The Structure of the Young Star Cluster NGC 6231. I. Stellar Population

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Abstract

NGC 6231 is a young cluster (age ~2–7 Myr) dominating the Sco OB1 association (distance ~1.59 kpc) with ~100 O and B stars and a large pre-main-sequence stellar population. We combine a reanalysis of archival Chandra X-ray data with multiepoch near-infrared (NIR) photometry from the VISTA Variables in the Vía Lactea (VVV) survey and published optical catalogs to obtain a catalog of 2148 probable cluster members. This catalog is 70% larger than previous censuses of probable cluster members in NGC 6231. It includes many low-mass stars detected in the NIR but not in the optical and some B stars without previously noted X-ray counterparts. In addition, we identify 295 NIR variables, about half of which are expected to be pre-main-sequence stars. With the more complete sample, we estimate a total population in the Chandra field of 5700–7500 cluster members down to 0.08 M⊙ (assuming a universal initial mass function) with a completeness limit at 0.5 M⊙. A decrease in stellar X-ray luminosities is noted relative to other younger clusters. However, within the cluster, there is little variation in the distribution of X-ray luminosities for ages less than 5 Myr. The X-ray spectral hardness for B stars may be useful for distinguishing between early-B stars with X-rays generated in stellar winds and B-star systems with X-rays from a pre-main-sequence companion (>35% of B stars). A small fraction of catalog members have unusually high X-ray median energies or reddened NIR colors, which might be explained by absorption from thick or edge-on disks or being background field stars.

Key words: open clusters and associations: individual (NGC 6231) – stars: formation – stars: massive – stars: pre-main sequence – stars: variables: T Tauri, Herbig Ae/Be – X-rays: stars

Supporting material: FITS files, machine-readable tables

1. Introduction

NGC 6231 is the dominant young stellar cluster (~2–7 Myr old) at the center of the Sco OB1 association (d ~ 1.59 kpc; Sung et al. 1998). This cluster is notable for having a large population of pre-main-sequence and early-type stars (Sung et al. 1998; Sana et al. 2007b; Reipurth 2008; Damiani et al. 2016). The natal molecular cloud has already been dispersed, leading to a cessation of star formation activity, so the cluster represents the final product of the star formation process. Nevertheless, Sco OB1 also contains other regions, some of which are forming stars, including the Large Elephant Trunk and the young stellar cluster Tr 21 to the northwest and IC 4628 to the northeast. NGC 6231 itself is probably substantially larger than the ~0.1 deg2 Chandra/ACIS-I field, which only includes the central region of the cluster.

Clusters containing OB stars can be important laboratories for understanding star formation because most low-mass stars, like our Sun, likely formed in regions containing massive stars (Dukes & Krumholz 2012; Gouenelle & Meynet 2012). NGC 6231 is host to a number of massive stars, including a Wolf–Rayet (WR) star, 15 O-type stellar systems, and at least 91 B-type stellar systems. In addition to the WR star (HD 152270; WC7+O5-8 binary), several other massive stars have evolved, including >20 OB stars classified as giants or supergiants by Humphreys (1978). Among them are the earliest-type star in the cluster, HD 152233 (O6III(f) +O9? binary; Lbol = 105.7 L⊙), and the most luminous system in the cluster, HD 152248 (O7.5III(f)+O7III(f) binary; Lbol = 105.8 L⊙). The massive star HD 153919 (O6.5Iaf+), with an angular separation of ~4° from the cluster, is probably a runaway cluster member (Feinstein & Forte 1974; Ankay et al. 2001) that was discovered to be a high-mass X-ray binary (HMXB) with a neutron-star or black-hole companion (Jones et al. 1973; Clark et al. 2002). Several other WR stars lie outside the cluster center, including HD 151932 (WN9ha) and HD 152408 (WN7h) (Faherty et al. 2014).

NGC 6231 is at a critical stage in its evolutionary history for either the birth of a bound open cluster or the dispersal of its stellar population into the Galactic field. Most clusters of newly formed stars disperse once the star formation activity in a region has ceased (Lada & Lada 2003). Clusters can become unbound due to either mass loss from the dispersal of molecular cloud mass (Tutukov 1978; Hills 1980) or tidal interactions with other giant molecular clouds (Kruipjssen 2012). Cloud dispersal has recently occurred in NGC 6231, possibly due to one or more supernovae, including a possible explosion 3 Myr ago that formed the HMXB.

In these two papers, we aim to understand the cluster’s evolution through investigation of the final stellar population produced by star formation and modeling of the cluster’s structure and dynamics. For a study of structure, a large representative sample of the cluster’s low-mass stars is essential. In particular, care must be taken to construct a mass-complete sample of stars to avoid systematic biases due to selection effects from missing stars (e.g., Ascenso et al. 2009).

In this article (Paper I), we obtain a new, more complete census of probable cluster members using deeper near-infrared
(NIR) survey data and a reanalysis of the archival Chandra X-ray Observatory observations. Paper II will model the spatial structure of the NGC 6231 cluster, including its density profile, subclusters of stars within the cluster, mass segregation, and age gradients. The results of these investigations will be used to comment on both the formation of NGC 6231 and its fate, based on theoretical understandings of cluster assembly and dissolution.

1.1. X-Ray and Infrared Methods for Young Stellar Populations

Low-mass stars in young stellar clusters and star-forming regions are difficult to disentangle from field stars (Feigelson et al. 2013), and this is particularly true for NGC 6231 in quadrant 4 of the Galactic plane, \((\ell, b) = (343.5, +1.2)\). Some previous studies have used optical methods to identify young stars, including \(H\alpha\) emission (e.g., Sung et al. 1998) or placement of objects on optical color–magnitude diagrams (e.g., Damiani et al. 2016). However, most cluster members have been discovered using X-ray observations by both XMM-Newton (Sana et al. 2004, 2005, 2006a, 2006b, 2006c, 2007a, 2007b, 2008a, 2008b) and the Chandra X-ray Observatory (Damiani et al. 2016, hereafter DMS2016).

Our study of NGC 6231 adopts methods for studying young stellar populations developed by the Penn State group in a variety of X-ray/infrared projects, most directly from the Massive Young Star-forming Complex Study in Infrared and X-ray (MYSiX; Feigelson et al. 2013). MYSiX combined a reanalysis of archival Chandra data with NIR catalogs from UKIDSS + Two Micron All Sky Survey (2MASS) and mid-infrared catalogs from Spitzer/IRAC to identify young stars at various evolutionary stages ranging from protostars to disk-free pre-main-sequence stars. The MYSiX project surveyed 20 star-forming regions, each containing at least one O-type star, that range in distance from 0.4 to 3.6 kpc and provided a catalog of >30,000 MYSiX Probable Complex Members (MPCMs; Broos et al. 2013). The MPCM catalog has served as a basis for investigations of cluster structure and evolution (Kuhn et al. 2014, 2015a, 2015b; Jaehnig et al. 2015), star formation history and spatial gradients in stellar ages (Getman et al. 2014a, 2014b), circumstellar-disk evolution (Richert et al. 2015), pre-main-sequence evolution of X-ray luminosity (Gregory et al. 2016), and previously unknown populations of protostars (Romine et al. 2016) and OB stars (Povich et al. 2017).

Other studies following similar strategies include the Chandra Orion Ultradeep Project (COUP; Getman et al. 2005), the Chandra Carina Complex Project (CCCP; Townsley et al. 2011), Star Formation in Nearby Clouds (SFNCs; Getman et al. 2017), and studies of many individual regions, including NGC 1333 (Getman et al. 2002), 30 Doradus (Townsley et al. 2006), Cep B (Getman et al. 2006), IC 1396N (Getman et al. 2007), NGC 6357 (Wang et al. 2007), M17 (Broos et al. 2007), RCW 49 (Tsujimoto et al. 2007), CG 12 (Getman et al. 2008b), W3 (Feigelson & Townsley 2008), the Rosette Nebula (Wang et al. 2008), NGC 6334 (Feigelson et al. 2009), W40 (Kuhn et al. 2010), and IC 1396A and Tr 37 (Getman et al. 2012).

In most of these studies, NIR counterparts to X-ray sources are used as the primary indicator of cluster membership, with only a small fraction of these sources pruned as likely foreground or background sources. In the case of NGC 6231, more than twice as many X-ray sources have \(K_s\)-band counterparts than have \(V\)-band counterparts in the optical and infrared catalogs that are available (Section 3.2). This is an effect of both the relative brightness of M stars (the typical spectral type of a 0.5 \(M_{\odot}\) star at 3–7 Myr) in the infrared compared to the optical and the moderate absorption of the cluster. Thus, restricting classification to sources detected in the optical will omit nearly half the detected cluster members. Furthermore, neither the optical nor the infrared color–magnitude diagrams can provide a definitive indication of membership, so some level of contamination is inevitable whether a sample is defined in the optical or NIR.

Our X-ray source detection and extraction methodology is designed to make optimum use of Chandra’s sensitivity. Source detection uses maximum-likelihood (ML) image reconstruction to identify sources in crowded regions, and point-source validation is performed using sophisticated source and background modeling (Broos et al. 2010; Townsley et al. 2014). The data analysis recipes and (ACIS) Extract software (Broos et al. 2010, 2012), which implement these strategies, typically detect 1.5–2 times more X-ray sources (many of which have counterparts in other wavebands) than other leading software, such as wavdetect (Freeman et al. 2002) and pwdetect (Damiani et al. 1997). We have developed techniques for the nonparametric estimation of X-ray luminosity and absorption for faint sources (Getman et al. 2010).

Both the X-ray and NIR strategies are designed to produce large catalogs of probable cluster members while allowing some contaminants. This allows us to take full advantage of the effective area of the Chandra X-ray Observatory, doubling our sample size. The contamination rate can be approximately estimated by simulations (Section 4.1) and is found not to be significantly higher than in previous studies. In the statistical literature of the last 20 years, the bias toward minimizing false positives has been revised in favor of less-stringent controls on Type I error that have greater statistical power (cf. False Discovery Rate; Benjamini & Hochberg 1995). For the scientific purpose of modeling the cluster structure in Paper II, the larger sample is a major advantage, while the contaminants have little effect and can be accounted for as a spatially uniformly distributed population of sources in the model (e.g., Kuhn et al. 2014).

1.2. Outline of This Paper

Section 2 provides basic cluster properties from the literature. Section 3 describes the observations and data reduction. Section 4 derives a catalog of probable cluster members. Section 5 derives stellar properties from infrared and X-ray data. Section 6 discusses the OB stellar population. Section 7 provides the conclusion.

2. Basic Cluster Properties

This work makes use of some basic cluster properties available from the literature. Summaries of older studies are provided by Sana et al. (2006b) and Reipurth (2008). Expanded catalogs of cluster members have been provided by Sung et al. (2013) and DMS2016.

Distance. Sana et al. (2006b) summarized a variety of estimates of the distance modulus and reported a weighted mean of \(DM = 11.07 \pm 0.04\). Distance can also be estimated independently using the parallax measurements.
of nine of the OB stars in the Tycho-Gaia Astrometric Solution (TGAS) catalog (Gaia Collaboration et al. 2016), yielding a distance estimate of \( d = 1.37 \pm 0.42 \) kpc (Appendix). We follow DMS2016 and adopt a distance modulus of \( DM = 11.0 \), corresponding to a distance of \( d = 1.59 \) kpc.

**Age.** Recent estimates of median stellar age have clustered around \( \sim 3-7 \) Myr and suggest a significant age spread of \( \Delta \) age \( \sim 3-7 \) Myr (Sana et al. 2007b; Sung et al. 2013; Damiani et al. 2016). The estimates of stellar ages in the literature come from both pre-main-sequence and post-main-sequence evolution on the Hertzsprung–Russell (HR) and color–magnitude diagrams. For high-mass stars, Sung et al. (2013) found that the distribution was bracketed by 3–4 Myr isochrones from Bott et al. (2011) or 4–7 Myr isochrones from Ekström et al. (2012). DMS2016 (their Figure 5) showed that spectroscopically identified OB stars on a \( B - V \) versus \( B - V \) diagram are scattered around the 3 Myr isochrone from Ekström et al. (2012). For low-mass, pre-main-sequence stars, Sung et al. (2013) estimated stellar ages using the Siess et al. (2000) models, finding ages ranging from 1 to 7 Myr, with a peak at \( \sim 3 \) Myr. For pre-main-sequence stars, DMS2016 reported a \( V \)-band magnitude distribution consistent with an age range of 1.5–7 Myr. They also noted that, on the \( J \) versus \( J - H \) color–magnitude diagram, the stars follow a 5 Myr isochrone well.

The HD 153919 HMXB may provide an additional constraint on age, as was previously noted by Ankay et al. (2001). The TGAS catalog reports a proper motion of \( \Delta \alpha = 2.28 \pm 0.04 \text{ mas yr}^{-1} \) and \( \Delta \delta = 4.95 \pm 0.03 \text{ mas yr}^{-1} \) for HD 153919. This traceback vector passes through NGC 6231 \( \sim 2.9 \) Myr ago. According to Ekström et al. (2012), the minimum lifetime of a massive star is 3.54 Myr, so the system must have been formed at least 6.4 Myr ago if it originated in NGC 6231. We note that this traceback vector also passes through other parts of the Sco OB1 association, so its origin in NGC 6231, while likely, is not certain, and constraints on its age would depend on where in Sco OB1 it originated. For example, the traceback vector also passes through the star-forming region IC 4628 \( 1.9 \) Myr ago.

To infer the stellar properties, we use an age of 3.2 Myr (Section 5.5) and an alternate age of 6.4 Myr. A younger median age of stars in the cluster is not necessarily inconsistent with the presence of an older star, given the considerable age spread indicated by previous studies. Absorption. The natal molecular cloud of NGC 6231 appears completely dispersed. Massa (2017) noted that stellar winds flow unimpeded for more than 2 pc in the center of the cluster, based on their observations of a C IV absorption feature.

Studies suggest that most of the reddening of the cluster occurs in foreground clouds between 100 and 1300 pc in distance and in a possible shell of material surrounding Sco OB1 (Sana et al. 2006b). A map of reddening by Sung et al. (2013, their Figure 4) shows variations \( E(B - V) \) from 0.40 to 0.55 mag in a \( 40' \times 40' \) region around the cluster. The cluster itself is in a local hole in the extinction with \( E(B - V) \approx 0.45 \) mag corresponding to \( A_V \approx 1.4 \) mag for \( R = 3.1 \). DMS2016 reported uniform extinction of cluster members.

### 3. Observations and Data Reduction

#### 3.1. X-Ray Data

*Chandra* X-ray observations were made using the imaging array on the Advanced CCD Imaging Spectrometer (ACIS-I; Garmire et al. 2003). This instrument is an array of four CCD detectors that subtends \( 17' \times 17' \). (The ACIS-S2 and S3 chips were also active during the observation, but we exclude these data due to *Chandra*'s reduced angular resolution far off axis.) The target was observed in 2005 July (Sequence 200307; PI: S. Murray) in two observations (ObsID 5372 and 6291), and the data were retrieved from the *Chandra* Data Archive. These observations were both taken in faint mode, with exposure times of 77,165 and 44,954 s, roll angles of 299° and 287°, and an aimpoint of \( 165^{h}12^{m}09^{s}, -41^\circ 50'23''02' \) (J2000). The *Chandra* event files provide the time, position, and energy of each photon-detection event on the CCD. The X-ray image of NGC 6231 is shown in Figure 1, produced by the Ebeling et al. (2006) adaptive-smoothing algorithm.

#### 3.1.1. X-Ray Source Extraction

The X-ray data reduction for NGC 6231 follows the MYSTIX data-reduction procedures given by Broos et al. (2010), Townsley et al. (2014), and Kuhn et al. (2013). These procedures make use of ACIS Extract and TARA recipes available from the Astrophysics Source Code Library (Broos et al. 2012). This analysis requires additional software such as CIAO (Fruscione et al. 2006), MARX (Davis et al. 2012), HEASoft (HEASARC 2014), and the Astronomy User’s Library (AstroLib; Landsman 1993), and the work was carried out using the IDL programming language. Briefly, data products are rebuilt from the “Level 1” satellite telemetry applying a variety of calibrations and corrections developed at Penn State. Source detection is performed on deconvolved images generated with the Lucy–Richardson algorithm (Lucy 1974). The source list is
| Column Label | Units | Description |
|--------------|-------|-------------|
| (1)          | (2)   | (3)         |
| **X-Ray Photometry** (Broos et al. 2010, ACIS Extract) | | |
| Name | ... | X-ray source name; prefix is CXOU J |
| Label | ... | Source name generated by ACIS Extract |
| RAdeg | deg | R.A. (J2000) |
| DEdeg | deg | Decl. (J2000) |
| PosErr | arcsec | 1σ error circle around (RAdeg, DEdeg) |
| PosType | ... | Algorithm used to estimate position (Broos et al. 2010, Section 7.1) |
| ProbNoSrc_min | ... | Smallest of ProbNoSrc_t, ProbNoSrc_s, and ProbNoSrc_h |
| ProbNoSrc_t | ... | p-value\(_b\) for no-source hypothesis (Broos et al. 2010, Section 4.3) |
| ProbNoSrc_s | ... | p-value for no-source hypothesis |
| ProbNoSrc_h | ... | p-value for no-source hypothesis |
| ProbKS_single | ... | Smallest p-value for the one-sample Kolmogorov–Smirnov statistic under the no-variability null hypothesis within a single observation |
| ProbKS_merge | ... | Smallest p-value for the one-sample Kolmogorov–Smirnov statistic under the no-variability null hypothesis over merged observations |
| ExposureTimeNominal | s | Total exposure time in merged observations |
| ExposureFraction | ... | Fraction of ExposureTimeNominal that source was observed |
| NumObservations | ... | Total number of observations extracted |
| NumMerged | ... | Number of observations merged to estimate photometry properties |
| MergeBias | ... | Fraction of exposure discarded in merge |
| Theta_Lo | arcmin | Smallest off-axis angle for merged observations |
| Theta | arcmin | Average off-axis angle for merged observations |
| Theta_Hi | arcmin | Largest off-axis angle for merged observations |
| PsrFraction | ... | Average PSF fraction (at 1.5 keV) for merged observations |
| SrcArea | (0.492 arcsec)² | Average aperture area for merged observations |
| AfterglowFraction | ... | Suspected afterglow fraction |
| SrcCounts_t | count | Observed counts in merged apertures |
| SrcCounts_s | count | Observed counts in merged apertures |
| SrcCounts_h | count | Observed counts in merged apertures |
| BkgScaling | ... | Scaling of the background extraction (Broos et al. 2010, Section 5.4) |
| BkgCounts_t | count | Observed counts in merged background regions |
| BkgCounts_s | count | Observed counts in merged background regions |
| BkgCounts_h | count | Observed counts in merged background regions |
| NetCounts_t | count | Net counts in merged apertures |
| NetCounts_s | count | Net counts in merged apertures |
| NetCounts_h | count | Net counts in merged apertures |
| NetCounts_Lo | count | 1σ lower bound on NetCounts_t |
| NetCounts_Hi | count | 1σ upper bound on NetCounts_t |
| NetCounts_Lo | count | 1σ lower bound on NetCounts_s |
| NetCounts_Hi | count | 1σ upper bound on NetCounts_s |
| NetCounts_Lo | count | 1σ lower bound on NetCounts_h |
| NetCounts_Hi | count | 1σ upper bound on NetCounts_h |
| MeanEffectiveArea_t | cm² count photon⁻¹ | Mean ARF value |
| MeanEffectiveArea_s | cm² count photon⁻¹ | Mean ARF value |
| MeanEffectiveArea_h | cm² count photon⁻¹ | Mean ARF value |
| MedianEnergy | keV | ME, observed spectrum |
| MedianEnergy | keV | ME, observed spectrum |
| MedianEnergy | keV | ME, observed spectrum |
| PhotonFlux_t | photon cm⁻² s⁻¹ | log incident photon flux |
| PhotonFlux_s | photon cm⁻² s⁻¹ | log incident photon flux |
| PhotonFlux_h | photon cm⁻² s⁻¹ | log incident photon flux |

**X-Ray Spectral Model** (Getman et al. 2010, XPHOT)

|   |   |   |
|---|---|---|
| F_H | erg cm⁻² s⁻¹ | X-ray flux, 2.8 keV |
| F_HC | erg cm⁻² s⁻¹ | Absorption-corrected X-ray flux, 2.8 keV |
| SF_HC_STAT | erg cm⁻² s⁻¹ | 1σ statistical uncertainty on F_HC |
| SF_HC_SYST | erg cm⁻² s⁻¹ | 1σ systematic uncertainty on F_HC |
| F_T | erg cm⁻² s⁻¹ | X-ray flux, 0.5:8 keV |
| F_TC | erg cm⁻² s⁻¹ | Absorption-corrected X-ray flux, 0.5:8 keV |
| SF_TC_STAT | erg cm⁻² s⁻¹ | 1σ statistical uncertainty on F_TC |
| SF_TC_SYST | erg cm⁻² s⁻¹ | 1σ systematic uncertainty on F_TC |
| LOG_NH | cm⁻² | Gas column density |
Table 1 (Continued)

| Column Label   | Units   | Description                                      |
|----------------|---------|--------------------------------------------------|
| SLOG_NH_STAT   | cm⁻²    | 1σ statistical uncertainty on SLOG_NH           |
| SLOG_NH_SYST   | cm⁻²    | 1σ systematic uncertainty on SLOG_NH            |
| LOG_LTC        | erg s⁻¹ | log X-ray luminosity, 0.5:8 keV                 |
| LOG_LHC        | erg s⁻¹ | log X-ray luminosity, 2.8 keV                   |
| ERR_LOG_LTC    | erg s⁻¹ | 1σ statistical uncertainty on LOG_LTC           |
| ERR_LOG_LHC    | erg s⁻¹ | 1σ statistical uncertainty on LOG_LHC           |

Notes. X-ray source properties from ACIS Extract and XPHOT. Column definitions are identical to those in Kuhn et al. (2013). Rows are sorted by R.A. The suffixes “_t,” “_s,” and “_h” on names of photometric quantities designate the total (0.5–8 keV), soft (0.5–2 keV), and hard (2–8 keV) energy bands. Source significance quantities (ProbNoSrc_t, ProbNoSrc_s, ProbNoSrc_h, ProbNoSrc_min) are computed using a subset of each source’s extractions chosen to maximize significance (Broos et al. 2010, Section 6.2). Source position quantities (RAdeg, DEdeg, PosErr) are computed using a subset of each source’s extractions chosen to minimize the position uncertainty (Broos et al. 2010, Sections 6.2 and 7.1). All other quantities are computed using a subset of each source’s extractions chosen to balance the conflicting goals of minimizing photometric uncertainty and avoiding photometric bias (Broos et al. 2010, Sections 6.2 and 7).

a Source labels identify a Chandra pointing; they do not convey membership in astrophysical clusters.
b In statistical hypothesis testing, the p-value is the probability of obtaining a test statistic as extreme as the one that was actually observed when the null hypothesis is true.
c See Broos et al. (2010, Section 7.6) for a description of the variability metrics and caveats regarding possible spurious indications of variability using the ProbKS_merge metric.
d Due to dithering over inactive portions of the focal plane, a Chandra source is often not observed during some fraction of the nominal exposure time. (See http://cxc.harvard.edu/ciao/why/dither.html.) The reported quantity is FRACEXP produced by the CIAO tool mkarf.
e Some background events arising from an effect known as “afterglow” (http://cxc.harvard.edu/ciao/why/afterglow.html) may contaminate source extractions, despite careful procedures to identify and remove them during data preparation (Broos et al. 2010, Section 3). After extraction, we attempt to identify afterglow events using the tool ae_afterglow_report and report the fraction of extracted events attributed to afterglow; see the ACIS Extract manual (http://www.astro.psu.edu/xray/acis/acis_analysis.html).
f Confidence intervals (68%) for NetCounts quantities are estimated by the CIAO tool aprates (http://asc.harvard.edu/ciao/ahelp/aprates.html).
g The ancillary response file (ARF) in ACIS data analysis represents both the effective area of the observatory and the fraction of the observation for which data were actually collected for the source (ExposureFraction).
h MedianEnergy is the ME of extracted events, corrected for background (Broos et al. 2010, Section 7.3).
i PhotonFlux = (NetCounts/MeanEffectiveArea/ExposureTimeNominal) (Broos et al. 2010, Section 7.4)
j XPHOT assumes X-ray spectral shapes of young, low-mass stars, which come from coronal X-ray emission. XPHOT quantities will therefore be unreliable for high-mass stars, for which X-ray emission is associated with the stellar wind (Getman et al. 2010).

This table is available in its entirety in FITS format.

The Chandra X-ray point-source catalog is presented in Table 1. This table includes both X-ray photometry quantities obtained from ACIS Extract and X-ray spectral model quantities that are inferred using the XPHOT software (Getman et al. 2010); the definitions of these quantities are identical to those from Kuhn et al. (2013, their Table 4). Photometric quantities are often calculated for several energy bands: a soft band, including X-ray events with energies between 0.5 and 2.0 keV; a hard band, including X-ray events with energies between 2.0 and 8.0 keV; and a total band, including X-ray events with energies between 0.5 and 8.0 keV. Several important quantities, including X-ray median energy (ME), X-ray luminosity, and X-ray variability, are described below.

X-ray ME is a measure of spectral hardness calculated by taking the median of the energies of a source’s events on the CCD detector. Estimates of ME are more robust than estimates of the hardness ratio for sources with few counts, which comprise the majority of X-ray sources in this observation. For thermal X-ray sources, ME is moderately sensitive to plasma temperature and strongly sensitive to absorption from a thick molecular cloud (Getman et al. 2010). However, in the case of NGC 6231, where the obscuration of the cluster is $N_H \approx 1.6 \times 10^{21}$ cm⁻² (Section 5.2), the attenuation of X-rays by interstellar gas will be on the order of 1%, so ME will be mostly affected by plasma temperature and local absorption.

X-ray luminosities and absorbing columns are estimated using the XPHOT algorithms from Getman et al. (2010). For the vast majority of sources, the number of counts in the low-resolution X-ray spectrum extracted from the event list is too low for parametric fitting with software like XSPEC (Arnaud 1996). XPHOT provides a more robust method of estimating spectral properties by using photometric quantities such as NetCounts_t and ME along with empirical relations.
relating these properties to the X-ray spectroscopic properties of pre-main-sequence stars. These empirical relations were found by Getman et al. based on a sample of low-mass stars from COUP (Feigelson et al. 2005; Getman et al. 2005). The XPHOT spectral model properties reported in Table 1 include both statistical errors due to measurement uncertainties in the source photometry and systematic uncertainties due to intrinsic scatter in the empirical relations. These relations are only valid for the spectral characteristics of pre-main-sequence stars, so XSPEC analysis is performed for early-type stars in Section 6. In this paper, the variable $L_X$ is used to denote absorption-corrected X-ray luminosity in the total band (listed as LOG_LTC in the table).

X-ray-variable stars were identified by ACIS Extract by testing for constant count rates (both within one observation and for the two observations combined) using the Kolmogorov–Smirnov (K–S) test. Most p-values lie between 0.01 and 0.001 (no statistically significant deviation from a constant count rate), but 356 sources have p-values ranging from $10^{-2}$ to 0.01. The K–S test is more sensitive to sources with more counts, so more-luminous X-ray variables are more likely to be identified than less-luminous X-ray variables.

Bright X-ray sources can be affected by pileup, which occurs when multiple X-ray photons arrive at the same location on the detector during a single 3.2 s frame, causing them to be read as a single event with greater energy. The ACIS Extract photometry recipe notes that a flux of 0.075 counts frame$^{-1}$ in a $3 \times 3$ pixel island leads to a decrease in count rate by a factor of 1.1. For NGC 6231, the sources most affected by pileup are CXOU J165401.84-414823.0 and CXOU J165410.06-414930.1, with photon fluxes of 0.07 and 0.06 counts frame$^{-1}$, respectively. CCD pileup has therefore been ignored in this study.

### 3.1.3. Comparison to the DMS2016 X-Ray Catalog

Our catalog of 2411 X-ray point sources includes ~1.5 times more sources than the 1613 X-ray sources reported by DMS2016, which is similar to the increase in the number of sources for other studies in which Chandra observations were reanalyzed using this methodology (Kuhn et al. 2013). In particular, many new faint X-ray sources are included. Figure 2 shows sources from the two X-ray catalogs marked on an X-ray image (left) and a VISTA Variables in the Vía Lactea (VVV) J-band image (right) of part of the field of view near the star CPD-41 7743. In this region, five of the new X-ray sources have J-band counterparts, while four do not. Although the deeper catalogs may include additional spurious sources or extragalactic X-ray sources, most of these will be filtered out later in the analysis by matching with NIR counterparts.

A comparison of reported X-ray source properties from the two catalogs shows that, for the majority of stars, X-ray net counts (CT from DMS2016 versus NetCounts$_t$) are scattered around the $y = x$ line with an rms deviation of 0.1 dex and a mean offset of 0.05 dex. (These differences are smaller than the typical Poisson $\sqrt{(N)}$ uncertainty on net counts.) Sources of scatter include differences in the shape and size of the extraction regions, filtering of events, and algorithms for estimating source background. A small fraction of X-ray sources have up to a factor of 2 times more counts in the DMS2016 catalog, but these are all sources with close neighbors in the ACIS Extract source list that are included as a single source by DMS2016.

A comparison of X-ray luminosities ($L_X$ from DMS2016 versus LOG_LTC) for probable cluster members shows that the X-ray luminosities derived here using XPHOT (LOG_LTC) are, on average, 0.1 dex lower than those derived by DMS2016 through spectral fitting with 0.2 dex scatter. The magnitude of this shift is similar to the typical magnitude of the discrepancies found in the SFiNCs project between X-ray luminosities derived using the same methods we use here and those from the published literature (Getman et al. 2017, their Figure A2), albeit usually in the opposite direction. Typical uncertainty on LOG_LTC (statistical and systematic added in quadrature) is 0.5 dex.

### 3.2. Infrared and Optical Photometry

The NIR ZYJHK$_s$ data were obtained from the VVV survey (Minniti et al. 2010; Saito et al. 2012). VVV is a multiepoch NIR survey that covers both the Galactic bulge and an adjacent Galactic disk region and was carried out using the 4.1 m VISTA telescope on Cerro Paranal. The VVV data were taken with the VISTA Infrared CAMera (VIRCAM; Dalton et al. 2006), a $4 \times 4$ array of Raytheon VIRGO 2048 $\times$ 2048 $20\mu$m pixel detectors with a pixel scale of 0.″34. The individual detectors are separated by gaps with a width that is 42.5% of the detector width in the vertical direction and 90% of the detector width in the horizontal direction, forming the...
“pawprint” field of view that covers 0.59 deg². A series of six exposures with various horizontal and vertical shifts combine to form a single rectangular tile with an area of 1.25 × 1.1 = 1.64 deg² (Saito et al. 2012).

For color–color and color–magnitude diagram analysis, we use the first-epoch ZYJHKs images from VVV tile d148 in the disk region of the survey. These images all had a top “Quality Control” grade and subarcsecond seeing. The observation log for these data is presented in Table 2. Aperture photometry was performed with version 1.3 of the VISTA pipeline developed by the Cambridge Astronomical Survey Unit (CASU; Lewis et al. 2010) and downloaded via the CASU website. Flags indicate the morphological classifications of sources, which are generated based on curve-of-growth analysis (Irwin et al. 2004). We make use of sources with flags “−1” stellar, “−2” borderline stellar, and “−9” saturated in the analysis. The flag “0” indicates noise, “−7” indicates bad pixels, and “+1” indicates nonstellar; catalog entries with these flags are omitted. For sources that are saturated in the JHKs VVV images, photometry from 2MASS (Skrutskie et al. 2006) is substituted using the transformations from Soto et al. (2013) to convert the photometry in the 2MASS system to the VVV system.

For variability analysis, photometry was obtained from ~30 Ks-band epochs with net exposure times of 8 or 40 s in both tile d148 and the adjacent tile d110. Only images with a top “Quality Control” grade and arcsecond or subarcsecond seeing were used. These images were observed between 2010 March and 2015 July, with a mean cadence of 0.025 day⁻¹ (gaps between observations were distributed with first-quartile, median, and third-quartile time delays of 0.07, 1.0, and 20 days). Data reduction followed the photometry procedures described by Navarro Molina et al. (2016), who used point-spread function (PSF) fitting photometry on individual chip images to avoid spurious photometric variability caused by PSF variability. The photometry was extracted using the DoPHOT pipeline (Schechter et al. 1993), and objects with DoPHOT flags indicating reliable photometry were kept. Photometry was calibrated using a set of isolated, nonvariable stars in the images with VVV Ks-band magnitudes between 11 and 15 mag.

In addition to the VVV photometry, public optical or infrared catalogs are available from surveys and publications. We have included VPHAS+ photometry (Drew et al. 2014), UBVRI (Johnson–Cousins system) and Hα photometry from Sung et al. (2013), and Spitzer/IRAC photometry from the GLIMPSE survey (Benjamin et al. 2003). These catalogs and the VVV catalog is performed using TOPCAT (Taylor 2005). Among the optical and NIR bands, there are significantly more counterparts for probable cluster members when going to longer wavelengths; e.g., there are more than 2 times as many Ks-band counterparts from VVV+2MASS than V-band counterparts from Sung et al. (2013). Reported R.A. and decl. in the merged catalogs are taken from the VVV Ks-band catalog where available.

### 3.3. NIR–X-Ray Catalog Matching

Matching between the X-ray and NIR sources was performed using the sky coordinate matching algorithm from the CRAN package `celestial` (Robotham 2016). A preliminary match radius of 2″ was used to identify candidate matches, which were then pruned based on uncertainty in the source positions. Uncertainty on the NIR source position was assumed to be 0′.3, while uncertainty on the X-ray source position was calculated by ACIS Extract and ranged from 0′.1 to 1′ (median 0′.2). Positions differing by less than 2 times the quadratically combined uncertainty were accepted. A total of 1735 matches were found between X-ray sources and VVV+2MASS sources, giving a match rate of 72% for sources in the X-ray catalog.

In deep images of the Galactic plane, the high numbers of sources in the NIR catalogs can lead to error in (1) whether an X-ray source has a NIR counterpart and, if so, (2) which NIR source is the correct counterpart (Naylor et al. 2013). We investigate these two problems for K-band–X-ray matching. For X-ray–K-band matching, 72% of X-ray sources have a primary match (the match to the closest K-band source within the matching radius), while 1% of sources have a secondary match (the second-closest K-band source within the matching radius), and 0.04% have a tertiary match (the third-closest K-band source within the matching radius). When multiple K-band matches are possible, the primary match is the brightest source in ~70% of the cases. This result agrees with the general expectation from Naylor et al. that, when there are multiple possible matches, the correct match is usually brighter.

The number of X-ray sources with spurious counterparts is estimated by artificially shifting the ~700 X-ray sources without K-band matches and redoing the matching procedure. This simulation indicates that 90 ± 10 (5%) of the counterparts are spurious for our catalog of 1735 X-ray/infrared matches. This contamination rate is significantly more optimistic than the contamination rate estimated by Sana et al. (2006b) for matching between XMM-Newt and NIR catalogs (>100 spurious counterparts for a catalog of 610 X-ray sources). The lower rate of such contaminants is an advantage of the higher spatial resolution of the Chandra X-ray Observatory. There is a strong correlation between K-band luminosity and X-ray net counts among actual matches, and

| Band | FOV Center (J2000) | Date | Exp. (s) | Airmass | Seeing (arcsec) | Mag. Lim. (mag) |
|------|-------------------|------|---------|---------|----------------|----------------|
| Z    | 16:52:52.5 –41:34:10 | 2011 Aug 14 T02:05:55 | 80 | 1.154 | 0.93 | 20.35 |
| Y    | 16:52:52.5 –41:34:11 | 2011 Aug 14 T01:58:51 | 80 | 1.140 | 0.84 | 19.73 |
| J    | 16:52:52.5 –41:34:10 | 2010 Mar 26 T07:38:12 | 80 | 1.124 | 0.88 | 19.05 |
| H    | 16:52:52.5 –41:34:11 | 2010 Mar 26 T07:24:26 | 80 | 1.148 | 0.87 | 18.13 |
| Ks   | 16:52:52.5 –41:34:10 | 2010 Mar 26 T07:31:27 | 80 | 1.135 | 0.85 | 17.52 |

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5. http://casu.ast.cam.ac.uk/vistasp/

6. The first and last epochs had longer exposure times.

7. Note that the GLIMPSE survey region only overlaps the southern corner of the Chandra/ACIS-I field of view.
this correlation is nonexistent for the simulated spurious matches.

3.4. Catalog Completeness Limits

The detection sensitivity for X-ray point sources is related to the photon flux (photon s$^{-1}$ cm$^{-2}$) in the bands used for source detection. This sensitivity varies across the ACIS-I field as a result of telescope vignetting and the degradation of the PSF with off-axis angle. As a result, a larger number of faint X-ray sources are detected near the center of the field, where the sensitivity is greatest; this can produce an artificial clustering effect, as noted by Broos et al. (2011). For studies of cluster structure, the artificial clustering can be corrected by using only X-ray sources with photon fluxes greater than the completeness limit for the full X-ray catalog. Such a strategy has also been recommended by Ascenso et al. (2009) to avoid interpretation of observational effects of varying sensitivity as astrophysical phenomena, such as cluster mass segregation. Feigelson et al. (2011) and Kuhn et al. (2014, 2015a, 2015b) truncated X-ray–selected samples of pre-main-sequence stars using photon-flux thresholds, allowing the identification of spatial structure masked in the full sample by artificial clustering.

For NGC 6231, the completeness limit is estimated empirically using histograms of the photon flux for X-ray point sources stratified by off-axis angle with radial divisions at 0/3, 5/3, 6/3, 7/5, 8/3, and 12/3. The photon-flux limit increases with each larger-radius stratum, giving a completeness limit for the full sample of $\log F_{\text{photon}} = -5.95$ in the 0.5–8.0 keV band. This limit is similar to the completeness limits of many of the MYSIX Chandra observations (Kuhn et al. 2013).

The completeness limits for the VVV catalogs reported in Table 2 were calculated by artificial source insertion and extraction by the CASU version 1.1 pipeline reduction, and these NIR catalogs are generally deeper than the X-ray catalogs.

4. Cluster Membership

4.1. Simulations of Contaminants

Classification of X-ray sources as cluster members and nonmembers is based on a decision tree using X-ray, NIR, and optical properties. The sources of contaminants include extragalactic sources, foreground field stars, and background field stars, with extragalactic sources being more numerous (Getman et al. 2011). A variety of rules have been used to select probable members in X-ray studies of young stellar clusters, which include machine-learning strategies based on training sets (e.g., Broos et al. 2013) and decision trees based on different criteria (e.g., Getman et al. 2017). However, unlike MYStIX and SFINCs, mid-infrared photometry from the Spitzer Space Telescope is available only for a small region at the south edge of the field. Optical catalogs can be used to remove some likely foreground or background field stars, but optical photometry is only available for half as many stars as is VVV NIR photometry.

We simulate X-ray contaminants (extragalactic sources, foreground field stars, and background field stars) to estimate the expected level of contaminants and see how their X-ray properties would compare with the properties of the observed stars. Extragalactic X-ray sources are mostly active galactic nuclei, with some starburst galaxies. These objects are seen through a Galactic neutral hydrogen column density $N_H = 1.2 \times 10^{22} \text{ cm}^{-2}$ (Dickey & Lockman 1990), with little contribution to absorption from the region itself. Galactic field stars are typically not detected in the X-ray; however, the high number of field stars means that they are an important source of contaminants. We follow the simulation methods described by Getman et al. (2011). For extragalactic sources, we use the extragalactic $N - \log S$ relationship from Moretti et al. (2003) and assume power-law X-ray spectra based on relations from Brandt et al. (2001). Stars are simulated using the Besançon models of the Galaxy (Robin et al. 2003), and we assume thermal plasma models based on observed distributions of main-sequence and giant-star X-ray luminosities. Artificial X-ray sources were simulated using the fakes tool in the XSPEC software package (Arnaud 1996), and count rates were obtained using the Portable Interactive Multi-Mission Simulator (PIMMS; Mukai 1993). A cut based on the detection sensitivity of the NGC 6231 source list was then applied to the artificial sources to produce the final lists. These simulations produced $100 \pm 10$ extragalactic sources, $80 \pm 10$ foreground stars, and $50 \pm 8$ background stars.

The distributions of X-ray net counts (NetCounts) and MEs for the simulated contaminants and observed X-ray sources (with and without NIR counterparts) are shown in Figure 4.

Typical simulated extragalactic sources have $J > 20$ mag, so these X-ray contaminants are not expected to have NIR counterparts in the VVV catalogs. By contrast, foreground and background field-star contaminants will have VVV counterparts, so they are harder to disentangle from cluster members. In addition, the lack of strong absorption by a molecular cloud associated with NGC 6231 means that the NIR reddening and X-ray extinction will not be very different for these three classes. However, cluster members are expected to dominate foreground and background field stars by a ratio of 28:1 and 44:1, respectively; thus, without additional evidence suggesting otherwise, an X-ray source with a NIR counterpart is more likely than not to be a cluster member. However, the $80 + 50 = 130$ stellar contaminants may have $K_S$-band counterparts and thus can constitute up to 7% of the 1735 X-ray sources matched to the NIR. We thus can conclude that 5% (spurious matches) + 7% (stellar contaminants) = 12% of these X-ray sources with NIR counterparts are not valid members.

The Besançon model approach may be limited because it does not take the spiral structure of the Galaxy into account. Robin et al. (2012) note that spiral arms do not significantly contribute to NIR star counts in 2MASS. However, younger stellar populations in spiral arms are more likely to be detectable in X-ray emission, so contamination by background field stars may be higher than estimated by the model.

4.2. Probable Cluster Members

Based on the arguments above, we classify any X-ray source with a NIR counterpart as a “probable cluster member” unless further evidence suggests that it is either a foreground or a background field star. Figure 3 guarantees that X-ray–derived field-star contamination is low.
Although optical photometry is not available for the faintest sources, these bands can help identify field stars when they are available. Foreground stars will lie above the cluster members on the V versus V − I color–magnitude diagram, and we use the polygonal regions in the (V, V − I) color space from DMS2016 (their Figure 4) to remove these sources. Background stars will lie below the zero-age main-sequence track on color–magnitude diagrams. We use both the V and I photometry from Sung et al. (2013) and the deeper r and i photometry from VPHAS+ to identify these sources. Overall, 16 X-ray sources are identified as likely foreground field stars, and 123 are identified as likely background field stars. The overall number of field stars is similar to the ~130 field-star predictions from the simulations, although the simulations anticipated more foreground contaminants and fewer background contaminants.

Variability of the X-ray light curve that is statistically significant (p < 0.01, as measured by ACIS Extract) is also considered to be evidence of membership, and these sources are included as probable cluster members. The X-ray contaminants are not expected to be as variable as the pre-main-sequence stars, while the pre-main-sequence stars typically have variability in the full (0.5–8.0 keV) X-ray band of 0.15–4.5 dex on timescales of 0.4–10 days due to stochastic flaring with some contribution from variable absorption (Flaccomio et al. 2012). There are 356 variable X-ray sources that meet this criterion.

Extragalactic sources are expected to have significantly higher X-ray MEs than cluster members, as seen in Figure 4, where their simulated ME values range from 1.9 to 5 keV. Thus, sources with ME < 1.9 keV are unlikely to be extragalactic and more likely to be either cluster members or field stars, and they are included as probable cluster members. On visual inspection of the 459 X-ray sources with ME < 1.9 that lack a match to a VVV source, many appear to have VVV counterparts that are either just outside the 2σ match radius or flagged as non–point sources by the CASU pipeline, while others are located near bright NIR sources. However, some have no obvious explanation for the lack of a NIR counterpart. These sources typically have 4–20 X-ray net counts (median of 7 net counts).

All X-ray sources that are in catalogs of previously known WR, O-type, and B-type cluster members (compiled by Sana et al. 2006c) are also included. The Chandra X-ray catalog provides improved detection of O- and B-type stars, with 13 out of 13 (100%) O-star systems detected and 41 out of 82 (50%) B-star systems detected (see Section 6). However, the X-ray emission for many of the systems containing later-type B stars (which are not expected to emit X-rays) may be produced by a T Tauri companion.

Late-B and A stars are not expected to produce X-ray emission, so stars with these spectral types are likely to be missing from the X-ray catalog (Hubrig et al. 2007). However, some AB stars may have pre-main-sequence companions that are detected in X-rays, and some >2.5 $M_{\odot}$ stars may have later spectral types of G or K if they are younger than ~2.5 Myr. Overall, 114 of the X-ray–selected probable cluster members lie in the region of the V versus V − I diagram consistent with OB or AF stars (as defined by DMS2016).

Of the 2411 X-ray sources, 2148 are classified as probable cluster members, while sources that do not meet any of the above criteria are considered unclassified and likely include extragalactic sources (mostly quasars and Seyfert galaxies), field stars, cluster members with missing NIR photometry, and
spurious sources. Spurious X-ray sources may be either fluctuations in the background level with significance $p < 0.01$ or X-ray events from the wings of bright sources that were erroneously deconvolved into distinct sources (cf. Kuhn et al. 2013). Most spurious sources will lack NIR counterparts and will therefore be listed as unclassified. Nevertheless, most of the faint (3–5 count) X-ray sources in our NGC 6231 catalog do have NIR counterparts (black histogram in Figure 4), which is evidence that these are bona fide X-ray sources. The unclassified sources (blue histogram) can mostly be explained as being astrophysical contaminants rather than spurious sources.

We note that we do not distinguish between young stars in NGC 6231 and possible other members of the Sco OB1 association that may be projected along the same line of sight. Superposition of clusters in the plane of the sky has been detected in other regions, such as the Orion Complex, where NGC 1980 and NGC 1981 lie in front of the Orion Nebula Cluster (Bouy et al. 2014). As in the case of Orion, source selection based on a simple X-ray/optical/infrared photometric analysis will not distinguish between these populations.

Table 3 lists 2148 probable cluster members and their properties. Each cluster member is given an IAU designation: a prefix “CXOVVV J” followed by a sequence based on the truncated source coordinates. For each item, the table provides X-ray source; VVV, GLIMPSE, and optical photometry; spectral types for OB stars; and cross-correlation with cluster members from DMS2016. In addition, inferred stellar properties are presented (derived in the next sections), including an indicator of $K_s$ variability, absorption ($A_K$), estimated stellar age, stellar mass (estimated using both 3.2 and 6.4 Myr age assumptions), bolometric luminosity (based on the mass estimates), an indicator of $K_s$-band excess, and classifications of GLIMPSE infrared excess sources.

4.3. $K_s$-band Variable Stars

Pre-main-sequence stars can show optical and NIR variability up to several magnitudes due to rotational modulation by star spots, accretion from a circumstellar disk, and variable extinction from the circumstellar disk (Joy 1945; Herbst et al. 1994). A study of variables in $\rho$ Ophiuchus by Parks et al. (2014) found that $\sim$10% were variable in the $JHK_s$ bands with amplitudes between 0.04 and 2.3 mag, and these stars showed both periodic and aperiodic behavior. Periodic variables were mostly associated with rotational modulation of a cool star spot, but, in a few cases, they were associated with accretion hotspots or eclipses by a disk. Aperiodic variability was typically associated with variability in accretion rate or extinction. Rice et al. (2015) studied NIR variables in the Orion Nebula Cluster and found that protostars had the greatest amplitude of variability ($\sim$0.6 mag), followed by disk-bearing sources ($\sim$0.2 mag) and disk-free stars ($\sim$0.1 mag). Most variability due to cool star spots will have amplitudes $<0.2$ mag in the $K$-band (e.g., Carpenter et al. 2001; Wolk et al. 2013), below the level that can be reliably detected using the VVV data. Instead, the majority of the pre-main-sequence VVV variables are expected to have aperiodic variability due to variable absorption and accretion and hot star spots.

Variability in the $K$-band has been suggested by Kaas (1999) as a method of identifying candidate young stellar objects (YSOs). Like X-ray selection, this method does not require that young stars have circumstellar disks, which is necessary for an object to be classified as a young star based on infrared excess or H$\alpha$ emission. Identification of $K_s$-band variables is one of the primary objectives of the VVV survey, so the VVV variability is an excellent method of searching for NGC 6231 cluster members with large angular separations from the center of the cluster. Due to the large numbers of field stars in the VVV survey, $K_s$ variability alone is not a definitive indicator of cluster membership, so objects identified this way should be
| Column Label | Units | Description |
|--------------|-------|-------------|
| Name         |       | IAU source name; the prefix is CXOVVV J |
| Catalog_RAdeg | deg   | R.A. in catalog (J2000) |
| Catalog_DEdeg | deg   | Decl. in catalog (J2000) |
| Xray_Name    | keV   | X-ray source name in IAU format |
| ME           |       | X-ray ME in the total 0.5–8.0 keV band |
| LogLx        | erg s⁻¹ | Absorption-corrected X-ray luminosity in the 0.5–8.0 keV band |
| PhotonFlux   | cm⁻² s⁻¹ | log incident photon flux in the 0.5–8.0 keV band |

**Counterparts in Other Catalogs**

HD
- OB star name in the HD catalog (Cannon 1936)
- OB star name in the CPD catalog (Gill & Kapteyn 1897)
- OB star name in the Seggewiss (1968) catalog
- OB star name in the Sung et al. (1998) catalog
- OB star name in the Baume et al. (1999) catalog

SpType
- Spectral type tabulated by Sana et al. (2006c)
- References for spectral type given by Sana et al. (2006c)

DSM2016_Name
- Source name in the DSM2016 catalog

DSM2016_Group
- Membership classification in the DSM2016 catalog

2MASS_ID
- Source name in the 2MASS catalog

J_synth
- Merged 2MASS and VVV photometry in the 2MASS system

umag
- VPHAS u-band magnitude

Qflg
- 2MASS J-band magnitude

Rflg
- 2MASS J-band magnitude

Bflg
- 2MASS J-band magnitude

Aflg
- 2MASS J-band magnitude

J_synth
- Merged 2MASS and VVV photometry in the 2MASS system

Ksynth
- Merged 2MASS and VVV photometry in the 2MASS system
Table 3
(Continued)

| Column Label | Units | Description |
|--------------|-------|-------------|
| e_remag      | mag   | 1σ uncertainty |
| imag         | mag   | VPHAS i-band magnitude |
| e_imag       | mag   | 1σ uncertainty |
| SSB2013_ID   |       | Source name in the Sung et al. (2013) catalog |
| Vmag         | mag   | V-band magnitude in the CIT system |
| e_Vmag       | mag   | 1σ uncertainty |
| V_I          |       | V − I color |
| e_V_I        | mag   | 1σ uncertainty |
| B_V          | mag   | B − V color |
| e_B_V        | mag   | 1σ uncertainty |
| U_B          | mag   | U − B color |
| e_U_B        | mag   | 1σ uncertainty |
| Ha_SSB       | mag   | Hα magnitude |
| e_Ha_SSB     | mag   | 1σ uncertainty |
| GLIMPSE_ID   |       | Source name in the GLIMPSE catalog (Benjamin et al. 2003) |
| 3_6mag       | mag   | Magnitude in the 3.6 μm band |
| e_3_6mag     | mag   | 1σ uncertainty |
| q_3_6mag     |       | GLIMPSE flag |
| 4_5mag       | mag   | Magnitude in the 4.5 μm band |
| e_4_5mag     | mag   | 1σ uncertainty |
| q_4_5mag     |       | GLIMPSE flag |
| 5_8mag       | mag   | Magnitude in the 5.8 μm band |
| e_5_8mag     | mag   | 1σ uncertainty |
| q_5_8mag     |       | GLIMPSE flag |
| 8_0mag       | mag   | Magnitude in the 8.0 μm band |
| e_8_0mag     | mag   | 1σ uncertainty |
| q_8_0mag     |       | GLIMPSE flag |
| Stellar Properties |
| Ak           | mag   | Estimated absorption in the K_s-band (A_K) |
| age_v        | Myr   | Age estimated from the V versus V − I diagram |
| logM_3_2Myr  | M_☉  | Estimated mass for an age of 3.2 Myr |
| logM_6_4Myr  | M_☉  | Estimated mass for an age of 6.4 Myr |
| logL_3_2Myr  | L_☉  | Estimated luminosity for an age of 3.2 Myr |
| logL_6_4Myr  | L_☉  | Estimated luminosity for an age of 6.4 Myr |
| Ks_excess    |       | Indicator of K_s-band excess |
| classI       |       | Indicator of classification as a Class I YSO |
| classII      |       | Indicator of classification as a Class II YSO |
| IR_excess    |       | Indicator of infrared excess |

(This table is available in its entirety in FITS format.)

regarded only as member candidates. In a study of high-amplitude K_s-band variables (ΔK_s > 1 mag) in the VVV, the fraction of pre-main-sequence stars was estimated to be 50%, while many others were asymptotic giant branch (AGB) stars (Contreras Peña et al. 2017a, 2017b). The variables clustered at the location of NGC 6231 are more promising candidates than the distributed variables and may provide information about the structure of NGC 6231 on larger spatial scales than is possible with the X-ray observations.

We search the 2°3 × 1°55 box around NGC 6231 covered by VVV tiles d148 and d110 for K_s-band variables. The procedures used to identify these sources are more fully presented by N. Medina (2017, in preparation). Briefly, the subset from which variables are drawn includes point sources on the VVV tiles with more than 25 epochs. For these stars, a variety of statistical measures are calculated: log χ² (e.g., Rebull et al. 2014), the von Neumann’s η index, the Stetson’s J and K indices for a single band, and the small kurtosis γ and skewness κ indices (Richards et al. 2011). The variable log χ² characterizes the statistical significance of variability without taking into account autocorrelation, while others, such as von Neumann’s η and Stetson’s J and K, identify light curves with autocorrelation; the use of multiple statistics can be effective for characterization of variability (Shin et al. 2009). A two-component normal mixture model is used to separate high-amplitude variables from other stars using these indices, with η and log χ² playing the most decisive roles. The variability analysis was performed twice for the small region of overlap between the tiles, once using the photometry from d148 and once using the photometry from d110. A total of 22 variables were found in this region, nine of which were identified for both of the tiles and 13 of which were identified for only one tile.

Table 4 provides the catalog of 295 variables selected by the method described above and provides coordinates, mean K_s-band magnitude, ΔK_s, and log χ² for the sources. Out of the full catalog of 295 variables, ~40 appear to be clustered at the approximate location of NGC 6231, while 16 lie within the Chandra field of view. Out of these 16, four were detected by the X-ray observations, including CXOU J165357.41-414912.8,
Columns 3–4: celestial coordinates. Column 5: mean $K_s$-band magnitude. Column 6: amplitude of the $K_s$-band variability. Column 7: $\log \chi^2$ statistic.

This table is available in its entirety in machine-readable form.

5. Properties of Cluster Members

5.1. X-Ray Properties

Figure 7 shows the X-ray color–magnitude diagram for all X-ray sources in the NGC 6231 Chandra field (both cluster members and contaminants) using the observed flux in the total (0.5–8.0 keV) band ($F_\text{x}$) for the magnitude and the ME of the observed X-ray photons in that band as the color. Black circles mark X-ray sources with NIR counterparts, while blue crosses mark sources without NIR counterparts. In addition, sources with X-ray variability (green circles) and O or B spectral types (orange circles), as well as the WR classification (magenta square), are shown. Likely field-star contaminants are also indicated (magenta and red triangles for foreground and background stars, respectively). The bulk of the black, green, and orange points have MEs between 1 and 2 keV, while most of the blue points have ME $> 2$ keV. X-ray color–magnitude diagrams for 10 other star-forming regions are shown by Kuhn et al. (2017 September Kuhn et al., The Astronomical Journal, 154:87 (32pp), 2017 September).
et al. (2013). They are similar to the NGC 6231 diagram with different ratios of lightly and heavily obscured X-ray sources.

X-rays from low-mass pre-main-sequence stars are due to tens of millions of kelvins gas in the stellar corona, which is heated by magnetic reconnection. Typical temperature components range from \(kT \sim 0.8\) keV to 4 keV with flares up to 10 keV (Getman et al. 2005, 2008a), which produce X-ray sources with MEs (unabsorbed) ranging from 1.0 to 1.5 keV (Getman et al. 2010). The majority of the probable cluster members in NGC 6231 are this type of X-ray source, a type that mostly lies along a fairly narrow locus on the X-ray color–magnitude diagram. A slight increase in spectral hardness with increasing flux is related to an increase in plasma temperatures for more massive pre-main-sequence stars (Getman et al. 2010; Kuhn et al. 2013).

The X-ray emission from massive stars is typically greater than or similar to the X-ray emission of the most X-ray-luminous pre-main-sequence stars (e.g., Povich et al. 2011). X-rays from both O- and early B-type stars originate in stellar winds (Lucy & White 1980; Owocki et al. 1988; Owocki & Cohen 1999; Cohen et al. 2008). Wind shocks due to the line-denshadowing instability will typically lead to soft (ME \(\leq 1\) keV), nearly constant X-ray emission, while the detection of a harder and variable X-ray component for some massive stars could be explained by colliding winds in a binary system (Zhekov & Skinner 2000) or magnetically channeled winds (Babel & Montmerle 1997; Gagné et al. 2005). On the X-ray color–magnitude diagram, all of the O stars and some early B stars lie at the upper end of the flux distribution and have X-ray MEs (\(\sim 1\) keV), consistent with X-ray emission with a wind origin. However, a number of X-ray sources matched to B stars lie along the locus for pre-main-sequence stars. Section 6.2 provides a more detailed discussion of pre-main-sequence binary companions to B stars.

Absorption by interstellar material will harden the X-ray spectrum and decrease the X-ray flux, shifting sources to the lower right on the X-ray color–magnitude diagram. This absorption is primarily due to He and inner-shell electrons in C, N, O, Ne, Si, S, Mg, Ar, and Fe atoms, which may be in any phase (Wilms et al. 2000). In embedded star-forming regions, such as those in MYStiX, a substantial population of pre-main-sequence stars may have ME > 2 keV due to absorption by the natal molecular cloud. In the case of NGC 6231, the lack of substantial absorption from clouds means that pre-main-sequence stars with high MEs likely have significant local absorption. A sample of 50 objects from the CXOVVV catalog with unusually hard X-ray spectra is discussed further in Section 5.8.

The simulations of X-ray contaminants predict that foreground and background field stars will have ME and \(F_t\) values similar to those of cluster members. The distributions of stars classified as foreground or background objects in Figure 7 overlap the lightly absorbed cluster members, but some background sources have MEs up to 5 keV. The simulated extragalactic sources typically have 2 keV < ME < 4.5 keV. In Figure 7, most X-ray sources without NIR counterparts have MEs in this range and are thus probable extragalactic sources. Overall, 199 X-ray sources without NIR counterparts have ME > 2 keV, compared to the 100 ± 10 simulated extragalactic X-ray sources. However, other types of cosmic object can also produce hard X-ray sources without NIR counterparts. One of the brightest sources in our X-ray catalog is CXOU J165334.41-414423.6 (= 2XMM J165334.4-414423), with \(\log F_t = -12.7\) erg s\(^{-1}\) cm\(^{-2}\), ME = 2.7 keV, and no NIR match. Lin et al. (2014) classified this object as a

Figure 6. Spatial distribution of \(K_s\) variable stars (black circles) in the VVV tiles d148 and d110. A smoothed surface density map of these objects is shown using the color scale. The map shows that some \(K_s\) variables are associated with clusters such as NGC 6231, while others are distributed in the field. A gradient in surface density increases toward the Galactic plane (lower left). The fields of view of the tiles and Chandra are outlined in black, and the four \(K_s\) variables with X-ray counterparts are highlighted in yellow. Known clusters within the field of view are indicated.
periodically varying magnetic cataclysmic variable that is unrelated to NGC 6231.

5.2. NIR Properties

Figures 8 and 9 show NIR color–magnitude diagrams and a color–color diagram, respectively, for probable cluster members in NGC 6231. The stars are plotted on both diagrams using either 2MASS photometry or VVV photometry converted to the 2MASS system using the Soto et al. (2013) color transformations. Model isochrones for 3.2 and 6.4 Myr from Siess et al. (2000) are shown, converted to the 2MASS system and reddened by $A_V = 1.6$ mag.

The color–magnitude diagrams ($J$ versus $J - H$ and $H$ versus $H - K_s$) have relatively narrow distributions of points. This reveals that there is no significant range in extinction within the cluster, unlike other very young clusters that are still embedded in molecular clouds. The width of the dispersion of points in color may be due to slight differential reddening, variability, binarity, age spreads, and photometric uncertainties. Although it is not possible to differentiate the 3.2 and 6.4 Myr models for low- and high-mass stars on these color–magnitude diagrams, intermediate-mass stars in the hooked region of this isochrone are sensitive to age (Lim et al. 2013). These stars are enclosed by the two isochrones on the $J$ versus $J - H$ diagram, suggesting that the ages of these stars are between 3.2 and 6.4 Myr.

Absorption in the NIR is estimated from the $J - H$ versus $H - K_s$ diagram using either 2MASS photometry or VVV photometry converted into the 2MASS photometric system. The Siess et al. (2000) isochrone is used to provide intrinsic stellar colors for stellar photospheres. (The complete overlap in the intrinsic NIR colors for 3.2 and 6.4 Myr isochrones means that the absorption estimates do not depend on assumed stellar age.) For stars with infrared excess, we use the T Tauri locus presented by Getman et al. (2014b) based on observations of Taurus stars by Luhman et al. (2010). To estimate absorption, stars are shifted along a dereddening vector based on NIR absorption relations from Rieke & Lebofsky (1985) until they reach the locus of intrinsic colors. In principle, there can be up to two possible absorption solutions for a star (one low-mass, low-absorption solution and one high-mass, high-absorption solution). However, in practice, most stars have sufficiently low absorptions that the nearest part of the intrinsic-color locus likely corresponds to the correct mass range.

The mean value of absorption of the stars is $A_K = 0.17$ mag (corresponding to $A_V = 1.6$ mag). Typical calculated absorptions range from $A_K = 0.086$ mag ($A_V = 0.76$ mag; first quartile) to $A_K = 0.21$ mag ($A_V = 1.9$ mag; third quartile). A lack of correlation between $A_K$ and ME in this range suggests that much of this scatter is due to uncertainties in photometry.

A small fraction of sources in the CXOVVV catalog (~2%) have $0.5$ mag $< A_K < 1$ mag ($4.5$ mag $< A_V < 9$ mag). The foreground cloud is incapable of producing absorptions this high, so these objects may be either field stars in the background or objects with high local absorption (e.g., objects with absorption from circumstellar material). A more thorough discussion of reddened NIR and hard ME sources is provided in Section 5.8.
Masses are estimated from each of the dereddened $J$, $H$, and $K_s$-band magnitudes using the mass–magnitude relations from the Siess et al. (2000) models. The $Z$ and $Y$ bands are excluded from this analysis because predictions for them are not provided by the models.

Given that NIR magnitudes decrease during the pre-main-sequence evolution of a star, the masses estimated from them will be dependent on the ages that are assumed for the stars, with younger ages systematically yielding lower masses and older ages systematically yielding higher masses. We estimate masses using two possible ages, 3.2 and 6.4 Myr, in order to see the magnitude of this effect on stellar mass estimates. Masses estimated using 6.4 Myr are $\sim$1.4 times greater (0.14 ± 0.10 dex) than masses estimated using 3.2 Myr. The magnitude of this effect is greatest for lower-mass stars ($M < 0.3 \, M_\odot$ with 0.2–0.3 dex differences), and there is no difference for stars that have reached the main sequence.

The bolometric luminosities calculated using these two models will also differ, with the greatest deviation occurring for the mass range $2 \, M_\odot < M < 5.6 \, M_\odot$, where the maximum deviation is a factor of $>10$ due to inconsistencies in mass estimate. However, outside this mass range, the deviation in estimated bolometric luminosity is minor.

### 5.4. Infrared Excess

The $J - H$ versus $H - K_s$ color–color diagram may also be used to define sources with infrared excess in the $K_s$ band. To define a region on this color–color diagram in order to identify $K_s$-excess stars, we use two lines: a reddening vector that starts from the intrinsic colors of a 0.1 $M_\odot$ star and the T Tauri locus. (We accept stars lying up to 0.1 mag below the T Tauri locus due to uncertainties in photometry; however, sources lying significantly below this line may have bad photometry or be reddened massive stars.) Overall, 30 $K_s$-excess sources are identified out of 1143 probable cluster members plotted on the diagram, corresponding to an observed fraction of 2.6%. Nevertheless, the $K_s$ excess is only sensitive to the hot inner disks of stars, and observed disk fractions for young clusters typically increase when longer wavelength photometry is included (e.g., Haisch et al. 2001).

NGC 6231 lies at the edge of the GLIMPSE survey of the Spitzer Space Telescope, so a low fraction of cluster members on the south side of the field of view have photometry in the IRAC 3.6, 4.5, 5.8, and 8.0 $\mu$m bands. We use the criteria from Gutermuth et al. (2009) to identify Class I and II YSOs using (1) the $JHK_s[3.6][4.5]$ bands and (2) the $K_s[3.6][4.5][5.8][8.0]$ bands. Given that the NGC 6231 field does not have significant nebulosity, this will not strongly affect our ability to detect disks. However, crowding of the field and the complex Galactic line of sight make the presence of mid-infrared excess sources unrelated to the cluster more likely. Using Gutermuth et al.’s first method, zero Class I sources and eight Class II sources are identified. Using their second method, zero Class I sources and 13 Class II sources are identified. Overall, a total of 16 YSOs are identified out of 92 probable cluster members with Spitzer/
IRAC photometry, corresponding to an observed fraction of 15%. Based on the exponential fit to disk fractions in various star-forming regions by Mamajek (2009), a 3.2 Myr old cluster would be expected to have a disk fraction of ~30%, and a 6.4 Myr old cluster would be expected to have a disk fraction of ~8%. However, selection effects in the crowded mid-infrared images make the sensitivity of our Spitzer/IRAC infrared-excess sample difficult to estimate.

5.5. Estimates of Median Stellar Age

Ages are difficult to estimate for individual pre-main-sequence stars because a star’s placement on the HR diagram or on various color–magnitude diagrams is affected by episodic accretion (Baraffe et al. 2009), uncertainty in models of pre-main-sequence stellar interiors (due to convection: Chabrier et al. 2007; magnetic fields: Mohanty et al. 2009; and rotation: Jeffries 2009), binarity, and variability (Jeffries et al. 2011). More complete discussions of these problems are provided by Preibisch (2012) and Getman et al. (2014b). Nevertheless, estimates of age that have high statistical uncertainty may still be capable of revealing real differences in the median ages of different groups of stars. For example, statistical methods can be used to find spatial gradients in average stellar age, revealing progressivestar formation (Getman et al. 2009, 2012). We use two independent methods to estimate stellar ages: the \( J \) versus \( L_X \) relations following Getman et al. (2014b) and the \( V \) versus \( V - I \) diagram following DMS2016.

For the star-forming regions in the MYStIX study (all younger than 5 Myr), Getman et al. (2014b) found that relations between absolute absorption-corrected \( J \)-band magnitude (\( M_J \)) and X-ray luminosity (\( L_X \)) differ in different regions, and the differences can be attributed to the median stellar age in each region (hereafter, the age derived from the \( M_J \) versus \( L_X \) diagram is denoted as \( \text{Age}_{X} \)). This can be shown in a plot of \( M_J \) (ordinate) versus \( L_X \) (abscissa), with a nonparametric regression curve used to show the center of the distribution.

Here, age produces a vertical shift, with older star-forming regions having higher values of \( M_J \) for the same \( L_X \) value compared to younger star-forming regions. This effect is shown in Figure 10. The left panel shows absorption-corrected absolute \( J \)-band magnitude versus \( L_X \) for low-mass\(^9\) NGC 6231 cluster members fitted with a local-regression (LOWESS; Cleveland 1979, 1981) curve. The right panel shows LOWESS curves for 17 star-forming regions from the MYStIX project compared to the curve for NGC 6231. This plot shows that NGC 6231 is most similar to the most evolved clusters included in the MYStIX study, including the Rosette Nebula Cluster, NGC 2264, and NGC 2362.

The stars used for the \( \text{Age}_{X} \) analysis described by Getman et al. (2014b) must have a sufficient number of X-ray photons to obtain an estimate of \( L_X \); uncertainties <0.1 mag on \( JHK_s \) colors and magnitudes, no \( K_s \) excess, X-ray luminosities of \(<10^{30.5} \text{erg s}^{-1}\), and \( J - H > 0.5 \). The last two requirements are used to remove stars with masses \( \gtrsim 1.2 \, M_\odot \) from the sample. Overall, 456 stars contribute to the calculation. Individual \( \text{Age}_{X} \) values are imprecise estimates of stellar age due to the large known scatter in the \( L_X - M \) relation, but \( \text{Age}_{X} \) can be more informative for determining the median age for groups of stars (Getman et al. 2014a, 2014b).

For NGC 6231, the median value of \( \text{Age}_{X} \) is 3.2 ± 0.2 Myr, where the uncertainty of the median is calculated by bootstrap resampling. If the distance to NGC 6231 were 1.37 kpc, as estimated from the Gaia data, the estimated median age would increase to 3.7 ± 0.2 Myr. These values are consistent with the previously published age estimates that were inferred both from pre-main-sequence stellar evolution and from the main-sequence turnoff for O-type stars (Section 2).

For probable cluster members with optical photometry, the \( V \) versus \( V - I \) diagram may be used to estimate stellar ages based on the Siess et al. (2000) pre-main-sequence evolutionary models. This method may provide more precise age estimates for individual stars that have \( V \)- and \( I \)-band magnitudes because the \( \text{Age}_{X} \) estimates are subject to the large statistical scatter in the X-ray–stellar-mass relation. However, ages estimated in this way are still subject to other systematic effects due to uncertainties in models and astrophysical effects that can affect stellar properties. The \( V - I \) colors are measured for approximately half of the probable cluster members.

Ages from the \( V \) versus \( V - I \) diagram are estimated for a variety of assumed absorptions ranging from \( A_V = 0.5 \) to 2.0 mag in steps of 0.1 mag. For \( A_V = 1.6 \) mag, the median age is 3.3 Myr (1.9–4.7 Myr interquartile range). If the absorption were higher, the estimated median age would increase—for

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\(^9\) We also exclude highly absorbed sources (\( A_V > 3 \) mag) that may include some background contaminants, but we find that their effect on the result is negligible.
example, $A_V = 2.0 \text{ mag}$ yields 4.0 Myr (2.2–6.4 Myr). By contrast, if the absorption were lower, the median age would decrease—for example, $A_V = 1.0 \text{ mag}$ yields 2.6 Myr (1.7–3.7 Myr). A median age of 3.3 Myr is completely consistent with the median age of 3.2 Myr found by the Age$_{\text{X}}$ method within the uncertainties on the estimates. Given that $A_V = 1 \text{ mag}$ and $A_V = 2 \text{ mag}$ are likely lower and higher, respectively, than the typical absorption of a star in the cluster, we conclude that most of the stars in the optical sample are less than 6.4 Myr old. Ages estimated with this method, assuming an average extinction of $A_V = 1.6 \text{ mag}$, are given in Table 3 (denoted Age$_{\text{X}}$).

Previous work has suggested that the cluster has a significant age dispersion (Sung et al. 2013; Damiani et al. 2016). Using the same photometric catalog as DMS2016 but with an increased sample of faint sources, we also find a distribution of Age$_{\text{X}}$ estimates over several million years, regardless of our assumption about absorption. Therefore, the existence of a 6.4 Myr HMXB is not inconsistent with a younger median age. If the progenitor of the HMXB were among the first generation of O stars to go supernova 3 Myr ago, this could have led to the end of star formation around this time. Several numerical simulations of star formation in collapsing molecular clouds have suggested that the star formation rate may increase to the point that star formation is ended by the destruction of the molecular clouds (e.g., Hartmann et al. 2012). Such a scenario for NGC 6231 could lead to most stars having been formed not long before the end of star formation in the cluster, even if star formation started several million years earlier.

Given that there may be significant systematic uncertainties in the median age of the cluster, and there is evidence of an age spread of several million years, we estimate the stellar properties (e.g., stellar mass) using both the lower median age estimate of 3.2 Myr and the higher age estimate of 6.4 Myr to investigate the effect of this assumption on the derived quantities.

5.6. X-Ray and Bolometric Luminosities and Stellar-mass Relations

Figure 11 shows the relationships between X-ray luminosity, bolometric luminosity ($L_{\text{bol}}$), and stellar mass. (Each graph is shown with each age estimate.) For observed pre-main-sequence stars, the scatter in $L_X$ plotted as a function of $M$ is ~0.5 dex, which can be partially attributed to uncertainty in both extinction-corrected X-ray luminosities and stellar masses. We show the relations found by Telleschi et al. (2007) for weak-line T Tauri stars (dashed lines) and classical T Tauri stars (dotted lines) in the XMM-Newton Extended Survey of the Taurus Molecular Cloud (XEST) in a sample of stars with a logarithmically averaged mean age of 2.4 Myr (Güdel et al. 2007). These relations predict that weak-line T Tauri stars will have higher X-ray luminosities than classical T Tauri stars of the same mass because the presence of a disk has been observed to suppress X-ray emission. However, the locus of NGC 6231 stars on the plot is shifted down in X-ray luminosity relative to the XEST relation for weak-line T Tauri stars. This shift has a magnitude of 0.2 dex (a factor of ~1.5) for an age of 3.2 Myr and 0.4 dex (a factor of ~2.5) for an age of 6.4 Myr. Gregory et al. (2016) showed that X-ray luminosity decreases for pre-main-sequence stars with radiative cores compared to fully convective ones. The mass range for most of the observed low-mass stars in NGC 6231 is $0.35 \lesssim M_* \lesssim 2.5$, and, for an age of 3.2 Myr, stars with $M > 0.9 M_\odot$ will have developed radiative cores (Siess et al. 2000), which may partially explain the lower X-ray flux.

The plots of $L_X / L_{\text{bol}}$ versus $M$ (similar to Figure 30 in DMS2016) show that most low-mass stars have a value of $L_X / L_{\text{bol}}$ that is slightly less than $10^{-3}$ (regardless of the age that is assumed). This luminosity ratio decreases to ~$10^{-7}$ for high-mass stars, the expected ratio for X-ray emission from a wind-shock mechanism. Between the low- and high-mass stars, the precise mass at which the ratio begins to rapidly decline varies from ~1.8 to 2.5 $M_\odot$, depending on assumptions about stellar age. For many objects with spectral types of A or B, X-ray and bolometric emission may be dominated by different components of a multiple star system.

5.7. Estimates of Total Population

Despite the enlarged probable cluster member catalog, the majority of stellar-mass objects in NGC 6231 are still missing...
from it. Completeness may be estimated through investigation of the observed mass distribution and X-ray luminosity distribution of probable cluster members, with a comparison to the results from other young clusters.

5.7.1. Initial Mass Function

Figure 12 shows the observed mass functions for NGC 6231 assuming an age of either 3.2 Myr (left panel) or 6.4 Myr (right panel). These distributions are compared to the theoretical initial mass function (IMF), for which we use the parameterization from Maschberger (2013). We expect the sample of pre-main-sequence stars to be complete above a certain mass limit. In addition, we assume that the catalog of OB stars taken from the literature is complete. Stars with A and late-B spectral types are expected to be missing from X-ray surveys; however, some stars in this range may have X-ray-emitting pre-main-sequence companions.

The completeness limit is estimated by fitting the observed mass function with a model in which the 50% completeness limit is a parameter. The model is generated by multiplying the Maschberger IMF by a completeness function that goes from
100% detection probability for high-mass stars to 0% detection probability for very-low-mass objects. We approximate the completeness function using the error function,

$$f(M) = 0.5 + 0.5 \text{erf}[(\log M - \log M_{50\%})/w],$$  \hspace{1cm} (1)

where $M_{50\%}$ is the mass at which a star has a 50% chance of being included and $w$ characterizes how quickly the probability falls to 0. So, the model for the observed mass function is

$$\frac{dN(M)}{d \log M} = f(M)\Phi_{\text{IMF}}(M),$$  \hspace{1cm} (2)

where $\Phi_{\text{IMF}}$ is the Maschberger IMF. We note that the vast majority of stars with $M \gtrsim M_{50\%}$ will be detected.

For both types of mass estimate, the 50% completeness limit was found to be 0.5 $M_\odot$, although the completeness rolls off more gradually for 3.2 Myr. For an age estimate of 3.2 Myr, the total number of stellar-mass objects (down to the hydrogen-burning limit of 0.08 $M_\odot$) is estimated to be 5700 cluster members within the field of view. For an age of 6.4 Myr, a total of 7500 cluster members are estimated to lie within the field of view. The assumption of an older age yields a larger total population estimate because the older ages yield higher stellar masses.

In both cases, the mass function above the completeness limit is consistent with a universal IMF. A small dip in the histogram at $2-4$ $M_\odot$ stars is likely not astrophysical, because our mass estimation method (or the method used by DMS2016) is degenerate in this range; thus, some stars that would be assigned these stellar masses are incorrectly assigned masses in the previous bins. There is also an apparent deficit of $\sim 100$ $M_\odot$ stars compared to the IMF prediction of $\sim 1$. Although this is entirely consistent with the $\sqrt{N}$ Poisson uncertainty, we also note that at least one supernova has occurred in this cluster.

The Baraffe et al. (1998) pre-main-sequence evolutionary tracks are used to estimate masses below 0.1 $M_\odot$. While the overall shape of the IMF changes relatively little depending on the specific age estimate used, the number of objects assigned substellar masses (i.e., $M < 0.08 M_\odot$) depends greatly on the age estimate, because the hydrogen-burning limit is near the sensitivity limit of the observation. An assumed age of 3.2 Myr yields 26 substellar objects with estimated masses ranging from 0.04 to 0.08 $M_\odot$. The median X-ray net count is 4.4 (3.7–12 net counts interquartile range), and the median X-ray luminosity is $\log L_X = 29.9$ erg s$^{-1}$ (29.8–30.4 interquartile range). These stars have moderate extinctions (median $A_K = 0.03$ mag) and typical X-ray hardnesses (median ME = 1.4 keV), and none of them have an indication of infrared excess. However, when an age of 6.4 Myr is assumed, only four of these sources are assigned masses less than 0.08 $M_\odot$.

5.7.2. X-Ray Luminosity Function

The X-ray luminosity function (XLF) of pre-main-sequence stars in a cluster is related to the cluster’s IMF due to the statistical link between X-ray luminosity and stellar mass. It has been hypothesized that, for pre-main-sequence populations less than $\sim 5$ Myr old, the XLF may be universal (Feigelson et al. 2005). Kuhn et al. (2015b) examined distributions of X-ray luminosity for pre-main-sequence stars in the MYStIX star-forming regions, finding that there is no evidence of a change in the shape of the XLF and that the different regions have approximately the same XLF shape (for $L_X$ above the completeness limit).

The age spread in NGC 6231 provides an opportunity to examine how the distribution of X-ray luminosities is affected by age. Figure 13 (left panel) is a scatter plot showing $L_X$ versus $Age$. We subdivide the points into four age groups: (a) 0–2.5 Myr, (b) 2.5–5 Myr, (c) 5–7.5 Myr, and (d) 7.5–10 Myr. The right panel shows the cumulative distribution plots of $L_X$ in each of these strata for sources brighter than the completeness limit $L_X > 10^{30.0}$ erg s$^{-1}$. For the two youngest strata, (a) and (b), the distributions are very similar, and the K–S test shows no statistically significant distinction. The two older strata, (c) and (d), are also relatively similar, without a statistically significant difference. However, when comparing stars
There is little change in the shape of the XLF during the first 5 Myr; but, for older ages, there is a deficit of stars with high X-ray luminosity.

Figure 13. Left: X-ray luminosity is plotted against stellar ages derived from the V vs. V − I diagram. Four age strata are indicated by dotted lines and labeled “A” through “D.” Right: cumulative distributions of X-ray luminosities of stars in each of these age strata down to the X-ray completeness limit at \( L_X = 10^{30.0} \text{ erg s}^{-1} \).

There is little change in the shape of the XLF during the first 5 Myr but, for older ages, there is a deficit of stars with high X-ray luminosity.

0–5 Myr old to stars 5–10 Myr old, the difference is moderately statistically significant with a \( p \)-value of 0.02. The older stars have a slightly fainter distribution of X-ray luminosities. We also note that only one star in the 5–10 Myr range has an X-ray luminosity greater than \( 10^{31.0} \text{ erg s}^{-1} \), while many in the 0–5 Myr range do.

No or minor variation in the shape of the XLF during the first 5 Myr is consistent with the results from Kuhn et al. (2015b), who found little variation in the XLF shapes of MYStIX star-forming regions, most of which are <5 Myr old. In contrast, Gregory et al. (2016) indicated that some decline in X-ray luminosities would be expected during this phase.

Figure 14 shows the XLF for pre-main-sequence stars in NGC 6231 (black histogram). This XLF is compared to a scaled “template” XLF (gray histogram) based on the sample of 839 lightly obscured, low-mass stars from the COUP study of the Orion Nebula Cluster (Feigelson et al. 2005).10 The COUP sample is approximately complete down to stellar masses of 0.1–0.2 \( M_\odot \). On the X-ray-luminous side of the distribution, the XLF of NGC 6231 declines more steeply than the COUP XLF. Above an X-ray luminosity of \( L_X = 10^{30.2} \text{ erg s}^{-2} \), the distribution of X-ray luminosities for NGC 6231 has a power-law form with exponent \( \alpha = -1.21 \pm 0.05 \), while COUP has a power-law form with exponent \( \alpha = -0.91 \pm 0.10 \) (cf. Kuhn et al. 2015b). The Anderson–Darling test suggests that these two distributions differ with a \( p \)-value of 0.007. Given that the Orion Nebula Cluster is a younger population (mean age \( \sim 2.5 \) Myr; Jeffries et al. 2011), the smaller number of very luminous sources in NGC 6231 relative to that in the Orion Nebula sample may result from a greater relative decline of X-ray luminosities for more-massive stars than for less-massive stars.

XLFs have been used to estimate total stellar populations of cluster members in young stellar clusters in cases in which there is little difference in XLF shape (e.g., Kuhn et al. 2015b and references therein). Although there does appear to be some variation in XLF shape for NGC 6231 (at least for stars older than 5 Myr), the differences are minor, and they may affect the brightest X-ray sources (which are a minority of the catalog) the most. Our template universal XLF (gray histogram) is scaled vertically until it matches the NGC 6231 XLF down to the completeness limit, which is located at \( \log L_X = 30.0 \text{ erg s}^{-1} \), requiring a scale factor of 4.9. Thus, the XLF analysis suggests that the number of pre-main-sequence stars in NGC 6231 is \( 839 \times 4.9 \approx 4100 \) down to 0.1–0.2 \( M_\odot \). The difference expected from extrapolating down to 0.08 \( M_\odot \) rather than 0.15 \( M_\odot \) is a factor of \( \sim 1.5 \); thus, applying this as a correction factor, we obtain a total population of 6000 cluster members. The estimates from the XLF and IMF methods are in approximate agreement considering the uncertainties of \( \sim 0.25 \text{ dex} \) on the estimates of total populations suggested by Kuhn et al. (2015b).

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10 We assume a distance to the Orion Nebula of 415 pc from Menten et al. (2007); however, an alternate distance of 388 pc has been recently suggested (Kounkel et al. 2016).
5.8. Highly Absorbed Sources in the CXOVVV Catalog

The X-ray and NIR color–magnitude and color–color diagrams (Figure 7–9) all show small fractions of CXOVVV objects with high absorption. Highly absorbed objects are not atypical compared to other X-ray/infrared observations of very young stellar clusters or star-forming regions (see the X-ray color–magnitude diagrams in Figure 6 of Kuhn et al. 2013). However, in the case of NGC 6231, which has neither sufficient cloud material to produce high extinctions nor ongoing star formation, the most likely remaining explanation for these sources is that they are either cluster members with disks, background field-star contaminants, or background extragalactic contaminants spuriously matched to NIR sources.

We define a high-ME source in the CXOVVV catalog as one that has ME > 2.0 with at least 5 net counts and is classified as a probable cluster member due to X-ray variability or J < 17.0, H < 16.5, or K < 16.0 mag.11 Although most extragalactic sources are expected to have J > 20 mag, the color–magnitude diagram in Figure 8 shows a few sources with J ~ 18 mag with red colors that may be extragalactic contaminants, so our magnitude cuts are designed to avoid these sources.

Using this definition, there are 50 high-ME sources in NGC 6231, 27 with 2.0 keV < ME < 3.0 keV, 20 with 3.0 keV < ME < 4.5 keV, and 3 with ME > 4.5 keV. This represents 2.5% of the 2148 X-ray–selected probable cluster members. The frequency of these sources decreases rapidly with increasing ME, having a power-law-like distribution with an index of −2.4 ± 0.4. About half of these X-ray sources have 5–10 net counts, while half have 10–100 net counts. Their spatial distribution resembles the underlying spatial distribution of X-ray sources, but there are too few objects to determine whether they are more strongly clustered than expected for contaminants.

If these high-ME sources are mostly extragalactic contaminants rather than cluster members, then we would expect the distribution of their MEs to be similar to that of the high-ME sources that are not classified as probable cluster members. We use the Anderson–Darling test to examine these two cases. Overall, for sources with ME > 2.0 keV, the Anderson–Darling test rejects the hypothesis that these samples have the same distribution (p < 0.0001); but, for sources with ME > 3.0 keV, the null hypothesis is marginally rejected (p ~ 0.04).

Another potential explanation is that these objects are background sources reddened by the interstellar medium behind the cluster. DMS2016 noted that the distribution of J − H colors for field stars is bimodal, possibly indicating the presence of a cloud. However, the far-infrared AKARI-FIS 160 μm maps (Kawada et al. 2007) show no indication of a cloud behind the cluster. In addition, the bimodality that DMS2016 noted exists over a wide range of Galactic longitudes and thus is not likely to be a discrete cloud associated with the cluster. Whether the high-ME objects lie behind the cluster can be examined with the VPHAS+ r − i versus i color–magnitude diagram (Figure 15). On this diagram, reddening is approximately parallel to the isochrone for low-mass stars, while stars that are more distant would be shifted vertically. The high-ME objects with r and i photometric measurements do not show any sign of a vertical shift relative to the cluster members, so they are most likely located at approximately the same distance and are possible candidate members. Nevertheless, not all high-ME objects have photometry in these bands.

Figure 15 shows the high-ME sources on scatter plots of X-ray, NIR, and optical source properties. Points are marked by sources’ MEs, with 2.0 < ME < 3.0 keV sources shown in red, 3.0 keV < ME < 4.5 keV sources shown in green, and ME > 4.5 keV sources shown in blue. On the J − H versus H − K color–color diagram, the points are shifted to the upper right (parallel to the direction of the reddening vector). The shift of the green sources is greater than the shift of the red sources, which would be expected if the high-ME values were caused by absorption. In contrast, one of the sources with ME > 4.5 keV does not have unusually red colors. The locations of the red and green sources are consistent with AV = 5–20 mag of absorption. These values of NIR extinction are similar to the extinctions required to produce the MEs of the sources—ME = 2.0 keV corresponds to AV = 6 mag, ME = 3.0 keV corresponds to AV = 15 mag, and ME = 4.5 keV corresponds to AV = 100 mag. On the r − i versus i diagram, most points lie within the locus of other cluster members, with green sources typically having lower masses than red sources.

On the X-ray flux versus J diagram, the full set of probable cluster members shows the positive correlation that is expected for cluster members. The locations of the high-ME sources on this diagram are also consistent with this trend; but, due to the large amount of scatter and low number of sources, the trend is not very clear. On the plot of X-ray ME versus J − H, most of the red sources are tightly grouped, with ME and J − H larger than the majority of the cluster members. In contrast, the green sources have much more scatter in J − H values, suggesting that some may be coincidental matches between background galaxies and unrelated foreground stars. The J − H color of one of the blue sources is inconsistent with it being a highly absorbed cluster member.

On the NIR color–color diagram presented in Figure 9, objects with high extinction can be noted on the upper right side of the plot. Overall, 40 objects have AV > 5 mag estimated from NIR photometry. These stars have Ks-band magnitudes ranging from 12 to 17 mag, but most are not detected in optical VPHAS+ bands. They have X-ray luminosities (assuming a distance of 1.59 kpc) in the range log Lx = 29.5–31.4 erg s⁻¹. They also have higher-than-average X-ray MEs, although only one-third of them meet the definition of high-ME objects given above. Although some of these objects have infrared excess in the Ks band, most do not. These stars are not uniformly distributed in the Chandra field of view but are loosely concentrated toward the center of the field.

While some of the highly absorbed sources may be cluster members, the sample likely includes contaminants. For any cluster member, the absorption producing the high ME or AV must be local. This absorption could come from either disks with fortuitously low inclination angles or thick circumstellar disks. Two examples of stars in the Orion Nebula Cluster with this effect have edge-on silhouette disks imaged with the Hubble Space Telescope (Kastner et al. 2005). X-ray source COUP 241 (Orion silhouette disk d053-717), with a disk aspect ratio R = 5.5, has an X-ray ME = 3.2 keV corresponding to log Nh = 22.7 cm⁻². X-ray source COUP 419 (d114-426), with R = 3.9, has ME = 5.3 keV with log Nh = 23.7 cm⁻². (Interestingly, the...
NIR colors of COUP 241 reveal neither $K$-band excess nor high absorption, so they may affect reflected light.

The observed disk fraction among the highly absorbed sources in NGC 6231 is not high: only one high-ME source has $K_s$ excess, and only a small fraction of the high-$AV$ sources do. However, not all stars with disks have $K_s$-band excess, which would be produced by the hot inner region of a circumstellar disk, and GLIMPSE photometry is not available for any of these sources to determine whether they have mid-infrared excess.

6. O- and B-Star Systems

NGC 6231 is unique in being a very young stellar cluster with a large, nearly complete spectroscopic census of OB stars (Table 5) that has also been observed with a deep X-ray observation. The catalog of O and B spectral types is obtained from Sana et al. (2006c). (Out of the 108 WR+OB NGC 6231 stars in the table, 95 are within the ACIS-I field of view.) Thus, the cluster makes an ideal testbed for statistical studies of X-ray emission from O and B stars/systems.

In the Chandra X-ray catalog, 100% (13 out of 13) of the known O stars/systems and 50% (41 out of 82) of the known B stars/systems have X-ray counterparts within 2". Sana et al. (2006c) studied 30 of these systems using XMM-Newton data, and they concluded that X-rays come from stellar winds of individual stars, colliding wind systems, and pre-main-sequence binary companions. The enlarged sample provided by the Chandra data can give a more complete view of the distributions of OB-star X-ray properties.

The XPHOT X-ray fluxes from Section 3.1 are based on relations derived from pre-main-sequence stars, so the XPHOT fluxes for objects where most of the X-rays come from a stellar wind may be biased due to an incorrect X-ray spectral model. Here, we perform spectral fitting in XSPEC using a thermal plasma model, \textit{apec} (Smith et al. 2001), attenuated by an absorption model, \textit{wabs} (Morrison & McCammon 1983), with a metallicity of $Z = 0.3 \ Z_\odot$ and Anders & Grevesse (1989) abundances.\footnote{We use typical metallicity and abundance assumptions for pre-main-sequence stars (e.g., Getman et al. 2005) to aid comparison with the literature.}

6.1. O and B Populations in the X-Ray

Figure 16 shows the O and B stars in the multivariate ($\log L_X$, ME, and spectral type) space. Given that these stars are only lightly absorbed (e.g., $N_H \sim 3.5 \times 10^{21}$ cm$^{-2}$), ME will be primarily an indicator of plasma temperature. For this absorption, a source with a temperature $T = 1$ MK corresponds to $ME \sim 0.7$ keV, 2.5 MK corresponds to 0.8 keV, 5 MK to 1 keV, 10 MK to 1.2 keV, 20 MK to 1.5 keV, 50 MK to 1.7 keV, and 100 MK to 1.9 keV. Each of the 54 X-ray–detected O and B stars are indicated by circles, while the undetected B stars are indicated by upper limits or tick marks at

Figure 15. Distributions of all probable cluster members (gray points) and probable cluster members with 2.0 keV < ME < 3.0 keV (red circles), 3.0 keV < ME < 4.5 keV (green circles), and ME > 4.5 keV (blue circles). Upper left: $JHK_s$ color–color diagram. Upper right: VPHAS+ $r-i$ color–magnitude diagram. Arrows in both diagrams indicate absorption of $A_V = 1.6$ mag. Lower left: $J$ mag vs. X-ray flux. Lower right: $J - H$ color vs. X-ray ME.
| Name            | SpTy | CXOU J            | NC (counts) | ME (keV) | $P_{\text{Ks}}$ (%) | log $N_{\text{H}}$ ($10^{22}$ cm$^{-2}$) | $kT$ (keV) | log $E_{\text{c}}$ ($\text{erg s}^{-1}$ cm$^{-2}$) | log $E_{\text{v}}$ ($\text{erg s}^{-1}$ cm$^{-2}$) | $X^2$ | d.o.f. |
|-----------------|------|-------------------|-------------|----------|-------------------|----------------------------------------|-----------|-------------------------------------------------|-------------------------------------------------|-------|-------|
| NGC 6231 724    | B0V/IV | 165320.24-414825.5 | 13.2 | 1.0     | >0.05             | 22.43 ± 0.17                           | 0.09 ± 0.00 | −14.97 ± 0.21                                 | −9.94                            | 13.3  | 9     |
| NGC 6231 723    | B3V   |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 726    | B1V   |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| HD 326326 B2V   |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| HD 326327 B1.5IV+shell |      |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 30     | B7V   |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 41     | B4V   | 165344.03-415036.9 | 202.3 | 1.3     | 0.04              | 20.47 ± 1.18                           | 1.92 ± 0.28 | −13.86 ± 0.04                                 | −13.83                           | 19.3  | 31    |
| HD 326328 B1V   |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 33     | B7V   |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 54     | B6III/IV | 165347.98-415505.0 | 14.4 | 1.3     | >0.05             | ...                                    | 1.33 ± 0.46 | −15.09 ± 0.16                                 | −15.09                           | 4.9   | 5     |
| NGC 6231 14     | B4IV  |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 300    | B8.5V?| 165349.71-415013.8 | 22.2 | 1.5     | >0.05             | ...                                    | 3.73 ± 8.37 | −14.58 ± 0.16                                 | −14.58                           | 2.3   | 4     |
| NGC 6231 265    | B8.5V | 165351.19-415053.9 | 136.8 | 1.4     | <0.0001           | ...                                    | 5.37 ± 2.53 | −13.91 ± 0.06                                 | −13.91                           | 19.6  | 20    |
| HD 152200 O9.7V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| CPD-41 7706 B1V+B1Ve |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| HD 152219 O9.5III+B1-2III/V |      |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 24     | B4V   |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 283    | B3V   | 165356.21-414815.8 | 32.5 | 1.2     | >0.05             | ...                                    | 1.54 ± 1.20 | −14.74 ± 0.19                                 | −14.74                           | 5.9   | 7     |
| NGC 6231 255    | B6V   |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| CPD-41 7711 B2V+B2V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| HD 152235 B1Ia |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 284    | B4.5V | 165359.33-415303.6 | 7.0  | 1.3     | >0.05             | ...                                    | ...                                 | ...                                               | ...                                               | ...   | ...   |
| NGC 6231 249    | B4.5V | 165400.02-414252.6 | 892.5 | 1.0     | >0.05             | 21.48 ± 0.05                           | 0.64 ± 0.03 | −13.11 ± 0.02                                 | −12.71                           | 81.2  | 55    |
| CPD-41 7712 B0.5V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 276    | B8Vp  | 165401.52-414923.7 | 49.4 | 1.5     | >0.05             | 20.55 ± 3.11                           | 6.24 ± 9.98 | −14.40 ± 0.26                                 | −14.38                           | 8.9   | 10    |
| CPD-41 7715 B2.7V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| HD 152234 O9.7Ia+O8V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 259    | B6V   | 165403.58-414253.2 | 21.0 | 1.1     | >0.05             | 20.94 ± 2.24                           | 0.45 ± 0.53 | −14.89 ± 0.11                                 | −14.74                           | 5.7   | 6     |
| HD 152233 O6III(f)+O9? |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 194    | B3.5V | 165403.60-414730.0 | 1326 | 1.1     | >0.05             | 21.66 ± 0.17                           | 0.52 ± 0.22 | −13.57 ± 0.20                                 | −12.94                           | 32.9  | 42    |
| CPD-41 7719 B1V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 274    | B3V   | 165405.09-415006.9 | 34.5 | 1.0     | >0.05             | 21.08 ± 0.97                           | 0.79 ± 0.19 | −14.79 ± 0.19                                 | −14.63                           | 4.4   | 7     |
| CPD-41 7717 BIV |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 272    | B3V   | 165406.71-415107.0 | 9.7  | 1.2     | >0.05             | ...                                    | ...                                 | ...                                               | ...                                               | ...   | ...   |
| CPD-41 7723 O9V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| CPD-41 7724 B1V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| HD 326340 B0.5V |       |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 273    | B9IVp | 165409.14-415012.8 | 12.6 | 1.2     | 0.06              | 22.48 ± 0.42                           | 0.11 ± 0.03 | −15.30 ± 0.09                                 | −10.68                           | 0.0   | 0     |
| HD 152248 O7.5III(f)+O7III(f) |   |                   |             |          |                   |                                        |           |                                                 |                                                 |       |       |
| NGC 6231 209    | B2.5V | 165410.72-414747.4 | 93.4 | 1.2     | >0.05             | 20.62 ± 2.43                           | 1.43 ± 0.40 | −14.32 ± 0.09                                 | −14.28                           | 12.9  | 13    |
| NGC 6231 374    | B2V   | 165410.97-414939.0 | 9.2  | 1.0     | >0.05             | ...                                    | ...                                 | ...                                               | ...                                               | ...   | ...   |
| Name                | SpTy       | CXOU J     | NC  | ME  | \( P_{KS} \) (%) | \( \log N_{H} \) \((\text{10}^{-22} \text{cm}^{-2})\) | \( kT \) \((\text{keV})\) | \( \log F_{\nu} \) \((\text{erg s}^{-1} \text{cm}^{-2})\) | \( \log F_{\nu} \) \((\text{erg s}^{-1} \text{cm}^{-2})\) | \( X^2 \) | d.o.f. |
|---------------------|------------|------------|-----|-----|------------------|---------------------------------|-----------------|--------------------------------|--------------------------------|-----------------|--------|
| CPD-41 7730         | B1V        | 165411.63-415057.3 | 1962.3 | 1.0  | >0.05            | 21.77 ± 0.03                                       | 0.26 ± 0.02 | -12.88 ± 0.02                                    | -11.76                       | 92.2            | 74     |
| HD 152249           | O9.5V(f)   | 165412.28-415237.6 | 3.3  | 1.2  | >0.05            | ...                                            | ...           | ...                                             | ...                                             | ...            | ...    |
| NGC 6231 243        | B8.5V      | 165413.24-415032.6 | 274  | 0.9  | >0.05            | 21.47 ± 0.62                                       | 0.17 ± 0.12 | -14.10 ± 0.14                                    | -13.25                       | 10.9            | 13     |
| NGC 6231 75         | B8.5V      | 165414.10-415008.5 | 327.7 | 1.1  | 0.006            | 21.60 ± 0.08                                       | 0.82 ± 0.07 | -13.38 ± 0.03                                    | -12.95                       | 27.9            | 23     |
| HD 326329            | O9.5V      | 165414.72-415111.0 | 59.7  | 1.5  | 0.02             | 57.55 ± 898.48                                     | -13.96 ± 0.96 | -13.96                       | 10.6             | 7               | ...    |
| HD 326330            | B2.5V      | 165415.14-415527.7 | 22.6  | 2.4  | 0.005            | 61.04 ± 1317.10                                   | -14.35 ± 1.02 | -14.35                       | 4.3              | 5               | ...    |
| HD 326331            | B8.5V      | 165415.73-414932.3 | 35.5  | 1.0  | >0.05            | ...                                             | 1.18 ± 0.82 | -14.94 ± 0.19                                    | -14.94                       | 0.3             | 1      |
| CPD-41 7736          | B1Vn       | 165416.29-415026.5 | 4.4  | 1.1  | >0.05            | ...                                             | ...           | ...                                             | ...                                             | ...            | ...    |
| HD 326332            | B8.5V      | 165418.13-415016.4 | 79.6  | 1.3  | 0.03             | 21.86 ± 0.14                                       | 1.02 ± 0.29 | -14.36 ± 0.10                                    | -13.81                       | 8.7             | 11     |
| NGC 6231 222         | B2.5V      | 165418.33-415135.2 | 3.5  | 0.8  | >0.05            | ...                                             | ...           | ...                                             | ...                                             | ...            | ...    |
| HD 326333            | B1V(n)     | 165419.69-414911.5 | 493  | 1.2  | >0.05            | ...                                             | ...           | ...                                             | ...                                             | ...            | ...    |
| HD 152270            | WC7+O5-8   | 165419.83-415009.3 | 1840.5 | 1.1  | <0.0001         | 21.62 ± 0.04                                       | 0.90 ± 0.03 | -13.03 ± 0.01                                    | -12.61                       | 145.2           | 92     |
| NGC 6231 227         | B7Vn       | 165420.31-415536.4 | 23.0  | 1.1  | >0.05            | 22.04 ± 0.25                                       | 0.22 ± 0.21 | -14.99 ± 0.13                                    | -13.07                       | 3.6             | 4      |
| NGC 6231 334         | B1Vn       | 165421.35-415536.4 | 23.0  | 1.1  | >0.05            | 21.88 ± 0.19                                       | 0.93 ± 0.34 | -14.64 ± 0.12                                    | -14.01                       | 7.8             | 10     |
| CPD-41 7742          | B9V        | 165422.84-414523.4 | 43.9  | 1.3  | >0.05            | 21.67 ± 0.42                                       | 0.99 ± 0.51 | -14.81 ± 0.21                                    | -14.38                       | 5.2             | 5      |
| HD 326334            | B2.5V      | 165425.99-414707.6 | 27.1  | 1.3  | >0.05            | 21.67 ± 0.42                                       | 0.97 ± 0.06 | -13.18 ± 0.03                                    | -12.56                       | 62.7            | 49     |
| NGC 6231 121         | B6V        | 165426.54-414951.0 | 24.3  | 1.4  | >0.05            | 21.50 ± 1.42                                       | 1.33 ± 0.87 | -14.98 ± 0.24                                    | -14.74                       | 3.5             | 3      |
| NGC 6231 123         | B4Vn       | 165427.88-415013.3 | 3.3  | 1.0  | >0.05            | ...                                             | ...           | ...                                             | ...                                             | ...            | ...    |
| NGC 6231 165         | B3III      | 165428.95-414826.0 | 52.2  | 1.4  | 0.02             | 21.83 ± 0.43                                       | 1.16 ± 0.63 | -14.45 ± 0.20                                    | -13.98                       | 9.3             | 6      |
| HD 152341            | B0.5V      | 165432.00-414818.8 | 528.0 | 1.0  | >0.05            | 21.63 ± 0.07                                       | 0.48 ± 0.07 | -13.34 ± 0.04                                    | -12.73                       | 32.6            | 36     |
| HD 326331            | B1.5V      | 165432.21-415652.4 | 29.2  | 1.3  | >0.05            | ...                                             | 3.43 ± 3.16 | -14.29 ± 0.22                                    | -14.29                       | 6.0             | 9      |
| NGC 6231 123         | B1V        | 165435.79-415011.6 | 11.3  | 0.8  | >0.05            | ...                                             | ...           | ...                                             | ...                                             | ...            | ...    |
| HD 326332            | B1III*     | 165436.10-415338.6 | 636.8 | 1.7  | <0.0001         | 21.28 ± 0.15                                       | 7.55 ± 2.44 | -13.09 ± 0.03                                    | -13.02                       | 51.3            | 54     |
| HD 326333            | B1V        | 165439.87-415338.7 | 104.7 | 1.4  | 0.002            | ...                                             | 2.74 ± 1.16 | -14.08 ± 0.07                                    | -14.08                       | 17.4            | 17     |
| NGC 6231 173         | B9V        | 165444.22-415627.3 | 49.2  | 1.5  | <0.0001         | 21.79 ± 0.42                                       | 1.22 ± 0.53 | -14.56 ± 0.21                                    | -14.14                       | 15.2            | 19     |
| Name           | SpTy | CXOU J          | NC (counts) | ME (keV) | $P_{KS}$ (%) | $\log N_H$ (10$^{22}$ cm$^{-2}$) | $kT$ (keV) | $\log F_1$ (erg s$^{-1}$ cm$^{-2}$) | $\log F_2$ (erg s$^{-1}$ cm$^{-2}$) | $\chi^2$ | d.o.f. |
|----------------|------|-----------------|-------------|---------|-------------|-------------------------------|-----------|--------------------------------|--------------------------------|---------|--------|
| NGC 6231 172  | B9V  | 165444.38-414642.7 | 55.3        | 1.2     | $>$0.05     | ...                           | 1.36 ± 0.39 | $-$14.45 ± 0.14                   | $-$14.45                     | 6.7     | 8      |
| NGC 6231 175  | B9V  | 165447.39-415250.6 | 37.3        | 1.3     | $>$0.05     | 18.74 ± 258.34                | 1.58 ± 0.35 | $-$14.52 ± 0.10                   | $-$14.52                     | 6.9     | 11     |
| NGC 6231 127  | B8III-IV | 165447.73-415047.7 | 71.9        | 1.3     | $>$0.05     | 21.77 ± 0.16                  | 0.86 ± 0.37 | $-$14.39 ± 0.15                   | $-$13.82                     | 13.5    | 10     |
| HD 326334     | B3V  | 165458.28-414917.5 | 19.3        | 1.1     | $>$0.05     | 21.90 ± 1.10                  | 0.09 ± 0.02 | $-$14.10 ± 0.02                   | $-$11.58                     | 5.2     | 6      |

Notes. Chandra X-ray properties of OB stars. Column 1: star name. Column 2: spectral type from Sana et al. (2006c) and references therein. Column 3: CXO designation. Column 4: net X-ray counts in the total (0.5–8.0 keV) band. Column 5: ME of X-ray photons in the 0.5–8.0 keV band. Column 6: K–S test for X-ray variability, where $P_{KS}$ is the null-hypothesis probability that the flux is constant. Columns 7–8: hydrogen column density and plasma temperature parameters from the wabs × apec model fit. Columns 9–10: observed and absorption-corrected X-ray flux from the model fit. Columns 11–12: $\chi^2$ and the number of degrees of freedom for the model fit. X-ray properties for stars that were not detected by Chandra are left blank, while missing X-ray properties for Chandra sources are indicated by an ellipsis.

(This table is available in machine-readable form.)
their spectral type. The upper limit on X-ray luminosity in the catalog is $L_X = 10^{30.0}$ erg s$^{-1}$. It is clear from a visual inspection that more than one distinct group of points is present.

We use a mixture-model cluster analysis of the points in \((\log L_X, \text{ME}, \text{spectral type})\) space to determine whether multiple classes of object are suggested by the data. We use the \textit{mclust} software (Fraley & Raftery 2002; Fraley et al. 2012), which implements a mixture-model analysis using multivariate normal distributions. This analysis will provide information about (1) the number of clusters present in the data, (2) the properties of these clusters, and (3) the classifications of individual objects. The Bayesian information criterion (BIC; Schwarz 1978) is a penalized likelihood used for model selection in which different models have different numbers of parameters (in this case, different numbers of clusters). The best model will be the one with the lowest value of the BIC, improvements of \(\Delta \text{BIC} > 6\) are considered strong evidence, and improvements of \(\Delta \text{BIC} > 10\) are considered very strong evidence (Jeffreys 1961; Kass & Raftery 1995).

For the O and B stars, the best model (\(\text{BIC} = 143\)) includes three clusters, which are indicated by the gray ellipses in Figure 16. The BIC value for one cluster is 187, two clusters BIC = 149, four clusters BIC = 150, and five clusters BIC = 175, so there is strong evidence (\(\Delta \text{BIC} = 6\)) of three clusters and very strong evidence (\(\Delta \text{BIC} = 44\)) of more than one cluster.

One group of points found by the \textit{mclust} analysis (filled black circles in Figure 16) includes every O-star system for which X-rays are generated by either the winds of individual stars or colliding stellar winds. The defining features of this subset are soft (~1 keV) MEs and high luminosities \((\log L_X > 30.6 \text{ erg s}^{-1})\). On the $L_X$ versus spectral type diagram, a dotted line indicating a constant $L_X = 10^{-7}$-$L_{\text{bol}}$ ratio is shown, and the points are mostly distributed near this line. This is similar to the results of other studies of X-ray emission from stars with strong winds (e.g., Figure 9 of Stelzer et al. 2005).

The B-type stars have been less well studied in the X-ray than the O-type stars, so the origin of X-ray emission from these stars is less certain. Spectroscopic X-ray studies of several early-B stars, including $\tau$ Sco (B0.2V; Cohen et al. 2003) and $\beta$ Cru A (B0.5III+B2V; Cohen et al. 2008), have revealed that X-ray emission comes from a stellar wind, which is indicated by forbidden-to-intercombination line ratios showing that the X-ray–emitting gas is located several stellar...
radii above the stellar photospheres and, in the latter case, Doppler-broadened X-ray lines. However, it is difficult to explain some effects (e.g., lower velocities and a higher X-ray-emitting wind fraction) using the standard wind-shock paradigm alone. The 41 X-ray-detected B stars in NGC 6231 are subdivided into two groups by the mixture-model cluster analysis: 12 are in a group with soft X-ray spectra, while 29 have harder spectra. These two groups are approximately separated by a cut at ME ≲ 1.15 keV.

The MEs of the former group (filled red circles in Figure 16) are identical to those of O stars and are significantly softer than the typical pre-main-sequence star’s ME; some of these objects have MEs as low as ME ≈ 0.7 keV. For comparison, the star β Cru A has an ME of 0.6 keV (similar to the softest of the NGC 6231 B stars), and τ Sco has an ME of 1.0 keV. The B4 limit on spectral type for this group also coincides with the theoretical transition between a fast wind and a weak wind (Stelzer et al. 2005 and references therein). We thus suggest that these early-B stars have X-ray-emitting winds.

The X-ray luminosity of this group of probable shocked-wind B stars (\(L_X \lesssim 30 \text{ erg s}^{-1}\)) is more than a factor of 10 lower than the X-ray luminosity of the O stars. If the X-rays from these stars are of wind origin, then there is a gap in the X-ray luminosity distribution for stellar-wind X-ray sources. This may indicate a different model for X-ray emission from the stellar winds of B stars, as has been suggested by the spectroscopic studies mentioned above. The X-ray luminosities of τ Sco and β Cru A (log \(L_X = 31.5\) and 30.4 erg s\(^{-1}\), respectively) are similar to or lower than the X-ray luminosities of the O stars in NGC 6231 but higher than those of its B stars. However, the dotted line in Figure 16, indicating a constant \(L_X = 10^{-7}L_{bol}\) ratio, passes through the cluster of O stars on this graph (black) but above most of the B-star wind-emission candidates (red). Thus, a ratio of 10\(^{-7}\) may be too large by 0.5 dex or more.

A third group of B-type stars (open black circles in Figure 16) have X-ray MEs higher than 1.15 keV. The spectral type for this group ranges from B0.5 to B9.5, and no apparent preference for early- or late-B spectral types. Their X-ray luminosities are mostly in a well-defined range 29.7 erg s\(^{-1}\) < \(L_X < 30.7 \text{ erg s}^{-1}\), with X-ray MEs 1.15 keV < ME < 1.6 keV. X-ray MEs in this range are harder than the typical MEs expected for X-rays generated by shock-heated plasma from the line-deshadowing instability in OB star winds. It has been suggested that hard components in X-ray spectra could be produced by colliding winds from OB+OB binaries or magnetically confined wind shocks (ud-Doula & Naze 2015). However, many of the O-star systems in NGC 6231 are known to have colliding winds (Sana et al. 2004, 2005, 2006a, 2008b), but they still have ME < 1.15 keV. The O-star ω Ori C has been suggested as a prototypical example of a magnetically confined wind-shock system, but its ME, if it were located in NGC 6231 rather than the Orion Nebula Cluster (i.e., adjusting for absorption and observational effects), would be 1.12 keV. Furthermore, two of these sources, CXOU J165354.52-415214.9 (CPD-41 7706; B1V+B1Ve) and CXOU J165436.10-415338.6 (CPD-41 7753; B0.5V), have large X-ray flares, which almost certainly come from low-mass companions. Thus, we conclude that the NGC 6231 B stars in this category are likely to have pre-main-sequence binary companions that are responsible for the X-ray emission.

We test whether the distributions of X-ray luminosity and ME of the B stars in the third group are different from the distributions of low-mass X-ray–selected cluster members with ME > 1.15 keV. For X-ray luminosity, the K–S p-value is 0.90 (no statistically significant difference), while for ME, the K–S p-value is 0.07 (very weak evidence of a difference). This result indicates that the X-ray properties of the third group of B stars are consistent with those of the X-rays from pre-main-sequence companions that were randomly drawn from the general population of pre-main-sequence stars in the cluster.

### 6.2. Lindroos Binary Fraction

OB-star systems that include a pre-main-sequence companion are sometimes known as Lindroos binaries, after the catalogs of Lindroos (1985, 1986). Low-mass binary companions are difficult to identify in the vicinity of B-type stars in optical or NIR wavelengths due to high contrast ratios. But in the X-ray band, pre-main-sequence stars may significantly contribute to or dominate the X-ray luminosity of the system. For example, the β Cru system, mentioned above, consists of both a B-star binary (β Cru A; 5 yr period) and a pre-main-sequence star with an ~400 au projected separation (β Cru D; Cohen et al. 2008). The pre-main-sequence companion is harder (1.0 keV) than the B-star system. At a distance of ~108 pc, components A and D are individually resolved by Chandra; however, if the system were at the distance of NGC 6231, it would appear as a single source with ME = 0.73 keV.

Several studies have used X-ray counterparts to B stars to characterize Lindroos binary populations, including work by Schmitt et al. (1993), Berghofer & Schmitt (1994), Huelamo et al. (2000, 2001), Hubrig et al. (2001), Stelzer et al. (2003), and Kuhn et al. (2010). This interpretation was also used in the deep COUP X-ray study of the Orion Nebula Cluster (Stelzer et al. 2005) and the Carina Nebula (Evans et al. 2011; Gagné et al. 2011; Nazé et al. 2011).

If we consider the B stars with ME > 1.15 (open black circles in Figure 16) to be our candidate Lindroos binaries, then the cluster has 29 such candidates, compared to 42 B stars with no X-ray counterpart and 83 total known B stars (within the Chandra field of view). The mass completeness limit\(^{13}\) calculated for X-ray selection of pre-main-sequence stars in Section 5.7 is 0.5 \(M_\odot\); so, assuming that pre-main-sequence stars in Lindroos binaries have the same X-ray–mass relation as isolated pre-main-sequence stars, we can apply this completeness limit here as well. Thus, between 35% (Lindroos binary candidates divided by the total number of B stars) and 41% (omitting wind-emission candidates) of B stars have possible pre-main-sequence binary companions with masses greater than ~0.5 \(M_\odot\).

Spectral type has no apparent effect on whether a B-star is a candidate Lindroos binary. We compare the distribution of spectral types for B stars without X-ray counterparts and Lindroos binary candidates using the two-sample K–S test and find a p-value of 0.30 (indicating no statistically significant difference). This effect suggests that the pre-main-sequence companion masses are randomly drawn from the same mass distribution as the isolated pre-main-sequence stars, at least for the \(M > 0.4 \ M_\odot\) range. If the random drawing extended down to the hydrogen-burning mass limit, but we were only seeing

\(^{13}\) This is the 50% completeness limit, defined as the mass at which a pre-main-sequence star has a 50% probability of being included in our Chandra catalog. Almost all pre-main-sequence stars with masses greater than this limit will be included in the catalog.

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Kuhn et al. 2017 September
the most X-ray–luminous pre-main-sequence companions, the fraction of B stars that are Lindroos binaries could be much larger. A recent study by Moe & Di Stefano (2016) also suggests that a high fraction of B stars have low-mass binary companions randomly drawn from the IMF.

7. Summary and Conclusion

NGC 6231 is a well-known young stellar cluster that makes an excellent testbed for studies of young stars and early cluster dynamics. It contains rich populations of lower-mass pre-main-sequence stars, main-sequence OB stars, and post-main-sequence supergiants, as well as a WR system. We present a catalog of 2148 probable cluster members, the largest available catalog for NGC 6231, based on an analysis of archival Chandra X-ray data, VVV photometry, and public catalogs of the region. X-ray selection using XMM-Newton and the Chandra X-ray Observatory has been the most effective method of identifying the low-mass cluster population, and our study builds on X-ray studies by Sana et al. (2004, 2005, 2006a, 2006b, 2006c, 2007a, 2007b, 2008a, 2008b) and DMS2016. We will use the large catalog of low-mass probable cluster members presented here for analysis of the structure of NGC 6231 in Paper II. A summary of our methods, catalogs, and results is given below.

1. The study is based on reanalysis of an archival 122 ks Chandra ACIS-I observation of NGC 6231. We use the data-reduction methodology from the MYStIX project, which has been optimized for the detection of faint X-ray sources, to create a list of 2411 point sources (Section 3.1). This source list contains ∼1.5 times more point sources than were detected by DMS2016, which is similar to the improvement seen in other regions (Broos et al. 2010; Kuhn et al. 2013). The X-ray sources are matched to proprietary NIR data from the VVV survey, which provides deep ZYJHKs photometry and ∼30 epochs of Ks photometry over a 5 yr period (Section 3.2). The data are also matched to the 2MASS, VPHAS+, and Spitzer GLIMPSE catalogs, as well as an optical catalog by Sung et al. (2013). NIR color–magnitude diagrams (Y versus Z − Y and Ks versus H − Ks; Figure 3) compare the distribution of X-ray–selected probable cluster members to that of nonmembers, showing that the new sample contains many new true positives not included in previous studies while adding few false positives.

2. The classification of X-ray–selected probable cluster members is based on NIR matches, X-ray variability, X-ray ME, and filtering of likely foreground and background field stars on optical color–magnitude diagrams (Section 4). Overall, in the Chandra field, 2093 X-ray sources and 106 OB stars are classified as probable cluster members, and 123 X-ray sources are classified as likely field stars. The catalog of 2148 probable cluster members (given the IAU prefix CXOVVV) is provided in Table 3, along with inferred values of stellar age, mass, bolometric luminosity, and infrared excess.

3. Using the variability criteria developed by N. Medina (2017, in preparation), 295 VVV sources showing significant Ks variability are identified (Section 4.3) in a 3.5 deg² region around NGC 6231. Sixteen Ks variables are located within the Chandra field of view, of which four have X-ray counterparts. Previous analysis suggests that approximately half of these objects are pre-main-sequence stars, while many others are AGB stars (Contreras Peña et al. 2017a, 2017b). The NGC 6231 cluster is associated with a clustering of Ks variables, and the presence of several young stellar clusters outside the Chandra field is indicated by overdensities in the data. The catalog of Ks variables is provided in Table 4.

4. Age estimates are obtained using stellar evolution on the V versus V − I color–magnitude diagram (AgeV) and evolution of X-ray luminosity versus dereddened J-band luminosity (AgeJ), with both methods suggesting that the median stellar age is ∼3.2–3.3 Myr (Section 5.5). These estimates of median age are consistent with previous age estimates, but systematic effects on age estimates may contribute to considerable uncertainty. The distribution of AgeV values suggests a significant age spread that has also been noted by DMS2016 and Sung et al. (2013). A large age spread would also be consistent with the likely birth of the progenitor of the runaway HMXB system HD 153919 ∼6.4 Myr ago.

5. The distribution of the X-ray luminosities of the brightest pre-main-sequence stars shows signs of a moderate decrease in luminosity relative to stars in younger regions, such as the Orion Nebula Cluster or Taurus Molecular Cloud (Section 5.6). This can be seen as a decrease in X-ray luminosity of 0.2–0.4 dex relative to the Telleschi et al. (2007) relation for weak-line T Tauri stars, an XLF with a steeper slope than that of the Orion Nebula Cluster, and a lack of bright X-ray sources with AgeV > 5 Myr. However, for stars with Age > 5 Myr, the distribution of LX appears not to vary with age.

6. We use the observed mass function and XLF to estimate the total number of stars in the cluster (down to the hydrogen-burning limit at 0.08 M⊙) and the completeness limit for pre-main-sequence stars (Section 5.7). Assuming that the cluster follows a normal IMF, we estimate 5700–7500 stars projected within the Chandra field. The sample has a 50% completeness limit at 0.5 M⊙ (meaning that a 0.5 M⊙ star has a 50% chance of detection). If we assume a universal XLF (neglecting effects of X-ray–luminosity evolution), we find a consistent result of 6000 stars and a completeness limit at LX = 10^{30.0} erg s^{-1}. The cutoff of the sample in mass is not sharp due to the large amount of scatter in the LX–M relation. Some substellar-mass objects are identified, but the number of objects (4–26) depends strongly on the assumption about stellar age. The typical X-ray luminosity of the detected substellar candidates is log LX = 29.9 erg s^{-1}.

7. With low foreground extinction (A_V ≈ 1.6 mag, corresponding to N_H ≈ 3.5 × 10^{21} cm^{-2}), X-ray ME (spectral hardness) is most sensitive to plasma temperature and local absorption. The ME and X-ray luminosity can be used to separate B-type stars into two groups: one with soft spectra (ME < 1.15 keV), lower X-ray fluxes, and spectral types of B4 or earlier, and another with harder spectra (ME > 1.15 keV), intermediate X-ray luminosities, and spectral types ranging from B0 to B9 (Section 6). We argue that the first group is most likely made up of stars with X-rays produced by stellar winds,
while the second group is most likely made up of stars with X-rays from coronal emission of pre-main-sequence binary companions. In two cases in the second group, X-ray flares are seen in the light curves, providing additional evidence that the X-ray emission is from a pre-main-sequence companion. We estimate that 35–41% of B stars have pre-main-sequence binary companions with masses > 0.5 $M_\odot$.

8. For low-mass stars, ME can also be used to identify highly absorbed cluster members (Section 5.8). A small fraction of sources have X-ray MEs between 2 and 6 keV. While some of these may be contaminants, analysis of various optical, infrared, and X-ray color–magnitude diagrams suggests that many are bona fide cluster members. We hypothesize that the absorptions may be produced by circumstellar disks.

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Facilities: CXO(ACIS-I), ESO:VISTA(VVV).

Software: ACIS Extract (Broos et al. 2010), astro (Kelvin 2014), astrolib (Landsman 1993), astrolibR (Chakraborty & Feigelson 2015), celestial (Robotham 2016), SAIImage DS9 (Joye & Mandel 2003), SIMBAD (Wenger et al. 2000), spatstat (Baddeley & Turner 2005), TOPCAT (Taylor 2005), XPHOT (Getman et al. 2010).

Appendix

Gaia Distance Estimate

Nine of the OB stars in NGC 6231 have parallax measurements in the Gaia-Tycho catalog (Gaia Collaboration et al. 2016) with uncertainties on the parallax of less than $\Delta\pi < 0.2$ mas. The distances indicated by the parallax measurements for these nine stars are shown in Figure 17 as tick marks. The probability density function created by smoothing these data with a kernel with bandwidth $\sigma = 0.1$ kpc is also shown, similar to the analysis performed for estimation of the distance to the Pleiades cluster using Gaia measurements by the Gaia Collaboration et al. (2016). The median of this distribution is $1.37 \pm 0.42$ kpc. The uncertainty on the median is calculated by bootstrap resampling, where uncertainties on individual measurements are simulated by adding a random variable drawn from the individual measurements’ uncertainty distributions. Contributions of systematic uncertainties of the order of $\pm 0.3$ mas (Lindegren et al. 2016) yield a distance estimate of $1.37 \pm 0.70$ kpc.
