X-Ray Binaries in M51 I: Catalog and Statistics

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Abstract

We used archival data from the Chandra X-ray Observatory (Chandra) and the Hubble Space Telescope, to identify 334 candidate X-ray binary systems and their potential optical counterparts in the interacting galaxy pair NGC 5194/5195 (M51). We present the catalog and data analysis of X-ray and optical properties for those sources, from the deep 892 ks Chandra observations, along with the magnitudes of candidate optical sources as measured in the 8.16 ks Hubble Space Telescope observations. The X-ray luminosity function of the X-ray sources above a few times $10^{36}$ erg s$^{-1}$ follows a power law $N(>L_{X,\text{b}}) \propto L_{X,\text{b}}^{-1.65 \pm 0.03}$. Approximately 80% of sources are variable over a 30 day window. Nearly half of the X-ray sources (173/334) have an optical counterpart within 0.55.

Unified Astronomy Thesaurus concepts: X-ray binary stars (1811); X-ray sources (1822); X-ray point sources (1270)

1. Introduction

The Whirlpool Galaxy (NGC 5194, M51) and its companion (NGC 5195) are a nearby interacting galaxy pair at a distance of 8.58 $\pm$ 0.1 Mpc (McQuinn et al. 2016) in the constellation Canes Venatici. NGC 5194 is a face-on grand-design galaxy that lends itself well to studies of its spiral arms, globular clusters, and X-ray binaries (XRBs). There have been a large number of studies of the X-ray sources in M51 going back decades. Terashima & Wilson (2004) studied the X-ray point-source population observed in the two of the earliest M51 Chandra X-Ray Observatories (Chandra) observations (ObsIDs 354 and 1622). In a follow-up, Terashima et al. (2006) investigated the candidate optical counterparts to those X-ray point sources using Hubble Space Telescope (HST; with the additional Chandra observation ObsID 3932). More recently, Kuntz et al. (2016) used most of the available (at the time) Chandra data.

XRBs are gravitationally bound systems containing a compact object (black hole or neutron star) accreting matter from a main-sequence or massive star companion. XRBs fall generally into two main classes: low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs), distinguished by the mass of the companion star. A LMXB has X-ray emission originating in an accretion disk supplied by Roche-lobe overflow of a low-mass ($M_{\text{donor}} \leq 1.0 M_\odot$) stellar companion. An HMXB has X-ray emission originating in the accretion of the stellar wind of a high-mass ($M_{\text{donor}} > 8.0 M_\odot$) stellar companion. HMXBs are divided into two subclasses: those with O-type companions and those with Be companions. Some excellent reviews on XRBs are found in Chevalier & Ilovaisky (1998), Wilson (2003), Kuntz et al. (2016), or McBride et al. (2008).

HST provides an avenue to investigate XRBs. While the optical magnitudes of LMXBs will be too small to detect, the massive donor stars of HMXBs can be detected with HST in the distance to M51. For example, supergiant donors are bright, with $M_V$ brighter than $\approx -6.5$ (Chevalier & Ilovaisky 1998), while Be donors tend to be fainter, with typical $M_V$ ranging from $-2$ to $-5$ (McBride et al. 2008). Deep photometry with HST can therefore be used to distinguish between the two main classes of HMXBs.

In this paper we present an analysis of Chandra X-ray and HST data for X-ray sources in M51. Our analysis is complementary to Kuntz et al. (2016) in that cross-matching the X-ray and optical sources is the primary goal. We describe the X-ray and optical observations used in this study in Section 2, discuss the results in Section 3, and describe our conclusions in Section 4. Due to the large amount of information, here (Paper I) we will primarily show the methodology used to compile our results. We will present a more in-depth analysis of individual X-ray sources and the entire population, plus a detailed comparison with previous X-ray-optical work on the same system (e.g., Kuntz et al. 2016) in a follow-up study (Paper II).

2. Observations and Data Reduction

2.1. Chandra X-ray Observatory

The Whirlpool Galaxy has been the focus of many Chandra programs since 2000. For this work, we select data with exposure time $t_{\text{exp}} \geq 10.0$ ks, resulting in 13 Chandra observations, the longest of which is 189 ks. Information about the X-ray data is listed in Table 1. The data were taken with the Advanced CCD Imaging Spectrometer (ACIS) instrument on board Chandra. The data were analyzed with the Chandra Interactive Analysis of Observations (CIAO) software version 4.10 and Chandra Calibration Data Base version 4.7.9.\textsuperscript{5}

We aligned all data sets with US Naval Observatory Robotic Astrometric Camera (USNO URAT\textsuperscript{6}) Catalog using the

\textsuperscript{5}http://cxc.harvard.edu/ciao/
\textsuperscript{6}https://www.usno.navy.mil/USNO/astrometry/optical-IR-prod/urat
CIAO scripts wcs_match and wcs_update. Taking into account the new aspect ratio solution and bad pixel files, the observation event files were merged into one event file using merge_obs. The CIAO script mkpsfmap was run on the full merged event file, taking the minimum point-spread function (PSF) map size at each pixel location.

We used the CIAO’s Mexican-hat wavelet source detection routine wavdetect (Freeman et al. 2002) on the merged data to create source lists. Waves of 1, 2, 4, 6, 8, 12, 16, 24, and 32 pixels and a detection threshold of 10–6 were used, which typically results in one spurious detection per million pixels.

We followed standard CIAO procedures,7 using an exposure-time-weighted average PSF map in the calculation of the merged PSF. We detected a total of 497 X-ray sources in the merged data set. In this paper we focus on the sources that are also within the HST field-of-view, of which there are left 334 (Figure 1). The srcflux CIAO tool was then run individually on each observation (using the coordinates found by wavdetect). The data have been restricted to the energy range between 0.5 and 7.0 keV and filtered in three energy bands, 0.5–1.2 keV (soft), 1.2–2.0 keV (medium), and 2.0–7.0 keV (hard). We corrected our source catalog to the effects of neutral hydrogen absorption along the line of sight using the Galactic Neutral Hydrogen Density Calculator (COLDEN8) tool, finding a mean neutral hydrogen absorption along the line of sight to each source of $n_h = (1.53 \pm 0.03) \times 10^{20} \text{cm}^{-2}$. Our fluxes are consistent with the Chandra Source Catalog v2 (CSC9).

### 2.2. Hubble Space Telescope

A six-image mosaic image of M51 with the HST Advanced Camera for Surveys (ACS) was obtained by the Hubble Heritage Team10 (PI: Beckwith, program GO 10452) in 2005 January (see Mutchler et al. 2005). The pixel scale of these observations is 0.05 pix$^{-1}$, corresponding to 2.1 pc pix$^{-1}$ at the observed distance of M51. The full mosaic consists of four bands $I$, $V$, $B$, and $H\alpha$ with exposure times of 1360, 1360, 2720, and 2720 s, respectively. The total exposure time is thus $t_{\text{exp}} = 8160$ s over 96 separate exposures. We identified sources in each of the four HST images to align with the URAT1 Catalog and improve the absolute astrometry of the images (similar to Chandra). The common sources totaled 43, distributed across the M51 system. In IRAF, the command ccmpmap was run on all four of the HST images. The ccmpmap command finds a six-parameter linear coordinate transformation (plate solution) that takes the $(X, Y)$ centroids and maps them to the more accurate astrometric positions (URAT1 Catalog). In the four bands ($I$, $V$, $H\alpha$, $B$) the mean (R. A., decl.) offsets were $(0''142, 0''119), (0''141, 0''124), (0''143, 0''124)$, and $(0''144, 0''117)$, respectively. We identified candidate HST point sources that fell within $0''5$ (10 px) of the 334 Chandra X-ray point-source centroids in our X-ray catalog. We chose $0''5$ to limit the total number of sources in the catalog while making sure all candidate optical counterparts were identified.

We used the AstroPy package photutils11 to perform photometry calculations on the candidate HST sources. Within photutils we created a circular aperture of radius $r = 3.0$ px around each source. The background counts were summed within an annulus centered on each HST point source with inner radius $r_{\text{in}} = 8.0$ px and outer radius $r_{\text{out}} = 11.0$ px. We corrected for the encircled energy fraction using the most recent ACS encircled energy values.12 The output of photutils on the HST data includes the corrected $(I, V, H\alpha, B)$ magnitudes in the VegaMag system13 for each candidate point source.

### 2.3. Optical Counterparts

Candidate point-source optical counterparts were found by identifying the brightest HST point source within the Chandra positional uncertainty of each X-ray source. We used a 90% confidence level positional uncertainty of 0.5″ typical for a 5″ off-axis X-ray source with 50 counts (see Equation (12) in Kim et al. 2007). This positional uncertainty corresponds to 20.8 pc at the distance of M51. In total, there are 173 such candidate optical counterparts. The closest HST source to the X-ray centroid is not always the brightest and often is not visible in all four HST bands, so we justify the optical counterpart candidate identification process in this way. It is possible that the true physical counterparts are invisible in the four HST bands, and we identify the incorrect physical counterpart using this method, but it seems to capture the majority of the sources sufficiently. We used the $I$-band images to select the brightest candidate optical counterpart within the Chandra 1σ uncertainty. If we select the closest candidate optical counterpart in the same way, we pick up ~65% (113/173) of the same sources; that is, 60 of the candidate HST counterparts are the brightest, but not closest sources to the X-ray centroids.

### 3. Results and Discussion

#### 3.1. X-Ray Variability

We look for short term X-ray variability using seven Chandra observations from 2012 (ObsIDs 13813, 13812, 15496, 13814, 13815, 13816, and 15553). These observations
span over a 1 month period (see Table 1). In Figure 2, we plot the broad X-ray flux light curves of the brightest 1–5 (black curves) and next brightest 6–10 (copper curves) X-ray sources. Right: broad X-ray flux light curves of the next brightest 10–15 (black curves) and next brightest 16–20 (copper curves) X-ray sources. The black triangles indicate upper limits, while the dashed black and copper lines indicate one particular source (xid = 199; R.A.: 13:30:06.0397, decl.: +47:15:42.477) was outside the FOV for ObsIDs 13814, 13815, and 13816 and thus had no measured X-ray counts in those observations, except for a 90% upper limit on the counts during ObsID 13814. In both panels, in the 30 day window of these observations, some sources vary in flux by approximately 2 orders of magnitude. Note: line thickness increases with decreasing net counts within each group of five curves. Also note the different y-axis scales. The time-averaged mean broad flux error of these 20 sources over the 30 day window of observations in this figure is $\langle \delta F_{X,b} \rangle \approx 5.7 \times 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1}$, and for most of the data points the error is within the line thickness.

\[
\chi^2 \equiv \sum_{i=1}^{\nu} \frac{(F_i - \mu_i)^2}{\sigma_i^2},
\]

where $F_i$ is the X-ray flux of the $i$th source, $\mu_i$ is the weighted mean error of the associated $i$th flux measurement, and $\sigma_i^2$ is the variance of the $i$th flux measurement. The reduced chi-square statistic is simply $\chi^2 = \chi^2 / \nu$. The mean of the chi-square distribution is $\nu$, so that $\chi^2_\nu = 1$ is a natural value with which to compare results. The value of $\chi^2_\nu$ should be approximately unity if the null hypothesis is to be accepted. Large values of $\chi^2_\nu$ indicate that the null hypothesis should be rejected. Thus, the sources with $\chi^2_\nu > 1$ are sources whose flux varies greatly in the 30 day window, and we label them “variable” sources. Sources with $\chi^2_\nu \lesssim 1$ are sources that have a light curve in the 30 day window that is consistent with the null hypothesis (uniform flux).

Approximately 80% (266/334) of the sources are considered variable by our $\chi^2_\nu \geq 1$ criterion. Approximately 69% (120/173) of the sources with at least one detected candidate stellar...
counterpart and no cluster counterparts are variable (see our upcoming follow-up Paper II for a discussion of cluster counterparts), while about 77% (124/161) of the sources without a stellar or cluster counterpart are variable. In addition, about 76% (22/29) of the X-ray sources that have both an associated candidate stellar source and candidate cluster are considered variable. There is a strong positive correlation between the variability and flux of the X-ray sources. Our findings are consistent with the inter-observation variability reported in the CSC (for sources that overlap, which is the majority of sources), even though we have limited our variability study to data within this 30 day window. We speculate that the observed strong correlation is due to the small uncertainty associated with very bright sources (see Figure 2), i.e., the time-averaged mean broad flux error over the 30 day window of observations is \( \langle \delta F_{\text{X},h} \rangle \approx 5.7 \times 10^{-15} \text{ erg cm}^{-2} \text{s}^{-1} \).

### 3.2. X-Ray Hardness Ratios

We calculate two X-ray HRs, “soft” and “hard” \((HR_1\) and \(HR_2\), respectively), for all X-ray sources using the same seven observations as follows:

\[
HR_1 \equiv \frac{M - S}{M + S} \quad \text{and} \quad HR_2 \equiv \frac{H - M}{H + M}
\]

where \(S\), \(M\), and \(H\) are the X-ray counts in each of the Chandra bands (soft, medium, and hard) discussed in Section 2.1. We also calculate the associated uncertainty in each of the HRs.

In Figure 3, top panel, we plot the X-ray color–color diagram for all sources, colored by the logarithm of their reduced chi-square statistic calculated in the 30 day window discussed in Section 3.1. The two X-ray colors are the measurements from the longest of the observations in the 30 day window, ObsID 13814.

Hardness ratio diagrams, such as Figures 3 and 4 in Prestwich et al. (2003), which uses a different definition\(^{\text{14}}\) of the X-ray HRs, have been used historically to assist with revealing the nature of the X-ray sources. The majority of the variable sources \((\chi^2 > 1)\) lie in the XRB (LMXB and HMXB) regions of the figure (see, e.g., Prestwich et al. 2003), while most of the low variability sources lie in the region of the diagram that is generally occupied by thermal supernova remnants. However, it is well established that X-ray information alone is not enough to accurately identify the nature of unknown X-ray sources. Therefore, we use the X-ray colors together with optical information (see Section 3.4) to classify these sources.

In Figure 3 we also plot the X-ray color–color diagrams of the brightest 20 (by net counts) X-ray sources; the top 10 brightest in the middle panel and the next 10 brightest in the bottom panel. Overlaid in all three plots are the hardness color evolution tracks of various accretion disk models. In blue are power-law models with increasing photon index \(^{\text{1}}\) from 0.4–4, in orange are absorbed power-law models with increasing hydrogen column density, in green are disk blackbody models with temperature ranging from 0.02–2.0 keV, and in red are absorbed bremsstrahlung models with temperature ranging from 0.1–10.0 keV. These color–color diagrams contain X-ray colors from all available data in the 30 day window, with appropriate 1σ error bars shown in black. Each source has multiple (the same plotted color) points in the diagram, and the color–color evolution is thus apparent. Typically, the color–color evolution

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\(^{\text{14}}\) In Prestwich et al. (2003), they define the hard and soft X-ray colors as \(HR_1 \equiv (M - S)/T\) and \(HR_2 \equiv (H - M)/T\), respectively, where \(S, M, H,\) and \(T = S + M + H\) are the soft, medium, hard, and total X-ray counts, respectively.
X-ray luminosity functions. The purple curve is the full sample of 288/334 X-ray sources that have a measured X-ray luminosity in ObsID 13814. For $L_{X,b} \geq 2 \times 10^{36}$ erg s$^{-1}$, the purple curve follows a power law $N(>L_{X,b}) \propto L_{X,b}^{-\alpha}$, where $\alpha = 1.65 \pm 0.03$; see the text for details. The green curve is a cut of the full sample with 130/334 X-ray sources that have only a stellar counterpart within 10 px. The blue curve is a cut of the full sample with 133/334 X-ray sources that have no stellar or cluster counterparts within 10 px. The vertical dashed black line is the Eddington luminosity of a 1.4 $M_\odot$ accretor, i.e., $L_{\text{Edd}} \approx 1.76 \times 10^{38}$ erg s$^{-1}$ (see Equation (7)). Right: combined fractional X-ray luminosity functions. Same as the left panel, but normalized.

Figure 4.

The X-ray luminosity function

$$N(>L_0) = A \left( \frac{L}{L_0} \right)^{-\alpha},$$

where the luminosity $L_0$ is an arbitrary lower limit and $A$ is some normalization constant. Integrating Equation (4) gives the luminosity function within a particular range:

$$N(>L_0) = A L_0 \left( \frac{L}{L_0} \right)^{1-\alpha},$$

and the fractional luminosity function is given by

$$f(>L_0) = \frac{A L_0}{N_{\text{tot}}(1-\alpha)} \left( \frac{L}{L_0} \right)^{1-\alpha},$$

where $f(>L_0)$ is the fraction of sources with $L > L_0$ and $N_{\text{tot}}$ is the total number of sources.

An important luminosity is the Eddington luminosity of a 1.4 $M_\odot$ compact object (the typical mass of NSs) accreting at the Eddington rate:

$$L_E \equiv \frac{M E c^2}{\sigma_T M} = \frac{4\pi G m_p c}{\sigma_T} M,$$

$$\approx 1.76 \times 10^{38} \text{ erg s}^{-1} \left( \frac{M}{1.4 M_\odot} \right),$$

where $M_E$ is the Eddington accretion rate, $M$ is the mass of the accretor, $G$ is Newton’s gravitation constant, $m_p$ is the proton mass, $c$ is the speed of light, and $\sigma_T$ is the Thomson scattering cross section for electrons.

In Figure 4, we plot the combined XLF (total and fractional) on various cuts of the data. The purple curve is the full sample of the 86% (288/334) of X-ray sources that have a measured X-ray luminosity inObsID 13814 (the observation with the longest exposure time). The green curve is the 39% (130/334) of X-ray sources that have a stellar counterpart in HST (within 10 px). Across a few orders of magnitude of X-ray luminosity starting at $L_{X,b} \geq 2 \times 10^{36}$ erg s$^{-1}$ the curves follow a power law $N(>L_{X,b}) \propto L_{X,b}^{-\alpha}$, i.e., we fit a power law to the differential luminosity function with $\alpha = 1.65 \pm 0.03$. This is consistent with XLFs for star-forming galaxies dominated by HMXBs, for example, Lehmer et al. (2019) who find $\alpha = 1.59 \pm 0.05$ for M51. The blue curve represents the X-ray sources that have no stellar or cluster counterparts within 10 px, 40% (133/334), and has the same slope. The black vertical dashed line indicates the Eddington luminosity of a canonical NS (e.g., 1.4 $M_\odot$) accretor of $L_{\text{Edd}} \approx 1.8 \times 10^{38}$ erg s$^{-1}$. Fewer than 10% of the sources have an X-ray luminosity that is greater than $L_{\text{Edd}}$ for the typical NS accretor.

A major obstacle in studying the extragalactic XRB population is differentiating HMXBs from LMXBs, which cannot be done by their X-ray properties alone. One attempt to solve this problem was done by Mineo et al. (2012), who used galactocentric distance to distinguish between the two types of XRBs. However, many galaxies, including spirals such as M51, show a spatially mixed population of “young” and “old” XRBs. Our results show that combining Chandra and HST data can break this degeneracy.
3.4. Optical Counterparts to X-Ray Sources

Due to the distance to M51 there are issues with crowding and source confusion. Many X-rays sources (51%; 173/334) have at least one HST stellar counterpart within the 0.75 Chandra positional uncertainty, whereas (75%; 252/334) have at least one HST stellar counterpart within the 2σ Chandra uncertainty. Just over half, 51% (88/173), of sources that have at least one detected HST stellar counterpart within 1σ have at least two detected candidate stellar counterparts.

Selecting the counterpart candidate can be challenging in cases where there are two or more optical sources in the search radius. One method of choosing the donor star candidate is to select the closest optical source to the Chandra position. On the other hand, a large fraction of the XRBs in M51 are expected to be HMXBs with early-type stars as the donors. Therefore, an alternative method of selecting an optical counterpart is to select the brightest optical sources within the 1σ radius (10 px). In Figure 5 we plot the $B - V$ and $V - I$ color–magnitude diagrams for the candidate HST optical counterparts that are the brightest or closest within 10 px of the X-ray point-source centroids. If we select the closest candidate HST optical counterpart within 10 px, out of 173 total optical candidate counterparts, ∼65.3% (113/173) of the sources are the same. That is, 113 of the HST counterparts are both the brightest and the closest source within 10 px. As expected, selecting the closest optical counterpart to the X-ray sources is biased toward fainter (and older) stellar sources. However, we performed a two-sample Kolmogorov–Smirnov (K-S) test on the following data from Figure 5:

1. $M_{V,\text{closest}}$ versus $M_{V,\text{brightest}}$ (y-axis of both panels);
2. $(m_B - m_V)_{\text{closest}}$ versus $(m_B - m_V)_{\text{brightest}}$ (x-axis of left panel);
3. $(m_V - m_I)_{\text{closest}}$ versus $(m_V - m_I)_{\text{brightest}}$ (x-axis of right panel).

We found that in each case the null hypothesis $H_0$, namely, that the two samples in 1, 2, and 3 above are drawn from the same unknown underlying continuous distribution, cannot be rejected. The two-sample K-S test statistic $D$ and $p$-values for each of the three tests above are:

1. $D = 0.13194$ and $p = 0.15056$;
2. $D = 0.07639$ and $p = 0.77899$;
3. $D = 0.06250$ and $p = 0.93376$.

At a level of significance $\alpha = 0.05$, we cannot reject $H_0$ since in each case $p \geq \alpha$. Thus, we cannot claim a statistically significant difference in choosing either the closest or the brightest sources as the candidate optical counterpart to our X-ray sources. The mean photometric error is approximately 0.1 mag in $V$ and $I$. In Table 2, we select the brightest source as the donor star candidate in the case of multiple matches.

Also in Figure 5 we plot four mass tracks: $5 M_\odot$, $8 M_\odot$, $20 M_\odot$, and $40 M_\odot$, respectively, from bottom to top, taken from the MESA Isochrones and Stellar Tracks15 (see Paxton et al. 2011, 2013, 2015, 2018; Choi et al. 2016; Dotter 2016). The initial protosolar bulk metallicity for the models used is $Z_i = 0.0147$, with extinction $A_V = 0$ ($R_V = 3.1$). It is clear from the color–magnitude diagram that most of the candidate HST optical counterparts lie above the $8 M_\odot$ mass track, indicating that most of our candidate sources are likely HMXBs. In classifying the candidate sources as HMXBs, there are no statistically significant differences in choosing either the brightest (black) or closest (light orange) sources (see the two-sample K-S test discussion above).

4. Conclusions

In this study we presented a catalog and statistical analysis of archival Chandra and HST data of point sources in the interacting galaxy pair NGC 5194/5195 (M51).

1. Using standard CIAO procedures, we detected 334 X-ray point sources in the 13 merged Chandra observations. We corrected the data for neutral hydrogen absorption along the line of sight and improved the astrometry using the USNO URAT1 catalog.
2. We identified 173 candidate optical counterparts to the X-ray sources in our catalog by finding the brightest HST point sources within 10 px of the X-ray source. We found no statistically different results by choosing the closest HST point sources by performing a two-sample K-S test (see the text for details). Similar to Chandra the

http://waps.cfa.harvard.edu/MIST/index.html

Figure 5. Color–magnitude diagrams for the potential HST optical counterpart candidates that are the brightest (black) or closest (light orange) within 10 px of the X-ray source centroids. The dark orange indicates a candidate optical counterpart is both the brightest and closest to the X-ray centroid. There are 173 candidate optical counterparts within 10 px of the 334 Chandra X-ray point sources. For both panels, the four mass tracks from bottom to top are from MESA Isochrones & Stellar Tracks (MIST; see the text) and have masses $5 M_\odot$, $8 M_\odot$, $20 M_\odot$, and $40 M_\odot$, respectively. Left: $B - V$ color–magnitude diagram. Right: $V - I$ color–magnitude diagram.
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Table 2
Catalog of X-Ray Sources

| XID | R.A.  | Decl. | Covar/10^3 | F_Xs/(10^{-15} erg s^{-1}) | I     | V     | Hs    | B     | HR1   | HR2   |
|-----|-------|-------|------------|-----------------------------|-------|-------|-------|-------|-------|-------|
| 178 | 202.504274 | 47.228885 | 6.73 | 441 | −8.26 | −7.58 | −8.08 | −6.62 | 0.073 | 0.012 |
| 62  | 202.531553 | 47.185057 | 6.03 | 263 | −6.70 | −5.10 | −7.27 | −4.69 | −0.083 | −0.37 |
| 166 | 202.496180 | 47.221801 | 3.63 | 240 | −6.18 | −3.83 | −4.91 | −2.62 | 0.64   | 0.069 |
| 190 | 202.473939 | 47.243281 | 2.25 | 153 | …     | …     | …     | −0.14 | 0.27   |
| 154 | 202.414552 | 47.212141 | 2.05 | 109 | −6.35 | −6.58 | −6.34 | −6.67 | 0.023 | −0.15 |
| 100 | 202.470043 | 47.194362 | 1.90 | 62.4 | −8.49 | −7.47 | −8.05 | −6.49 | −0.64 | −0.79 |
| 94  | 202.430548 | 47.193022 | 1.77 | 70.7 | −6.97 | …     | …     | −0.83 | −0.82 |
| 149 | 202.416637 | 47.210268 | 1.65 | 64.1 | −5.72 | −5.74 | −6.14 | −5.67 | −0.36 | −0.55 |
| 168 | 202.517998 | 47.222471 | 1.38 | 92.0 | −8.06 | −7.23 | −8.15 | −6.80 | 0.22   | −0.033 |
| 54  | 202.489953 | 47.180183 | 1.08 | 56.7 | −7.11 | −5.65 | −5.86 | −5.42 | 0.065 | −0.21 |

3. We calculated a reduced chi-square statistic, χ^2, as a measurement of the broad flux variability in a 30 day window of the longest seven observations for the X-ray sources in our catalog and found that approximately 86% of the sources are considered variable, i.e., χ^2 ≥ 1.

4. Approximately 69% of the sources with at least one detected candidate stellar counterpart (but no cluster counterpart) are considered variable, and about 77% of the sources without a stellar counterpart are variable (see our upcoming follow-up Paper II for a discussion of candidate cluster counterparts to our X-ray sources).

5. The majority of optical counterparts are above the 8 M_⊙ line in Figure 5, which is consistent with these sources being HMXB candidates.

6. There is a strong positive correlation between the broad X-ray flux and the variability of the X-ray sources in the 30 day window, consistent with the inter-observation variability in the CSC catalog.

7. We calculated X-ray HRs for all sources and found that the majority of the variable sources lie in the XRB region of the X-ray color–color diagram (e.g., hard or absorbed X-ray sources; see Figure 3).

8. The broad XLF above a few times 10^36 erg s^{-1} follows a power law N(>L_X) ∝ L_X^{-α} with α = 1.65 ± 0.03, consistent with XLFs of star-forming galaxies dominated by HMXBs.

9. Most of the brightest 20 sources do not show any evidence of flux variability.

10. Fewer than 10% of the X-ray sources have a broad X-ray luminosity greater than the Eddington luminosity of a typical NS accretor.

As mentioned earlier, a detailed analysis of individual sources will be presented in a follow-up paper.

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Software: CIAO (Fruscione et al. 2006), IRAF (Tody 1986, 1993), SAOImageDS9 (Joye & Mandel 2003), NumPy (Harris et al. 2020), SciPy (Virtanen et al. 2020), Matplotlib (Perez & Granger 2007), Astropy (Astropy Collaboration et al. 2013, 2018).

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