The Massive Star-forming Regions Omnibus X-ray Catalog, Second Installment

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Abstract

We present the second installment of the Massive Star-forming Regions (MSFRs) Omnibus X-ray Catalog (MOXC2), a compilation of X-ray point sources detected in Chandra/ACIS observations of 16 Galactic MSFRs and surrounding fields. MOXC2 includes 13 ACIS mosaics, three containing a pair of unrelated MSFRs at different distances, with a total catalog of 18,396 point sources. The MSFRs sampled range over distances of 1.3 kpc to 6 kpc and populations varying from single massive protostars to the most massive Young Massive Cluster known in the Galaxy. By carefully detecting and removing X-ray point sources down to the faintest statistically significant limit, we facilitate the study of the remaining unresolved X-ray emission. Through comparison with mid-infrared images that trace photon-dominated regions and ionization fronts, we see that the unresolved X-ray emission is due primarily to hot plasmas threading these MSFRs, the result of feedback from the winds and supernovae of massive stars. The 16 MSFRs studied in MOXC2 more than double the MOXC1 sample, broadening the parameter space of ACIS MSFR explorations and expanding Chandra’s substantial contribution to contemporary star formation science.

Key words: H II regions – stars: early-type – stars: formation – X-rays: stars

Supporting material: FITS file

1. Introduction

To explore basic questions of Galactic star formation and structure, the first step is to identify the stars that make up massive star-forming regions (MSFRs), where most massive stars form (Motte et al. 2017). This simple goal is surprisingly hard to achieve; MSFRs are typically far away, behind large absorbing columns in the Galactic Plane. Infrared (IR) surveys are sensitivity-limited by bright extended emission and confusion-limited at longer wavelengths; only IR-excess stars found outside the brightest cluster cores can be reliably cataloged. This problem is not remedied as massive clusters age; by the time the natal dust and gas in a giant H II region have been dispersed by massive star feedback, their clusters have expanded in size and their pre-main sequence (pre-MS) stars have dissipated their disks (and their IR-excesses), so they are lost in the overwhelming contamination of unrelated field stars.

Ushering in the 21st century, the Chandra X-ray Observatory brought high spatial resolution to X-ray astronomy, opening a new window into the workings of MSFRs. Chandra observations, combined with IR surveys, provide the best stellar census available for MSFRs. This is because Chandra has a large field of view that often captures an entire MSFR in a single pointing, it has sub-arcsecond spatial resolution on-axis, the instrumental background is low, and pre-MS stars are strong X-ray emitters independent of their disk status. Even the faintest X-ray sources that are matched to IR sources usually indicate MSFR membership. Additionally, Chandra observations do not suffer the bright, highly variable backgrounds that plague IR studies.

Because of its fine spatial resolution and hard X-ray spectral response, Chandra is good at finding massive stars and intermediate-mass pre-MS stars (IMPS) as well as lower-mass pre-MS stars. Once all of these X-ray point sources are identified and removed from Chandra images, it is possible to use the remaining unresolved Chandra emission to map the hot, shocked interstellar medium (ISM) created by massive star winds and supernova feedback. This diffuse X-ray emission fills H II region bubbles and permeates superbubbles; these structures trace the framework of star formation in the Galaxy and in turn define starburst clusters in other galaxies. Chandra has established definitively that star formation proceeds in the presence of 1–10 million degree plasmas (Townsley et al. 2003) and that even the youngest massive stars, still ionizing hyper- and ultra-compact H II regions (UCHIIRs), blast their cold, molecular birth environments with hard X-rays (Anderson et al. 2011). Thus no picture of a MSFR’s evolution and environmental impact is complete without the Chandra perspective.

Chandra has amassed a large body of MSFR observations, giving new insights into the stellar populations and energetics of individual regions and enabling ambitious multi-target comparison projects. Examples focusing on individual MSFR complexes include The Astrophysical Journal Supplement Series special issues on the Chandra Orion Ultradeep Project (COUP; volume 160, number 2; e.g., Getman et al. 2005) observations of the Orion Nebula Cluster and the Chandra Carina Complex Project (CCCP; volume 194 number 1; e.g., Townsley et al. 2011a) observations of the Great Nebula in Carina. We look forward to the Chandra Cygnus OB2 Legacy Survey (Wright et al. 2014). Multi-target comparisons include...
the Massive Young Star-forming Complex Study in Infrared and X-ray (MYSiX; e.g., Feigelson et al. 2013) and the Star Formation in Nearby Clouds project (SFiNCs; e.g., Getman et al. 2017).

The immediate precursor to the current work was the first installment of the MSFRs Omnibus X-ray Catalog (MOXC1; Townsley et al. 2014), which presented Chandra point source lists and images of diffuse X-ray emission for 12 MSFRs (seven for MYSiX and five more distant regions). This paper (hereafter MOXC2) closely follows the structure of MOXC1 and does not repeat the methodologies and analysis details explained there; thus we refer readers to MOXC1 for more background on the MOXC2 effort. All of the Chandra data used for our MSFR studies come from the Advanced CCD Imaging Spectrometer (ACIS) instrument (Garmire et al. 2003).

With MOXC2, we expand our analysis of Chandra/ACIS data to include off-axis CCDs and archival data on fields adjacent to our target MSFRs, which were observed for other reasons. These ancillary pointings often go well beyond most cluster radii and provide the Galactic context for our MSFRs, informing our efforts to understand the ecology of large-scale star formation and feedback. In particular, these wide-field ACIS mosaics create new opportunities to understand distributed populations of young stars, multi-epoch star formation, and the extent of hot plasmas surrounding massive molecular filaments and threading giant molecular clouds (GMCs). The influence of evolving MSFRs extends over 10–100 pc scales and includes supernova remnants (SNRs), pulsars and pulsar wind nebulae (PWNe), gamma-ray sources, X-ray binaries, and diffuse plasmas from massive star feedback (both winds and supernovae). We are using these new wide-field X-ray analysis capabilities to improve our understanding of the energetics, populations, and environments of GMCs, their networks of massive filaments, and their multiple MSFRs, and how they drive Galactic evolution.

The MSFR targets featured in this paper are shown in Table 1. As in MOXC1, we include a rough limiting luminosity $L_{\text{ac}}$ and the corresponding limiting mass $M_{\text{50\%}}$ where the brighter half of the X-ray population is sampled, based on COUP results (Preibisch et al. 2005). This $L_{\text{ac}}$ comes from a $\text{PIMM}^S$ calculation for a five-count detection on-axis, for a source with an $apec$ thermal plasma with $kT = 2.7$ keV and abundance $0.4^{+0.2}_{-0.3}Z_{\odot}$. These values are typical for a pre-MS star (Preibisch et al. 2005).

We have assembled and analyzed 13 wide-field ACIS mosaics for MOXC2, amassing a catalog of 18,396 X-ray point sources and adaptively smoothed images of the remaining unresolved X-ray emission in each mosaic. In three of these regions, MOXC2 exploits chance superpositions of unrelated MSFRs that just happen to be superposed on the sky; these are IRAS 19410+2336 and NGC 6823, W42 and RSGC1, and W33 and Cl 1813-178. The number of X-ray point sources found for each target (Table 1 Column 10) varies substantially between targets. This is due to a combination of field of view and sensitivity; short observations and/or single pointings naturally result in fewer source detections than deeper observations and/or wide-field mosaics. Additionally, the MOXC2 sample of MSFRs includes a wide variety of contexts in which we find massive stars, from sparse clumps containing just a handful of young stars to Young Massive Clusters (YMCS) containing tens of thousands of members.

### 2. Chandra Observations and Data Analysis

#### 2.1. Observations

The Chandra/ACIS observations used for MOXC2 are summarized in Table 2 and are identified by a unique Observation Identification (ObsID) number. All of these data sets are available in the Chandra archive. Observations are ordered by date for each target; target names as used in this paper are given in Column (1) in bold, followed by the original name assigned by the study’s principal investigator (PI), noted in Column (11). Those observations where Gordon Garmire is listed as PI came from the ACIS Instrument Team Guaranteed Time Observation (GTO) program; those listing Stephen Murray as PI came from the HRC Instrument Team GTO program. We note this fact because the Chandra GTO programs provided many of the original seed observations for the MSFRs studied here and for many other Galactic Plane observations that we use in our wide-field mosaics.

Virtually all of the ACIS data we have previously published were taken with the Observatory in the ACIS imaging array (ACIS-I) configuration (Garmire et al. 2003), with the optical axis near the center of a $2 \times 2$ array of 1024 × 1024-pixel CCDs covering roughly $17' \times 17'$ on the sky (with 0.492 pixels). Although such observations commonly include data from two CCDs lying far off-axis in the ACIS spectroscopy array (ACIS-S), we previously chose to discard data from those CCDs due to the poor angular resolution of the Chandra mirrors at large off-axis angles.7

In order to widen the field coverage around MSFRs and to include more archival data, MOXC2 includes the off-axis CCDs in ACIS-I observations and imaging observations taken in the ACIS-S configuration (Garmire et al. 2003), as shown in the MOXC2 exposure map mosaics in Section 4. Four of our MSFRs were observed with the ACIS-S imaging configuration.

One side effect of this more liberal data selection policy is that most observations presented here include both frontside-illuminated (FI) and backside-illuminated (BI) CCD detectors (Garmire et al. 2003). Because FI and BI detectors exhibit very different background spectra, their analysis must be done separately; thus we split each Chandra ObsID into separate FI and BI “virtual” observations within our data analysis workflow.

#### 2.2. Data Analysis

Our data reduction, diffuse emission analysis, and point source detection, extraction, and masking techniques employ several innovations beyond standard Chandra procedures, as discussed at length by Broos et al. (2010). These techniques were standardized for MSFRs by the CCCP and improved during the MYSiX and MOXC1 studies. Many of the CCCP data analysis steps were implemented by the ACIS Extract (AE) software package8 (Broos et al. 2012; Broos & Townsley 2016).

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5. http://asc.harvard.edu/toolkit/pimms.jsp

6. See Figure 4.12 in the Chandra Proposers’ Observatory Guide http://asc.harvard.edu/proposer/POG/.

7. The ACIS Extract software package and User’s Guide are available at http://personal.psu.edu/p86/TARA/ac_users_guide.html.
| MOXC2 Target   | Galactic (l, b) (R.A., Decl.) (kpc) | Celestial J2000 (arcmin/pc) | Distance Scale (mag) | Nominal Exp (ks) | log $L_{\text{c}}$ (erg s$^{-1}$) | $M_{50\%}$ ($M_\odot$) | X-ray Srcs (#) | Distance References |
|----------------|-------------------------------------|-----------------------------|----------------------|------------------|----------------------------------|----------------------|-----------------|-------------------|
| NGC 6334       | 350.99 +0.62                       | 17 19 47.1 – 36 08 35       | 1.3                  | 2.64             | 4                                | 30.63                | 1.3             | see IRAS 19410    |
| W75N           | 81.89 +0.79                        | 20 38 36.5 +42 38 46        | 1.3                  | 2.64             | 50                               | 30.53                | 1.2             | Chibueze et al. (2014), Wu et al. (2014) |
| RCW 120        | 348.22 +0.46                       | 17 12 20.8 – 38 29 31       | 1.34                 | 2.57             | 40                               | 30.08                | 0.6             | Zavagno et al. (2007) |
| IRAS 20126+4104| 78.13 +3.62                        | 20 14 29.1 +41 13 33        | 1.64                 | 2.10             | 70                               | 30.79                | 1.8             | Moscadelli et al. (2011) |
| W31N           | 10.32 –0.15                        | 18 08 59.1 – 20 05 08       | 1.75                 | 1.96             | 18                               | 30.36                | 1.0             | Deharveng et al. (2015) |
| IRAS 19410+2336| 59.78 +0.06                        | 19 43 11.4 +24 44 06        | 2.16                 | 1.59             | 20                               | 31.14                | bright          | Xu et al. (2009)   |
| W42            | 25.36 –0.19                        | 18 38 14.6 –06 49 19        | 2.2                  | 1.56             | 11                               | 30.27                | 0.8             | Blum et al. (2000) |
| NGC 6823       | 59.40 –0.15                        | 19 43 11.0 +23 17 45        | 2.3                  | 1.49             | 3                                | 30.63                | 1.3             | Massey et al. (1995) |
| W33            | 12.81 +0.20                        | 18 14 13.5 –17 55 42        | 2.4                  | 1.43             | 20                               | 30.68                | 1.5             | Immer et al. (2013) |
| NGC 7538       | 111.54 +0.81                       | 23 13 45.5 +61 28 17        | 2.65                 | 1.32             | 11                               | 30.66                | 1.4             | Moscadelli et al. (2009) |
| G333           | 333.03 –0.44                       | 16 20 39.5 –50 39 59        | 2.6                  | 1.32             | 15                               | 30.44                | 1.1             | Figueredo et al. (2005) |
| AFGL 2591      | 78.89 +0.71                        | 20 29 24.9 +40 11 21        | 3.33                 | 1.03             | 100                              | 31.66                | bright          | Rygl et al. (2012)  |
| G34.4+0.23     | 34.40 +0.23                        | 18 53 18.5 +01 24 48        | 3.7                  | 0.93             | 200                              | 31.79                | bright          | Rathborne et al. (2005) |
| Cl 1813–178    | 12.74 –0.01                        | 18 13 24.3 –17 53 31        | 3.8                  | 0.90             | 9                                | 30.65                | 1.4             | Messineo et al. (2011) |
| Wd1            | 339.55 –0.40                       | 16 47 04.0 –45 51 05        | 4.0                  | 0.86             | 11                               | 30.69                | 1.5             | Gennaro et al. (2011) |
| RSGC1          | 25.27 –0.16                        | 18 37 58.0 –06 53 00        | 6                   | 0.57             | 23                               | 31.24                | bright          | Froebrich & Scholz (2013) |

**Note.** Col. (5): Image scale assuming the distance given in Col. (4). Col. (6): Approximate average absorption to the target, estimated from a variety of literature sources. Most MSFRs have highly variable and spatially complex obscuration, so this value should be used only as a rough indicator. Col. (7): A typical exposure time for the main MSFRs. Most mosaics have a wide range of exposures; detailed exposure maps are shown in Section 4. Col. (8): A rough limiting luminosity where the brighter half of the X-ray population is sampled. Subscripts mean total band 0.5–8 keV, corrected for extinction. Col. (9): The corresponding limiting mass, where the brighter half of the X-ray population is captured. For shallow observations, this limit is higher than pre-MS masses, so only “bright” sources (some massive stars and IMPS) are expected. Col. (10): Total number of X-ray sources found across the entire mosaic.
| Target          | ObsID  | Start Time (UT) | Exposure (s) | Aimpoint (°) | Roll (°) | Mode | Detector | PI | TGAIN |
|----------------|--------|-----------------|--------------|--------------|----------|------|----------|----|--------|
| NGC 6334       | 2574   | 2002-08-31T12:49 | 39648        | I3           | 17:20:54.00 | -35:47:03.9 | 269 | TE-F   |
| NGC 6334       | 2573   | 2002-09-02T00:12 | 25473        | I3           | 17:20:01.00 | -35:56:07.0 | 268 | TE-F   |
| G351.2+0.1     | 3844   | 2003-10-04T19:21 | 14773        | S3           | 17:22:24.70 | -36:10:59.9 | 261 | TE-VF  |
| G351.2+0.1     | 4591   | 2004-07-31T00:30 | 38012        | S3           | 17:22:28.00 | -36:10:59.9 | 278 | TE-VF  |
| IGR J17204-3554| 8975   | 2009-01-26T12:19 | 1015         | I3           | 17:20:25.00 | -35:53:31.2 | 98  | TE-F   |
| NGC 6334       | 13436  | 2011-07-13T09:37 | 62810        | I3           | 17:19:47.10 | -36:08:35.0 | 288 | TE-VF  |
| NGC 6334       | 12382  | 2011-07-17T19:19 | 32045        | I3           | 17:19:47.10 | -36:08:35.0 | 288 | TE-VF  |
| GM 24          | 18876  | 2016-06-27T12:52 | 16744        | I3           | 17:17:06.90 | -36:21:27.2 | 302 | TE-VF  |
| GM 24          | 18082  | 2016-06-30T16:45 | 22658        | I3           | 17:17:06.90 | -36:21:27.2 | 302 | TE-VF  |
| G350.776+0.831 | 18081  | 2016-07-23T18:50 | 37566        | I3           | 17:18:19.30 | -36:12:09.6 | 281 | TE-VF  |
| W75N           | 8893   | 2008-02-02T01:15 | 29740        | I3           | 20:38:36.49 | +42:38:46.2 | 5   | TE-VF  |
| RCW 120        | 6721   | 2006-10-07T05:13 | 19905        | I3           | 17:14:35.80 | -38:31:24.5 | 259 | TE-VF  |
| HESS J1713-381 | 6692   | 2007-02-02T11:55 | 24836        | I3           | 17:14:04.09 | -38:11:05.3 | 96  | TE-VF  |
| RCW 120        | 13621  | 2012-06-30T12:28 | 49117        | I3           | 17:12:20.80 | -38:29:30.5 | 303 | TE-VF  |
| RCW 120        | 13276  | 2013-02-11T07:39 | 29688        | I3           | 17:12:20.80 | -38:29:30.5 | 93  | TE-VF  |
| IRAS 20126+4104| 3758   | 2003-03-13T02:43 | 38761        | I3           | 20:14:29.05 | +41:13:32.4 | 58  | TE-VF  |
| W31N           | 1827   | 2000-07-24T18:22 | 4393         | S3           | 18:08:40.32 | -20:24:41.6 | 265 | TE-F   |
| SGR 1806-20    | 6224   | 2005-02-09T07:01 | 18620        | S3           | 18:08:39.29 | -20:24:38.9 | 88  | TE-F   |
| AX J180816-2021| 8151   | 2007-10-26T07:15 | 2107         | S3           | 18:08:16.79 | -20:21:43.1 | 272 | TE-F   |
| AX J180857-2004| 10518  | 2009-02-10T08:00 | 6467         | S3           | 18:08:57.40 | -20:04:33.6 | 88  | TE-F   |
| G9.95-0.81     | 10713  | 2009-02-10T10:21 | 9914         | S3           | 18:10:41.09 | -20:43:33.4 | 88  | TE-VF  |
| W31 North      | 18452  | 2016-08-14T05:31 | 39243        | S3           | 18:08:59.09 | -20:05:08.1 | 268 | TE-VF  |
| NGC 623        | 1868   | 2001-10-15T22:25 | 8679         | S3           | 19:43:11.40 | +23:44:05.9 | 276 | TE-VF  |
| AX J194152+2251| 8164   | 2007-07-16T40:55 | 2714         | S3           | 19:41:52.99 | +22:51:43.1 | 179 | TE-VF  |
| AX J194332+2323| 10517  | 2009-02-15T10:18 | 5879         | S3           | 19:43:32.59 | +23:23:52.7 | 45  | TE-F   |
| AX J194310+2318| 10502  | 2009-02-26T09:52 | 2054         | S3           | 19:43:10.30 | +23:18:50.4 | 58  | TE-VF  |
| W42; RSGC1     | 6719   | 2006-08-19T16:30 | 19897        | I3           | 18:37:43.00 | -06:54:20.9 | 259 | TE-VF  |
| W42            | 16673  | 2016-02-13T16:26 | 53865        | I3           | 18:38:14.59 | -06:49:18.9 | 78  | TE-VF  |
| W33; CI 1813-178| 6685   | 2006-09-15T00:56 | 29568        | I3           | 18:13:28.80 | -17:52:00.8 | 270 | TE-VF  |
| W33            | 16674  | 2015-07-27T21:36 | 38188        | I3           | 18:14:13.49 | -17:55:41.9 | 262 | TE-VF  |

Table 2
Log of Chandra Observations

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The time variability of the ACIS background is discussed in Section 6.16.3 of the Proposers’ Observatory Guide (http://asc.harvard.edu/proposer/POG/) and in the ACIS Background Memos at http://asc.harvard.edu/cal/Acis/Cal_prods/bkgmd/current/.

The aimpoints (given in celestial coordinates) are obtained from the satellite aspect solution before astrometric correction is applied. Units of R.A. (α) are hours, minutes, and seconds; units of decl. (δ) are degrees, arcminutes, and arcseconds.

ACIS observing modes are described in Section 6.12 of the Chandra Proposers’ Observatory Guide (http://asc.harvard.edu/proposer/POG/).

The layout of the 10 CCD detectors (numbered 0 through 9 here) in the ACIS focal plane is shown in Section 6.1 of the Chandra Proposers’ Observatory Guide (http://asc.harvard.edu/proposer/POG/).

The ACIS Time-Dependent Gain file used for calibration of event energies.

Version N0010 of the Optical Blocking Filter model was used for the calibration of Ancillary Response Files and exposure maps.

**Notes.**

| Target | ObsID | Start Time (UT) | Exposure (s) | Aimpoint | Roll (°) | Mode | Detectors | PI | TGAIN |
|--------|-------|----------------|-------------|----------|----------|------|-----------|----|--------|
| Cl 1813-178 | 17695 | 2016-05-29T22:12 | 12886 | I3 | 18:13:24.29 | -17:53:30.8 | TE-VF | 01237 | Gordon Garmire |
| Cl 1813-178 | 17440 | 2016-06-05T21:05 | 16725 | I3 | 18:13:24.29 | -17:53:30.8 | TE-VF | 012367 | Gordon Garmire |
| NGC 7538 | | | | | | | | | |
| NGC 7538 | 5373 | 2005-03-25T22:55 | 28785 | I3 | 23:13:45.49 | +61:28:16.6 | TE-VF | 012367 | Gordon Garmire |
| G333 | | | | | | | | | |
| IGR J16195-4945 | 5471 | 2005-04-29T17:25 | 4750 | I3 | 16:19:30.00 | -49:45:00.0 | TE-F | 012367 | John Tomsick |
| AX J162246-4946 | 8161 | 2007-06-13T15:01 | 2900 | S3 | 16:22:46.99 | -49:46:55.1 | TE-F | 235678 | Stephen Murray |
| AX J162260-5005 | 8141 | 2007-06-21T02:36 | 1529 | S3 | 16:22:08.39 | -50:05:41.9 | TE-F | 235678 | Stephen Murray |
| AX J162611-5002 | 9602 | 2008-05-28T19:52 | 1531 | S3 | 16:20:11.50 | -50:02:09.6 | TE-F | 235678 | Stephen Murray |
| AX J162646-4942 | 10507 | 2009-01-26T20:06 | 3333 | S3 | 16:20:46.60 | -49:42:46.8 | TE-F | 235678 | Bryan Gaensler |
| G333.6-0.2 | 9911 | 2009-06-14T12:19 | 60996 | S3 | 16:22:09.19 | -50:06:03.4 | TE-VF | 012367 | Leisa Townsley |
| PSR J1622-49 | 10929 | 2009-07-10T07:21 | 19879 | S3 | 16:22:52.90 | -49:49:35.1 | TE-F | 012367 | Nanda Rea |
| G333.3-0.4 | 15617 | 2013-02-26T01:12 | 26131 | S3 | 16:21:32.59 | -50:24:20.3 | TE-VF | 012367 | Leisa Townsley |
| G333.3-0.4 | 14532 | 2013-02-28T16:50 | 28204 | S3 | 16:21:32.59 | -50:24:20.3 | TE-VF | 012367 | Leisa Townsley |
| G333.1-0.4 | 14531 | 2013-06-25T01:41 | 60271 | S3 | 16:20:39.49 | -50:39:58.6 | TE-VF | 01237 | Leisa Townsley |
| RCW 106 | 15393 | 2013-07-03T00:22 | 59149 | I3 | 16:20:02.80 | -50:58:18.6 | TE-VF | 01237 | Gordon Garmire |
| AFGL 2591 | | | | | | | | | |
| AFGL 2591 | 6442 | 2006-02-08T01:26 | 29791 | S3 | 20:29:24.89 | +40:11:21.0 | TE-VF | 235678 | Arnold Benz |
| G34.4+0.23 | | | | | | | | | |
| IRDC G34.4+0.23 | 14541 | 2013-06-17T12:03 | 28125 | I3 | 18:53:18.49 | +01:24:47.9 | TE-VF | 01236 | Jonathan Tan |
| IRDC G34.4+0.23 | 15664 | 2013-08-12T17:44 | 34526 | I3 | 18:53:18.49 | +01:24:47.9 | TE-VF | 012367 | Jonathan Tan |
| Wd4 | | | | | | | | | |
| Westerlund1 | 6283 | 2005-05-22T20:38 | 18808 | S3 | 16:47:05.40 | -45:50:36.7 | TE-F | 234678 | Stephen Skinner |
| Westerlund1 | 5411 | 2005-06-18T16:09 | 36596 | S3 | 16:47:05.40 | -45:50:36.7 | TE-F | 234678 | Stephen Skinner |
| AFGL 1648.1-4606 | 11836 | 2010-01-24T03:00 | 10035 | I3 | 16:48:34.59 | -46:07:10.9 | TE-VF | 012367 | Gordon Garmire |

**Table 2**

(Continued)
and are described in detail in Broos et al. (2010). Nearly identical procedures were applied to the MOXC2 MSFRs, so we do not provide an exhaustive review of those procedures here. A few of the basic steps and improvements to methodologies previously published are described below.

The Chandra data analysis system, CIAO9 (Fruscione et al. 2006), the SAOImage DS910 visualization tool (Joye & Mandel 2003), and the Interactive Data Language11 (IDL) are used throughout our data analysis workflow, from data preparation through science analysis. Models of the local point-spread function (PSF) of each source, built by the MARX12 observatory simulator (Davis et al. 2012), play a central role in source finding, constructing extraction apertures, accounting for source crowding when extracting local backgrounds, calculating energy-dependent aperture corrections for calibration data products, modeling detector pile-up effects (Section 3.2), and masking point sources for diffuse analysis (Section 2.2.4). As recommended by the Chandra X-ray Center,13 we tuned two MARX parameters to produce PSFs that match our own data: AspectBlur=0°/7 and pix_adj=NONE for ACIS-I observations; AspectBlur=0°/7 and pix_adj=EDSER for ACIS-S observations. Note that this tuning applies only to MARX version 5.3.0.

### 2.2.1. Point Source Detection Strategy

As in previous studies, our point source detection workflow first identifies a liberal set of candidate sources, derived mostly from maximum likelihood image reconstruction, then iteratively prunes candidates found to be insignificant after extraction and careful local background estimation. Extraction apertures are normally sized to contain 90% of the PSF (at 1.5 keV), but are reduced when necessary to minimize overlap among crowded sources. (Aperture correction is discussed in Section 3.1.) Iteration is necessary because backgrounds and extraction apertures depend upon neighboring sources, so as insignificant source candidates are pruned from the catalog, remaining source candidates must be re-extracted and re-evaluated for validity.

The goals of completeness and validity of a source list are always in conflict. Our point source detection procedure is designed to be aggressive, emphasizing sensitivity and accepting a reasonable occurrence of possibly spurious detections to achieve that sensitivity. In the CCCP study, Broos et al. (2011, Figure 9) showed that when deep near-IR catalogs are available, the fraction of X-ray detections without apparent near-IR counterparts rises only slowly as detection significance falls; this is indirect evidence that our procedures do not lead to a large number of false sources. Broos et al. (2011, Section 6.2) discuss the impracticality of quantifying the false detection rate in our X-ray catalog, and point out that such an estimate would be nearly useless because most science analyses select subsets of the X-ray catalog (e.g., sources with IR photometry available, or sources classified as young stars).

Detection of source candidates has changed in various ways since MOXC1. Since different ACIS pointings now commonly overlap considerably in our wide-field mosaics, pointing-based tiling has been eliminated. Now the whole field is tiled, tile sections are extracted from every ObsID, and only tile extractions with similar off-axis angles are merged, to avoid combining data with very different angular resolutions. These merged tile images, along with tile images from each constituent ObsID, are independently searched for sources.

We now use a more complex method to estimate the background in a reconstructed image, separately modeling particle and X-ray backgrounds. This accounts for the energy-dependent and time-dependent distribution of the X-ray background across the detector, caused by the spatially non-uniform and time-dependent contamination on the ACIS Optical Blocking Filter.14

Our procedure for searching reconstructed tile images for source candidates now involves several steps, in order to improve our ability to detect faint sources. After source candidates are identified in each reconstructed tile image, those candidates are removed, the resulting image is smoothed, and the smoothed image is searched again for fainter sources. At the end of the source-finding process, the resultant candidate source lists are combined (and duplicates removed); the final candidate source list for the entire target is then assessed for validity.

### 2.2.2. Astrometric Alignment

Since tremendous resources have been invested to achieve Chandra’s superb angular resolution, we make considerable efforts to preserve that angular resolution by carefully aligning overlapping ACIS observations and assigning absolute astrometry by using the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) catalog as the astrometric reference (this near-IR catalog works best for our targeted sources). This alignment work is iterative. The first round of alignment is performed by finding bright X-ray sources in each ObsID, and then matching those independent single-ObsID catalogs of bright X-ray sources to each other and to the 2MASS catalog. (This matching scheme, considering relative astrometry shifts between ACIS ObsIDs as well as absolute astrometry shifts to align to 2MASS, is very helpful for aligning ACIS observations with a wide range of integration times. Short ObsIDs are best aligned to longer ObsIDs; then the longer ObsIDs provide the absolute alignment to 2MASS.) A weighted analysis of the resulting offsets between pairs of matched sources produces recommended shifts for each ObsID; no rotational correction is attempted. Those shifts are applied; then the process is repeated until no further shifts are recommended. The final cumulative shifts are applied to the aspect calibration files for each ObsID, and the event lists are re-projected onto the sky. Those single-ObsID catalogs of bright sources, which now have obsolete coordinates, are not considered further.

A fresh list of candidate sources (Section 2.2.1) is obtained from these aligned data, and the iterative process of extracting and validating those candidates begins. During this process we assess the alignment of ObsIDs at least twice more. As above, shift recommendations for each ObsID are obtained by combining error-weighted estimates of all pairs of inter-ObsID offsets and error-weighted estimates of single-ObsID offsets with respect to 2MASS; no rotational correction is

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9 http://cxc.harvard.edu/ciao/
10 http://ds9.si.edu
11 www.harrisgeospatial.com/ProductsandTechnology/Software/IDL.aspx
12 http://space.mit.edu/ASC/marx/index.html
13 http://cxc.harvard.edu/ciao/why/aspectblur.html
14 http://cxc.harvard.edu/ciao/why/acisqecontamN0010.html
attempted. We believe this second round of alignment work is worthwhile for two reasons. First, estimates of inter-ObsID
shifts made at this point should be more accurate, because a single target-wide catalog is extracted from every ObsID—no
matching is required. Second, the (single target-wide) catalog of source candidates available at this point, built after our first
alignment of the data (described above), is expected to be a better representation of the sky (e.g., crowded sources are
more likely to be resolved).

2.2.3. Validation of Source Candidates

For sources with multiple observations, Broos et al. (2011, Section 6.2) point out that a subset of the observations may
produce higher quality measurements of source properties than the full set of observations would. This is often true
when the observations have very different off-axis angles, and thus very different angular resolutions and degrees of
crowding. As in previous studies, MOXC2 builds spectra and
photometry from a set of observations that favors the
crowding. As in previous studies, MOXC2 builds spectra and
and thus very different angular resolutions and degrees of
crowding. As in previous studies, MOXC2 builds spectra and
photometry from a set of observations that favors the
photometry from a set of observations that favors small position
uncertainty.

In previous studies, source validation followed the same
strategy: the validity of a source (in each energy band) was
calculated from the set of observations in which the source was
most valid. Broos et al. (2010, Section 6.2) point out that this
selection process increases sensitivity to variable sources at the
cost of an increased false detection rate arising from the
additional number of data sets that are searched.

Recently, while reducing a Chandra target with a large
number of overlapping ObsIDs, we found this source validation
strategy to be inadequate, since the number of possible ways to combine N ObsIDs grows rapidly with N.
Thus, in MOXC2, we have adopted a different strategy to
balance false detection rate and sensitivity to variable sources.
Source validity is now evaluated on a pre-defined, small set of
ObsID combinations. Those combinations do not depend on
characteristics of the data; they consist simply of (1) each ObsID by itself and (2) ObsIDs with similar off-axis angles.
Empirically determined off-axis angle ranges are 0°–3°, 2°–6°,
5°–9°, 8°–14°, and >13°. These ranges overlap to avoid
missing sources at the boundaries.

As described in MOXC1, our procedures account for the
Chandra PSF hook, a structure that extends ~0.7′ from the
main PSF peak and contains ~5% of the flux. This artifact is
significant for us, since our detection efforts emphasize faint
sources and hooks around bright sources can be reconstructed
as fainter neighboring candidate sources. We mark the hook
location around bright sources, and then visually examine those
locations for source candidates that are consistent with the
expected hook brightness. Such spurious “hook sources” are
removed from the catalog.

2.2.4. Diffuse Emission

As always, our strategy for studying diffuse X-ray emission is to
mask (remove) events that are likely to be associated with point
sources, to subtract particle background, and to normalize by the
exposure map (Townsley et al. 2003; Broos et al. 2010, Section 9).
The resulting diffuse image represents observed surface brightness,
which has units of photon cm⁻² s⁻¹ arcsec⁻². Masked data
products (observed event list, particle background event list, and
exposure maps) are built independently for each ObsID, and then
combined into target-level images. A surface brightness image is
computed from those observed, background, and exposure map
images using an adaptive smoothing algorithm (Townsley et al.
2003; Broos et al. 2010, Section 9.1), in which the smoothing
kernel is sized to achieve a target signal-to-noise ratio in the surface
brightness.

The adaptively smoothed X-ray flux images presented below
(Section 4) cover the energy band 0.5–7.0 keV and are
smoothed to a signal-to-noise ratio of 15. The exposure map
used in these images represents the instrument response at 1 keV.

3. MOXC2 Data Products

3.1. The MOXC2 Chandra Point Source Catalog

The primary data product of MOXC2 is a catalog of properties for 18,396 point sources found in our 13 ACIS
mosaics of MSFRs and their surrounding Galactic Plane
environments. This catalog provides the same source information
as that given in MOXC1 and is similar to catalogs from
CCCP (Broos et al. 2011), MYStIX (Kuhn et al. 2013), and
SFfINcs (Getman et al. 2017).

Table 3 defines the columns of the MOXC2 point source
catalog. This catalog is available in FITS format from the
electronic edition of this article and may be available in many
other formats from VizieR (Ochsenbein et al. 2000). All
photometric quantities in this table are apparent (not corrected for absorption). 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. Energy-dependent correction for finite extraction
apertures is applied to the ancillary reference file (ARF)
calibration products (see Broos et al. 2010, Section 5.3); the
SrcCounts and NetCounts quantities characterize the extrac-
tion and are not aperture-corrected. The only calibrated
quantities in the catalog are apparent photon flux in units of photon cm⁻² s⁻¹ (see Broos et al. 2010, Section 7.4), and an
estimate for apparent energy flux in units of erg cm⁻² s⁻¹
(Getman et al. 2010). Additional information regarding the
definition of source properties is provided in the table notes.

We caution potential users of these results that we have not
attempted to clean the point source catalog for sources that
might be spurious reconstruction peaks (e.g., over-reconstruc-
tions of diffuse emission). This can be a problem for bright
PWNe, SNRs, and dust-scattering halos around X-ray binaries.
As we describe each target mosaic in Section 4 below, we will
point out areas of particular concern for such spurious point
sources.

3.2. Piled Sources

As described in detail in MOXC1, ACIS detections of bright
X-ray sources can suffer from a nonlinearity known as photon
pile-up, where multiple X-ray photons are mistakenly

15 The “MERGE_FOR_PHOTOMETRY” option for combining ObsIDs in AE
tries to balance the goals of maximum signal-to-noise ratio and zero
photometry bias.
16 http://cxc.harvard.edu/ciao/caveats/psf_artifact.html
17 For diffuse images, the “total-band” omits the energy range 7–8 keV to
avoid a bright emission line in the instrumental background.
18 http://cxc.harvard.edu/ciao/why/pileup_intro.html
### Table 3

MOXC X-Ray Sources and Properties

| Column Label               | Units | Description                                                                 |
|---------------------------|-------|----------------------------------------------------------------------------|
| (1) Name and position, derived from the ObsIDs that minimize the position uncertainty (Broos et al. 2010, Section 6.2 and 7.1) |
| RegionName                |       | name of the MSFR                                                         |
| Name                      |       | X-ray source name in IAU format; prefix is CXOU J                        |
| Label<sup>a</sup>         | deg   | X-ray source name used within the project                                 |
| RAdeg                     | deg   | R.A. (J2000)                                                            |
| DEdeg                     | deg   | Decl. (J2000)                                                           |
| PosErr                    | arcsec| 1-σ error circle around (RAdeg,DEdeg)                                    |
| PosType                   |       | algorithm used to estimate position (Broos et al. 2010, Section 7.1)     |

Validity metrics, derived from a pre-defined set of ObsID combinations (Section 2.2.3)

| Column Label               | Units | Description                                                                 |
|---------------------------|-------|----------------------------------------------------------------------------|
| ProbNoSrc_MostValid       |       | smallest of ProbNoSrc_t, ProbNoSrc_s, ProbNoSrc_h, ProbNoSrc_v            |
| ProbNoSrc_t               |       | smallest p-value<sup>b</sup> under the no-source null hypothesis (Broos et al. 2010, Section 4.3) among validation merges |
| ProbNoSrc_s               |       | smallest p-value under the no-source null hypothesis among validation merges |
| ProbNoSrc_h               |       | smallest p-value under the no-source null hypothesis among validation merges |

Variability indices, derived from all ObsIDs

| Column Label               | Units | Description                                                                 |
|---------------------------|-------|----------------------------------------------------------------------------|
| ProbKS_single<sup>c</sup> |       | smallest p-value under the null hypothesis (no variability within each single ObsID) for the Kolmogorov–Smirnov test on the timestamps of each ObsID's event list |
| ProbKS_merge<sup>c</sup>  |       | p-value under the null hypothesis (no variability) for the Kolmogorov–Smirnov test on the timestamps of the multi-ObsID event list |
| ProbChisqPhotonFlux       |       | p-value under the null hypothesis (no variability) for the χ<sup>2</sup> test on the single-ObsID measurements of PhotonFlux<sub>t</sub> |

Observation details and photometric quantities, derived from the set of ObsIDs that optimizes photometry (Broos et al. 2010, Section 6.2 and 7)

| Column Label               | Units | Description                                                                 |
|---------------------------|-------|----------------------------------------------------------------------------|
| ExposureTimeNominal       | s     | total exposure time in merged ObsIDs                                       |
| ExposureFraction<sup>d</sup>|       | fraction of ExposureTimeNominal that source was observed                  |
| RateIn3x3Cell<sup>f</sup> | count/frame | 0.58 keV, in 3 × 3 CCD pixel cell                                           |
| NumObsIDs                 |       | total number of ObsIDs extracted                                           |
| NumMerged                 |       | number of ObsIDs merged to estimate photometry properties                 |
| MergeBias                 |       | fraction of exposure discarded in merge                                    |
| Theta_Lo                  | arcmin| smallest off-axis angle for merged ObsIDs                                 |
| Theta                     | arcmin| average off-axis angle for merged ObsIDs                                  |
| Theta_Hi                  | arcmin| largest off-axis angle for merged ObsIDs                                  |
| PsfFraction               |       | average PSF fraction (at 1.5 keV) for merged ObsIDs                        |
| SrcArea                   | (0.492 arcsec)<sup>2</sup> | average aperture area for merged ObsIDs                                  |
| AfterglowFraction<sup>f</sup>|       | suspected afterglow fraction                                              |
| SrcCounts<sub>t</sub>     | count | observed counts in merged apertures                                        |
| SrcCounts<sub>s</sub>     | count | observed counts in merged apertures                                        |
| SrcCounts<sub>h</sub>     | count | observed counts in merged apertures                                        |
| BkgScaling                |       | scaling of the background extraction (Broos et al. 2010, Section 5.4)     |
| BkgCounts<sub>t</sub>     | count | observed counts in merged background regions                              |
| BkgCounts<sub>s</sub>     | count | observed counts in merged background regions                              |
| BkgCounts<sub>h</sub>     | count | observed counts in merged background regions                              |
| NetCounts<sub>t</sub>     | count | net counts in merged apertures                                             |
| NetCounts<sub>s</sub>     | count | net counts in merged apertures                                             |
| NetCounts<sub>h</sub>     | count | net counts in merged apertures                                             |
| NetCounts<sub>Lo_t</sub>  | count | 1-σ lower bound on NetCounts<sub>t</sub>                                 |
| NetCounts<sub>Hi_t</sub>  | count | 1-σ upper bound on NetCounts<sub>t</sub>                                 |
| NetCounts<sub>Lo_s</sub>  | count | 1-σ lower bound on NetCounts<sub>s</sub>                                 |
| NetCounts<sub>Hi_s</sub>  | count | 1-σ upper bound on NetCounts<sub>s</sub>                                 |
| NetCounts<sub>Lo_h</sub>  | count | 1-σ lower bound on NetCounts<sub>h</sub>                                 |
| Column Label     | Units       | Description                                                                 |
|-----------------|-------------|-----------------------------------------------------------------------------|
| NetCounts_Hi_h  | count       | $1-\sigma$ upper bound on NetCounts_h                                       |
| MeanEffectiveArea_t^b  | cm² count photon⁻¹ | mean ARF value                                                               |
| MeanEffectiveArea_s^b  | cm² count photon⁻¹ | mean ARF value                                                               |
| MeanEffectiveArea_h^b  | cm² count photon⁻¹ | mean ARF value                                                               |
| MedianEnergy_t  | keV         | median energy, observed spectrum                                            |
| MedianEnergy_s  | keV         | median energy, observed spectrum                                            |
| MedianEnergy_h  | keV         | median energy, observed spectrum                                            |
| PhotonFlux_t^t  | photon cm⁻² s⁻¹ | apparent photon flux                                                         |
| PhotonFlux_s    | photon cm⁻² s⁻¹ | apparent photon flux                                                         |
| PhotonFlux_h    | photon cm⁻² s⁻¹ | apparent photon flux                                                         |
| EnergyFlux_t    | erg cm⁻² s⁻¹ | $\text{max}(\text{EnergyFlux_s}, 0) + \text{max}(\text{EnergyFlux_h}, 0)$ |
| EnergyFlux_s^b  | erg cm⁻² s⁻¹ | apparent energy flux                                                         |
| EnergyFlux_h^b  | erg cm⁻² s⁻¹ | apparent energy flux                                                         |

**Notes.** These X-ray columns are produced by the **ACIS Extract** (AE) software package (Broos et al., 2010, 2012). Similar column labels were previously published by the CCCP (Broos et al., 2011) and by MOXC1 (Townsley et al., 2014). The AE software and User’s Guide are available at [http://personal.psu.edu/psb6/TARA/ae_users_guide.html](http://personal.psu.edu/psb6/TARA/ae_users_guide.html). The suffixes “_t,” “_s,” and “_h” on names of photometric quantities designate the total (0.3–8 keV), soft (0.5–2 keV), and hard (2–8 keV) energy bands. Source name and position quantities (Name, RAdeg, DEdeg, PosErr, PosType) 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). Source significance quantities (ProbNoSrc_MostValid, ProbNoSrc_t, ProbNoSrc_s, ProbNoSrc_h) are computed using a pre-defined set of ObsID combinations, which do not depend on the data observed (Section 2.2.3). Variability indices (ProbKS_single, ProbKS_merge, ProbChisq_PhotonFlux) are computed using all ObsIDs. All other quantities are computed using a subset of ObsIDs chosen, independently for each source, to balance the conflicting goals of minimizing photometric uncertainty and avoiding photometric bias (Broos et al., 2010, Sections 6.2 and 7).

^b Source “labels” identify each source during data analysis, as the source position (and thus the Name) is subject to change.

^t In statistical hypothesis testing, the $p$-value is the probability of obtaining a test statistic at least as extreme as the one that was actually observed, when the null hypothesis is true. The $p$-value of the observed extraction under the no-source hypothesis is calculated by the method described by (Weisskopf et al., 2007, Appendix 2A), which is derived under the assumption that X-ray extractions follow Poisson distributions.

^c See (Broos et al., 2010, Section 7.6) for a description of the ProbKS_single and ProbKS_merge variability indexes, and caveats regarding possible spurious indications of variability using the ProbKS_merge index. The ProbChisq_PhotonFlux variability index is the $p$-value under the null hypothesis (no variability) for the standard $\chi^2$ test on the single-ObsID measurements of PhotonFlux_t.

^d Due to dithering over inactive portions of the focal plane, a *Chandra* source often is not observed during some fraction of the nominal exposure time. (See [http://cxc.harvard.edu/ciao/why/dither.html](http://cxc.harvard.edu/ciao/why/dither.html). The reported quantity is FRACEXPO, produced by the CIAO tool mkarf.

^e ACIS suffers from a nonlinearity at high count rates known as *photon pile-up*, described in Section 3.2 below. RateIn3x3Cell is an estimate of the observed count rate falling on an event detection cell of size $3 \times 3$ ACIS pixels, centered on the source position. When RateIn3x3Cell $>0.05$ (count/frame), the reported source properties may be biased by pile-up effects. See Table 4 for a list of MOXC2 sources with significant pile-up. All source properties in this table are not corrected for pile-up effects.

^f Some background events arising from an instrumental effect known as “afterglow” ([http://cxc.harvard.edu/ciao/why/afterglow.html](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 AE tool *ae_afterglow_report*, and report the fraction of extracted events attributed to afterglow; see the ACIS Extract manual ([http://personal.psu.edu/psb6/TARA/ae_users_guide.html](http://personal.psu.edu/psb6/TARA/ae_users_guide.html)).

^g Confidence intervals (68%) for NetCounts quantities are estimated by the CIAO tool aprates ([http://asc.harvard.edu/ciao/ahelp/aprates.html](http://asc.harvard.edu/ciao/ahelp/aprates.html)).

^h 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).

^i MedianEnergy is the median energy of extracted events, corrected for background (Broos et al., 2010, Section 7.3).

^j PhotonFlux = (NetCounts/MeanEffectiveArea/ExposureTimeNominal) (Broos et al., 2010, Section 7.4).

EnergyFlux = $1.602 \times 10^{-9}$ (erg/keV) $\times$ PhotonFlux $\times$ MedianEnergy (Getman et al., 2010, Section 2.2).

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

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detected as a single event because they fell close to each other on the CCD and arrived during the same readout frame. Pile-up causes photometry to be underestimated and the spectrum to be hardened. We check for pile-up in every observation of a source by estimating the observed count rate in a $3 \times 3$ pixel detection cell centered on the source position. (The highest rate found in all observations of the source is reported by the source property RateIn3x3Cell.)

For each source extraction in which RateIn3x3Cell exceeded a threshold of 0.05 count/frame, we modeled pile-up using a Monte Carlo approach that reconstructs a pile-up-free spectrum from a piled ACIS observation (Broos et al., 2011). Table 4 lists those extractions; column (8) characterizes the inferred level of pile-up. For those sources, several entries in Table 3 are expected to be biased by pile-up effects (in an energy-dependent way). Users are warned that photometric quantities for piled-up sources should be used with caution; higher pile-up corrections and narrower bandpasses should evoke the most caution. Alternatively, we choose not to use the terms “pile-up fraction” or “pile-up percentage” because the ACIS community has several conflicting definitions for those terms; see Section 1.2 in “The Chandra ABC Guide to Pileup” ([http://cxc.harvard.edu/ciao/download/doc/pileup_ab.pdf](http://cxc.harvard.edu/ciao/download/doc/pileup_ab.pdf)).
provide pile-up corrected spectra for all source/ObsID entries in Table 4, as described below. Fitting those spectra will result in more meaningful source properties than possible from pile-up distorted photometry.

### 3.3. Archive of Reduced Data Products

The Zenodo data repository\(^{20}\) archives many MOXC2 reduced data products\(^{21}\) (Townsley & Broos 2017), including astrometrically aligned event lists and exposure maps, DS9 region files representing point source extraction apertures and PSF hooks, source photometry in 16 energy bands, reconstructed spectra for sources that suffer from photon pile-up (Section 3.2), lightcurve plots for the brighter sources, event lists and exposure maps with point sources masked, and smoothed images of diffuse emission (Section 4). For the piled sources in Table 4, we provide reconstructed spectra for each ObsID in which the source suffered from pile-up. The “README” file in the Zenodo archive describes the files there.

### 3.4. MOXC2 Sources in Published Chandra Catalogs

Many of the brighter X-ray point sources in MOXC2 also appear in the *Chandra* Source Catalog\(^{22}\) (Evans et al. 2010). Some may also have data available from the *XMM-Newton* mission’s EPIC camera; catalogs of *XMM* sources are available from the *XMM-Newton* Survey Science Centre.\(^{23}\) In crowded regions such as MSFRs, care should be taken in matching MOXC2 sources to *XMM* sources due to the mismatch in spatial resolution between the *Chandra* and *XMM* telescopes.

Several short archival *Chandra* observations in and around MSFRs were obtained by the snapshot survey Chasing the Identification of ASCA Galactic Objects; Anderson et al. 2014. We use these data sets in the MOXC2 mosaics, and the brighter X-ray sources in these fields are contained in the ChIcAGO catalog. Several examples are mentioned in the descriptions of individual MSFRs below.

We have one target (RCW 120) in common with SF\(\text{inNCs}^\) (Getman et al. 2017) and two targets (NGC 6334 and G333) for which a subset of MOXC2 ObsIDs were included in MOXC1; comparisons of these catalogs are mentioned briefly in the specific target descriptions of Section 4. A few other individual MOXC2 MSFRs have published *Chandra* point source catalogs. MOXC2 typically recovers all or most of these sources and goes on to find additional faint sources; again, details are given in Section 4.

### 4. X-Ray Characterizations of MOXC2 Targets

Following the format we established in MOXC1, we now provide short vignettes of each MSFR included in MOXC2, to

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\(^{20}\) https://zenodo.org

\(^{21}\) https://doi.org/10.5281/zenodo.1067749

\(^{22}\) http://cxc.cfa.harvard.edu/csc/

\(^{23}\) http://xmmssc.irap.omp.eu
illustrate the distribution of X-ray point sources in the Chandra mosaics and to give a qualitative sense of the diffuse X-ray emission present in and around these fields. We do not attempt comprehensive reviews of the literature, which is often vast and multi-generational for these famous targets; rather, we provide only the most cursory set of references, focusing on recent papers and X-ray studies. These references (and the papers they cite) provide a much better introduction to the MOXC2 MSFRs than space allows here. We also do not attempt extensive quantitative analysis either of the MSFR X-ray source populations or diffuse X-ray emission; such work is beyond the scope of MOXC2 and must await future efforts by ourselves and the wider star formation community.

For each target we show two basic figures (in celestial J2000 coordinates): the distribution of brighter X-ray sources (>5 net counts) on the exposure map of our ACIS mosaic (with ObsID numbers given in blue) and an adaptively smoothed image of unresolved X-ray emission presented in the context of mid-IR data. In the first of these, X-ray sources are represented as colored dots, with the color indicating the median energy of the extracted X-rays. The legend shows the number of sources plotted in each median energy range. The hardest sources were plotted last, so some softer sources may be covered by the symbols for harder sources. Fainter sources are not included because their spatial distribution is strongly dependent on Chandra sensitivity (their numbers necessarily fall off sharply with off-axis angle). The number of faint sources can be calculated as the total number of detected sources (noted on the figure below the target name) minus the numbers given in the legend. Since we have made great efforts to detect the faintest X-ray sources possible, most targets have well over half of their ACIS detections absent from these plots. They do, however, serve to indicate important clumps and clusters of X-ray sources that trace the structure of the MSFRs they sample. Often those groupings of X-ray sources are shown in more detail in further images that show soft and hard X-ray events in the context of unresolved X-ray emission or Spitzer/IRAC 8 µm structures.

The second basic figure shown for each target is a three-color image intended to place unresolved X-ray emission in the context of the cold ISM traced by mid-IR images from Spitzer or WISE. In many instances, we include zoomed panels of this three-color image to highlight particularly interesting regions, with more informative image scaling tailored specifically for the diffuse X-ray emission in those regions. For diffuse emission, we consider “total-band” to be 0.5–7 keV, not the 0.5–8 keV used for point source photometry, because the ACIS particle background24 rises sharply above 7 keV.

Since MSFRs are full of stars and all of our Chandra observations are too shallow to trace the complete initial mass function of a MSFR, we expect some of the unresolved X-ray emission (especially in cluster centers) to come from pre-MS stars. It is clear from these images, however, that we are teasing out faint, truly diffuse X-ray emission in these complexes, as demonstrated by the dramatic anticoincidence of the unresolved X-ray emission with extended IR structures. Thus, for convenience, we will refer to unresolved X-ray emission as “diffuse,” keeping in mind that this is simply shorthand for “a mix of unresolved point source emission and truly diffuse X-ray structures.”

As mentioned above, we additionally show the ACIS binned event data in two false-color images for selected regions of each target. These are often cluster centers or other interesting clumps of X-ray sources. For all such images, ACIS soft (0.5–2 keV) events are shown in red and hard (2–7 keV) events are shown in green; the binsize is one “sky pixel” (0′′5; since ACIS X-ray events have real-valued positions, an image can be made with whatever binsize is helpful to the eye). In the superposition of these two event images, pixels that contain both soft and hard events appear yellow. Point source extraction regions are outlined with blue polygons. Those polygons may come from different ObsIDs, so they do not all have the same default size and orientation. Superposed on the event images is a blue image; this is either the ACIS total-band diffuse emission or Spitzer/IRAC 8 µm emission.

Throughout this section, we occasionally note X-ray spectral fit parameters for massive stars or other bright X-ray sources of particular significance in MSFRs. Massive stars generate X-rays via a variety of emission mechanisms (e.g., Güdel & Nazé 2009). Individual massive stars emit soft X-rays (<1 keV) from shocks caused by velocity differences in their line-driven winds (see CCCP X-ray spectral fit examples in Gagné et al. 2011; Nazé et al. 2011). Magnetic massive stars can generate harder X-rays (up to a few keV) when their winds are channeled along magnetic field lines and collide (Babel & Montmerle 1997). In massive binaries, hard X-rays (several keV) can be generated when the powerful winds from the two massive stars collide; these “colliding-wind binaries” (CWBs) can be bright X-ray sources and have been studied extensively with XMM-Newton and Chandra (e.g., Rauw & Nazé 2016).

These X-ray spectral fits were performed with XSPEC (Arnaud 1996) usually employing the absorption model TBabs with solar abundances and the thermal plasma emission model apec; the model form used is TBabs*apec unless otherwise noted. Other bright X-ray sources are often collapsed objects with synchrotron X-ray emission; their X-ray spectra are fitted with absorbed power law models. The X-ray luminosities (LX) are intrinsic (absorption-corrected) and calculated for total-band (now 0.5–8 keV, the typical band used for ACIS point source fits in the literature). We intentionally do not give errors on fit parameters to emphasize that these are rough, preliminary characterizations of source spectra.

Since soft X-rays are readily absorbed by intervening material and such absorption may be strong (and spatially complex) in MSFRs, our estimates of X-ray luminosities are often lower limits. Especially in massive stars, soft X-ray plasma components are likely to be present but may be completely absorbed by heavy obscuration; thus they remain uncharacterized by our ACIS spectra. The same holds true for diffuse X-ray emission; its spatial complexity is probably due to a combination of absorption by intervening material and displacement of hot plasmas by colder ISM structures.

As described above, our analysis machinery uses image reconstruction to find candidate X-ray point sources. Regions of bright diffuse emission (e.g., PWNe or SNRs) can be erroneously over-reconstructed in this process, leading to spurious point sources in our catalogs. We have chosen to leave such suspicious point sources in place, as long as they satisfy all point source validity criteria, because PWNe or SNRs can certainly have real X-ray point sources superposed on them. We caution users of our catalog to be aware of this decision and to employ more sophisticated means (such as searching for multiwavelength

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24 http://cxc.cfa.harvard.edu/contrib/maxim/stowed/
Figure 1. NGC 6334. (a) ACIS exposure map with brighter ($\geq$5 net counts) ACIS point sources overlaid; colors denote median energy for each source. ObsID numbers and regions named in the text are shown in blue. (b) ACIS diffuse emission in the Spitzer context.
counterparts) to assess the validity of our sources that lie in close proximity to pulsars or in other regions of highly structured, bright diffuse X-ray emission.

4.1. NGC 6334

Using the example of the massive filamentary infrared dark cloud (IRDC) known as “Nessie,” Jackson et al. (2010) suggested that multiple star formation sites can form at regular intervals along a cylindrical IRDC via the “sausage instability.” This instability was originally described by Chandrasekhar and Fermi (1953), and is essentially the analog of Jeans collapse in a self-gravitating sphere, applied now to a self-gravitating fluid cylinder. The dominant path for the intense star formation that results in MSFRs is now recognized to be such massive molecular filaments (Goodman et al. 2014)—structures up to 100 pc long formed by supersonic flows that compress the gas of the ISM into a web of dense, cylindrical structures criss-crossing GMCs (André et al. 2014). These pressurized “ridges” are crucibles for creating MSFRs; material flows down the filaments, feeding hot cores and clumps that eventually collapse to become massive stars and star clusters (Tackenberg et al. 2014). Our closest example is the G352 GMC, a 90-pc-long massive filament made famous by Herschel (Russell et al. 2013). G352 hosts the two multi-MSFR complexes NGC 6357 and NGC 6334 (Persi & Tapia 2008); such complexes are known as “clusters of clusters” (e.g., Bastian et al. 2007; Elmegreen 2008). Each of these sports a string of MSFRs with multiple bubbles and degree-sized “bowl” filled with hot plasma (MOXC1); they are situated on opposite sides of G352’s main filament.

NGC 6334 is the best nearby example we have of the ongoing transfiguration of such a massive molecular filament into stars; it is thought to contain ~175 O–B3 stars (Russell et al. 2012) distributed among several MSFRs. It hosts a large number of H II regions of various sizes and evolutionary states, spread across >2° of the Galactic Plane (Russeil et al. 2016). Many of its most massive clusters line up along a dense molecular ridge with a complicated filament morphology and many subfilaments. In some of these subfilaments, densities are high enough that gravity should dominate the energetics and they should be collapsing to form stars (Russell et al. 2013). This is substantiated by a recent IR study (Willis et al. 2013) that identifies 2283 Class I and II young stellar objects in NGC 6334; these sources tend to cluster along the subfilaments and extend many parsecs beyond the main ridge. As shown in MOXC1 and earlier studies, the three ACIS pointings along the main ridge capture several collapsing subfilaments and add a large number of Class III (diskless) pre-MS stars to the census of young stars populating those regions (Ezoe et al. 2006; Feigelson et al. 2009; Broos et al. 2013).

Recent maser parallax measurements by the VLBA BeSSeL Survey (Wu et al. 2014) and VERA (Chibueze et al. 2014) both yield a distance of ~1.3 kpc for NGC 6334, which we adopt for MOXC2. Readers should note, however, that some recent papers (e.g., Russell et al. 2016; Tigé et al. 2017) use a distance of ~1.75 kpc.

NGC 6334 serves as a transition target for us, illustrating the changes in our ACIS data analysis code and procedures between the MOXC1 analysis (circa 2013) and the current analysis for MOXC2. The same three ObsIDs analyzed for MOXC1 are re-analyzed here, augmented by several surrounding archival ACIS-I and ACIS-S pointings and our recent Chandra Cycle 17 General Observer (GO) data on the western side of NGC 6334’s main filament, including the MSFR GM 24 (GM 1–24 in SIMBAD; Tapia & Persi 2008; Tapia et al. 2009).

Our final 1°4-wide ACIS mosaic is shown in Figure 1. Chandra typically characterizes diskless young stellar populations, both older pre-MS stars distributed across MSFRs and younger sources still embedded in their natal clouds. That generalization appears to hold true for NGC 6334; widely distributed X-ray sources are seen across the entire ACIS mosaic, extending far from the main ridge of MSFRs typically studied in NGC 6334.

The original ACIS pointings on the main ridge have been described at length (Ezoe et al. 2006; Feigelson et al. 2009) and were presented in MOXC1, so we do not discuss them further here, except to note that they are pervaded by diffuse X-ray emission (Figure 2). Comparing the MOXC1 and MOXC2 catalogs in this region (where the two epochs of analysis used the same data), we find that both recover the same brighter sources (>12 net counts) at all off-axis angles. For faint sources, the catalogs differ in several ways. Sometimes one analysis splits a group of counts into a close pair of sources while the other finds a single source. Sometimes faint sources were deemed valid in one analysis but not the other; this is especially true at large (>7') off-axis angles. These results are expected, given the strong interdependencies between faint candidate sources, the iterative nature of source validation, and the many decisions made, both algorithmic and by the analyst during visual reviews. Close examination of source positions shows that the inter-ObsID alignment is improved in MOXC2. Given this and the algorithmic improvements made over the years between MOXC1 and MOXC2, we recommend the use of the MOXC2 source list.

Figure 2. NGC 6334’s main ridge of MSFRs. Zoomed version of Figure 1(b) for the central clusters on the main star-forming ridge, now with the MIPS data omitted because they are largely saturated. This figure is included to emphasize the extensive diffuse X-ray emission associated with this famous star-forming ridge.
4.1. GUM 61

Continuing down the G352 molecular filament southwest of the main ridge in NGC 6334, we find deep archival ACIS data on the large H II region GUM 61 (Russel et al. 2016; Figure 3). This hosts a populous diffuse cluster, as shown by the large number of X-ray sources seen across the entire ACIS-I field in this pointing (Figure 1(a)).

At the center of the cluster (Figure 3), the piled ACIS source c1934 (CXOU J171946.16-360552.2) matches HD 319703A, a spectroscopic binary of type O7V(f) + O9.5V (Maíz Apellániz et al. 2016). A spectral fit to the pile-up corrected spectrum of c1934 (from ObsID 13436) requires two thermal plasma components, $TB_{\text{abs}} (apec1 + apec2)$, for an acceptable fit. This yields $N_H = 1.1 \times 10^{22} \text{cm}^{-2}$, $kT1 = 0.7 \text{keV}$, $kT2 = 1.9 \text{keV}$, and $L_X = 1.6 \times 10^{32} \text{erg s}^{-1}$. The hard thermal plasma component dominates the spectrum. In ObsID 12382, obtained 4 days after ObsID 13436, c1934 shows slightly different spectral parameters ($N_H = 1.4 \times 10^{22} \text{cm}^{-2}$, $kT1 = 0.6 \text{keV}$, $kT2 = 2.5 \text{keV}$) and is brighter, with $L_X = 2.0 \times 10^{32} \text{erg s}^{-1}$. The softer plasma component dominates the spectrum below 2 keV. A hard, variable X-ray spectrum and changing X-ray luminosity often indicate wind interactions in binary systems; this may be yet another CBW discovered by Chandra.

Nearby is HD 319703B, a visual binary of type O6V(f) (Sana et al. 2014), matching ACIS source c1800 (CXOU J171945.05-360547.0). It has 432 net counts and a median energy of 1.3 keV. The spectral fit yields $N_H = 1.4 \times 10^{22} \text{cm}^{-2}$, $kT = 0.5 \text{keV}$, and $L_X = 9 \times 10^{31} \text{erg s}^{-1}$. Source c1800 has four close neighbors in the ACIS data. We also detect HD 319703D, spectral type O9.5; Vn (Sana et al. 2014), as ACIS source c2162 (CXOU J171948.94-360602.8), with 98 net counts and a median energy of 1.4 keV.

For the spectral fit, we find $N_H = 1.9 \times 10^{22} \text{cm}^{-2}$, $kT = 0.6 \text{keV}$, and $L_X = 3 \times 10^{32} \text{erg s}^{-1}$.

There is prominent diffuse X-ray emission near these massive stars and at the southwest (open) edge of the IR bubble (Figure 3(a)), where Russell et al. (2016) note outflow in the kinematics of this region. This is probably a good example of diffuse X-ray emission tracing hot gas from massive star feedback in an H II region, flowing out of that region to enrich and heat the surrounding ISM. It might be compared to M17, a spectacular example of this phenomenon (Townesley et al. 2003, MOXC1).

4.1.2. Southwest Pointings

Extending the ACIS mosaic southwest along NGC 6334’s natal molecular filament past GUM 61, our ACIS pointing named G350.776+0.831 (ObsID 18081) captures a complex network of subfilaments (Figure 4(a)) and known clumps of pre-MS stars (Russell et al. 2013; Willis et al. 2013). It is centered on the base of a large “bowl” of bright 8 μm emission seen opening to the northwest in Figure 1(b); the main molecular filament forming NGC 6334’s backbone makes up the southern edge of this 30′-diameter structure. This pointing shows substantial shadowing or displacement of hot plasma in a large oval region at the base of the bowl, but other parts of the bowl contain diffuse X-ray emission, as does the large elongated cavity on the southern side of the main filament, opening from Gumi 61 to the southwest.

The ACIS mosaic continues down the main filament to the isolated, embedded IR cluster GM 24 (Figures 4(b) and (c)). This very young, midsized cluster (~250 $M_\odot$; Tapia et al. 2009) is ionized by an O8 star (Bik et al. 2006); it sits at the southern edge of the Spitzer bowl, separated from the cluster-of-clusters complex by more than 40′. GM 24 could have formed as a result of the bowl’s dynamical influence on NGC 6334’s main molecular filament. GM 24 appears to support a strong bipolar outflow that is carving cavities in the surrounding GMC (Tapia et al. 2009). ACIS finds a strong concentration of X-ray point sources coincident with GM 24, plus a large distributed population. Hot plasma clearly fills the
western bowl above the main filament; this pointing also captures the edge of the southwestern elongated cavity and again finds diffuse X-ray emission there.

The piled ACIS source GM24_c717 (CXOU J171701.53-362100.6), near the center of GM 24, has a reduced extraction aperture due to a close, faint neighbor (c715) to the northwest. The position for the O8 star from Bik et al. (2006) is 3″ north of GM24_c717, so it is not clear that this X-ray source is the counterpart of the O8 star. There is no X-ray source close to the O8 star’s position.

We fit GM24_c717’s pile-up corrected spectrum (from ObsID 18876) with the same simple spectral model used for other massive stars. Unlike the GUM 61 sources described
above, GM24_c717 has a very hard spectrum, with $N_H = 4 \times 10^{22}$ cm$^{-2}$, $kT = 9$ keV, and $L_X = 2 \times 10^{32}$ erg s$^{-1}$. Any additional soft thermal plasma component could easily be absorbed away by this high column, so the luminosity we report is a lower limit. In the second GM 24 data set taken 3 days later (ObsID 18082), the X-ray luminosity of GM24_c717 is lower by a factor of 20 but the spectrum remains very hard. Such extremely hard X-ray spectra and variability have certainly been seen in other young stars (e.g., W51 IRS2E in MOXC1 and two early-B stars in IRAS 20126+4104; Anderson et al. 2011), but this is still an exceptional source due to its high luminosity and extreme variability; it deserves further attention.

4.1.3. H II 351.2+0.5

East of GUM 61 lies another prominent H II region south of NGC 6334’s main ridge, called H II 351.2+0.5 by Russell et al. (2016). Comparatively few X-ray point sources are found in this part of our ACIS mosaic, even though it is captured by three ACIS pointings, because it is only observed far off-axis in each of these pointings (Figure 5(a)). This region does serve to illustrate the usefulness of including off-axis CCDs in our mosaics; diffuse X-ray emission is seen throughout this area. It appears at the center of H II 351.2+0.5 and at the bubble rim, perhaps indicating hot plasma flowing out its southeast side.

The brightest X-ray source in this part of the ACIS mosaic is c6709 (CXOU J172052.63-360420.6); it is the X-ray counterpart to the massive binary HD 156738 (Sana et al. 2014), spectral type O6III(f) (Sota et al. 2014), located near the center of H II 351.2+0.5. Source c6709 has 948 net counts and a median energy of 1.2 keV. As for ACIS source c1934 above, c6709 requires a two-temperature fit, with $T_{\text{abs}}(\text{apec}1 + \text{apec}2)$, although the plasmas are much softer here. Fit parameters are $N_H = 1.4 \times 10^{22}$ cm$^{-2}$, $kT1 = 0.2$ keV, $kT2 = 0.5$ keV, and $L_X = 5.5 \times 10^{32}$ erg s$^{-1}$. These soft plasmas are consistent with instability-driven wind shocks in the individual stars.

4.1.4. SNR G351.2+0.1

Two archival ACIS-S observations of SNR G351.2+0.1 are included in our mosaic, totaling ~53 ks exposure (Figure 5(b)). This composite mosaic sits to the southeast of NGC 6334 and was observed by Chandra to search for its neutron star and pulsar wind nebula; no clear detection was made. Radio observations show a 4$'$ x 6$'$ shell, flattened along the northern side, with a 16$''$ diameter central object (Becker & Helfand 1988), shown in Figure 5(b). Dubner et al. (1993) note that the flattened northern edge of the remnant may indicate that it is encountering dense molecular material that is slowing its expansion in this direction. Perhaps this is an indication that the SNR is associated with the G352 GMC, although the SNR distance is not well-determined.

There is no bright ACIS source that is clearly the counterpart of the central radio object. The wider field, however, shows a large number of X-ray sources concentrated in the vicinity of the SNR (Figure 1(a)). Perhaps these constitute another young cluster; this should be investigated at longer wavelengths. Excising those point sources leaves some faint, soft diffuse X-ray emission apparent in Figure 5(b); this may be the feeble X-ray signature of the SNR. A large region surrounding this faint diffuse emission is conspicuously lacking in diffuse X-rays (Figure 1(b)); cold material in the G352 GMC may be shadowing any hot plasma generated by the SNR or NGC 6334 there.

4.2. W75N

W75N is part of the great concentration of star formation in the Cygnus X North molecular cloud complex (Reipurth & Schneider 2008). It contains several UCHIIRs ionized by early-B stars (Shepherd et al. 2004) and exhibits complicated dynamics from multiple molecular outflows (Shepherd et al. 2003; Davis et al. 2007). Persi et al. (2006) find at least 25 cluster members based on their IR-excess; we find that several of these have X-ray counterparts. Kumar et al. (2007), also using near- and mid-IR data, find a distributed population of young stars across the region, tracing the molecular filaments.

The single ACIS observation of W75N (Figure 6) shows a concentration of hard sources near the aimpoint. ACIS source c202 (CXOU J203836.47+423733.7) appears to be the X-ray counterpart to VLA_3 (Bb), an UCHII with Lyman continuum flux consistent with ionization by a B1 star (Shepherd et al. 2004). Source c202 has only five counts, but its median energy is 6.7 keV and all five counts have energies >6 keV. The spectral fit gives $N_H \sim 3 \times 10^{22}$ cm$^{-2}$, $kT \sim 7$ keV, and $L_X \sim 8 \times 10^{30}$ erg s$^{-1}$, but the fit parameters are not well-constrained. This is just a rough characterization given the limited counts, but there is no doubt that this is an extreme X-ray source, exceptionally hard and highly obscured; such emission is not expected from a single B1 star.

Diffuse X-ray emission is seen on the west side of W75N despite the high obscuration and short (<30 ks) observation. It is brightest in the southwest corner of the ACIS-I image, outside the large dark arc in the Spitzer images that runs vertically at R.A. ~ 20:38:15. In Figure 6(b) we have scaled the ACIS image to show the fainter diffuse emission surrounding the central cluster and filling apparent cavities in the Spitzer emission. Bright diffuse emission is seen far off-axis on the ACIS-S CCDs; this may be associated with the wider Cygnus X star-forming complex. The central region also shows extensive diffuse X-ray emission (Figure 6(c) extending all the way down to the cluster center (Figure 6(d))).
Figure 6. W75N. (a) ACIS exposure map with brighter (>5 net counts) ACIS point sources overlaid; colors denote median energy for each source. The ObsID number is shown in blue. (b) ACIS diffuse emission in the Spitzer context. (c) Zoom of (b) showing the center of W75N and surrounding diffuse X-ray emission. Green rings are artifacts due to MIPS saturation. Red polygons show extraction regions for ACIS sources. (d) ACIS event data and diffuse emission at the center of W75N. The hard X-ray counterpart to the radio UCHIIIR VLA_3 (Bb) is marked.
4.3. RCW 120

The innocuous visual H II region RCW 120 was catapulted to fame by the Spitzer GLIMPSE survey (Churchwell et al. 2006; Zavagno et al. 2007), which revealed it to be a canonical example of a single, dusty bubble hosting massive star formation (Deharveng & Zavagno 2008). It has since
received much attention at long wavelengths, especially from 
*Herschel*, which detects several very young stars forming in
dense, cold material around the edge of the bubble (Zavagno et al. 2010; Figueira et al. 2017). The bubble appears to be
ruptured at its northern edge and is leaking photons at
several points around its rim (Zavagno et al. 2007; Deharveng et al. 2009; Anderson et al. 2015). Such “leaky” H II regions may demonstrate that ionizing radiation from
massive stars extends well beyond classical H II region
boundaries, influencing star formation over a much wider area (Zavagno et al. 2007).

The *Chandra* observations of RCW 120 were presented in the
SFiNCs (Star Formation in Nearby Clouds) survey (Getman et al. 2017). SFiNCs studies X-ray point sources in *Chandra*
observations of nearby, typically lower-mass star-forming regions, so this is the only target that MOXC2 and SFiNCs
have in common. We included RCW 120 in MOXC2 (Figure 7), primarily to facilitate study of the diffuse X-ray
emission in this iconic *Spitzer* bubble, but this common target
does give us the opportunity to compare our point source
catalog with that of SFiNCs. This is a useful check, since the
two projects use similar (but not identical) analysis methods.
The SFiNCs analysis is a few years older than the MOXC2
analysis.

In MOXC2, we find 999 X-ray sources in the main ACIS-I
array observations of RCW 120 itself; SFiNCs found 678 X-ray sources in the same data. Matching the two catalogs, we find 604 formal matches, 395 MOXC2 sources not
matched, and 74 SFiNCs sources not matched. One goal of
MOXC2 is to detect fainter sources; thus we expect to have
many unmatched MOXC2 sources. In several cases, either
MOXC2 or SFiNCs found a pair of sources while the other
catalog found a single source. Many of the unmatched
sources (in both catalogs) are far off-axis and faint. For such
sources, the source validity metric can be sensitive to slight
source position differences, algorithmic changes to the
background calculation, and differences in the catalogs
(nearby sources affect the background calculation).

Because source candidates are pruned by a simple threshold
on this noisy validity metric, two reductions of the same
data will not produce identical catalogs near the detection
limit.

For our ACIS mosaic of the RCW 120 region (Figure 7(a)),
we included neighboring observations of SNRs to get a wider
context for RCW 120’s diffuse X-ray emission: ObsID 6721
on CTB 37A (Pannuti et al. 2014) and ObsID 6692 on
CTB 37B (Aharonian et al. 2008). Large masks were applied
to these SNRs to keep them from dominating our smoothed
diffuse X-ray image of the mosaic (Figure 7(b)). For completeness, we include the point sources we found in these
fields in our X-ray source list for RCW 120.

Extensive diffuse X-ray emission is seen in RCW 120
(Figure 7(c)). It appears to trace hot plasma through a breach in
the northeast side of the bubble and out into the surrounding ISM. The whole bubble apparently shadows background
diffuse X-ray emission.

Clumps of X-ray point sources are shown in Figures
7(d)–(f). Panels (d) and (f) show groups of sources on the
bubble rim; panel (e) shows the central cluster. The main
ionizing source for RCW 120 is LSS 3959 (CD-28 11636 in

25 The source validity metric is a p-value for the no-source (“null”) hypothesis
(i.e., that all extracted counts are background).

SIMBAD), an O8V star (Zavagno et al. 2007). Its X-ray
counterpart is ACIS source c1121 (CXOU J171220.84-
382930.3, prominent in Figure 7(e)), with 682 net counts and
a median energy of 1.4 keV. The spectral fit requires two
thermal plasma components, \( \text{TBabs}(apec1 + apec2) \); the softer
plasma dominates the spectrum. Parameters are \( N_H = 1.4 \times
10^{22} \text{ cm}^{-2} \), \( kT1 = 0.5 \text{ keV}, kT2 = 2 \text{ keV}, \) and \( L_X = 1.4 \times
10^{32} \text{ erg s}^{-1} \). The harder plasma component is not expected
from a single late-O star and is perhaps suggesting magnetic
activity or binarity.

4.4. IRAS 20126+4104

Like W75N described above, the IRAS 20126+4104
MSFR is another component of the extensive and diverse
star formation complex in Cygnus (Reipurth & Schneider 2008). Its distance is well-determined by maser parallax
(Moscadelli et al. 2011). IRAS 20126+4104 itself is a famous
massive young stellar object (MYSO) with a prominent
molecular outflow that has long been the subject of
radio study (e.g., Cesaroni et al. 2005). Cesaroni et al. (2014)
have imaged this MYSO at 1.4 mm, finding a distorted disk and associated jet rotating around a proto-B star.
De Buizer et al. (2017) presents a recent SOFIA
detection of the MYSO; he finds that SOFIA and *Herschel*
data show elongation in the direction of the outflow. The
*Chandra* data were first presented by Anderson et al. (2011),
with details on the X-ray counterparts to radio sources I20S
and I20Var (Hofner et al. 2007). These authors note the
detection of 150 point sources in the *Chandra* data and
suggest that IRAS 20126+4104 is surrounded by a young
stellar cluster. Those sources are cataloged in a recent paper
by the same group (Montes et al. 2015), who determine that
~80 of the 150 X-ray sources are likely members of this
MSFR. They find that the surface density of X-ray sources
peaks on the MYSO; thus IRAS 20126+4104 is a young
cluster forming an early-B star at its center.

Our analysis of the same *Chandra* data found more faint point
sources, as designed (Figure 8); we recovered all 150 X-ray sources reported by Montes et al. (2015). Many X-ray sources
near the center of the cluster resolve into close pairs in our
analysis (Figure 8(d)). Anderson et al. (2011) described
the exceptional X-ray spectra of the ACIS counterparts to I20S
and I20Var; we find similar spectral fit results. They concluded
that I20S was an early-B MYSO and I20Var a likely IMS. We
concur with these findings and emphasize their implications:
in some cases, stars that will become X-ray-quiet on the main
sequence are extraordinarily hard, bright X-ray emitters in their
youth, perhaps due to magnetic activity similar to that found
in lower-mass pre-MS stars (Povich et al. 2011; Gregory et al. 2016).
We find prominent diffuse X-ray emission in this ACIS
field (Figures 8(b)–(d)), with a bright ridge running the
length of the ACIS-I array to the east of the cluster
(Figure 8(b)). The image center shows an arc of X-ray
emission just to the east of the large pillar that hosts the
embedded cluster (Figure 8(c)); between this and the eastern
ridge is an absence of diffuse X-rays coincident with faint
WISE 22 μm emission. This may be material shadowing the
diffuse X-rays. Faint diffuse X-ray emission pervades
the pillar as far west as the central cluster (Figure 8(d));
then drops off sharply. The western side of the ACIS-I
field shows a complex mix of fainter diffuse X-ray emission
anticoincident with bright WISE structures. This fades
to only minimal diffuse X-ray emission on the off-axis ACIS-S CCDs. Again, shadowing or displacement of hot gas is likely here.

4.5. W31N

The vicinity of the famous giant H II region W31 has several Chandra/ACIS observations of a variety of targets at a wide range of distances. As for other MOXC2 targets, we have combined them into a wide-field mosaic (Figures 9(a) and (b)) to sample the X-ray point source populations and diffuse emission present in large Galactic Plane fields.

Deharveng et al. (2015) showed that the northern component of the W31 complex (W31N, which they call G010.32-0.15) is actually a foreground MSFR unassociated with the other major MSFRs along this sightline, at a distance of just 1.75 kpc. W31N (G10.3-0.1) is a bipolar H II region ionized by an O5–O6 star (Bik et al. 2005) and containing an IR cluster; it is
triggering a menagerie of second-generation massive stars and their UCHIIRs in the dense filament at its waist (Deharveng et al. 2015b; Dewangan et al. 2015).

At this modest distance, it makes a rich Chandra target; we find >50 X-ray point sources in the central cluster and 490 sources across the ACIS-I field centered on W31N. As demonstrated below, with these data we can study both the first-generation ionizing cluster and the onset of X-ray emission in massive stars just formed. Figure 9(c) shows that W31N also contains diffuse X-ray emission and strongly shadows (or displaces) the diffuse emission seen in the wider W31 field.

The original 6.5 ks ACIS-S observation (ObsID 10518) of W31N detected the ionizing O5 star (source ChI J180857-2004_2 in Anderson et al. 2014); these authors suggest that it could be a CWB. In our data (Figure 9(d)), this is source c1345 (CXOU J180859.12-200508.4), with 553 net counts and a median energy of 3.3 keV. A spectral fit gives \( N_H = 4.9 \times 10^{22} \, \text{cm}^{-2} \), \( kT = 3.8 \, \text{keV} \), and \( L_X = 2.4 \times 10^{32} \, \text{erg s}^{-1} \). Once again, this high column could be hiding an additional soft plasma component, so this luminosity is a lower limit. We concur with Anderson et al. (2014); this hard spectrum suggests a CWB.

Our source c1447 (CXOU J180901.48-200507.5) is the MYSO (YSO #4) in clump C2 of Deharveng et al. (2015). It has 43 net counts, a median energy of 4.6 keV, and is variable; fit parameters are \( N_H = 21 \times 10^{22} \, \text{cm}^{-2} \), \( kT = 5.5 \, \text{keV} \), and \( L_X = 5 \times 10^{31} \, \text{erg s}^{-1} \). This extremely high column explains the high median energy. The hard thermal plasma and variability demonstrate that dramatic X-ray

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**Figure 9.** W31. (a) ACIS exposure map with brighter (>5 net counts) ACIS point sources overlaid; colors denote median energy for each source. ObsID numbers and regions named in the text are shown in blue. (b) A wide-field ACIS mosaic of the W31 region, featuring ACIS diffuse emission in the Spitzer context. A region around the bright X-ray source SGR 1806-20 has been masked so that fainter diffuse X-ray emission across the field can be displayed. (c) Zoomed version of (b) for the nearby MSFR W31N. (d) ACIS event data on W31N. For context, Spitzer/IRAC 8 μm emission is shown in blue. (e) Zoomed version of (b) for the GLIMPSE bubble CN139 at the southeast corner of our W31 ACIS mosaic.
emission turns on early in the formation process of at least some massive stars.

Near the center of our ACIS mosaic of the W31 complex (Figure 9(b)), the conspicuous MSFR not yet observed by Chandra is G10.2-0.3, a giant HII region at a distance of 3.4 kpc (Blum et al. 2001). It contains four O stars and four MYSOs in a very young (0.6 Myr) cluster (Furness et al. 2010), several UCHIIRs (Ghosh et al. 1989), and XMM source detections (Nebot Gómez–Morán et al. 2015); it would make an excellent Chandra target. Southwest of G10.2-0.3, our mosaic includes the piled-up soft gamma repeater SGR 1806-20; we have masked its bright X-ray halo of dust-scattered light (Kaplan et al. 2002) in our image of diffuse X-ray emission.

At the southeast corner of our ACIS mosaic, we have included a 9.9 ks ACIS-I observation (ObsID 10713) of the radio-bright SNR G9.95-0.81 (Brogan et al. 2006). This field also includes the large GLIMPSE bubble CN139, with a near kinematic distance of 4.3 kpc (Churchwell et al. 2007; Watson et al. 2009). Quite surprisingly (given the short observation), Figure 9(e) clearly shows diffuse X-ray emission coincident with this bubble, somewhat offset to the northwest from the center of the radio SNR. Spectral analysis to determine the absorbing column to this X-ray emission should help determine whether it is really associated with the bubble.

Through further serendipity, the globular cluster 2MASS GC02 is captured far off-axis on the S3 CCD in ObsID 10713, visible (by zooming) at the bottom of the Spitzer/IRAC 8 μm image in Figure 9(b). ACIS source c2200 (CXOU J180936.55-204645.1) is centered on 2MASS GC02. It has 38 net counts and a median energy of 4.0 keV. It is most likely a composite of emission from multiple members of the globular cluster, but its properties might help to establish the feasibility for a longer ACIS observation of this target.

4.6. IRAS 19410+2336 and NGC 6823

Starting with a 20 ks observation of the MSFR IRAS 19410+2336, we built a 4-pointing ACIS-S mosaic of overlapping short observations from archival Chandra data in this region (Figures 10(a) and (b)). This is the shallowest mosaic in MOXC2 (just 2–20 ks). This mosaic also features a second MSFR, NGC 6823, presumably not associated with IRAS 19410+2336, although at a similar distance. This is the first of three examples of ACIS mosaics in MOXC2 that feature two unrelated MSFRs that just happen to be projected near each other on the sky.

IRAS 19410+2336 is a young, compact, embedded MSFR made up of two main star-forming clumps (Beuther et al. 2002; Rodón et al. 2012), both exhibiting masers (Beuther et al. 2002) and a large number of outflows (Beuther et al. 2003). The Chandra observation of IRAS 19410+2336 (ObsID 1868, 20 ks) was analyzed by Beuther et al. (2002), who tabulated 13 X-ray sources in the vicinity of the two clumps (Figure 10(d)). They find these sources to have hard X-ray spectra and to be heavily obscured, with fairly high intrinsic luminosities. They conclude that the X-ray sources are mainly IMPS; as noted above, subsequent work has confirmed that such sources can be strong X-ray emitters (Povich et al. 2011; Gregory et al. 2016).

Beuther et al. (2002) included the full 20 ks exposure in their analysis; our standard processing of this data set leaves just 8.7 ks of usable data on the aimpoint CCD S3 and on S1, the other backside-illuminated device, due to space weather resulting in high backgrounds for these chips. The ACIS frontside-illuminated devices in operation for this observation (I2, I3, S2, and S4) were unaffected by these background flares, so they retain the full integration time in our analysis. Unfortunately, the two main embedded clumps in IRAS 19410+2336 are imaged on CCD S3, so we report source detections in only 8.7 ks of data for these clumps. As we will see below, this is comparable to the ACIS integration time we have on the second MSFR imaged in this multi-pointing ACIS-S mosaic, NGC 6823.

As shown in Figures 10(c) and (d), we find X-ray sources in the same regions as Beuther et al. (2002), although not always the same sources. The southern clump is well-populated with X-ray sources, but the northern one is not; rather, a second group of X-ray sources sits to the east of the northern clump. Diffuse X-ray emission appears between the two groups of X-ray sources.

About 2′ south of IRAS 19410+2336 we find the other MSFR in our mosaic, NGC 6823 (Prato et al. 2008), captured on two short ACIS-S observations (Figure 10(e)). It features a tight grouping of massive stars at its center (Shi & Hu 1999; Ríos et al. 2012), with pre-MS stars distributed out to the cluster radius of 16.2′ (Kharchenko et al. 2005). Its earliest star is HDE 344784 A, with a spectral type of O6.5 V((f)(f)) (Haislip et al. 2015). Anderson et al. (2014) detect its X-ray counterpart as their source ChI J194310+2318_5. In our analysis, this is Chandra source c228 (CXOU J194310.96+231745.5), with 72 net counts and a median energy of 1.1 keV. Our simple thermal plasma fit yields $N_H = 9.0 \times 10^{22}$ cm$^{-2}$, $kT = 0.6$ keV, and $L_X = 1.9 \times 10^{32}$ erg s$^{-1}$.

Anderson et al. (2014) list several other X-ray sources in this region; we also find many other sources. Despite having just 7.9 ks total integration on this target and with the cluster center placed 8′ off-axis on the 6 ks ObsID, ACIS still clearly detects this MSFR. Several of our X-ray sources are counterparts to young stellar objects tabulated in Ríos et al. (2012).

In the fourth pointing of this mosaic (ObsID 8164, 2.7 ks), we have two sources at the aimpoint: the piled-up source c19 (CXOU J194154.60+225112.3) and its close neighbor c20 (CXOU J194154.60+225112.8). Due to crowding, extraction apertures are reduced to 45% for c19 (25 net counts, median energy 3.3 keV) and just 36% for c20 (10 net counts, median energy 2.4 keV). With so few counts, we cannot correct c19 for pile-up. Rough spectral fits to these sources show them both to be very hard (kT $\sim$ 10 keV) but with very different absorbing columns and absorption-corrected total-band fluxes: $N_H = 4 \times 10^{22}$ cm$^{-2}$, $F_X \sim 8 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ for c19, and $N_H = 1 \times 10^{22}$ cm$^{-2}$, $F_X \sim 2 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ for c20. Anderson et al. (2014) find a single X-ray source (ChI J194152+2251_2) at this location (a blend of our c19 and c20), using this same data set; they fit it with a power law with $N_H = 0.9 \times 10^{22}$ cm$^{-2}$, slope $\Gamma \sim 0.4$, and absorption-corrected total-band flux $F_X \sim 7 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. They noted that the near-IR image of this source appears extended, consistent with a blend of sources.

Despite the very short integration times, diffuse X-ray emission is seen throughout this mosaic. It is brightest around NGC 6823 (Figure 10(e)), likely indicating a mix of unresolved pre-MS stars in the cluster and perhaps hot plasma from the winds of the O6 star. We see highly structured diffuse emission suffusing the
deeply embedded IRAS 19410+2336 (Figure 10(d)) and pervading the surrounding field (Figure 10(c)). The wider field contains SNR G59.5+0.1 (Xu & Wang 2012), which may also be contributing to diffuse X-ray emission in our mosaic.

4.7. W42 and RSGC1

In a recent Chandra GO+GTO program, we targeted the newly formed MSFRs W42 and W33, both offering rich samples of very young (<0.2 Myr) massive stars ionizing UCHIIRs, to study the emergence of X-ray emission in these objects and their influence on the early evolution of MSFRs. At the same time we explored two of the Galaxy’s extremely rare YMCs, with >10^5 M_☉ (Portegies Zwart et al. 2010), Red Supergiant Cluster 1 (RSGC1), age 10 Myr (Froebrich & Scholz 2013), and CI 1813-178, age 4.5 Myr (Messineo et al. 2011). YMCs persist for >10 Myr because of their extraordinarily large masses; they allow us to explore changes in X-ray emission from massive stars as they approach the ends of their lives, along with the neutron stars and SNRs that they leave behind.

Here our ACIS-I mosaic (Figure 11) captures both the nearby MSFR W42 (Blum et al. 2000) and the unrelated background YMC RSGC1 (Figer et al. 2006), along with two pulsars and their PWNe (Gotthelf & Halpern 2008). We
recover all X-ray sources tabulated by Gotthelf & Halpern (2008). We find a dense cluster of X-ray sources at the center of W42 (Figure 11(c)).

W42 hosts at least 4 UCHIIRs (Urquhart et al. 2013) and contains more than 500 candidate young stellar objects based on IR-excesses (Dewangan et al. 2015a). The brightest near-IR source, W42 No. 1, is an O5–O6 star (Blum et al. 2000). W42’s edge-on orientation illustrates the connection between molecular filaments and MSFRs: part of a massive filament has collapsed to form the MSFR that is now blowing a bipolar bubble normal to the filament’s long axis (Deharveng et al. 2010; Dewangan et al. 2015a). We find few X-ray sources along this filament south of the W42 cluster.

The bright yellow X-ray source slightly northeast of field center in Figure 11(c) is c1575 (CXOU J183815.27-064758.8), the counterpart to W42 No. 1 (Blum et al. 2000). It has 148 net counts and a median energy of 2.4 keV; the spectral fit gives $N_T = 2.3 \times 10^{12} \text{ cm}^{-2}$, $kT = 3.3 \text{ keV}$, and $L_X = 5.5 \times 10^{31} \text{ erg s}^{-1}$. Again this thermal plasma temperature is too hard for a single mid-O star, although the luminosity is modest compared to many CWBs. Alternatively, the W42 complex may be more distant than the 2.2 kpc (Blum et al. 2000) we have assumed; Dewangan et al. (2015a) use a distance of 3.8 kpc. That distance increases the X-ray luminosity of source c1575 to $L_X = 1.6 \times 10^{32} \text{ erg s}^{-1}$.

RSGC1 (Figer et al. 2006) is a 10 Myr old obscured cluster (Davies et al. 2008; Froebrich & Scholz 2013), the fifth most massive Galactic YMC known (Richards et al. 2012). It has >200 massive stars, far more than the other known RSGCs (Froebrich & Scholz 2013), that form a compact cluster. The X-ray-bright pulsar AX J1838.0-0655 is thought to be a member of RSG1 (Gotthelf & Halpern 2008). Despite almost 74 ks of ACIS-I integration, we still do not detect any of the red supergiants in RSGC1 (Table 1 in Figer et al. 2006). There are many X-ray sources in this region of the mosaic, however, and several are quite hard. These highly absorbed sources may well be members of RSGC1.

Gotthelf and Halpern (2008) analyzed ObsID 6719 and noted that their soft X-ray source #12 is the high-proper-motion spectroscopic binary HD 171999. Our source c747 (CXOU J183758.77-064822.2) is their source #12. Nearby in our data is the similarly soft X-ray source c738 (CXOU J183758.67-064826.0). ObsID 16673 was obtained 9.5 years after ObsID 6719. Using SIMBAD proper motions for HD 171999, we calculate that this source should have moved about $-1''$2 in R.A., $-3''$8 in decl., in the 9.5 years between ACIS observations. Separations between c747 and c738 are about $-1''$5 in R.A., $-3''$8 in decl. Thus we conclude that our sources c747 and c738 are in fact the same X-ray source, the counterpart to HD 171999.

Diffuse X-ray emission around the pulsars AX J1838.0-0655 and AX J1837.3-0652 (Gotthelf & Halpern 2008) extends far beyond the brightest regions that we masked and dominates our ACIS mosaic of this field (Figure 11(b)). The bright PWN around pulsar AX J1838.0-0655 (our piled source c898) may have been over-reconstructed into point sources by our machinery; thus the six sources surrounding c898 may be spurious.

Fainter X-ray emission pervades much of the wider field, filling bubbles and voids in the Spitzer images. The brightest unresolved emission at the center of the W42 cluster (Figure 11(c)) undoubtedly includes a substantial contribution from faint cluster members; spectral analysis will be required to establish if any of this emission is truly diffuse.

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**Figure 11.** W42 and RSGC1. (a) ACIS exposure map with brighter (>5 net counts) ACIS point sources overlaid; colors denote median energy for each source. ObsID numbers and regions named in the text are shown in blue. (b) ACIS diffuse emission in the Spitzer context. The two pulsars in the field, AX J1838.0-0655 and AX J1837.3-0652 (Gotthelf & Halpern 2008), along with the brightest parts of their associated diffuse X-ray emission, have been masked so that fainter diffuse X-ray emission across the field can be displayed. (c) ACIS event data and diffuse emission at the center of W42.
The other targets in our recent GO program to study MSFRs at a range of ages were the very young W33 complex and the older, more distant YMC Cl 1813-178. As we found in the ACIS mosaic of W42 and RSGC1, here again we have a superposition of unrelated MSFRs separated by just a few arcminutes on the sky (Figure 12). In this case, Cl 1813-178 is so big and so well-populated with X-ray sources that it will be a challenge to assign membership in the part of the field where it overlaps with the foreground W33 complex.

The W33 MSFR consists of a chain of very young stellar clumps and sparse clusters. It appears that these clusters formed separately and nearly simultaneously (Beck et al. 1998); this may indicate that they formed at sausage-instability density enhancements along a massive molecular filament (Chandrasekhar & Fermi 1953; Jackson et al. 2010). The distance to W33 has recently been firmly established at 2.4 kpc via maser trigonometric parallax (Immer et al. 2013).

The ACIS-I aimpoint for our study of W33 was centered on W33 Main (Figure 13), which contains at least five mid-O stars (Beck et al. 1998) ionizing at least three distinct UCHIIRs, separated by dense material. We find a clear concentration of X-ray sources consistent with the cluster position as given by Immer et al. (2014) (Figure 13(b)), but no counterparts to the infrared sources IRS1, IRS2, or IRS3 from Dyck & Simon (1977), using SIMBAD positions.

W33A, a deeply embedded MSFR that features a well-studied MYSO (Davies et al. 2010), is captured at the northeast corner of the ACIS-I field. W33A may be forming due to the intersection of two massive molecular filaments (Galván-Madrid et al. 2010). We find five faint X-ray sources in a
clump at the location of W33A; all have median energies above 3 keV, indicating that they are highly obscured. If these sources are associated with star formation in W33A, they indicate either that X-ray emission turns on very early in the star formation process or that W33A has experienced multiple epochs of star formation, with today’s MYSO and dusty cores representing current and future star formation, while the X-ray sources represent an older population.

The ACIS data cover four more clusters associated with H II regions across the W33 complex: radio region W33B and IR clusters cl1, cl2, and Mercer 1 (Messineo et al. 2011). While all of these regions contain X-ray sources, none of them shows a clear central concentration indicative of an X-ray clump, as we saw in W33 Main and W33A.

The monolithic YMC Cl 1813-178 was discovered serendipitously (Messineo et al. 2008), just ~13’ west of W33 Main, but Messineo et al. (2011) estimate that it is much more distant (3.8–4.8 kpc) and hence unrelated to W33. Cl 1813-178 is one of fewer than 20 YMCs known in the Milky Way (Clark et al. 2013), with a mass of $10^4 M_\odot$ and many known massive stars (Messineo et al. 2011).

Helfand et al. (2007) analyzed the original 30 ks ACIS-I observation of this field (which targeted SNR G12.82-0.02) and cataloged 75 X-ray sources; we recover all of those sources in our analysis. Our combined (ACIS GTO + archival) 59 ks Chandra data set provides a wealth of candidate members of Cl 1813-178 (Figure 14), with 572 X-ray sources within the reported cluster radius of 3.5 (Messineo et al. 2011) and hundreds more beyond that.

We have X-ray counterparts to at least 16 of the 25 massive stars listed in Messineo et al.’s (2011) Table 1. They find two Wolf-Rayet (WR) stars in this cluster: their #4 and #7, both of type WN7. The first of these, #4, is our source c807 (CXOU J181314.20-175343.4), with 348 net counts and a
median energy of 3.6 keV; a spectral fit gives $N_H = 8 \times 10^{22} \text{cm}^{-2}$, $kT = 2.8 \text{ keV}$, and $L_X = 1.2 \times 10^{33} \text{erg s}^{-1}$. The second of these, #7, is our source c1281 (CXOU J181322.48-175350.2), with 68 net counts and a median energy of 2.8 keV. It is crowded with the faint source c1286 (CXOU J181322.56-175350.1), with 6 net counts and median energy 3.7 keV. A spectral fit to c1286 gives $N_H = 4 \times 10^{22} \text{cm}^{-2}$, $kT = 2.6 \text{ keV}$, and $L_X = 1.3 \times 10^{32} \text{erg s}^{-1}$. Based on the high thermal plasma temperatures and X-ray luminosities for these WR stars, we concur with Messineo et al. that they are likely CWBs.

We also fit the X-ray spectrum of Messineo et al. (2011) source #5, which they find to be a late-O star but with an unusually hard X-ray spectrum. This is our source c1346 (CXOU J181323.71-175040.5), with 265 net counts and a median energy of 3.0 keV; fit parameters are $N_H = 2.0 \times 10^{22} \text{cm}^{-2}$, $kT > 10 \text{ keV}$, and $L_X = 3.5 \times 10^{32} \text{erg s}^{-1}$. This spectrum is equally well fit by a power law ($TBabs \text{ pow}$ in XSPEC) with $N_H = 2.0 \times 10^{22} \text{cm}^{-2}$, slope $\Gamma = 1.5$, and $L_X = 3.6 \times 10^{32} \text{erg s}^{-1}$. As Messineo et al. suggest, this source may be another CWB. Its spectrum is so hard that it might be compared to that found for source I20S in IRAS 20126+4104 (Anderson et al. 2011).

Our ACIS mosaic reaches approximately the same sensitivity in both W33 and Cl 1813-178; W33 is closer but more obscured. As shown in all figures in this section, diffuse X-ray emission pervades the entire W33 mosaic. As we saw in our W42 mosaic, the brightest diffuse emission here is associated with the PWN around a pulsar (PSR J1813-1749) and its SNR (G12.82-0.02; Funk et al. 2007; Hellfand et al. 2007; Gotthelf & Halpern 2009). Some of our cataloged point sources that are superposed on this bright diffuse emission could be artifacts of image reconstruction; identifying counterparts to these X-ray sources at longer wavelengths is the best way to set aside such a concern. Fainter diffuse emission extends to the west across the entire Cl 1813-178 ACIS pointing. It appears at the W33 Main and Cl 1813-178 cluster centers and around the edges of the W33 ACIS-I field. It is faint but present on the easternmost ACIS-S CCD. The W33 MSFR probably shadows background diffuse emission across most of the W33 pointing.

4.9. NGC 7538

NGC 7538 is a clumpy Outer Galaxy MSFR, made up of several separate star-forming sites with a range of ages (McCaughean et al. 1991; Balog et al. 2004; Ojha et al. 2004), similar to W33. It hosts the O3V star IRS6 and the O9V star IRS5 (Puga et al. 2010), along with a variety of MYSOs that are well-studied in the radio (e.g., Beuther et al. 2017).

The Chandra data were analyzed recently as part of two multiwavelength studies (Mallick et al. 2014; Sharma et al. 2017), finding 182 and 190 X-ray point sources respectively, but neither of these papers gives full catalogs for their Chandra sources. Mallick et al. tabulate 27 X-ray sources with NIR counterparts in the IRS1–3 and IRS9 regions; they provide some X-ray properties for that subset of their X-ray detections. We recover all of these sources in our analysis and go on to find almost 500 X-ray sources and diffuse X-ray emission in this single 30 ks ACIS-I observation (Figures 15(a) and (b)).

In fact we find clumps of X-ray sources associated with all the well-known star-forming regions in NGC 7538: IRS1–3, IRS4–8, IRS9, IRS11/NGC 7538S, and the globules described by Sharma et al. (2017). ACIS images of most of these regions are presented in Figures 15(c)–(f); the IRS9 region is omitted because it has few X-ray sources and the IRAC 8 μm image is dominated by the single bright source IRS9 itself. Sharma et al. (2017) give short summaries of these star-forming regions; they all harbor massive stars or MYSOs, many ionizing various types of H II regions. Here we briefly describe X-ray counterparts to the famous IRS sources.

IRS1–3 (Figure 15(c)). We find many X-ray sources in this young MSFR. Chandra source c343 (CXOU J231345.32 +612810.9) is the counterpart to the MYSO IRS1; it has just five X-ray events but all have energies >3 keV, with a median energy of 4.4 keV. This indicates that the X-ray source is highly obscured, as expected for this massive protostar. Chandra source c351 (CXOU J231345.47+612820.1) is the counterpart to IRS2, an O9.5V star; its eight counts have a median energy of 1.6 keV. IRS3 has no X-ray counterpart in our data.

IRS4–8 (Figure 15(d)). This is the main star-forming complex in NGC 7538; it is well-populated with X-ray sources. Chandra source cc228 (CXOU J231330.22+613010.7) is the counterpart to the O9V star IRS5, with nine counts and a median energy of 1.4 keV, similar to IRS2. Chandra source c222 (CXOU J231334.40+613014.6) is the counterpart to the O3V star IRS6, with 400 counts and a median energy of 1.4 keV. A spectral fit yields $N_H = 1.7 \times 10^{22} \text{cm}^{-2}$, $kT = 0.8 \text{ keV}$, and $L_X = 8 \times 10^{31} \text{erg s}^{-1}$. Sources IRS4, IRS7, and IRS8 have no X-ray counterparts.

IRS9. The faint Chandra source c460 (CXOU J231401.78+612718.8) is the counterpart to the MYSO IRS9. It has just eight counts and an extreme median energy of 5.0 keV; event energies span the wide range of 1.5–7.5 keV. Sandell et al. (2005) find multiple outflows in this region, suggesting an embedded cluster rather than a single MYSO, but we find just a few X-ray sources here.

IRS11/NGC 7538S (Figure 15(e)). Chandra source c322 (CXOU J231343.92+612657.6) may be a match to the MYSO IRS11. It has 17 counts and a median energy of 4.0 keV, with event energies ranging over 2.6–5.0 keV. The spectral fit is not well-constrained, but the source is certainly highly obscured, with $N_H > 20 \times 10^{22} \text{cm}^{-2}$, $kT \sim 1 \text{ keV}$ plasma with $L_X \sim 1 \times 10^{33} \text{erg s}^{-1}$. We do not detect an X-ray counterpart to NGC 7538S.

Globules (Figure 15(f)) as defined by Sharma et al. (2017). These host small groups of X-ray sources at the eastern edge of NGC 7538. Sharma et al. noted that they resemble bright-rimmed clouds and point back to the O3 star IRS6.

The brightest diffuse X-ray emission in the ACIS observation is far off-axis on the ACIS-S chips. On-axis, a diffuse enhancement is coincident with the central cavity around the cluster. Faint patches of diffuse X-rays extend north and south to the edges of the ACIS-I field, anticoincident with the WISE mid-IR emission. Luisi et al. (2016) find ionizing radiation leaking past the primary photodissociation region (PDR) to a second PDR northeast of the main bubble, demonstrating the influence of MSFRs on the surrounding ISM. Diffuse X-ray emission extends at least as far as the second PDR to the northeast. It also spreads to the south and southwest, past the main NGC 7538 bubble seen in the WISE data, once again demonstrating that the hot ISM around MSFRs is more complex and extensive than might be predicted from IR data alone.
4.10. G333

The elongated G333 GMC hosts several obscured MSFRs, spread over 80 pc across its long axis (e.g., Russeil et al. 2005; Nguyên et al. 2015). G333 has formed several massive young clumps and clusters, all at nearly the same time and with nearly regular spacing along the cloud. These clusters are too young to have hosted supernovae and their wind-blown bubbles do not overlap significantly, so it is unlikely that we are witnessing a “sequential triggering” process (Elmegreen & Lada 1977).

G333 may be a more evolved version of the 80-pc-long massive molecular filament and IRDC “Nessie” (Jackson et al. 2010). Near-IR dust extinction maps (Kainulainen et al. 2011) show that IRDCs are often surrounded by molecular clouds with >10 times more mass; thus a massive (but not extraordinary) IRDC of $10^4M_\odot$ can easily represent just the densest part of a typical $10^5M_\odot$ GMC. So G333 may be a rare example of a very massive IRDC with an unusually favorable sky orientation that has nearly completely collapsed into regularly spaced sites of coeval massive star formation. Soon supernovae in these embedded clusters will destroy the last vestiges of the original IRDC and start blowing superbubbles to feed the hot ISM, as we see in Carina (Townsley et al. 2011a, 2011b) and NGC 6357 (MOXC1). But since the underlying elongated structure still remains in G333, we can study the transformation of a massive molecular filament into a cluster of clusters. Similar to G352 described above but more distant (so the entire GMC can be captured in a few ACIS-I pointings), G333 provides an important observational and evolutionary link between giant molecular filaments such as Nessie and cluster-of-clusters star-forming complexes such as Carina.

This study required four 60 ks ACIS-I pointings to mosaic MSFRs across the entire G333 GMC. We included additional archival Chandra data on surrounding pointings to create a wide-field, high-resolution X-ray mosaic of the entire G333 GMC (Figure 16). The young SNR RCW 103 lies just off the southwest edge of our G333 mosaic. We have omitted its ACIS
data from our mosaic because there is a recent analysis of those data (Frank et al. 2015). It is also extremely bright and swamps the fainter diffuse X-ray emission in our mosaic. As in MOXC1, we continue to assume a distance of 2.6 kpc to G333 (Figuerêdo et al. 2005; Roman-Lopes et al. 2009). Recent papers (e.g., Lo et al. 2015; Nguyên et al. 2015) use a distance of \( \sim 3.6 \) kpc to this GMC; assuming this larger distance would increase our X-ray source luminosities by nearly a factor of two. Below we describe each of our four main ACIS-I pointings on G333 MSFRs.

### 4.10.1. G333.6-0.2

The most prominent MSFR in G333 is the bipolar bubble and giant H II region G333.6-0.2 (Figure 17(a)). We presented a single-ObsID (60.1 ks) ACIS-I study of this region in MOXC1. The MOXC2 analysis used slightly more data (61.6 ks). In both epochs of analysis, ACIS reveals more than 100 X-ray sources in a central compact cluster powering the giant H II region, a distributed population of over 500 more point sources across this ACIS-I pointing, and soft diffuse X-ray emission tracing hot plasma apparently leaking from the embedded cluster (Figure 17(b)). As we found for the main ridge in NGC 6334, MOXC1 and MOXC2 catalogs are the same for brighter sources but find different sources at the faint limit. As before, we favor the MOXC2 results because they reflect improvements in our analysis methodologies over the years.

### 4.10.2. G333.3-0.4

This pointing (Figure 18) contrasts an IR-bright MSFR with the only part of the G333 GMC that is not bright at 24 \( \mu \)m. The upper half of Figure 18(a) shows this dark bay; we see no diffuse X-ray emission from this region. Water masers are found even in the IR-dark part of the field, indicating ongoing massive star formation (Breen et al. 2007). A near-IR study of G333.3-0.4 (Roman-Lopes et al. 2003) found 41 reddened massive stars in a \(^{\prime}\) cluster behind \( A_v \sim 28 \) mag, with spectral types \( \sim O5.5–B5 \). We find X-ray counterparts to at least 13 of those massive stars, sometimes resolving two or three X-ray sources at the location of the IR source.

The MSFR G333.3-0.4 is associated with IRAS 16177-5018, powered by an O3If\(^{+}\) star at 2.6 \( \pm 0.7 \) kpc (Roman-Lopes et al. 2009). Our X-ray counterpart to that star is c5623 (CXOU J162131.60-502508.3), with 13 net counts and a median energy of 3.2 keV; it has two close neighbors (each \( <1'' \) away). With so few counts, spectral fit parameters for
c5623 are not well-constrained, but they are roughly $N_H \sim 13 \times 10^{22} \text{ cm}^{-2}$, $kT \sim 0.9 \text{ keV}$, and $L_X \sim 4 \times 10^{32} \text{ erg s}^{-1}$.

In Figure 18(a) we do see diffuse emission from the G333.3-0.4 cluster and around the edges of this field, sometimes filling Spitzer bubbles. The center of the cluster (Figure 18(b)) contains a substantial number of X-ray sources; the overdensity of hard events not captured by detected sources implies that there are many more X-ray sources just below the detection limit. Diffuse X-ray emission is seen around the cluster but is fainter in the center, perhaps shadowed by the high absorbing column in this region. The X-ray sources are typically hard and faint, again probably due to high absorption. No other major grouping of X-ray sources is found in this pointing.

### 4.10.3. G333.1-0.4

This pointing (Figure 19) captures two powerful H II regions: G333.12-0.45 and G333.03-0.45 (GAL 333.1-00.4 and GAL 333.0-00.4 in SIMBAD). A near-IR study of G333.12-0.45 also finds a cluster distance of 2.6 kpc, a range of extinctions ($A_V \sim 12$–32 mag), several MYSOs with spectral types O4–B4, and a total cluster mass of $>10^3 M_\odot$ (Figuerêdo et al. 2005), but no source positions are provided. G333.12-0.45 shows direct evidence for large-scale infall (Lo et al. 2015), implying that it is very young.

The grouping of X-ray sources closest to G333.12-0.45 is shown in Figure 19(b), in the northeast region of this pointing. Bright diffuse X-ray emission is seen here. This region is several arcminutes off-axis, where ACIS PSFs are large and
sensitivity is reduced; thus point sources are typically faint. The diffuse emission may be due partially to unresolved pre-MS stars from this obscured cluster.

Another group of X-ray sources is shown in Figure 19(c), in the eastern part of this ACIS pointing. Faint diffuse X-ray emission pervades the field. There is an UCHIIIR candidate here (Mookerjea et al. 2004). These X-ray sources may be part of GLIMPSE IR cluster #78 (Mercer et al. 2005).

The H II region G333.03-0.45 is not as well-studied as G333.12-0.45 but shows a large number of dust cores and UCHIIIR candidates (Mookerjea et al. 2004). It is as bright in Lyman continuum as the other G333 MSFRs (Conti & Crowther 2004). G333.03-0.45 is at the center of this ACIS pointing. It shows diffuse X-ray emission distributed throughout a fairly loose grouping of point sources (Figure 19(d)).

4.10.4. RCW 106

The final pointing (Figure 20) in our G333 mosaic of MSFRs again shows diffuse X-ray emission at the periphery and in a Spitzer bubble, with strong shadowing at the center (Figure 20(a)). We find two main clumps of X-ray sources. The first is on
the northeast side of the pointing (Figure 20(b)). Two bright X-ray sources are found here: c2691 (CXOU J162026.75-505417.1; 398 net counts, median energy 1.7 keV) and c2412 (CXOU J162022.75-505420.4; 110 net counts, median energy 4.2 keV, variable). A spectral fit to c2691 requires two thermal plasma components, with $N_H = 2.2 \times 10^{22} \text{ cm}^{-2}$, $kT_1 = 0.5 \text{ keV}$, $kT_2 > 3 \text{ keV}$, and $L_X = 9.0 \times 10^{32} \text{ erg s}^{-1}$. The harder source, c2412, can be fit with a one-temperature thermal plasma, although that temperature is so high that it is not well-constrained by the ACIS data: $N_H = 10 \times 10^{22} \text{ cm}^{-2}$, $kT > 10 \text{ keV}$, and $L_X = 1 \times 10^{32} \text{ erg s}^{-1}$.

The second clump of X-ray sources is on the southwest side of the pointing, in a prominent Spitzer bubble (Figure 20(c)). These sources may be associated with GLIMPSE IR cluster #76 (Mercer et al. 2005).
4.10.5. Archival Pointings

We included several archival Chandra data sets in the G333 mosaic, to broaden the field and provide a wider context for the diffuse X-ray emission. ObsIDs 8141, 8161, 9602, and 10507 were from the ChIcAGO project (Anderson et al. 2014). ObsID 10929 re-observed a bright ChIcAGO source, which was determined to be the magnetar PSR J1622-4950 (Levin et al. 2010; Anderson et al. 2012). This is our source c8972 (CXOU J162244.91-495052.8); it is piled up in ObsID 8161.

We find prominent diffuse X-ray emission surrounding the magnetar (Figure 21(a)). This could be the X-ray signature of its SNR; Anderson et al. (2012) found a radio arc just north of this region (G333.9+0.0) and suggested that it might be an SNR associated with PSR J1622-4950. Our diffuse X-ray emission could be tracing hot plasma filling that radio-bright partial shell. Additionally, Anderson et al. showed PSR J1622-4950 to be coincident with a potentially nonthermal diffuse radio source (“Source A”) that may be a PWN associated with the magnetar. Since the diffuse X-ray emission is concentrated in the vicinity of PSR J1622-4950 and the diffuse radio source, this adds further support for the existence of a magnetar wind nebula.

ObsID 5471 targeted IGR J16195-4945, which is a likely high-mass X-ray binary (Tomsick et al. 2006). This is our source c439 (CXOU J161932.20-494430.6); it is piled up, but there are too few counts to perform pile-up correction. There are bright diffuse X-ray emission in this region (Figure 21(b)). Pandey et al. (2006) note extended radio emission in the vicinity of IGR J16195-4945, so perhaps we are once again seeing X-ray emission from a SNR.

4.11. AFGL 2591

AFGL 2591 is an embedded MYSO with prominent outflows and maser emission, surrounded by a small cluster (Trinidad et al. 2003); it is seen in the direction of the Cygnus X star-forming complex (Reipurth & Schneider 2008), but it is now believed to be substantially behind Cygnus X (at 3.33 kpc), from parallax of its water masers (Rygl et al. 2012).

The radio-bright source VLA-3 provides most of the IR emission and is thought to be a late-O-type MYSO (Sanna et al. 2012). Parkin et al. (2009) analyzed the Chandra data on AFGL 2591, finding 62 sources on the S3 CCD; our analysis of the same data (Figure 22) yields 152 sources on S3 and 288 sources in the entire observation. In the vicinity of VLA-3, Parkin et al. find four X-ray sources but do not detect the MYSO. We recover those four X-ray sources and add several more in our analysis (Figure 22(d)), but again we do not detect VLA-3. Parkin et al. interpreted a small excess of counts close to VLA-3 as possible diffuse emission from the winds of the proto-O star. We find a few of those counts to be consistent with a point source east of VLA-3; the remaining small number of counts could come from other point sources (including VLA-3) fainter than our detection limit, from the background, or from other sources of diffuse emission. Firmly establishing diffuse X-ray emission from VLA-3 wind interactions would require much more Chandra data.

Extensive diffuse X-ray emission is seen in this ACIS field, including off-axis on the I2 and I3 CCDs. Figure 22(c) demonstrates that diffuse emission surrounds AFGL 2591; Figure 22(d) shows that faint structures extend down to the embedded core. Some of this diffuse emission could be associated with the foreground Cygnus X complex; future X-ray spectral fitting to infer the absorption across the field may help us locate it along the line of sight.

4.12. G34.4+0.23

The first compact IRDC targeted by Chandra was G014.225-00.506 (Povich & Whitney 2010), part of a large molecular cloud complex associated with the M17 giant H II region known as the M17 Southwest Extension (Elmegreen et al. 1979), located at a distance of 2.0 kpc (Xu et al. 2011). Using the same analysis methods as those presented here, we cataloged 840 X-ray sources in a 99 ks ACIS-I observation of G014.225-00.506 (Povich et al. 2016). The second IRDC observed by Chandra was the more well-studied object G34.4+0.23 (Rathborne et al. 2005; Shepherd et al. 2007), observed with ACIS-I for just 63 ks under the assumption that it lies at a maser parallax distance of 1.56 kpc (Kurayama et al. 2011), substantially closer than G014.225-00.506. This distance was soon questioned, however (Foster et al. 2012), and recent papers (Foster et al. 2014; Xu et al. 2016) favor the kinematic distance of around 3.7 kpc (Rathborne et al. 2005).

This Chandra observation (Figure 23) reveals few X-ray sources along the G34.4+0.23 IRDC compared to G014.225-00.506 (Povich et al. 2016), again suggesting that the kinematic distance is correct and that the 63 ks ACIS exposure was too short to detect much of the young stellar population embedded in this IRDC. Nevertheless, we do find a large number of X-ray point sources in this field (Figure 23(c)). Some will be foreground and background contaminants, but many hundreds are likely pre-MS stars associated in some way with the star formation going on in this region.

We have X-ray counterparts to a few of the young stellar objects listed in Shepherd et al. (2007). In particular, we find three faint, very hard X-ray sources in close proximity to source 11 from Shepherd et al., at the center of the UCHIIIR (Figure 23(d)): c284 (CXOU J185318.71+012449.1, eight net counts, median energy 4.1 keV); c283 (CXOU J185318.71 +012446.3, six net counts, median energy 4.5 keV); cc554 (CXOU J185318.54+012445.2, four net counts, median energy 4.2 keV).

Foster et al. (2014) found a distributed population of low-mass protostars associated with the IRDC but located outside the densest parts of the filament. Perhaps our X-ray sources sample an even older and more distributed stellar population. Further multiwavelength analysis is necessary to understand this X-ray source population and the history of star formation across this region.

The G34.4+0.23 Chandra mosaic shows abundant diffuse X-ray emission. A small patch at field center may contain unresolved point sources from the central proto-cluster (Figure 23(d)). This is largely surrounded by dark regions, perhaps due to shadowing by the IRDC and surrounding molecular material. Diffuse emission is seen again at the field edges, especially at the east and west corners of the ACIS-I image. As often demonstrated in other MOXC2 targets, the off-axis ACIS-S CCDs hint at more diffuse X-ray structures far

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off-axis. This emission is anticoincident with moderately bright \textit{Spitzer} 8 μm emission to the southeast of G34.4+0.23.

The more developed MSFR G34.26+0.15 was partially imaged off-axis in this observation, at the southern corner of the ACIS-I array (Figure 23(b)). A few X-ray point sources are found there (likely limited by low sensitivity and source confusion), and the region is surrounded by diffuse X-ray emission. A \textit{Chandra} observation centered on this MSFR would probably reveal a rich young stellar population and an interesting network of hot plasma from massive star feedback in G34.26+0.15.

4.13. Westerlund 1

We finish our tour of MOXC2 MSFRs with Westerlund 1 (Wd1), the most massive YMC known in the Galaxy (Andersen et al. 2017). It is a monolithic cluster, not part of a complex of multiple MSFRs, as we have seen in many MOXC2 targets. The center of Wd1 is known to be elongated (Gennaro et al. 2011), but recent work (Gennaro et al. 2017) finds that its massive stars are not strongly concentrated toward the center (mass-segregated); these authors conclude that Wd1 has changed little in size or density since its formation. Its combination of mass and age explains its uniquely large population of evolved massive stars, including red supergiants, yellow hypergiants, and WRs; Wd1 may have weathered ∼100 supernovae already (Clark et al. 2008). Twelve WRs (Skinner et al. 2006) and a magnetar (Muno et al. 2006) were among the 241 point sources detected in the original 57 ks ACIS-S observation (Clark et al. 2008).
We recover all but six of the X-ray sources tabulated in Clark et al. (2008). We find many hundreds more X-ray sources and diffuse emission across our ACIS mosaic (Figure 24). The magnetar (CXOU J164710.2-455216) suffers from photon pile-up in these observations. Clark et al. (2008) presented X-ray spectral fits for the brightest ACIS sources, so we will not report further spectral fitting results here.

Wd1 is four times as massive as NGC 3603 (featured in MOXC1) but eight times lower in central density (Figer 2008). This and the relatively short Chandra exposure on Wd1 means that our X-ray point source list suffers much less confusion than we found in NGC 3603 (MOXC1). After excising resolved point sources, the ACIS event data still show a substantial overdensity of counts at the center of Wd1 (Figure 24(c)); a longer Chandra observation would undoubtedly resolve out a large number of additional X-ray point sources in the cluster core.

The second pointing, to the south of Wd1 in our ACIS mosaic (ObsID 11836, 10 ks), is an ACIS-I GTO observation of 0FGL J1648.1-4606, part of a snapshot survey of unidentified Fermi/LAT GeV sources. PSR J1648-4611 in this field is listed as a non-detection in Table 2 of Kargaltsev et al. (2012). This source remains undetected in our analysis.

Diffuse X-ray emission from Wd1 was studied by Muno et al. (2006) (Chandra) and Kavanagh et al. (2011) (XMM). In our ACIS mosaic (Figure 24(b)), we see diffuse emission across much of the field, including the cluster center (Figure 24(c)). The unresolved X-ray emission at the northwest corner of the mosaic is due in large part to the bright LMXB GX340+0, located off the field. We have masked the brightest
of this scattered light from our diffuse images. Northeast of Wd1, far off-axis on the S0 chip of ObsID 6283, we have another serendipitous detection of diffuse X-ray emission apparently associated with a bubble structure in the Spitzer data (Figure 24(d)).

5. Summary

Expanding on the results presented in MOXC1 (Townsley et al. 2014), with MOXC2 we have assembled and analyzed 13 Chandra/ACIS Galactic Plane mosaics featuring 16 MSFRs. These mosaics combine Chandra archival, GO, and GTO data sets to form the most complete high-resolution X-ray picture possible of the MSFRs and their surrounding environments. Major software and procedural changes for MOXC2 have made it possible to include far off-axis data from ACIS-I observations and archival data using the ACIS-S imaging configuration. This broadens the fields covered by our mosaics and the MSFRs we can access; most importantly, these changes reveal...
the ubiquity of hot plasmas pervading the Plane and Chandra’s amazing ability to trace their diffuse X-ray emission.

We present properties for more than 18,000 X-ray point sources found in these fields. From past experience, most of these sources will turn out to be pre-MS MSFR members; Chandra will increase the census of young stars in every MOXC2 MSFR. We find likely CWBs, IMS, and the ionizing sources of well-known radio UCHIIRs; these sources are rare and stand out because of their extremes in X-ray luminosity, variability, and hard spectra. They demonstrate that X-ray emission turns on early in the star formation process, at least in some cases, bombarding cold molecular environments with hard radiation and shocks.

We excised the X-ray point sources from each mosaic and made adaptively smoothed images from the remaining X-ray emission. We find that this unresolved emission appears to be truly diffuse in many cases, tracing hot plasma in and around these MSFRs. This hot plasma appears to pervade cluster centers, fill Spitzer bubbles, and leak out of perforated H II region boundaries. Although MOXC2 MSFRs display a wide variety of diffuse X-ray morphologies and surface brightnesses, none lacks diffuse X-ray emission. With detailed spectral studies, pressures and densities of these hot plasmas will give physical insights into the birth of the hot ISM.

We hope that our X-ray point source catalogs will be useful to the wider star formation community for understanding young stellar populations in and around MSFRs. The next step is to match these X-ray source lists to longer-wavelength data sets in order to deduce which X-ray sources are cluster members and, in turn, to study multiwavelength properties of those cluster members. For diffuse X-ray emission, bright fields need to be tesselated, spectra from each tessellate extracted and fitted, and maps generated of spectral fit parameters (Townsley et al. 2011b). Even for faint fields, a rough spectral characterization should be possible for the diffuse emission pervading every clump and cluster of young stars in MOXC2.

The Chandra Cycle 18 archival program MSFRs Across the Galaxy in X-rays (MAGiX) is underway; it will provide ACIS source lists and map diffuse X-ray emission for another 16 Galactic MSFRs. MAGiX2 is a new Chandra Cycle 19 archival program that will perform similar ACIS data analysis on a further 13 Galactic MSFRs, plus three more in the Magellanic Clouds. With these and other ongoing Chandra programs, by the end of the decade we will add \( \sim 40 \) MSFRs analyzed with similar methods to the body of work amassed already by COUP, CCCP, MYStIX, MOXC1, SFiNCs, MOXC2, and other Chandra projects. We hope that these efforts demonstrate the benefit of Chandra observations to MSFR studies and facilitate the use of Chandra data by the multiwavelength star formation community.

Finally, MOXC2 shows that there are still many important observations for Chandra to make on MSFRs. Coverage is shallow or absent for a surprising number of famous MSFRs that are mainstays of longer-wavelength star formation science. We need to explore younger regions (IRDCs) and older regions (red supergiant clusters), rich MSFR complexes near (G352) and far (W31), molecular filaments anchoring the spiral arms (Nessie), and cauldrons of massive star evolution (Wd1). Much discovery awaits us.

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Facilities: CXC (ACIS), Spitzer (IRAC, MIPS), WISE
Software: ACIS Extract (Broos et al. 2010, 2012; Broos & Townsley 2016), CIAO (Fruscione et al. 2006), DS9 (Joye & Mandel 2003), MARX (Davis et al. 2012).

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