
| 53      |      |       |          |        |      |      |         |
| 54      |      |       |          |        |      |      |         |
| 55      |      |       |          |        |      |      |         |
| 56      |      |       |          |        |      |      |         |
| 57      |      |       |          |        |      |      |         |
| 58      |      |       |          |        |      |      |         |
| 59      |      |       |          |        |      |      |         |
| 60      |      |       |          |        |      |      |         |
| 61      |      |       |          |        |      |      |         |
| 62      |      |       |          |        |      |      |         |
2.2. Stellar Counterparts

Stellar counterparts are sought within 5" of the Chandra positions from five databases: the JHK-band 2MASS all-sky catalog, the IJK-band DENIS catalog, our VI-band CCD images of the region (§ 3), the SIMBAD databases of published stars, and the list of Cha I cloud members collected from the literature by Carpenter et al. (2002). Twenty-seven previously known cloud members in Carpenter et al. (2002) were recovered in the Chandra observation, nearly all with positional
offsets less than $0.5$ as indicated in columns (7) and (8) of Table 1. Ten additional X-ray sources associated with previously unstudied stars are described in § 5. We also discuss in § 8.1 some published candidate cloud members lying in our Chandra field of view that were not X-ray detected. Figure 3 shows the stellar counterparts superposed on the dark cloud.

2.3. Stellar X-Ray Spectra and Luminosities

Table 2 provides results from subsequent analysis of the X-ray properties of the stellar sources. The analysis used acis_extract, version 1.1, for extraction and variability analysis, and XSPEC, version 11.2, for spectral modeling. $C_X$ events were extracted in the polygon containing 95% of the full point-spread function. $B_X$ values are the background counts scaled to the extraction region.

The distribution of photon energies was modeled as emission from a thermal plasma with energy $kT$ on the basis of the emissivities calculated by Kaastra & Mewe (2000), subject to interstellar absorption. The absorption is expressed in equivalent hydrogen column densities, $\log N_H$ (in cm$^{-2}$), assuming solar metallicities in the intervening gas. (Note, however, that the recent X-ray absorption study by Vuong et al. [2003] suggests that dark clouds have metallicities 20%–30% lower than standard solar values.) Our modeling is limited by statistical considerations; weak sources (typically <100 counts) are successfully modeled with one-temperature plasmas, while stronger sources (100–1000 counts) usually require two-temperature plasmas, and the strongest sources (1000–3000 counts) often require two or three temperatures with nonsolar elemental abundances. These flux-dependent differences are unphysical because magnetically active PMS stars, like the Sun, undoubtedly have continuous distributions of plasma emission measures over a wide range of temperatures. The fitted temperatures represent only the dominant plasma components of the star during the observation. The presence of nonsolar abundances, particularly involving elements such as iron and neon with extreme first ionization potentials, has been confirmed in high-resolution X-ray grating studies of stars with strong flare levels (Audard et al. 2003 and references therein). We thus caution that the spectral modeling does not reflect the full range of plasma properties and, for the fainter sources, may be nearly useless for interpreting plasma properties due to statistical uncertainties.

However, the broadband luminosities integrated over the best-fit model are insensitive to spectral fitting uncertainties and have roughly $C_X^{-1/2}$ errors (Getman et al. 2002). The spectral model is used here as a nonlinear spline curve through the data. X-ray luminosities, $L_\gamma$ in the soft 0.5–2 keV band and $L_\gamma$ in the

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**Fig. 2.—** Chandra ACIS image of the Cha I North field shown here at reduced resolution (2'0 pixels). Sources are numbered as in Table 1. Large numbered labels indicate sources with stellar counterparts (Table 2), while the others are probably extragalactic.
covered the Cha I North core but missed the extreme corners of the rotated ACIS field (Fig. 2), where a number of counterparts are located. Comparison of source magnitudes obtained in the different surveys (SAAO I- vs. DENIS i-band magnitudes and DENIS vs. 2MASS J/K-band magnitudes) indicates that the various survey magnitudes can be freely interchanged, with discrepancies mostly comparable to the photometric errors. In Table 3 we list USNO-B1.0 R, DENIS i or SAAO I, and 2MASS JHK magnitudes for the stellar counterparts.

For three of the brighter candidates, we obtained 2 Å resolution spectroscopy in the region near Hα and covering the Li i line at 6707.8 Å using the 2.3 m telescope and dual-beam spectrograph (DBS) at Siding Spring Observatory during 2003 April. In addition, 4 Å resolution spectra of six of the candidates were obtained for us by K. Luhman, using the IMACS on the Magellan I telescope. We discuss the outcomes of our photometric and spectroscopic analysis of the new Chandra sources in § 5.

4. RELIABILITY AND COMPLETEENESS OF THE STELLAR CENSUS

4.1. X-Ray Completeness Limit

Our ability to detect sources in the ACIS field degrades with off-axis angle (because of broadening of the mirror point-spread function) and with absorption (due to loss of soft X-ray photons). Feigelson et al. (2002a; see their § 2.12) develop formulae for such detection limits, taking into account technical factors such as optimal extraction radii, telescope vignetting, and background subtraction. We adopt here a simpler approximation that fits the lower envelope of sources in Table 1. The limit in extracted counts as a function of off-axis angle \( \theta \) (in arcminutes) is then

\[
C_{\text{lim}} \approx 4 \times 10^{0.5(\theta/5)} \quad \text{for } \theta < 5' \quad \text{and } C_{\text{lim}} \approx 4 + (\theta/5) \quad \text{for } 5' < \theta < 11'.
\]

The limiting luminosity in the total 0.5–8 keV band for a source with a typical PMS spectrum is then

\[
L_{\text{lim}} = 26.3 + 0.3(\log N_{\text{HI}} - 20.0) \quad \text{ergs s}^{-1}.
\]

Since cloud absorption is concentrated in the center of the ACIS field, it is doubtful that both \( C_{\text{lim}} \) and \( N_{\text{HI}} \) are simultaneously high. For reasonable values of \( C_{\text{lim}} \approx 4–10 \text{ counts and } \log N_{\text{HI}} = 21–22 \text{ cm}^{-2} \), the typical limiting sensitivity across the entire field is then

\[
26.9 < \log L_{\text{lim}} < 27.5 \quad \text{ergs s}^{-1}.
\]

4.2. Stellar Counterpart Completeness

The O/NIR photometric surveys of Cha I North (§ 3) provide counterpart information to limits of \( R \approx 20, I \approx 18, J \approx 16, \) and \( H = K \approx 15. \) At the distance to Cha I North \( (d = 160 \text{ pc}) \), if we adopt a maximum cloud absorption of \( A_V \approx 6–10 \text{ mag} \), these completeness limits exceed those of the zero-age main sequence (ZAMS) for spectral types earlier than M5 \( (M > 0.2 \text{ M}_\odot) \). For objects free from the regions of high extinction, the substellar models of Baraffe et al. (1998) suggest that all cloud members with \( M > 20 \text{ M}_J \) and age \( t < 10 \text{ Myr} \) (and still lower masses for younger ages) will appear as an O/NIR counterpart to any ACIS source.

Unlike earlier satellites for which the poor resolution of proportional counters permitted multiple counterparts, Chandra’s excellent point-spread function and satellite alignment give centroids accurate to a few tenths of an arcsecond on-axis. Counterpart ambiguities are thus restricted to multiple systems with component separations less than \( \approx 100 \text{ AU} \).

The remaining challenge is then to distinguish the stellar population from the dominant extragalactic source population. This is facilitated by two tools. First, unresolved extragalactic...
counterparts of \textit{Chandra} sources in our flux range are typically active galactic nuclei with redshifts $z < 3$ and faint magnitudes, $R \approx 20–28$ (Hornschemeier et al. 2001; Barger et al. 2002). They rarely have $R < 19$. Second, extragalactic sources rarely vary on intraday timescales. Of the 70 nonstellar sources in Table 1, 66 are consistent with constancy, three are possibly variable (consistent with a population of constant sources), and one is rapidly variable.$^6$ In contrast, 11 of the 37 stellar sources are definitely variable, and six are probably variable. Most of the remaining stellar sources have fewer than 100 photons, so only the most dramatic variations can be seen.

Together, the optical magnitude and the X-ray variability distributions indicate that little if any erroneous confusion between extragalactic and stellar sources is present. The more subtle distinction between stars associated with the cloud and background field stars is discussed in §5 and 8.1.

5. NEW STELLAR COUNTERPARTS TO \textit{CHANDRA} SOURCES

We describe here the 10 ACIS sources coincident with O/NIR stars that have not previously been considered to be candidate members of the Cha I North star-forming cloud. The relevant information includes the photometric magnitudes and colors, our three Siding Spring Observatory and Magellan spectra ($\S$ 3), and the X-ray properties. The magnitudes and colors alone prove to be a major constraint. Most of these stars are too faint to be PMS stars or even ZAMS stars at the distance of the cloud and do not have the very red colors associated with a low-luminosity young BD. They also lie in the outer regions of the ACIS field away from the core of the young stellar cluster. We conclude that they are mostly more distant stars unrelated to the cloud. In only one case in which a strong emission line is present (source 16) is it feasible that the \textit{Chandra}-discovered star may be a cloud member.

\begin{table}[h!]
\centering
\begin{tabular}{lcccccccc}
\hline
Source & Name & $C_X$ & $B_X$ & Var & $\log N_{2}\$ & $kT_1$ & $kT_2$ & $L_X$ & $L_1$ & $L_2$ & $L_3$
\hline
8.............. & CHXR 33 & 993 & 3 & c & 21.8 & 0.7 & 0.3 & ... & 29.3 & 29.4 & 30.0
15............. & T37 & 68 & 24 & a & 0 & 0.0 & 1.3 & ... & 27.5 & 29.1 & 28.1
16............. & Field? & 57 & 3 & a & 22.1 & 0.3 & 0.4 & ... & 27.9 & 28.3 & 28.7
22............. & Field & 15 & 7 & a & 0.2 & 0 & 0.1 & ... & 27.1 & 27.4 & 27.4
24............. & Field & 25 & 2 & a & 22.3 & 0.3 & 0 & ... & 27.4 & 27.4 & ...
25............. & CHXR 35 & 164 & 6 & a & 21.8 & 0.2 & 0 & ... & 28.6 & 28.6 & 30.1
26............. & CHXR 37 & 2357 & 9 & a & 21.7 & 0.4 & 2.2 & ... & 29.6 & 29.8 & 30.4
27............. & CHXR 79 & 845 & 2 & a & 21.8 & 0.6 & 0.1 & ... & 28.9 & 29.7 & 29.8
29............. & C1-6 & 27 & 1 & c & 22.4 & 2.2 & 1.3 & ... & 27.3 & 28.3 & 28.8
33............. & ISO 192 & 47 & 1 & a & 23.0 & 1 & 0 & ... & 27.1 & 28.6 & 28.6
38............. & CHXR 40 & 2853 & 7 & a & 0.8 & 0 & 2.5 & ... & 29.8 & 29.9 & 29.9
41............. & C1-25 & 2329 & 1 & c & 22.2 & 10 & ... & 29.2 & 30.3 & 30.4
43............. & Hn 10E & 76 & 1 & a & 22.1 & 0.9 & 0.2 & ... & 28.1 & 28.2 & 28.9
44............. & T41 & 1106 & 1 & a & 21.3 & 0.8 & 0 & 3.2 & ... & 29.2 & 29.5 & 29.7
46............. & ISO 217 & 17 & 2 & c & 22.4 & 5 & ... & 27.1 & 28.3 & 28.5
47............. & T42 & 699 & 0 & b & 21.8 & 0.1 & 0 & 4.9 & ... & 29.2 & 29.7 & 30.0
48............. & T43 & 1192 & 3 & c & 21.8 & 0.4 & 0 & 2.5 & ... & 29.6 & 29.6 & 30.1
49............. & ISO 225 & 61 & 1 & b & 22.7 & 10 & ... & 26.8 & 28.9 & 29.1
50............. & Field & 25 & 8 & a & 21.9 & 1.3 & 2.1 & ... & 27.5 & 27.8 & 28.3
51............. & C1-2 & 38 & 1 & b & 22.4 & 3.2 & 2.1 & ... & 27.4 & 28.5 & 28.8
53............. & T44 & 2517 & 1 & c & 21.8 & 0.6 & 0 & 2.8 & ... & 29.8 & 30.2 & 30.5
55............. & Hn 11 & 63 & 1 & b & 21.9 & 2.1 & 0.8 & ... & 27.9 & 28.4 & 28.7
56............. & T45a & 2056 & 1 & b & 21.6 & 0.8 & 0 & 2.4 & ... & 29.5 & 29.8 & 30.1
58............. & T46 & 1784 & 3 & c & 21.1 & 0.6 & 0 & 2.4 & ... & 29.6 & 29.7 & 29.8
61............. & ISO 237 & 332 & 1 & a & 22.0 & 0.7 & 4.2 & ... & 28.8 & 29.2 & 29.7
74............. & T48 & 74 & 1 & c & 0 & 0.8 & 0.2 & ... & 28.2 & 28.4 & 28.4
75............. & Hn 13 & 130 & 24 & c & 22.4 & 1.4 & 0.4 & ... & 28.0 & 28.8 & 29.6
79............. & Field & 23 & 4 & b & 21.0 & 0.5 & 0.6 & ... & 27.6 & 27.6 & 28.6
84............. & Field & 18 & 6 & a & 1 & 0.1 & 0.4 & ... & 27.3 & 27.3 & 27.3
86............. & Field & 44 & 4 & c & 0 & 10 & ... & 27.8 & 28.3 & 28.3
88............. & Field & 8 & 1 & a & 0 & 1 & ... & 27.1 & 27.2 & 27.2
91............. & CHXR 48 & 1771 & 3 & c & 21.4 & 0.4 & 0 & 1.7 & ... & 29.6 & 29.7 & 30.0
98............. & Field & 15 & 5 & a & 0 & 0.8 & 0.2 & ... & 27.6 & 27.6 & 27.6
99............. & Field & 25 & 4 & a & 0 & 2.1 & 1.1 & ... & 27.6 & 27.8 & 27.8
100........... & CHXR 84 & 119 & 6 & a & 0 & 1.0 & 0.1 & ... & 28.4 & 28.5 & 28.5
103........... & T50 & 65 & 5 & a & 22.3 & 0.9 & 0.4 & ... & 28.0 & 28.3 & 29.4
105........... & T51 & 53 & 3 & a & 21.8 & 0.8 & 0.2 & ... & 28.6 & 28.7 & 29.3
\hline
\end{tabular}
\end{table}

\begin{notes}
\item Notes.— The X-ray luminosities assume the star lies at a distance of 160 pc. The field stars discussed in § 5 lie on the far side of the cloud at unknown distances, so their X-ray luminosities are greater than the tabulated values.
\item See text, § 6.
\item Source 105 lies at the edge of the ACIS detector where, because of the broad telescope point-spread function and satellite dithering, many of the source photons may be lost. This can result in an underestimate of the source luminosity and an apparent positional offset of the centroid.
\end{notes}

$^6$ This source 42=CXO 110945.1–763022 has 17 events, 16 of which arrived in the final 14 ks of the exposure. Its spectrum is consistent with either a hot plasma ($kT > 3$ keV) or a power law ( photon index $\Gamma \sim 1$) subject to log $N_{\ion{H}{ii}} < 22.0$ cm$^{-2}$ absorption. This spectrum could emerge from either a star of an active galactic nucleus.
Fig. 4.—*Chandra* ACIS light curves of variable X-ray stars in Cha I North: (a) ACIS source 29=C1-6, (b) source 41=C1-25, (c) source 44=T41=HD 97300, (d) source 46 ISO 217, (e) source 47=T42=HM 23, (f) source 53=T44=WW Cha, (g) source 56=T45a=GK 1, (h) source 58=T46=WY Cha, (i) source 5=HN 13, (j) source 86, background dwarf, and (k) source 91=CHXR 48. The abscissae show the photon arrival time from 0 to 66.3 ks. The ordinates show counts that arrived in bins ranging from 1000 to 5000 s, as specified in each panel. No background has been subtracted, and standard $\sqrt{N}$ errors apply.
Qualitatively, it is not surprising that Chandra detects distant high-magnetic activity members of the Galactic field sequence G, K, and early M population. Studies of solar neighborhood stars show that ∼10% of K and early M disk stars and ∼30% of G disk stars have X-ray luminosities around 28.0 < log Lx < 29.5 ergs s⁻¹ (Schmitt et al. 1995; Schmitt 1997). Such stars could be seen out to distances around 0.5–2 kpc in our ACIS exposure. A quantitative study of the background source contamination is complicated by absorption effects and stellar distributions in the Galactic disk; this lies beyond the scope of this investigation.

Source 16.—This source lies ∼6′ southwest of the cloud core but suffers considerable soft X-ray absorption with moderate X-ray brightness. It has JHK colors consistent with a lightly to moderately reddened (AV ≃ 2–3) late M or early K star without K-band excess. The IMACS spectrum confirms the late K spectral type and detects Hα emission, suggesting it is a young star. But the star is fainter than the ZAMS for its spectral type at the cloud distance of 160 pc, on the basis of evolutionary models of Siess et al. (2000). If it is a cloud member, this might indicate that the star is being seen in scattered light, although this usually occurs only in very heavily obscured PMS stars. While the preponderance of evidence points to a background star, we classify this as “field?”

Source 22.—This source lies ∼6′ north of the cloud core and is one of the weakest detected X-ray sources in the cloud. The JHK colors are consistent with a wide range of stellar types, from a weakly reddened M3 to a moderately reddened (AV ≃ 5) G star. But the star lies below the ZAMS for any of these possible spectral types. Displaying strong interstellar Ca II absorption, the IMACS spectrum shows this is a background-reddened G or K field star.
Source 24.—This weak X-ray source lies 18′′ west-northwest of source 27 (CHXR 79), which is ≈40 times brighter in the ACIS image. The ACIS spectrum is somewhat unusual, peaking around 1.3 keV and quickly dropping at both higher and lower energies, probably indicating a high NH column density. As with source 22, degeneracy in the JHK colors permits a spectral type between G and early M but requires that it be a background star for any spectral type and extinction (AV ≈ 6–10). IMACS spectroscopy also indicates a heavily reddened background star, although of uncertain spectral type.

Source 50.—This weak source lies ~8′′ north of the cloud core near the edge of the ACIS field. The ACIS spectrum appears moderately absorbed, with its best-fit column density equivalent to AV = 5, but statistical errors are consistent with the ambient cloud column density of AV ≈ 1–2. The DBS and IMACS spectra indicate a weakly reddened G star with strong Ca ii absorption, showing it must lie considerably beyond the cloud.

Source 79.—This weak X-ray source appears about 7′′ northeast of the cloud core. A brief flare may have occurred during the observation when 10 photons arrived within 1.5 hr, although only ~1 photon was expected for the remainder of the observation. The JHK colors are similar to star 22, and thus, we believe it is another background field star.

Source 84.—This weak source lies about 1′′ northeast of the previous new X-ray star 79. The spectrum peaks at 1 keV and is consistent with no absorption, although moderate absorption up to a few magnitudes in AV cannot be excluded. The JHK colors suggest a B or A star with AV ≈ 3, which is confirmed by DBS and IMACS spectroscopy. Its faintness requires a distance considerably farther than the cloud. We note that BA stars themselves are not thought to be X-ray emitters because of the absence of an outer convective zone to generate and disrupt magnetic fields. X-ray emission from such stars is usually attributable to unseen late-type companions (Daniel et al. 2002; Stelzer et al. 2003).

Source 86.—This source lies 8′′ southeast of the cloud core and was detected only by virtue of a dramatic flare during the final 4 hr of the 19 hr observation (Fig. 4j). The peak luminosity is log Lx ≈ log L⊙ = 29.0 ergs s−1, and the quiescent luminosity is less than 27.3 ergs s−1 if the distance is 160 pc. The flare spectrum is very hard, exceeding Chandra’s ability to measure the temperature, which we estimate to be kT ≳ 10 keV. No soft energy absorption is evident. This is the only X-ray candidate source to show the unequivocal high-amplitude flaring commonly seen in PMS stars.

The stellar counterpart to source 86 appears as a marginal detection on photographic sky surveys with R ≳ 20.5 and I ≳ 18.4. It is present at the sensitivity limits of the 2MASS J and H bands and is undetected in their K band. While source 86 is thus a candidate low-luminosity cloud member, IMACS spectroscopy indicates a mid-M spectral type, and the distance modulus indicates it is probably a background flaring field star.

Source 88.—This very faint ACIS source lies ~7′′ west of the cloud core. The 2MASS JHK colors are unusual but are roughly consistent with a lightly reddened (AV ≲ 1) M0 star. The star is too faint at this spectral type to be a cloud member, and thus, we classify it as a background field star.

Source 98.—This very weak source lies ~9′′ east-northeast of the cloud core in a region of low interstellar obscuration. The spectrum is soft, with most of the events appearing below 1.2 keV. We note that such faint and soft sources will be missed in regions of higher interstellar absorption. The JHK colors suggest an unreddened G star, and the faint magnitudes require a location considerably beyond the cloud.

Source 99.—This source lies 34′′ west of the weakly reddened weak-lined T Tauri (WTT) star 103=T50=Sz 40, about 10′ east of the cloud core. It has ordinary X-ray properties, with its spectrum peaking at 1 keV and a low X-ray brightness. The DBS spectrum indicates a G star, consistent with JHK colors with no reddening. Here again, the star is too faint to lie at the cloud distance even if it were on the ZAMS.

6. PREVIOUSLY KNOWN CHA I NORTH STARS

Previously identified cloud members from Table 1 are briefly described here with a summary of their X-ray properties. Table 3 provides photometric, spectroscopic, and inferred quantities (see table notes for details). Star designations and cross-identifications with various catalogs are obtained from Carpenter et al. (2002). Properties of these stars are obtained as follows: optical photometry and spectroscopy (Hartigan 1993; Huenemoerder et al. 1994; Alcala et al. 1995; Lawson et al. 1996; Saflle et al. 2003; López-Martí et al. 2004; Luhman 2004), pre-Chandra X-ray (Feigelson & Kriss 1989; Feigelson et al. 1993), near-IR photometry (Cambresy et al. 1998; Oasa et al. 1999; Persi et al. 2000; Gómez & Kenyon 2001; Kenyon & Gómez 2001; Carpenter et al. 2002), and spectroscopy (Gómez & Persi 2002; Gómez & Mardones 2003). Both optical and near-IR spectroscopy permit placement of stars on the H–R diagram from which masses and ages can be inferred by comparison with PMS evolutionary tracks. As discrepancies in reported properties are often present, for consistency we give spectral types and bolometric luminosities, from the Magellanic spectroscopic study of Luhman (2004), when available, with masses and ages inferred from Baraffe et al. (1998) evolutionary tracks. Note, however, that other studies often derive different inferred properties.

For convenience in this section, we use the terms “light,” “moderate,” and “heavy” to modify “absorption” when referring to AV < 3, 3 < AV < 8, and AV > 8, respectively; “weak,” “moderate,” and “strong” to modify “X-ray emission” when referring to log Lx < 28.5, 28.5 < log Lx < 29.5, and log Lx > 29.5 ergs s−1, respectively; “high,” “intermediate,” and “low” to modify “bolometric luminosity” when referring to log Lbol > 4.1, 4.1 < log Lbol < 4.5, and log Lbol < 4.5, respectively; and “very young,” “young,” and “older” to modify “age” when referring to t < 1, 1 < t < 5, and t > 5 Myr, respectively. The nomenclature WTT (weak-lined T Tauri) and CTT (classical T Tauri) stars is used here loosely on the basis of a combination of accretion and disk indicators.

Source 8, CHXR 33=CHX 13a=C1-10=Cam1 65=ISO 153=KG 52=Cha I 752.—This is a moderately absorbed, young M0 WTT star with intermediate Lbol and mass M ≳ 0.7 M⊙. It has strong X-ray emission seen with both the Einstein and ROSAT satellites. The source exhibited a slow 30% increase over the 19 hr ACIS exposure, which could easily arise from evolution in magnetically confined plasma or in the rotational modulation of coronal structures.

Source 15, T37=SZ 28=Cam1 68=ISO 157=KG 54=Cha I 709.—This is a moderately absorbed CTT M5 star with strong Hα but low Lbol, indicating an older age. The X-ray emission is weak.

Source 25, CHXR 35=Hn 8=C1-15=Cam1 73=KG 75.—This is a lightly absorbed M5 M ≃ 0.2 M⊙ CTT star with low Lbol and weak X-ray emission.
Source 26, CHXR 37=Cam1 74=ISO 185=KG 77=RX J1109.4−7627.—This is a high-\(L_{bol}\) star, moderately absorbed, very young K7 WTT star with \(M \approx 0.8\) M\(_\odot\). The ACIS count distribution in the 0.9–1.3 keV spectral region can be successfully fitted only with weak emission from the iron L-shell lines, implying a subsolar (Fe/Fe) abundance of iron in the heated plasma. This is commonly seen in the X-ray spectra of magnetically active stars. The X-ray luminosity is constant at \(\log L_x \approx 30\) erg s\(^{-1}\). This combination of strong but constant emission is often attributed to heating by many microflares (Güdel et al. 2003).

Source 27, CHXR 79=Hn 9=C1-18=Cam1 75=ISO 186=KG 79.—This is a heavily absorbed, young K7 CTT star with intermediate \(L_{bol}\) and \(M \approx 0.6\) M\(_\odot\). A companion is present, separated by 0\(''). (Brandner et al. 1996). The X-ray emission is strong and constant.

Source 29, C1-6=Cam1 76=ISO 189=KG 82=OTS 10=Cha I 731.—This is a very young, heavily absorbed, photometrically variable M1 CTT star with intermediate \(L_{bol}\) and strong H\(\alpha\). The moderate X-ray emission arises entirely from a flare during the first 3 hr of the exposure, with peak \(\log L_x \approx 29.6\) ergs s\(^{-1}\) (Fig. 4a).

Source 33, ISO 192=Cha I North a2=Cam2 41=KG 87=OTS 15.—This star is an unusual outlier in JHKL color–color diagrams, with the strongest reddening (\(A_v \approx 20\)) and highest K- and L-band excess among Cha I members. This deeply embedded Class I protostar may be the driving source for the molecular bipolar flow at the center of the Cha I north cloud core (Persi et al. 1999). Together with its very low bolometric luminosity, these characteristics point to a protostar near or below the substellar boundary (Tamura et al. 1998). Mid-infrared spectroscopy shows strong absorption bands from silicates and ices characteristic of deeply embedded protostars (Pontoppidan et al. 2003; Alexander et al. 2003). Near-IR spectroscopy shows strong continuum veiling and strong molecular H\(_2\) emission lines. After correcting for veiling, Gómez & Mardones (2003) derive the spectral type M6.5, with absorption \(A_v \approx 22\), \(L_{bol} \approx 0.06\) L\(_\odot\), \(M \approx 0.06\) M\(_\odot\), and \(t \approx 0.4\) Myr. Perhaps most surprisingly, the K-band continuum has apparently brightened by over 2 mag during the past several years (Pontoppidan et al. 2003).

The X-ray spectrum is heavily absorbed and, with less than 50 counts, unique spectral parameters cannot be obtained. One satisfactory fit has a single \(kT = 2\) keV plasma component with \(\log N_{H} \approx 22.6\) cm\(^{-2}\) (\(A_v \approx 25\)), giving an intrinsic absorption-corrected luminosity of \(L_x \approx 28.8\) erg s\(^{-1}\). Other possibilities have absorption ranging up to \(\log N_{H} \approx 23\) cm\(^{-2}\) (\(A_v \approx 80\)) with a strong soft plasma component and \(L_x\) ranging up to \(\approx 30\) ergs s\(^{-1}\). The emission is not dominated by a high-amplitude flare. ISO 192 is thus a relatively strong X-ray emitter compared with most young BDs.

Source 38, CHXR 40=Cam1 78=ISO 198=KG 92.—This is a low-luminosity \((L_{bol} \approx 0.03\) L\(_\odot\)) M6 star with estimated mass \(M \approx 0.07\) M\(_\odot\), moderate absorption, and a young age. It is thus a probable proto–brown dwarf. It may also be a visual binary. The X-ray source was observed only by virtue of a flare with \(L_x \approx 29.0\) ergs s\(^{-1}\), all but one of the 19 events arrived during the last 7 hr of the 18 hr observation (Fig. 4d). The X-ray absorption suggests \(A_v \approx 30\), but this is poorly constrained by the few counts.

Source 41, C1-25=Cam1 79=ISO 199=KG 93=OTS 19.—C1-25 is a heavily absorbed, photometrically variable star with a weak K-band photometric excess and no emission lines. Analysis of near-IR spectra give the spectral type M1.5–M2, \(L_{bol} \approx 1\) L\(_\odot\), \(M \approx 0.2\) M\(_\odot\), and \(t < 0.1\) Myr. It is thus a very young low-mass WTT star with a remarkably strong X-ray flare. The X-ray light curve shows a dramatic flare, rising steeply over the first 2 hr of observation, peaking at \(\log L_x = 30.7\) erg s\(^{-1}\) and then decaying over several hours with secondary flares to a quiescent level of \(L_x = 29.7\) ergs s\(^{-1}\) (Fig. 4b). The plasma temperature soared from 1 keV during the rise phase to higher than 10 keV at the peak, falling to \(\approx 5\) keV during the decay phase and 2 keV at quiescence. The column density throughout was steady at \(\log N_{H} = 22.2\) cm\(^{-2}\) (\(A_v \approx 10\)).

Source 43, Hn 10E=T42=Sz 32=Cam1 82=ISO 204=KG 97=OTS 24.—This is an optically bright, moderately absorbed, very young M3 CTT star with intermediate \(L_{bol}\) and mass \(M \approx 0.2\) M\(_\odot\) (Gómez & Mardones 2003). Its mid-IR spectrum shows unusually strong silicate emission around 10 \(\mu m\) with no ice absorption features, possibly indicating a more evolved disk (Alexander et al. 2003). The X-ray luminosity is moderate, with a relatively soft spectrum.

Source 44, T41=HD 97300=CHXR 42=C1-11=Cam1 85=ISO 211=KG 103=OTS 26=IRAS 11082−7620.—HD 97300 illuminates the reflection nebula Ced 112 and is one of the highest mass members of the Cha I cloud. With spectral type B9 V and mass \(M \approx 2\) M\(_\odot\), it has been classified as a Herbig Ae/Be star without emission lines (The et al. 1994). Its far-IR flux, presumably from a massive circumstellar disk, is very strong, with an IRAS 60 \(\mu m\) flux of 87 Jy. The primary has a lower mass companion with \(\Delta K \approx 3\) lying 0\('') to the northwest (Ghez et al. 1997). At the beginning of our X-ray exposure, the emission rapidly (<1 hr) dropped from \(L_x \approx 30.1\) ergs s\(^{-1}\) to a quiescent level of \(L_x \approx 29.6\) ergs s\(^{-1}\), which persisted for the remainder of the observation (Fig. 4c). The flare peak luminosity could have been significantly higher.

The origin of X-ray emission from intermediate-mass stars that have no outer convection zone has been the subject of long debate. The preponderance of evidence supports an origin in late-type companions (Feigelson et al. 2002a; Stelzer et al. 2003). In the case of HD 97300, our X-ray position is accurate to \(\pm 0.2\) agrees with the primary position to within 0\('')1, so it seems unlikely that the resolved companion with its \(0.7\) offset is the X-ray source. We suggest that the X-rays arise from a yet unresolved third component, although no evidence for spectroscopic binarity has been found in the primary (Corporon & Lagrange 1999).

Source 46, ISO 217=KG 106=GIK 29=Cha 1 726.—This is a low-luminosity \((L_{bol} \approx 0.03\) L\(_\odot\)) M6 star with estimated mass \(M \approx 0.07\) M\(_\odot\), moderate absorption, and a young age. It is thus a probable proto–brown dwarf. It may also be a visual binary. The X-ray source was observed only by virtue of a flare with \(L_x \approx 29.0\) ergs s\(^{-1}\), all but one of the 19 events arrived during the last 7 hr of the 18 hr observation (Fig. 4d). The X-ray absorption suggests \(A_v \approx 30\), but this is poorly constrained by the few counts.

Source 47, T42=IRAS 11083−7618=HM 23=Sz 32=C1-5=Cam1 86=HBC 579=ISO 223=KG 109=OTS 27=Cha I 753.—HM 23 is one of the more luminous CTT stars in the Cha I cloud, with \(L_{bol} = 3.5\) L\(_\odot\). It has a K5 spectrum, an estimated mass of 1 M\(_\odot\), strong H\(\alpha\) emission, heavy absorption, and a massive disk emitting 50 Jy in the IRAS 60 \(\mu m\) band. The X-ray emission is typically strong for PMS solar analogs (Feigelson et al. 2002b). A powerful flare with peak \(L_x > 30.5\) ergs s\(^{-1}\) began during the last 1/2 hr of the observation (Fig. 4e).
weak H$_\alpha$ emission. The X-ray emission, seen earlier with the Einstein and ROSAT satellites, is strong. The luminosity decreased monotonically during the observation by 40%, plausibly because of either a slow decay of a flare or rotational modulation of magnetic structures. The X-ray spectrum shows evidence for reduced iron and enhanced neon in the emitting plasma.

Source 49, ISO 225=–GK 31.—This is a moderately absorbed, photometrically variable, very low luminosity ($L_{\text{bol}} \simeq 0.013 L_\odot$) CTT star in the cloud. The nature of this star has been difficult to unravel. The optical spectrum can be modeled as an M2 star from a $M \simeq 0.5 M_\odot$ star that is seen only in reflection (Luhman 2004), while the near-IR spectrum can be modeled as an M5 star with $M \simeq 0.1$, strong continuum veiling, and $A_V \simeq 5$ (Gómez & Mardones 2003). The X-ray luminosity of log $L_X \simeq 29.0$ erg s$^{-1}$ is consistent with any PMS star with $M \leq 0.5 M_\odot$ (Feigelson et al. 2003). The X-ray spectrum indicates an unusually hot plasma that is heavily absorbed, equivalent to $A_V \simeq 30$, considerably higher than that inferred from either the optical or infrared spectrum. The geometry of obscuring material around this star, which has the low luminosity of a proto–brown dwarf, may therefore be unusually complex.

Source 51, C1-2=–Cam1 88=ISO 226=–KG 111=–OTS 28.—C1-2 is a heavily absorbed CTT star invisible in the optical bands. The NIR spectrum indicates spectral type M1.5, heavy continuum veiling, $M \simeq 0.2 M_\odot$, and a very young age, less than 0.1 Myr (Gómez & Mardones 2003). The X-ray emission is heavily absorbed ($A_V \simeq 20$ with large uncertainty), and this source has intermediate luminosity. Although statistically marginal, there may have been a flare lasting $\sim$6 hr during the middle of the observation.

Source 53, T44=WW Cha=HM 24=–Sz 34=C1-7=–HBC 580=–Cam1 90=ISO 231=–KG 116=–OTS 29=–CHXR 44.—WW Cha is a luminous, variable, rapidly rotating ($v \sin i = 56$ km s$^{-1}$; Franchini et al. 1988), $M \simeq 0.8$–$1.0 M_\odot$, very young K5 CTT star with moderate absorption. It is one of the most luminous stars in the cloud, with $L_{\text{bol}} \simeq 6 L_\odot$. The mid-IR spectrum shows unusually strong silicate emission around $10 \mu$m with no ice absorption features, possibly indicating a more evolved disk (Alexander et al. 2003). Its X-ray emission is very strong, exhibiting a short-lived ($\sim$1/2 hr) flare with a peak flux of log $30.6$ erg s$^{-1}$ superposed on a high and more slowly variable emission (Fig. 4f).

Source 55, Hn 1=–C1-4=–Cam1 91=ISO 232=–KG 117=–OTS 35.—Hn 11 is a moderately absorbed, young CTT star with spectral type K8, intermediate $L_{\text{bol}}$, and $M \simeq 0.75 M_\odot$. The X-ray emission is unremarkable, with intermediate luminosity, absorption equivalent to $A_V \simeq 5$, and possible flaring.

Source 56, T45a=–HBC 582=–GK 1=–C1-9=–HBC 582=–Cam1 92=ISO 233=–KG 118=–IRAS 11085$-$7613=–CHXR 45=–CHX 16.—GK 1 is a lightly absorbed, photometrically variable $M \simeq 0.7 M_\odot$ M0 WTT star with strong X-ray emission seen earlier with the Einstein and ROSAT satellites. The X-ray luminosity is strong, and the light curve shows two short (0.5–2 hr) flares superposed on a high quiescent level (Fig. 4g).

Source 58, T46=–WY Cha=–HM 26=–Sz 36=C1-16=–HBC 583=–Cam1 93=ISO 234=–KG 119=–IRAS 11085$-$7613=–CHXR 46.—WY Cha is a lightly absorbed, photometrically variable, young $M \leq 0.8 M_\odot$ K8 CTT star with $L_{\text{bol}} \simeq 0.75 L_\odot$. The X-ray emission is strong. The light curve shows a flare with peak log $L_X > 29.9$ erg s$^{-1}$ superposed on a slower decline (Fig. 4h).

Source 61, ISO 237=–C1-8=–Cam2 48=–KG 121=–OTS 45=–Cha 1 760.—ISO 237 is a moderately absorbed, young K5 CTT star with estimated mass $M \simeq 0.9 M_\odot$ and luminosity $L_{\text{bol}} \simeq 1.3 L_\odot$. Its X-ray emission is moderately strong and constant.

Source 74, T48=WZ Cha=–HM 28=–Sz 38=C1-23=–HBC 585=–Cam1 98=ISO 258=–CHXR 82.—WZ Cha is a lightly absorbed, variable M1 CTT star with $M \simeq 0.7 M_\odot$, $L_{\text{bol}} \simeq 0.15 L_\odot$, and an unusually strong H$_\alpha$ line. Because of its low luminosity, it has an old inferred age around $\tau \simeq 10$–20 Myr. This appears to be a case in which accretion has endured for many millions of years. It has weak, soft, and unabsorbed X-ray emission.

Source 75, Hn 13=C2-5=–Cam1 99=ISO 259=–Cha 1 755.—This is a lightly absorbed, older M6 CTT star with $L_{\text{bol}} \simeq 0.16 L_\odot$, and $M \simeq 0.08 M_\odot$, around the substellar limit. The X-ray spectrum implies heavier absorption around $A_V \simeq 20$ (with considerable uncertainty), which implies a strong intrinsic luminosity around log $L_X \simeq 29.6$ erg s$^{-1}$, far above the typical level for proto–brown dwarfs. The light curve shows a 6 hr flarelike variation (Fig. 4i).

Source 91, CHXR 48=E1-7=–Cam1 101=ISO 280.—This is a lightly absorbed, photometrically variable M2.5 WTT star with $L_{\text{bol}} = 0.25 L_\odot$, and $M \simeq 0.4 M_\odot$. It lies on the periphery of the cloud. The X-ray emission is strong and exhibits spectacular flaring with both rapid ($\gtrsim 1$ hr) and slow ($\sim$6 hr) components, with peak luminosity around log $L_X \simeq 30.5$ erg s$^{-1}$ (Fig. 4k).

The X-ray spectrum implies subsolar iron abundance in the plasma, as commonly found in flaring stars.

Source 100, CHXR 84=–Hn 16=Cam1 105=E1-10=–Cha 1 742.—This is a heavily absorbed M5.5 cloud member lying off the cloud core, with estimated mass $M \simeq 0.1 M_\odot$ and $L_{\text{bol}} \simeq 0.12 L_\odot$. With only one measurement of H$_\alpha$ with 20 Å equivalent width and no K-band excess, it probably should be classified as a WTT star. The X-ray emission is moderate, with spectral evidence for a reduced iron abundance.

Source 103, T50=–Sz 40=E1-5=–HBC 587=–Cam1 106=–CHXR 85=–Cha 1 757.—This is a very young, photometrically variable M5 CTT star with $M \simeq 0.1 M_\odot$ and $L_{\text{bol}} \simeq 0.19 L_\odot$. The optical spectrum indicates light absorption of $A_V \simeq 1$, and the source lies in an unobscured region off the cloud core, but the strong X-ray emission has an unusual spectrum best fitted by a soft plasma suffering heavy absorption equivalent to $A_V \simeq 12$ (with considerable uncertainty). But with only 60 counts for analysis, this finding cannot be considered definitive.

Source 105, T51=–Sz 41=–HBC 588=E1-9a=–Cam1 107=–IRAS 11108$-$7620=–CHXR 20b=–CHXR 50.—This is a visually very bright, unabsorbed, older K3.5 WTT star off the cloud core with $L_{\text{bol}} \simeq 1.1 L_\odot$ and $M \simeq 1.2 M_\odot$. It is a visual binary, with a fainter companion 15′ to the southeast; the similarly bright star $\simeq 12''$ to the east is not a cloud member (Ghez et al. 1997; Walter 1992). It has no K-band excess but nonetheless appears to have a faint outer disk seen with IRAS. The star appears relatively faint during the Chandra observation, with only 50 counts and log $L_X \simeq 29.0$ erg s$^{-1}$; this is an order of magnitude fainter than that during the earlier ROSAT pointed, ROSAT All-Sky Survey, and Einstein observations. However, the source is at the edge of the ACIS detector, and, because of the broad off-axis point-spread function, many photons are probably lost during satellite dithering.

7. RELATIONSHIPS BETWEEN X-RAYS AND OTHER PROPERTIES OF PMS STARS

Despite many years of empirical investigation, some fundamental uncertainties remain in our understanding of the
astrophysical origins of X-ray emission from PMS stars. It is clear that the X-rays are produced by plasma magnetically confined and heated to $10^7$--$10^8$ K. Violent magnetic reconnection events similar to, but more powerful than, contemporary solar flares are often seen in the X-ray light curves. But the geometry of the reconnecting magnetic fields has been debated: solar-type fields rooted in the stellar surface, long field lines connecting the star to the corotation radius of the disk, and fields entirely associated with the disk have been proposed (Feigelson & Montmerle 1999). It is further puzzling that X-ray luminosities show a strong correlation with the closely intertwined properties of stellar bolometric luminosity, size, and mass that is not closely linked to stellar rotation as seen in main-sequence stars (Feigelson et al. 2003; Flaccomio et al. 2003). Soft X-ray absorption can also be compared with optical-infrared reddening to constrain the gas-to-dust ratio of the cloud. We consider these issues only briefly here because the Cha I North population is small, and our findings are not novel. Stellar properties are presented in Table 3; for consistency, most values are adopted from Luhman (2004).

Figure 5a shows a broad correlation extending over 2–3 orders of magnitude between X-ray luminosity and $K$-band magnitude. The $L_X$-$L_{bol}$ correlation, commonly seen in PMS populations, looks very similar to this plot. The similar rough correlation between $L_X$ and mass $M$ (Fig. 5b) is expected from the link between mass and $L_{bol}$ in a roughly coeval PMS population. A weak anticorrelation between $L_X$ and age may be present (Fig. 5c), but this may be an indirect effect of the below-average bolometric luminosities and masses of the few older stars in the field.

The outlier with high $L_{bol}$ and $M$ but only average $L_X$ is HD 97300. The low $L_X/L_{bol}$ ratio of intermediate-mass B and A PMS stars is often seen in PMS populations and is usually attributed to X-ray production by an unresolved magnetically active low-mass companion rather than the more massive star, which does not have an outer convection zone (e.g., Feigelson et al. 2002a; Stelzer et al. 2003).

Past studies have discussed whether or not the X-ray luminosities of nonaccreting WTT stars are systematically elevated compared with accreting CTT stars (Preibisch & Zinnecker 2002; Flaccomio et al. 2003 and references therein). This issue is important for interpreting the astrophysical origin of PMS X-ray emission but is complicated by sample biases and the log $L_X$-$L_{bol}$ correlation. Adopting the classifications given in column (4) of Table 3 and the intrinsic absorption-corrected 0.5–8 keV luminosities $L_\text{c}$, we find mean values of $\langle L_\text{c} \rangle = 29.8 \pm 0.2$ ergs s$^{-1}$ for 10 cataloged WTT stars and $\langle L_\text{c} \rangle = 29.3 \pm 0.2$ ergs s$^{-1}$ for 16 cataloged CTT stars. As our sample is likely complete to $M \geq 0.1 M_\odot$ ($\S$ 8), the reported excess of WTT over CTT X-ray emission appears to be confirmed. However, we see no systematic difference between CTT and WTT stars in the bivariate $L_X$-$K$ diagrams or in X-ray variability or spectral type. Our results are thus not conclusive on this issue.

The $N_H$ column densities obtained from X-ray spectral fitting represent a measurement of the total (i.e., solid, molecular, atomic, and ionized) intervening interstellar gas that can be compared with the independent optical/IR measurement of reddening by dust alone (Vuong et al. 2003). The six most heavily absorbed stars with more than 100 ACIS counts, CHXR 79, C1-25, T42, T43, T44, and ISO 237 ($A_V \geq 7$), have $5 < A_V < 16$. Together these stars give an interstellar absorption ratio $N_H/A_V \approx 1.0 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$, lower than the traditional value of $2 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$. This difference is in the same direction as the more reliable and well-substantiated value $N_H/A_V = 1.6 \times 10^{21}$ cm$^{-2}$ mag$^{-1}$ derived by Vuong et al. (2003) from a larger sample of heavily absorbed PMS stars in the $\rho$ Oph cloud.

8. DISCUSSION: THE CLOUD POPULATION

As outlined in $\S$ 1, X-ray surveys provide a method to obtain the census of a PMS stellar cluster with different selection effects and different sources of contamination than encountered in O/NIR surveys. The value of Cha I North is its proximity, compactness, and unusually intensive study at O/NIR wavelengths (Cambresy et al. 1998; Oasa et al. 1999; Comerón et al.)
correlation and scatter in the log $L_X$ should not be viewed as complete (in particular, there are additional COUP members seen with an unusual geometry. On the basis of the correlation, giving a very sensitive X-ray survey down to log $L_X \approx 27$ ergs s$^{-1}$ to give new insight into the cloud population and its IMF.

8.1. A Complete Sample of 27 Cloud Members

We have already argued that our X-ray source list is complete to log $L_x \approx 26.9–27.5$ ergs s$^{-1}$, where the value depends on the individual stars’ absorption and location in the ACIS field (§ 4.1). This is more sensitive than almost all previously published studies of young stellar populations, which generally have limiting log $L_x \geq 28.0$ ergs s$^{-1}$. Of the 107 ACIS sources (Table 1), 69 are confidently classified as extragalactic, and 37 are confidently classified as stellar (§ 4.2). The remaining ambiguous source (42) shows rapid variability resembling a PMS star but has no O/NIR counterpart. Of the 37 stellar X-ray sources, nine are classified as non-PMS background stars (§ 5). One additional X-ray source (16) has a stellar counterpart that is probably a magnetically active field star but could be a cloud member seen with an unusual geometry.

The remaining 27 ACIS sources discussed in § 6 constitute the X-ray–selected sample of cloud members. This sample has no known contaminants and (except for the possible additions of sources 16 and 42) is complete in X-ray luminosity. There are no anomalies in which a confidently known bright O/NIR member is undetected in X-rays. On the basis of the correlations between $L_x$, $L_{bol}$, and $M$ (§ 7), we now argue that this sample is also complete to interesting limits in bolometric luminosity and mass. If we recall that the O/NIR surveys of the region are not limited by sensitivity (they can detect all objects with $M > 20M_J$ and $t < 10$ Myr; § 4.2), the issue here is the evaluation of noncloud contaminants in various O/NIR samples.

Figure 6 compares the log $L_x$–$K$ relationship for the 27 Cha I North stars (previously seen in Fig. 5a) with that seen in the more populous Orion Nebula cluster (ONC). The Chamaeleon I and Orion samples clearly occupy the same region in the diagram and show the same correlation. The shaded band indicates our Cha I North X-ray completeness limit (§ 4.1).

We use the Orion sample in Figure 6 to argue that, at a distance of 160 pc, an X-ray survey complete to log $L_x \approx 26.9–27.5$ ergs s$^{-1}$ is also complete to $K \approx 11$ and captures the majority of stars with $11 < K < 12$. We are confident of this conclusion even without knowing the exact nature of the log $L_x$–$K$ relation and its scatter at low luminosities because no cloud members were found below log $L_x = 28.2$ ergs s$^{-1}$. We consider this to be important: The ACIS image should have detected all cloud members in the range (26.9–27.5) ergs s$^{-1} < \log L_x < 28.2$ ergs s$^{-1}$. Half the extragalactic sources and most of the field star sources (Fig. 5a, open circles) were found at these low flux levels, so there clearly is no operational difficulty in detecting such sources. The exception would be cloud members with extremely high absorption, log $N_H > 23$ cm$^{-2}$ or $A_F > 100$, such as the Class 0 protostar Cha-MMS 2 (Reipurth et al. 1996). With this caveat, we conclude that the X-ray–complete sample of 27 cloud members represents a complete and uncontaminated census of cloud members with $K \leq 12$ lying in the ACIS field.

One by-product of this result is a clarification of the membership status of several O/NIR stars discussed in the literature. Six stars—ISO 154, ISO 164, ISO 165, Ced112 IRS2, ISO 247 (Carpenter et al. 2002), and ESO-Hα 564 (Comerón et al. 2004)—have $10.2 < K < 11.7$ and are undetected in the ACIS image. These can be excluded from cloud membership with considerable confidence. Most of these X-ray–quiet stars have been independently evaluated to be background stars on the basis of optical spectra by Luhman (2004). The exception is the M5.5 star ISO 165, a slightly reddened $\sim$M5 star with strong Hα but negligible infrared excess (Kenyon & Gómez 2001; López-Martí et al. 2004), which Luhman classifies as a cloud member but which we believe is a nonmember because of the X-ray nondetection. With only one such disagreement, we find a gratifying agreement between our X-ray and Luhman’s spectroscopic census of cloud members, considering that the selections are based on very different criteria.

8.2. The KLF and IMF

Having established that our sample of 27 stars is largely complete and uncontaminated to $K \approx 12$, we readily construct the $K$-band luminosity on the basis of $K$ magnitudes in Table 3.

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8 The Orion sample is obtained from the tables of COUP provided by K. V. Getman et al. (2004, in preparation). The sample here consists of 399 COUP sources with counterparts in the JHKZ catalog of Muench et al. (2002). The Orion $K$ magnitudes have been artificially decreased by 2.0 to place them at a distance of 160 pc rather than 450 pc. The log $L_X$ values were obtained using the acis_extract package consistent with our analysis here. This Orion sample should not be viewed as complete (in particular, there are additional COUP sources with fainter $K$-band counterparts; M. McCaughrean, private communication), but rather it gives a larger PMS population to better define the correlation and scatter in the log $L_X$–$K$ diagram.

9 The X-ray measurement does not clarify the membership status of C1-14, a reddened F0 star with $K = 7.8$, because F stars often have soft coronal X-ray spectra that could be fully absorbed by interstellar gas.
Figure 7a compares our Cha I North KLF with that of the ONC derived by Muench et al. (2002) after scaling (as in Fig. 6) by 
\( \Delta K = 2.0 \) to account for the difference in distance. We see that both KLFs show a similar rise from bright magnitudes to a peak around \( K' \approx 9.5 \). The falloff at faint magnitudes appears somewhat steeper in Cha I North, but the difference is not statistically significant.

Figure 7b shows the Cha I North IMF for our sample using masses given in Table 3 and compares it with the IMF inferred for the ONC (Hillenbrand & Carpenter 2000) and a general Galactic IMF derived by Kroupa (2001) from a variety of cluster and field star populations. Here a deficiency of lower mass stars in Cha I North is clearly present. The Cha I North IMF peaks in the 0.3–1.0 \( M_\odot \) bin, while the other IMFs peak around 0.1 \( M_\odot \). The effect is statistically significant. A Kolmogorov-Smirnov two-sample test between the ONC and Cha I North IMFs indicates only a 0.3\% probability (3 \( \sigma \) equivalent) that they are drawn from the same population. Alternatively, if one considers the ratio of stars in the 0.1–0.3 bin to those in the 0.3–1.0 \( M_\odot \) bin, the observed ratio in Cha I North of 5:14 has a 99\% confidence ratio, 0.09–0.72, while the Orion and Kroupa IMFs predict a ratio around 1.5. The difference can be erased only if a considerable number of Cha I North stars are present that simultaneously have \( K \) below our completeness limit of \( \approx 12 \) and masses above \( M \approx 0.1 M_\odot \), i.e., an older PMS population superposed on the younger well-characterized population.

We thus establish a deficit of 0.1–0.3 \( M_\odot \) stars in Cha I North compared with standard IMFs. We can tentatively and qualitatively extend this inference to the BD regime. Three previously known objects at or below the stellar limit are detected: ISO 192, ISO 217, and Hn 13. But no additional X-ray–selected population (with the possible exception of the rapidly variable source 42, which has no reported O/NIR counterpart) is seen. If a large number of BDs were present, we would expect a fraction of them to have X-ray luminosities above our sensitivity and appear in the ACIS image. This result is consistent with reports of poor BD populations in the Taurus-Auriga and IC 348 star-forming regions (Luhman 2000; Briceño et al. 2002; Preibisch et al. 2003). However, this argument cannot be made quantitatively until the Chandra Orion Ultradeep Project (COUP) survey establishes the scatter about the \( L_r-L_{bol} \) and \( L_r-K \) relationships in substellar PMS objects.

It may be that the Cha I North cloud has an intrinsically nonstandard IMF because of its star formation process. For example, the population of lowest mass stars may be sensitive to the spectrum of the turbulent velocity field in the cloud (Delgado-Donate et al. 2004). But it is critical to recall that the deficiency of lower mass stars applies only to the 16’×16’ (0.8×0.8 pc) ACIS field. We thus cannot exclude alternative hypotheses that place the lower mass stars preferentially outside the ACIS field of view. It seems plausible that mass segregation is present, leading to a surfeit of higher mass stars in the cloud core. This could be either a characteristic of the primordial cluster formation process or a later dynamical development. Evidence for primordial mass segregation has been found both in the rich ONC (Bonnell & Davies 1998) and in the sparse \( \eta \) Cha cluster (Lyo et al. 2004). Dynamical segregation could also occur if lower mass stars are preferentially born with a velocity dispersion greater than that of the higher...
mass stars or if they are ejected from multiple systems because of close gravitational encounters (e.g., Reipurth & Clarke 2001; Kroupa & Bouvier 2003). A velocity dispersion difference as small as $\geq 0.2 \text{ km s}^{-1}$ is sufficient for stars to travel outside the ACIS field in $\approx 2 \text{ Myr}$, a typical age for the Cha I North stars.

9. CONCLUSIONS

The low-mass population of the Chamaeleon I cloud has been investigated in the O/NIR bands by several groups but with discrepant samples and differing conclusions (Cabrera et al. 1998; Persi et al. 2000; Comerón et al. 2000; Gómez & Mardones 2003; López-Martí et al. 2004; Luhman 2004). Some are optimistic that a significant population of low-mass stars and substellar objects are being found within the heavily contaminated infrared samples, while others suggest that BDs are deficient or that the census is too incomplete to reach clear conclusions. We bring to bear here a distinct and complementary method for identifying PMS stars of all masses: high-sensitivity, high-resolution imagery with the Chandra X-Ray Observatory.

Our Chandra survey with limiting log $L_x \approx 27 \text{ ergs s}^{-1}$, sufficient to detect the contemporary active Sun, should be complete to $M \approx 12$ or $M \geq 0.1 \text{ M}_\odot$. Equally important, X-ray surveys of this type can confidently tell when an O/NIR star is not a cloud member because of the enormous difference in $L_x/L_{bol}$ ratios for PMS and old disk stars that frequently contaminate O/NIR surveys.

We find no cloud members with $(26.9-27.5) \text{ ergs s}^{-1} < \log L_x < 28.3 \text{ ergs s}^{-1}$ (0.5–8 keV band), and no more than one new X-ray–discovered cloud member is present. We furthermore confirm that several previously suspected cloud members are probably background stars. The result is a nearly complete and uncontaminated sample of 27 cloud members in the ACIS field of the Cha I North cloud. The IMF of this sample is significantly deficient in $0.1-0.3 \text{ M}_\odot$ stars compared with the IMF of the rich ONC and the general stellar IMF. This supports recent observational studies that report deficits in the BD population in low-density star formation regions (Briceno et al. 2002; Preibisch et al. 2003). However, our X-ray field of view is rather small, so we cannot discriminate between a true deficiency in low-mass stars and alternative explanations such as mass segregation or dynamical ejection of the lowest mass PMS stars.

From the forthcoming COUP study, we are likely to learn how the relationships between $L_x$ and $L_{bol}$, $K$, and $M$ extend into the substellar regime. This will permit us to derive quantitative inferences regarding the BD population in Cha I North. At the present time, we can say only qualitatively that this population appears to be small, as we would expect some fraction to have X-ray luminosities exceeding $\log L_x \approx 27 \text{ ergs s}^{-1}$. Three of the 27 stars in our complete sample, ISO 192, ISO 217, and (probably) Hn 13, lie below the substellar limit and, by virtue of their X-ray emission, are confirmed cloud members.

The reliability of the X-ray census method used here rests on the empirical relationships between $L_x$ and $K$ and the closely related correlations between $L_x$, $L_{bol}$, and masses $M$ among PMS stars. These relationships have been seen in nearly all well-studied PMS stellar clusters with Chandra: the ONC (Flaccomio et al. 2003; Feigelson et al. 2003), NGC 1333 (Getman et al. 2002), IC 348 (Preibisch & Zinnecker 2002), Mon R2 (Kohno et al. 2002), and NGC 2024 (Skinner et al. 2003). Given their importance, it is worrisome that these relationships between magnetic activity and bulk stellar properties are largely unexplained (Feigelson et al. 2003). But if one accepts them, these relationships permit a translation between an observational X-ray flux limit and limits in the KLF and IMF. Our confidence in the reliability and completeness of X-ray surveys will increase as we improve our characterization of these relationships and the scatter about them.

Finally, we bring to attention one remarkable low-mass PMS star. ISO 192 was already known to have the heaviest absorption and strongest NIR color excess among Cha I members with heavy spectroscopic veiling and large photometric variability. It has been interpreted as a substellar ($\sim 60 \text{ M}_\oplus$) Class I protostar and the likely source of the Cha I North molecular bipolar flow. We add here another unusual characteristic: strong magnetic activity with intrinsic X-ray luminosity around $10^{29} \text{ ergs s}^{-1}$.

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