DEEP \textit{CHANDRA} MONITORING OBSERVATIONS OF NGC 3379: CATALOG OF SOURCE PROPERTIES

N. J. Brassington, G. Fabbiano, D.-W. Kim, and A. Zezas

Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138; nbrassington@head.cfa.harvard.edu

S. Zepp and A. Kundu
Department of Physics and Astronomy, Michigan State University, East Lansing, MI 48824-2320

L. Angelini
Laboratory for X-Ray Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771

R. L. Davies
Sub-Department of Astrophysics, University of Oxford, Oxford OX1 3RH, UK

J. Gallagher
Department of Astronomy, University of Wisconsin, Madison, WI 53706-1582

V. Kalogera and T. Fragos
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208

A. R. King
Theoretical Astrophysics Group, University of Leicester, Leicester LE1 7RH, UK

S. Pellegrini
Dipartimento di Astronomia, Universita di Bologna, Via Ranzani 1, 40127 Bologna, Italy

G. Trinchieri
INAF-Osservatorio Astronomico di Brera, Via Brera 28, 20121 Milan, Italy

Received 2007 October 26; accepted 2008 June 25

ABSTRACT

We present the properties of the discrete X-ray sources detected in our monitoring program of the ‘typical’ elliptical galaxy, NGC 3379, observed with \textit{Chandra} ACIS-S in five separate pointings, resulting in a co-added exposure of 324 ks. From this deep observation, 132 sources have been detected within the region overlapped by all observations, 98 of which lie within the $D_{25}$ ellipse of the galaxy. These 132 sources range in $L_X$ from $6 \times 10^{35}$ erg s$^{-1}$ (with 3 $\sigma$ upper limit $\leq 4 \times 10^{36}$ erg s$^{-1}$) to $\sim 2 \times 10^{37}$ erg s$^{-1}$, including one source with $L_X > 1 \times 10^{39}$ erg s$^{-1}$, which has been classified as a ULX. From optical data, 10 X-ray sources have been determined to be coincident with a globular cluster; these sources tend to have high X-ray luminosity, with three of these sources exhibiting $L_X > 1 \times 10^{38}$ erg s$^{-1}$. From X-ray source photometry, it has been determined that the majority of the 132 sources that have well constrained colors, have values that are consistent with typical LMXB spectra. In addition to this, a subpopulation of 10 sources has been found to exhibit very hard spectra and it is expected that most of these sources are absorbed background AGN. There are 64 sources in this population that exhibit long-term variability, indicating that they are accreting compact objects. Five of these sources have been identified as transient candidates, with a further 3 possible transients. Spectral variations have also been identified in the majority of the source population, where a diverse range of variability has been identified, indicating that there are many different source classes located within this galaxy.

Subject headings: galaxies: individual (NGC 3379) — X-rays: binaries — X-rays: galaxies

Online material: color figures, extended figure sets, machine-readable tables

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) are the only direct fossil evidence of the formation and evolution of binary stars in the old stellar populations of early-type galaxies. First discovered in the Milky Way (see Giacconi 1974), these binaries are composed of a compact accretor, neutron star or black hole, and a late-type stellar donor. The origin and evolution of Galactic LMXBs has been the subject of much discussion, centered on two main evolution paths (see Grindlay 1984; review by Verbunt & Van den Heuvel 1995): the evolution of primordial binary systems in the stellar field, or their formation and evolution in globular clusters (GCs).

With the advent of \textit{Chandra} (Weisskopf et al. 2000), many LMXB populations have been discovered in early-type galaxies (see review Fabbiano 2006), and the same evolutionary themes (field or GC formation and evolution) have again surfaced, supported and stimulated by a considerably larger and growing body of data. These \textit{Chandra} observations have provided important results on the spatial distributions and X-ray luminosity functions of LMXB populations (e.g., Kim & Fabbiano 2004; Gilfanov 2004), their average spectra, and their association with GCs (e.g., Angelini et al. 2001; Kundu et al. 2002; White et al. 2002; Sivakoff et al. 2007b). However, most of the \textit{Chandra} observations of LMXB systems so far consist of fairly shallow individual snapshots for each observed galaxy, with limiting luminosity ($\sim 0.3$–8.0 keV) of a few $10^{37}$ erg s$^{-1}$. These data give us information on the high luminosity LMXB sources, but do not cover the typical luminosity range of the well-studied LMXB populations of the Galaxy and M31, which extends down a decade toward dimmer
luminosities. Moreover, apart from rare exceptions, these observations do not have the time sampling that would permit variability studies and the identification of X-ray transients. However, from this limited sample of multipeoch observations with higher limiting luminosities, a variety of different variability behaviors of LMXBs have already been observed (e.g., Irwin 2006; Sivakoff et al. 2007a). Both multipeoch observations and low luminosity thresholds are important aspects of the observational characteristics of Galactic LMXBs and are needed to constrain the evolution of these populations (e.g., Piro & Bildsten 2002; Bildsten & Deloye 2004). For these reasons, we proposed (and were awarded) a very large program of monitoring observations of nearby elliptical galaxies with Chandra ACIS-S3.

NGC 3379, in the nearby poor group Leo (D = 10.6 Mpc; Tonry et al. 2001) was chosen for this study because is a relatively isolated, unperturbed “typical” elliptical galaxy, with an old stellar population (age of 9.3 Gyr; Terlevich & Forbes 2002) and a poor globular cluster system (S$_{GC}$ = 1.3 ± 0.7, where S$_{GC}$ = N$_{GC}$$10^{-0.4(M_{V}+15)}$; Harris 1991). These characteristics make NGC 3379 ideal for exploring the evolution of LMXB from primordial field binaries.

Observationally, NGC 3379 is an ideal target for LMXB population studies, because of its proximity, resulting in a resolution of ~30 pc with Chandra, and the lack of a prominent hot gaseous halo, demonstrated by a previous short Chandra observation (David et al. 2005). These characteristics optimize the detection of fainter LMXBs, and minimize source confusion; because of its angular diameter ($D_{25} = 4.6$, RC 3), NGC 3379 is entirely contained in the ACIS-S3 CCD chip, and is not affected by the degradation of the Chandra PSF at large radii.

Here we publish the catalog of LMXBs with their properties resulting from the entire observational campaign of NGC 3379 (four observations between 2006 January and 2007 January, for a total of ~300 ks), which has been recently completed, and including the first 30 ks observation taken in 2001, from the Chandra archive. In the companion paper (Fabbiano et al. 2007) we summarize our results relative to GC-LMXB associations and discuss their implications for our understanding of LMXB formation.

In addition to these two papers, further highlights from the X-ray binary population of NGC 3379 will be presented in N. J. Brassington et al. (2008, in preparation), where the properties of the transient population of NGC 3379 will be presented. Forthcoming papers will also present the properties of the ULX, the X-ray luminosity function, and the diffuse emission of the galaxy, as well as the properties of the nuclear source and the intensity and spectral variability of the luminous X-ray binary population. Preliminary results from the first Chandra observations of our program were reported in Kim et al. (2006) and Fabbiano et al. (2006). This paper is organized as follows: § 2. details the observational program and describes the data analysis methods and results, including pipeline processing of the data, source detection, astrometry and matching of sources from the different observations, X-ray photometry and overall population results, variability analysis, and optical counterpart matching (GC and background objects); § 3 is the source catalog, including the results from the individual observations and the co-added data; § 4 presents the discussion of the properties of the sources catalog; and § 5 summarizes the conclusions of this work.

2. OBSERVATIONS AND DATA ANALYSIS

The five separate Chandra observations of NGC 3379 have been carried out over a 6 yr baseline, with the first of these, a 30 ks pointing, performed in 2001 February. This observation was followed by four deeper pointings, all carried out between 2006 January and 2007 January, resulting in a total exposure time of 337 ks.

The initial data processing to correct for the motion of the spacecraft and apply instrument calibration was carried out with the Standard Data Processing (SDP) at the Chandra X-ray Center (CXC). The data products were then analyzed using the CXC CIAO software suite (v3.4) and HEASOFT (v5.3.1). The data were reprocessed, screened for bad pixels, and time filtered to remove periods of high background. Following the methods of Kim et al. (2004b), time filtering was done by making a background light curve and then excluding those time intervals beyond a 3 $\sigma$ fluctuation above the mean background count rate, where the mean rate was determined iteratively after excluding the high-background intervals. This resulted in a total corrected exposure time of 324 ks; the log of these exposures is presented in Table 1.

From the five individual data sets, a combined observation has been produced. This has been created by using the merge_all script, where the reprocessed level 2 event files from each observation were reprojected to a given R.A. and decl., and then combined, and a combined exposure map was also created. The methods that were applied to correct for the astrometry of the individual observations, used to create the co-added observation, are discussed in § 2.2.

From this combined data set, a 0.3–8.0 keV (from here on referred to as “full band”) Chandra image was created and adaptively smoothed using the CIAO task camsmooth. This uses a smoothing kernel to preserve an approximately constant signal-to-noise ratio (S/N) across the image, which was constrained to be between 2.6 and 4 $\sigma$. In Figure 1, both the optical image, with the full-band X-ray contours overlaid (top), and the “true color” image of the galaxy system (bottom) are shown. The “true color” image was created by combining three separate smoothed and exposure-corrected images in three energy bands, 0.3–0.9 keV, 0.9–2.5 keV, and 2.5–8.0 keV, using the same smoothing scale for each image. These energy bands correspond to red, green, and blue, respectively.

2.1. Source Detection and Count Extraction Regions

Discrete X-ray sources were searched for over each observation (the five single observations and the combined observation) using the CIAO tool wavdetect, where the full band, with a significance threshold parameter of 1 $\times$ 10$^{-6}$, corresponding to roughly one spurious source over one CCD, was searched over. This CIAO tool searches for localized enhancements of the X-ray emission, and does not set any a priori thresholds on the S/N of

| Obs. No. | ObsID | Date     | Exposure (s) | Cleaned Exposure (s) |
|---------|-------|----------|--------------|----------------------|
| 1........... | 1587  | 2001 Feb 13 | 31519.0 | 28951.9 |
| 2........... | 7073  | 2006 Jan 23 | 84099.0 | 80347.1 |
| 3........... | 7074  | 2006 Apr 09 | 69066.2 | 66696.6 |
| 4........... | 7075  | 2006 Jul 03 | 83110.1 | 79555.7 |
| 5........... | 7076  | 2007 Jan 10 | 69249.5 | 68657.1 |
| Total ........... | ...... | ...... | 337043.8 | 324208.4 |

---

1 See http://asc.harvard.edu/ciao.
2 See http://asc.harvard.edu/ciao/ahelp/merge_all.html.
When running wavdetect, a range of 1, 2, 4, 8, 16, and 32 pixel wavelet scales were selected (where pixel width is 0.49”), with all other parameters set at the default values. Exposure maps were created for the S3 chip from each observation, at 1.5 keV. The wavdetect tool was used in preference to other source-detection software, as this detection package can be used within the low-counts regime, as it does not require a minimum number of background counts per pixel for accurate computation of source detection thresholds. Furthermore, wavdetect also performs better in confused regions, such as the nuclear regions of elliptical galaxies (Freeman et al. 2002).

Once the X-ray sources had been detected, and their position had been determined by wavdetect, counts were extracted from a circular region, centered on the wavdetect position, with background counts determined locally, in an annulus surrounding the source, following the prescription of Kim et al. (2004b). The extraction radius for each source was chosen to be the 95% encircled energy radius at 1.5 keV (which varies as a function of the off-axis angle5), with a minimum of 3” near the aim point. Similarly, background counts for each source were estimated from a concentric annulus, with inner and outer radii of 2 and 5 times the source radius, respectively.

When nearby sources were found within the background region, they were excluded before measuring the background counts. Net count rates were then calculated with the effective exposure (including vignetting) for both the source and background regions. Errors on counts were derived following Gehrels (1986). For cases where sources have fewer than 4 counts, the Gehrels approximation begins to differ to Poissonian errors. However, these error values are still accurate to 1%, and, if anything, provide a more conservative estimate, since the Gehrels approximation does not account for the smaller error value at the lower limit. When the source-extraction regions of nearby regions were found to overlap, to avoid an overestimate of their source count rates, counts were calculated from a pie-sector, excluding the nearby source region, and then rescaled, based on the area ratio of the chosen pie to the full circular region. Once the correction factor was determined, it was applied to correct the counts in all energy bands. For a small number of sources that overlapped with nearby sources in a more complex way (e.g., overlapped with more than 2 sources), instead of correcting the aperture photometry, the source cell determined by wavdetect was used to extract the source counts.

From these source counts, fluxes and luminosities were calculated in the 0.3–8.0 keV band, with an energy conversion factor (ECF) corresponding to an assumed power-law spectral shape, with $\Gamma = 1.7$ and Galactic $N_H^4$ (see Fig. 11 for a justification of this assumption). The ECF was calculated with the arf (auxiliary response file) and the rmf (redistribution matrix file) generated for each source in each observation. For each source, the temporal quantum efficiency variation5 was accounted for by calculating the ECF in each observation and then taking an exposure-weighted mean ECF. The ECF over the 0.3–8.0 keV band varied by ~14% between 2001 and 2006, and by only ~0.3% between the four observations taken in 2006.6 This procedure was applied to each single observation and to the total co-added exposure.

3 See http://cxc.harvard.edu/cal/Hrma/psf/index.html.
4 $N_H = 2.78 \times 10^{20}$ cm$^{-2}$ (from COLDEN: http://cxc.harvard.edu/toolkit/colden.jsp).
5 See http://cxc.harvard.edu/cal/Acis/Cal__prod/qsDeg/ for the low-energy QE degradation.
6 See http://asc.harvard.edu/ciao/why/acisqdeg.html.

Fig. 1.—Top: Optical image of NGC 3379, with full-band, adaptively smoothed X-ray contours overlaid. Also shown is the outline of the total area covered by the ACIS-S3 chips, from the five separate observations, and the smaller region overlapped by all five of the pointings. Bottom: A “true-color” image of the galaxy, where red corresponds to 0.3–0.8 keV, green to 0.8–2.5 keV, and blue to 2.5–8.0 keV. The $D_{25}$ ellipse of this galaxy, the coverage from all observations, and the overlapping region are also shown.

Each source (in contrast to sliding-cell algorithms; Freeman et al. 2002). In Kim et al. (2004b) simulations were carried out to investigate the number of false detections compared to the expected $\sim 1$ false source per image provided by the threshold significance of $1 \times 10^{-6}$. These simulations and results are detailed in § 4.4.1 of that paper, where they find that the performance of wavdetect is as expected, resulting in $\sim 1$ spurious source per image. These simulations cover the values of background ($\sim 0.2$ counts pixel$^{-1}$) of our co-added observation. These simulations were then compared to Chandra observations with relatively long exposures ($\sim 100$ ks), where 0.3 spurious sources per exposure were detected, fully consistent with the simulation results. A similar approach was also used by Kenter et al. (2005).

Following the results of these simulations, it is clear that, when setting a detection threshold of $1 \times 10^{-6}$ in wavdetect, only one of the formally identified sources per image is expected to be a false detection, and so this prescription has been followed here. We reiterate that using this method does not set any a priori thresholds on the S/N of each source; it is therefore possible to include sources that have a high detection significance but at the same time a low flux significance, or S/N, therefore resulting in sources with poorly constrained flux.
In the instances where wavdetect did not formally identify a source in a single observation, source counts have been extracted from a circle with a 95% encircled energy radius, centered on the position from the co-added observation (or in cases where the source was not formally detected in the co-added observation, the source position from the single observation was used). The definition of background regions and the treatment of overlapping sources are outlined above. From these extracted source counts, a Bayesian approach, developed by Park et al. (2006), has been used to provide 68% source intensity upper confidence bounds on the full-band counts. These values have then been used to calculate upper limits on the flux and luminosity of these sources.

### 2.2. Astrometry and Source Correlation

Prior to merging the five exposures into a single co-added observation, the astrometry of the individual pointings was checked, to correct for any systematic shifts in the coordinate systems of the event lists. This was done by selecting the longest single observation, Obs. 7073, as a point of reference, and then comparing the positions of the 20 brightest point sources detected in all five separate observations to the source positions of these 20 sources in each of the individual observations. From these comparisons it was found that the fifth observation, Obs. 7076, showed a significant declination offset of 0.44”, compared to values less than 0.2” in all other observations. It is believed that this systematic offset is a result of a change in thermal environment, following the procedure to cool the ACA CCD from −15°C to −19°C, which took place between late November 2006 and early January 2007.\(^7\)

At the time of data processing, there were no calibration files to correct for this offset, and therefore offsets had to be defined and corrected for individually.\(^8\) This was done by producing a co-added file of the first four individual observations, all of which show offset values of ≤0.2” in both R.A. and decl. from the single reference observation. With this co-added observation, the CIAO tool reproject_aspect was used calculate offset values for the fifth observation, and from these, produce a new, corrected aspect solution file, which was used to create a new level 2 event file. This new corrected event file, alongside the four other individual observations, was then combined to produce a co-added observation, using the merge_all script, as described in § 2. From this co-added file the astrometry was once again checked; a summary of these offset values is given in Table 2, where it can be seen that all five of the individual observations have offsets of ≤0.12” in both R.A. and decl. when compared to the corrected, co-added observation.

From the co-added observation only, 164 sources were detected by wavdetect. From this list, sources external to the overlapping area covered by the S3 chip in all five individual observations were excluded, reducing this total number to 125 point sources. Using this source list from the co-added observation, sources detected in the individual observations were matched with this combined observation source list, where source correlations were searched for up to a separation of 3”. In the cases where multiple matches were detected for a source, the closer correlation was selected. From these matches, a histogram of source separations, shown in the left panel of Figure 2, was produced. In this figure it is clear that the peak separation between sources lies at ∼0.2”, with the number of correlated sources dropping at ∼1.6”, and this is therefore the value we set for maximum separation when cross-correlating sources.

Once a cut of 1.6” had been applied to the cross-matched source list, the remaining unmatched sources, detected in the separate pointings only, were investigated individually, resulting in further matches being established. These matches correspond to sources with fewer counts, and hence a greater positional uncertainty, leading to larger values of separation. From the list of sources detected in individual observations, seven of these point sources were determined to be well separated from the sources detected in the co-added observation, and were therefore included in the final list of detected sources, increasing the total number of detected sources to 132.

These source correlations were then further investigated by calculating the ratio of the source separation and the combined position uncertainty. The position uncertainty at the 95% confidence level has been defined by Kim et al. (2007a) as

$$\log \text{PU} = \begin{cases} 0.1145 \text{OAA} - 0.4958 \log C \\ + 0.1932, \quad 0.0000 < C \leq 2.1393, \\ 0.0968 \text{OAA} - 0.2064 \log C \\ - 0.4260, \quad 2.1393 < C \leq 3.3000, \end{cases}$$

where the position uncertainty, PU, is in arcseconds, and the off-axis angle, OAA, is in arcminutes. Source counts, C, are as extracted.

\(^7\) See http://cxc.harvard.edu/cal/ASPECT/celmon/.

\(^8\) Data between these dates have now been reprocessed to correct for this offset; see http://cxc.harvard.edu/bulletin/bulletin_64.html.
by wavdetect. Using this ratio of source separation and position uncertainty allows low-L_X source correlations to be identified. Often these sources, particularly at greater off-axis angles, cannot be matched by source-separation cuts alone, due to the increasing PSF spread and asymmetry at larger OAA. Therefore, by using this source-separation/PU ratio, the greater position uncertainties in these weak sources can be accounted for, resulting in smaller ratios, and thereby identifying correlations that would otherwise be missed with source-separation cuts alone.

In the right panel of Figure 2, a histogram of the ratio of separation and the combined position uncertainty is shown, where sources with a ratio of greater than 1 were investigated individually. In all but two instances it was found that these higher ratio sources lie in the central region of the galaxy, where source confusion is likely and diffuse gas is also present. This emission results in higher background fluctuations, which can lead the PU of these sources to be underestimated, therefore resulting in a falsely high ratio value. For the two sources that were detected outside the central region, both are too faint (net counts < 100) to allow their radial profiles to be compared with corresponding model PSF profiles, generated for the position of each source using the CIAO tool mkpsf, and have been flagged as possible double sources.

From this complete list, light curves were produced for sources with net counts < 20, which were detected in single observations, to screen for the possibility of false sources by cosmic-ray afterglows. None of the 24 sources that were examined exhibited light curves consistent with cosmic-ray afterglows, as is expected from the S3 chip (a back-illuminated CCD), due to this problem mostly occurring in the front-illuminated chips. From this screening, the total number of detected point sources remains at 132. These sources are presented in Figure 3, which shows the unsmeared full-band image from the co-added data set, with regions overlaid in white.

2.3. Hardness Ratios and X-Ray Colors

Within NGC 3379, the range of net counts for the pointlike sources in the co-added observation is ~2–7200 (with S/N values ranging from 0.5 to 83.7), corresponding to 0.3–8.0 keV luminosities of 6 × 10^{35} erg s^{-1} (3 σ upper limit ≤ 4 × 10^{36} erg s^{-1}) –2 × 10^{39} erg s^{-1}, when using the energy conversion factor described in § 2.1. Most of these sources are too faint for detailed spectral analysis; therefore, their hardness ratio and X-ray colors were calculated in order to characterize their spectral properties. The X-ray hardness ratio is defined as HR = (Hc – Sc)/(Hc + Sc), where Sc and Hc are the net counts in the 0.5–2.0 keV and 2.0–8.0 keV bands, respectively. Following the prescription of Kim et al. (2004a), the X-ray colors are defined as C21 = log(S1/S2) and C32 = log(S2/H), where S1, S2, and H are the net counts in the energy bands 0.3–0.9 keV, 0.9–2.5 keV, and 2.5–8.0 keV, respectively (energy bands and definitions are summarized in Table 3). These counts were corrected for the temporal QE variation, referring them all to the first, recent observing epoch (2006 January; Table 1), and for the effects of Galactic absorption, using N_H = 2.78 × 10^{20} cm^{-2}.10

By definition, as the X-ray spectra become harder, the HR increases and the X-ray colors decrease. For faint sources with a small number of counts, the formal calculation of the HR and colors often results in unreliable errors, because of negative net counts in one band and an asymmetric Poisson distribution. Therefore, a Bayesian approach has been applied to derive the uncertainties associated with the HR and colors. This model was developed by Park et al. (2006), and calculates values using a method based on the Bayesian estimation of the “real” source intensity, which takes into account the Poisson nature of the probability distribution of the source and background counts, as well as the effective area at the position of the source (van Dyk et al. 2001), resulting in HR and color values that are more accurate than the classical method, especially in the small-counts regime (less than 10 counts), where the Poisson distributions become distinctly asymmetric. More details of this technique and the source and background counts used in the derivation of the HR, color values, and 1 σ confidence bounds are provided in Appendix A.

2.4. Source Variability

Due to the monitoring approach that has been used when observing NGC 3379, both long-term and short-term variations can

---

9 See § 5 in Kim et al. (2004b) for a full discussion.

10 From COLDEN: http://cxc.harvard.edu/toolkit/colden.jsp.
be searched for in the galaxy’s LMXB population. Long-term variability was defined by the $\chi^2$ test, where a straight line model was fitted to the luminosities derived for each individual observation, with errors based on the Gehrels approximation (Gehrels 1986). For cases where sources only had upper limit values of $L_X$, the associated error was defined to be the standard deviation of the upper limit from the mode value attained from the Bayesian estimates method, resulting in a conservatively large error, due to the nature of the Poissonian statistics. From these best-fit models, sources were determined to be variable if $\chi^2 > 1$, and those with fits with $\chi^2 < 1$ were defined as nonvariable sources. For sources that were only detected in the co-added observation, long-term variability was not searched for. This long-term behavior will be further investigated in a forthcoming paper, where a full Poissonian error treatment will be applied to sources with very low observed counts.

In addition to the $\chi^2$ test variability criterion, transient candidates (TC), sources that either appear or disappear, or are only detected for a limited amount of “contiguous” time during the observations, were searched for. Typically, sources are defined to be TCs if the ratio between the “on-state,” the peak $L_X$ luminosity, and the off-state,” the lower $L_X$ luminosity or nondetection upper limit, is greater than a certain value (usually between 5 and 10; e.g., Williams et al. 2008). However, such a criterion can overestimate the number of transient candidates, when the on-state X-ray luminosity is poorly constrained. To address this, the Bayesian model developed by Park et al. (2006) was used to derive the uncertainties associated with the ratio between the on-state and the off-state. In this model, source and background counts from both the peak $L_X$ luminosity and the nondetection observations were used to estimate the ratio, where the differences in the exposure and ECF values were also accounted for. From this Bayesian approach, a value of the peak $L_X$/nondetection upper limit was calculated, along with a lower bound value of this ratio. This lower bound value was then used to determine the transient nature of the source, where a ratio of greater than 10 indicated a TC, and sources with a ratio between 5 and 10 were labeled as possible transient candidates (PTC). This transient behavior was only searched for in sources that were only detected for a limited amount of contiguous time during the observations and were determined to be variable using the $\chi^2$ test.

In addition to these four long-term variability classifications, the variation of the source luminosity between each observation was also investigated, by comparing the significance (in $\sigma$) of the change in luminosity between exposures, where the significance has been estimated by

$$\text{sign} = \frac{|L_{X1} - L_{X2}|}{\sqrt{\sigma_1^2 + \sigma_2^2}},$$

where $\sigma_n$ is the error value of the luminosity from that individual observation, based on the Gehrels approximation, or, where upper limits have been used, the standard deviation of the estimated luminosity.

Short-term variations in each source were investigated when net counts $> 20$ in a single observation. In these instances, the variability was identified by using the Kolmogorov-Smirnov (K-S) test, where sources with variability values >90% confidence
were labeled as possible variable sources, and sources with values >99% confidence were defined as variable sources. This short-term variability was also quantified by using the Bayesian blocks (BB) method (Scargle 1998; J. D. Scargle et al. 2008, in preparation). This method searches for abrupt changes in the source intensity during an observation, and therefore is very efficient at detecting bursts or state changes. Because it is based on the Poisson likelihood, it can be used on the unbinned light curves of sources with very few counts. The implementation of the method used in this analysis is the same as in the ChaMP pipeline (see § 3.3.2 in Kim et al. 2004b). This assumes a prior of $C_1 / C_2 = 4/0$, which roughly translates to a significance level of ~99% for each detected block (however, see J. D. Scargle et al. 2008, in preparation, for a caveat on this interpretation of the value of the prior).

See also http://space.mit.edu/CXC/analysis/SITAR/functions.html.

---

**TABLE 3**

**Definition of Energy Bands and X-Ray Colors**

| Band            | Definition          |
|-----------------|---------------------|
| Broad (B)       | 0.3–8 keV           |
| Soft (S)        | 0.3–2.5 keV         |
| Hard (H)        | 2.5–8 keV           |
| Soft 1 (S₁)     | 0.3–0.9 keV         |
| Soft 2 (S₂)     | 0.9–2.5 keV         |
| Conventional broad (Bc) | 0.5–8 keV   |
| Conventional soft (Sc) | 0.5–2 keV   |
| Conventional hard (Hc) | 2–8 keV    |
| Hardness ratio HR | $(Hc−Sc)/(Hc+Sc)$  |
| X-ray color C21 | $−\log (S_2) + \log (S_1) = \log (S_1/S_2)$ |
| X-ray color C32 | $−\log (H) + \log (S_2) = \log (S_2/H)$ |

Fig. 3—Continued
2.5. Radial Profile

From the complete source list from the co-added observation, a radial distribution of LMXBs has been created, using annuli centered on the nucleus of the galaxy (source 81). This profile has been compared to a multi-Gaussian expansion model of the I-band optical data (Cappellari et al. 2006), which is assumed to follow the stellar mass of the galaxy (Gilfanov 2004). This X-ray source density profile is presented in Figure 4, where the optical profile has been normalized to the X-ray data by way of a $\chi^2$ fit. Also indicated in this figure is the $D_{25}$ ellipse and the horizontal dot-dashed line indicates the expected number of background sources.

![Figure 4](image1.png)

**Fig. 4.**—X-ray source density profile compared to the optical profile. The histogram indicates the X-ray data, and the thick black line is the I-band surface brightness best fit of Cappellari et al. (2006). The vertical dashed line is the $D_{25}$ ellipse, and the horizontal dot-dashed line indicates the expected number of background sources.

2.6. Optical Counterparts

The globular cluster system of NGC 3379, observed with WFCPC2 on-board HST, is reported in Kundu & Whitmore (2001), where images in both the $V$ and $I$ bands have been analyzed. In addition to this GC system identified in the HST data, background objects have also been classified (A. Kundu 2007, private communication). These have been identified as objects that were well-resolved in the HST images and were clearly more extended than any known globular cluster. These background objects also often had other features, such as visible disks, indicative of a galaxy rather than a globular cluster. In addition to the HST data, radial velocities and $B-R$ values of spectroscopically confirmed GCs within this galaxy have been reported in Bergond et al. (2006), Puzia et al. (2004), and Pierce et al. (2006). Further BVR photometry information is provided by images obtained with the Mosaic detector on the Kitt Peak 4 m telescope (Rhode & Zepf 2004).

Right ascension and declination corrections have been applied to the astrometry of these data sets, relative to the co-added Chandra observation. These offsets were calculated and corrected for using the methods described in § 2.2, where correlations between the X-ray and optical sources were made, and systematic offsets in RA and decl. were removed. In the case of the Rhode & Zepf (2004) data, only two correlations were found between the X-ray and optical sources; therefore, the corrected HST data were used to make these offset adjustments.

After correcting the astrometry of the optical data, correlations up to an offset of 3$''$ with the X-ray sources were searched for. When multiple matches were found, the closer matching object was selected. In the left panel of Figure 5, a histogram of these matches is shown, where it can be seen that, due to the poor statistics, it is not clear where the separation cut off should be made. Initially, this was set to 1$''$, and sources between 1$''$ and 3$''$ were

![Figure 5](image2.png)

**Fig. 5.**—Left:Histogram of the separation between the co-added X-ray source position and the optical counterpart. Right: Histogram of the ratio of separation divided by the position uncertainty from the X-ray point source for all optical–X-ray correlations with separations smaller than 1$''$. Shaded regions indicate correlations with optical objects that have been classified as background sources (details of this classification are given in the text).
defined as “excluded matches.” This cutoff value was then tested by comparing these correlations with the ratio of the separation divided by the combined position uncertainty from the co-added X-ray point sources (this definition is given in eq. [1]) and the uncertainty in the astrometry in the optical data, which has been conservatively set at 0.2”. These ratios are shown in the right panel in Figure 5, where a histogram of all optical–X-ray correlations is presented, with a shaded histogram of the background correlations only overlaid. From this figure, it can be seen that the correlated sources with a separation/position uncertainty ratio of greater than 2 are background objects. Both of these objects have separations >0.9”, and from both of the histograms presented in Figure 5, the separation value cutoff was redefined to be 0.6”. This results in 14 X-ray–optical correlations, 4 of which have been classified as background objects, leaving 10 GC–X-ray source correlations, one of which lies outside the HST FOV, although this source has been detected in two separate studies (Bergond et al. 2006; Rhode & Zepf 2004). The optical properties of these GC–LMXB sources and the excluded matches are shown in Tables 11 and 12, respectively (full descriptions of these tables are given in § 3).

In order to estimate the chance coincidence probability of the sources within the HST FOV, the same method as in Zezas et al. (2002) was followed, where the positions of the globular clusters were randomized by adding a random shift between 0.6” and 30”, and for each new fake data set the cross-correlation was performed using the same search radius as for the observed list of globular clusters. The limits of the shifts were chosen so that the new positions did not fall within the search radius and so that they follow the general spatial distribution of the globular clusters. A total of 500 such simulations were performed, resulting in 0.35 ± 0.59 associations expected by chance. If the cross-correlation radius is increased to 1”, the chance associations rises to 0.5 ± 1.1. Increasing this radius to 3” results in 8.4 ± 14.2 associations expected by chance, which compares well with the nine excluded matches that have been found within this radius.

The 10 GC–X-ray correlations that have been found in NGC 3379 are shown in Figure 6, where an X-ray image with confirmed GCs is shown. In this figure the GCs are indicated by white crosses, and the corresponding X-ray sources are indicated by square regions, sources that are “excluded matches” are indicated with a diamond region, and X-ray sources without a GC counterpart are shown as circular regions. X-ray luminosities are also shown, where sources with $L_X \geq 1 \times 10^{38}$ erg s$^{-1}$ are shown in yellow, sources with $1 \times 10^{38} \geq L_X \geq 1 \times 10^{37}$ erg s$^{-1}$ are shown in red, and sources with $L_X \leq 1 \times 10^{37}$ erg s$^{-1}$ are indicated in cyan.

3. SOURCE CATALOG AND VARIABILITY ATLAS

Table 4 presents the properties of the master list of the 132 X-ray sources detected within NGC 3379, from the co-added...
### TABLE 4
**MASTER SOURCE LIST**

| MASTER ID (1) | CXOU NAME (2) | R.A. (J2000) (3) | DECL. (J2000) (4) | RADIUS (arcsec) (5) | PU (arcsec) (6) | S/N (7) | log \( L_x \) (0.3–8.0 keV) (8) | LT (9) | BB (10) | K-S (11) | OPTICAL CORRELATION (12) | DG (arcsec) (13) | FLAG (14) |
|---------------|---------------|------------------|------------------|---------------------|-----------------|--------|----------------------|------|------|--------|------------------------|---------------|--------|
| 1....................... | J104806.4+123621 | 10:48 06.4 | +12 36 21.0 | 3.13 | 0.54 | 5.8 | 37.3 | V | ... | ... | ... | ... | ... |
| 2....................... | J104806.2+123534 | 10 48 06.2 | +12 35 34.3 | 3.10 | 0.68 | 4.2 | 37.1 | V | ... | ... | ... | ... | 261.1 |
| 3....................... | J104805.5+123423 | 10 48 05.5 | +12 34 22.7 | 3.29 | 1.09 | 3.5 | 37.0 | ... | ... | ... | ... | 246.3 |
| 7....................... | J104803.0+123438 | 10 48 03.0 | +12 34 37.8 | 3.00 | 0.68 | 4.4 | 37.1 | V | ... | ... | ... | ... | 235.5 |
| 8....................... | J104801.9+123607 | 10 48 01.9 | +12 36 07.2 | 3.00 | 0.72 | 3.1 | 36.9 | V | ... | ... | ... | ... | 197.5 |
| 9....................... | J104801.7+123145 | 10 48 01.7 | +12 31 44.8 | 4.42 | 0.27 | 30.0 | 38.5 | V | N | N | ... | ... | 259.4 |
| 10..................... | J104801.4+123426 | 10 48 01.4 | +12 34 26.4 | 3.00 | 1.28 | 3.4 | 36.9 | ... | ... | ... | ... | 175.5 |

**Notes.**—Table has been divided into two parts. The first part lists all sources with S/N > 3, in at least one observation. The second part lists the remaining sources, which have S/N < 3 in all observations. Col. (1): Source number. Col. (2): IAU name (following the convention CXOU Jhhmmss.s+/ddmmss). Cols. (3)–(4): right ascension and declination. Col. (5): Source extraction radius, in arcseconds. Col. (6): position uncertainty (from \( x^2, eq. [1] \)). Col. (7): signal-to-noise ratio. Col. (8): \( \log L_x \) (0.3–8.0 keV), assuming \( D = 10.6 \text{ Mpc} \) (for the sources with S/N < 3, \( 3 \sigma \) upper limits are also quoted in brackets). For sources only detected in a single observation, \( 1 \sigma \) upper limits from the co-added observation are quoted (with \( 3 \sigma \) upper limits from the detected observation presented in brackets). Col. (9): long-term source variability: (N) nonvariable sources, (V) variable sources, (TC) transient candidates, (PTC) possible transients. Cols. (10)–(11): Short-term variability, where (BB) indicates Bayesian block analysis and (K-S) indicates the Kolmogorov-Smirnov test. In both columns (N) indicates nonvariable in all observations, (V) variable in at least one observation, (P) possible variability in at least one observation. Col. (12): Optical associations: (GC) indicates that the optical source is a confirmed globular cluster, (BG) indicates that optical source is a background object, (corr) denotes matches that have been defined as correlations, and (exmt) denotes matches between 0.6" and 3" in separation; (none) indicates sources inside the field of view of the HST observation, but have no optical counterpart, (X) indicates sources within the HST FOV, but also within 5" of the nucleus. All other sources are external to the HST FOV. Col. (13): Distance from the Galactic center (in arcseconds), where values in parentheses indicate sources that lie within the \( D_{25} \) ellipse. Col. (14): Flag information: (X) sources detected in a single observation only, O1 and O2 overlapping sources (single and complicated cases, respectively), (BKG?) possible background objects and (double?) possible double sources. Table 4 is published in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content.
observation of 324 ks. This table has been divided into two sections, where the first part presents all sources with S/N > 3 in at least one observation, and the second part lists all sources with S/N < 3. In this table column (1) gives the source number used through out this series of papers, column (2) gives the IAU name (following the convention CXOU Jhhmss.s±dmmss), columns (3) and (4) give the R.A. and decl. of the source aperture, columns (5) and (6) give the radius and the position uncertainty (PU) of the source (both in arcseconds), column (7) gives the S/N, and column (8) gives the log value of the co-added luminosity in the 0.3–8.0 keV energy band (for sources with S/N < 3, 3 σ upper limit values are also presented in brackets). For sources detected in a single observation only, 1 σ upper limit from the co-added observation are shown, with 3 σ upper limit values from the detected observation presented in brackets. Column (9) provides information about the long-term variability of the source, indicating if the source is nonvariable (N), variable (V), a transient candidate (TC), or a possible transient (PTC). In all other cases the source was only detected in the combined observation, providing insufficient information to investigate long-term variability. In columns (10) and (11) the short-term variability of the source is indicated from both Bayesian block (BB) analysis and the Kolmogorov-Smirnov (K-S) test, where “V” indicates that the source is variable in at least one observation and “N” indicates that is has been found to be nonvariable in all five observations. In the K-S column, sources have also been labeled as possible variable sources (P) (see § 2.4 for further information). In all other cases there were insufficient counts to investigate the short-term variability. In column (12) the optical associations with the X-ray source are indicated, where “GC” indicates that the associated optical sources has been confirmed as a globular cluster, and “BG” indicates that the sources has been classified as a background object; in addition, “corr” denotes matches that have been defined as correlations, and “exmit” denotes the excluded matches, between 0.6” and 3” in separation. Sources with a “none” label were inside the field of view of the HST observation, but have no optical counterpart, and sources denoted with an “X” were within the HST FOV, but were also within 5” of the nucleus, and were therefore not considered for optical associations. All other sources were outside the HST FOV. Column (13) gives the distance from the galactic center (in arcseconds), where values in parentheses indicate sources that lie within the D_{25} ellipse. Column (14) provides source flag information, indicating sources that have been detected in a single observation only (X), overlapping sources (O_1 for single overlaps and O_2 for more complicated cases), possible background objects (BKG?) (see § 4.2 for details of this classification), and possible double sources (double?).

In this table, the 132 sources presented are the complete list detected by wavdetect, for which we estimate that ~1 source is a spurious detection (see § 2.1). Since this catalog of X-ray sources is intended to be as complete a study as possible, all detected sources are included in the complete list, although for sources with S/N < 3 source parameters such as flux, hardness ratio, and color values are not as well constrained as for sources with higher flux significance. We have therefore separated the table into two sections; the top presents sources with S/N > 3 in at least one observation and well-constrained properties, and the bottom lists the sources with low S/N values.

Table 5 presents the detailed source parameters from the co-added observation; column (1) gives the source number, columns (2)–(8) give the net counts, in each of the seven energy bands (see Table 3 for definitions of these bands), column (9) indicates the hardness ratio, columns (10) and (11) show the color–value colors, and column (12) gives the log value of the luminosity in the 0.3–8.0 keV energy band. Where sources were not detected in the co-added observation, upper limits for net broadband counts and L_X are given.

Tables 6–10 present the source parameters measured for each observation, where columns (1)–(11) provide the same information presented in Table 5; further provided in this table is source variability information, where columns (12)–(14) present results of Bayesian block analysis (BB), the Kolmogorov-Smirnov test (K-S), and the significance of the change in L_X between the previous observation and the current observation. Column (15) indicates the log value of the luminosity in the 0.3–8.0 keV energy band.

Table 11 presents the optical properties of the counterparts found from the optical data of NGC 3379, where 10 GCs and 4 background objects have been found to be coincident with X-ray sources. Table 12 summarizes the results for the excluded matches sources. In both tables, column (1) gives the X-ray source number, column (2) the V band magnitude, column (3) the I band magnitude, column (4) the V−I colors, column (5) the B−V colors, column (6) the V−R colors, column (7) the B−R colors, column (8) gives the radial velocity, column (9) the separation between the X-ray source and the GC, column (10) the ratio between separation and the combined position error, and column (11) gives the source of the GC information. The tables are separated into confirmed GCs (top section of table) and background objects (bottom section of table).

Figure Set 7 presents the intensity and spectral variability of each of the 132 X-ray sources, over all five pointings, where the temporal properties of each point source are shown in four separate panels. In the top panel the long-term light curve of each source is presented, with error bars indicating the 1 σ uncertainty in the intensity of the source, with upper limit values provided for sources that were not detected in a single observation. The second panel shows the hardness ratio variation of each source, and the bottom two panels show the temporal properties of C21 and C32 respectively. In all four panels, the co-added values are also indicated by a horizontal dashed line.

Figure Set 8 presents the L_X–HR plots for sources with measured hardness ratios in at least two observations. Each point shows the X-ray luminosity and hardness ratio value of a source during each pointing, as well as the values derived from the co-added observation. Each point is labeled to indicate observations 1–5, and the solid box represents the co-added observation value. Similarly, Figure Set 9 presents the color-color values for sources with measured color-color values in at least two observations, where again individual observations are labeled and the co-added observation is indicated by the solid box.

4. DISCUSSION

4.1. X-Ray Source Population

In the previous sections the data analysis methods used to determine the properties of the X-ray binary population of NGC 3379 have been presented. From the five individual Chandra pointings, taken between 2001 February and 2007 January, a co-added observation, totaling an exposure time of 324 ks, has been produced. From this deep observation of the galaxy, 132 X-ray point sources have been detected in the region overlapped by all of the individual pointings, with 98 of these sources residing within the D_{25} ellipse of the system. These 132 sources are presented in Figure 3, where a raw, full-band image from the
## TABLE 5
### SOURCE COUNTS, HARDNESS RATIOS, AND COLOR-COLOR VALUES: CO-ADDED OBSERVATIONS

| Net Counts | Net Counts |
|------------|------------|
| B Band     | S1 Band    | S2 Band     | S Band     | H Band     | Sc Band     | He Band     | HR         | HR         | C32        | log $L_X$(0.3–8.0 keV) |
| (1)        | (2)        | (3)         | (4)        | (5)        | (6)         | (7)         | (8)        | (9)        | (10)       | (11)       | (12)       |
| 1............. | 58.9 ± 10.2 | 14.2 ± 5.6  | 36.4 ± 7.5 | 50.6 ± 8.9 | 8.3 ± 5.6   | 45.7 ± 8.3  | 11.9 ± 6.1 | -0.65 ± 0.13 | -0.31 ± 0.18 | 0.65 ± 0.34 | 37.3       |
| 2............. | 36.2 ± 8.7  | 1.5 ± 3.6   | 23.0 ± 6.5 | 24.5 ± 7.0 | 11.7 ± 5.8  | 24.8 ± 6.6  | 13.4 ± 6.1 | -0.39 ± 0.19 | -0.27 ± 0.15 | 0.30 ± 0.16 | 37.1       |
| 3............. | 28.9 ± 8.3  | 7.3 ± 4.7   | 15.1 ± 5.7 | 22.4 ± 6.9 | 6.5 ± 5.3   | 16.5 ± 5.9  | 9.1 ± 5.8  | -0.39 ± 0.19 | -0.22 ± 0.28 | 0.43 ± 0.40 | 37.0       |
| 4............. | 1.8 ± 3.6   | -0.1 ± 2.3  | -0.1 ± 2.3 | -0.2 ± 2.7 | 0.8 ± 2.7   | 1.7 ± 3.2   | 0.20 ± 0.18 | -0.12 ± 0.08 | -0.07 ± 0.07 | -0.38 ± 0.76 | 35.8       |
| 5............. | 4.6 ± 3.6   | -0.3 ± 1.9  | 2.6 ± 2.9  | 2.3 ± 2.9  | 1.6 ± 2.7   | 3.2 ± 3.2   | 0.29 ± 0.10 | -0.69 ± 0.09 | 0.08 ± 0.08 | 0.46 ± 0.46 | 36.2       |
| 6............. | ≤10.6       | …           | …         | …         | …         | …         | …         | …         | …         | …         | ≤36.6      |
| 7............. | 38.7 ± 8.8  | 7.0 ± 4.6   | 23.9 ± 6.5 | 30.8 ± 7.5 | 7.8 ± 5.3   | 23.1 ± 6.5 | 14.5 ± 6.2 | -0.31 ± 0.21 | -0.39 ± 0.21 | 0.44 ± 0.39 | 37.1       |
| 8............. | 24.7 ± 8.0  | 8.6 ± 4.7   | 15.4 ± 5.7 | 24.0 ± 6.9 | 0.7 ± 4.7   | 17.2 ± 5.9 | 3.0 ± 5.2  | -0.78 ± 0.22 | -0.13 ± 0.25 | 0.75 ± 0.45 | 36.9       |
| 9............. | 997.6 ± 33.2 | 271.4 ± 17.8 | 567.3 ± 25.0 | 838.7 ± 30.3 | 159.0 ± 14.4 | 725.7 ± 28.1 | 224.4 ± 16.7 | -0.58 ± 0.02 | -0.23 ± 0.04 | 0.59 ± 0.03 | 38.5       |
| 10............ | 27.9 ± 8.1  | 1.5 ± 3.8   | 3.5 ± 4.1  | 5.0 ± 5.1  | 22.9 ± 6.8  | 1.7 ± 4.0  | 25.6 ± 7.1 | 0.90 ± 0.10 | -0.11 ± 0.04 | -0.66 ± 0.56 | 36.9       |

Notes.—Col. (1): Master ID. Cols. (2)–(8): Net counts in each of the seven energy bands (see Table 3 for definitions of these bands). Col. (9): Hardness ratio. Cols. (10)–(11): Color values. Col. (12): log $L_X$ (0.3–8.0 keV). Upper limit $L_X$ values are at the 68% confidence level. Table 5 is published in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content.

## TABLE 6
### SOURCE COUNTS, HARDNESS RATIOS, COLOR-COLOR VALUES, AND Variability: Observation 1

| Net Counts | Variability | Variability |
|------------|-------------|-------------|
| B Band     | S1 Band     | S2 Band     | S Band     | H Band     | Sc Band     | He Band     | HR         | C21        | C32        | BB         | K-S        | Signif.     | log $L_X$ (erg s$^{-1}$) |
| (1)        | (2)         | (3)         | (4)        | (5)        | (6)         | (7)         | (8)        | (9)        | (10)       | (11)       | (12)       | (13)       | (14)       | (15)       |
| 1............. | 8.3 ± 4.3   | 2.6 ± 2.9   | 4.7 ± 3.4  | 7.3 ± 4.0  | 0.9 ± 2.7   | 6.6 ± 3.8   | 1.9 ± 2.9  | -0.66 ± 0.17 | -0.13 ± 0.32 | 0.53 ± 0.69 | …         | …         | …         | 37.5       |
| 2............. | ≤1.3        | …           | …         | …         | …         | …         | …         | …         | …         | …         | ≤36.7      | …         | …         | ≤36.7      |
| 3............. | ≤3.0        | …           | …         | …         | …         | …         | …         | …         | …         | …         | ≤37.0      | …         | …         | ≤37.0      |
| 4............. | ≤2.7        | …           | …         | …         | …         | …         | …         | …         | …         | …         | ≤36.2      | …         | …         | ≤36.2      |
| 5............. | ≤0.5        | …           | …         | …         | …         | …         | …         | …         | …         | …         | ≤36.9      | …         | …         | ≤36.9      |
| 6............. | ≤2.1        | …           | …         | …         | …         | …         | …         | …         | …         | …         | ≤36.9      | …         | …         | ≤36.9      |
| 7............. | 14.9 ± 5.1  | 4.7 ± 3.4   | 8.6 ± 4.1  | 13.3 ± 4.8 | 1.6 ± 2.7  | 12.4 ± 4.7 | 2.6 ± 2.9  | -0.68 ± 0.16 | -0.21 ± 0.24 | 0.64 ± 0.46 | …         | …         | …         | 37.7       |
| 8............. | ≤3.3        | …           | …         | …         | …         | …         | …         | …         | …         | …         | ≤37.0      | …         | …         | ≤37.0      |
| 9............. | 92.3 ± 10.8 | 41.9 ± 7.6  | 35.4 ± 7.1 | 77.3 ± 9.9 | 15.0 ± 5.2 | 62.0 ± 9.0 | 17.0 ± 5.4 | -0.58 ± 0.08 | 0.10 ± 0.09 | 0.39 ± 0.13 | N         | N         | …         | 38.5       |
| 10............ | ≤5.4        | …           | …         | …         | …         | …         | …         | …         | …         | …         | ≤37.2      | …         | …         | ≤37.2      |

Notes.—Col. (1): Master ID. Cols. (2)–(8): Net counts in each of the seven energy bands (see Table 3 for definitions of these bands). Col. (9): Hardness ratio. Cols. (10)–(11): Color values; errors are given as 1σ. Cols. (12)–(13): Short-term variability, where (BB) indicate Bayesian block analysis and (K-S) indicates the Kolmogorov-Smirnov test. In both columns (N) indicates nonvariable in all observations, (V) variable in at least one observation, (P) possible variability in at least one observation. Col. (14): Significance of the change in $L_X$ between the previous observation and the current observation (eq [2]). Col. (15): log $L_X$ (0.3–8.0 keV). Upper limit values of $B$ and $L_X$ are at the 68% confidence level. Table 6 is published in its entirety in the electronic edition of the *Astrophysical Journal Supplement*. A portion is shown here for guidance regarding its form and content.
### TABLE 7
**Source Counts, Hardness Ratios, Color-Color Values, and Variability: Observation 2**

| MID (1) | B Band (2) | S1 Band (3) | S2 Band (4) | S Band (5) | H Band (6) | Se Band (7) | He Band (8) | HR (9) | C21 (10) | C32 (11) | BB (12) | K-S (13) | Signif. (14) | log $L_X$ (erg s$^{-1}$) (15) |
|--------|------------|-------------|-------------|------------|------------|-------------|-------------|--------|----------|----------|--------|--------|--------------|-----------------------|
| 1........ | ≤16.6      | ...         | ...         | ...        | ...        | ...         | ...         | ...    | ...      | ...      | ...    | ...    | ...          | ≤37.4                |
| 2........ | ≤2.2       | ...         | ...         | ...        | ...        | ...         | ...         | ...    | ...      | ...      | ...    | ...    | ...          | ≤36.5                |
| 3........ | ≤9.9       | ...         | ...         | ...        | ...        | ...         | ...         | ...    | ...      | ...      | ...    | ...    | ...          | ≤37.1                |
| 4........ | ≤1.0       | ...         | ...         | ...        | ...        | ...         | ...         | ...    | ...      | ...      | ...    | ...    | ...          | ≤36.1                |
| 5........ | ≤1.4       | ...         | ...         | ...        | ...        | ...         | ...         | ...    | ...      | ...      | ...    | ...    | ...          | ≤36.3                |

... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ...)
## TABLE 9
### SOURCE COUNTS, HARDNESS RATIOS, COLOR-COLOR VALUES, AND VARIABILITY: OBSERVATION 4

| MID (1) | B Band (2) | S1 Band (3) | S2 Band (4) | S Band (5) | H Band (6) | Sc Band (7) | He Band (8) | HR (9) | C21 (10) | C32 (11) | BB (12) | K-S (13) | Signif. (14) | log $L_X$ (15) |
|---------|------------|-------------|-------------|------------|------------|-------------|-------------|--------|----------|----------|---------|----------|-------------|----------------|
| 1.............. | 24.3 ± 7.2 | 7.7 ± 4.3  | 13.3 ± 5.2  | 21.0 ± 6.3 | 3.3 ± 4.3  | 16.0 ± 5.6  | 5.5 ± 4.7  | -0.65 ± 0.21 | -0.03 ± 0.22 | 0.54 ± 0.01 | N | N | 2.7 | 37.6 |
| 2.............. | ≤16.1      | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤37.4 |
| 3.............. | ≤10.8      | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤37.2 |
| 4.............. | ≤0.8       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤36.1 |
| 5.............. | ≤2.4       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤36.6 |
| 6.............. | ≤2.5       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤36.6 |
| 7.............. | ≤6.3       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤37.1 |
| 8.............. | ≤0.7       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤36.0 |
| 9.............. | 244.4 ± 16.8 | 56.1 ± 8.6 | 147.9 ± 13.2 | 204.0 ± 15.4 | 40.3 ± 7.6 | 172.8 ± 14.2 | 62.0 ± 9.1 | -0.59 ± 0.04 | -0.14 ± 0.05 | 0.64 ± 0.08 | N | N | 7.0 | 38.6 |
| 10..........   | ≤17.1      | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤37.4 |

**Notes.**—Col. (1): Master ID. Cols. (2)–(8): Net counts in each of the seven energy bands (see Table 3 for definitions of these bands). Col. (9): Hardness ratio. Cols. (10)–(11): Color values; errors are given as 1σ. Cols. (12)–(13): Short-term variability, where (BB) indicate Bayesian block analysis and (K-S) indicates the Kolmogorov-Smirnov test. In both columns (N) indicates nonvariable in all observations, (V) variable in at least one observation, (P) possible variability in at least one observation. Col. (14): Significance of the change in $L_X$ between the previous observation and the current observation (eq. [2]). Col. (15): log $L_X$ (0.3–8.0 keV). Upper limit values of net B and $L_X$ are at the 68% confidence level. Table 9 is published in its entirety in the electronic edition of the Astrophysical Journal Supplement. A portion is shown here for guidance regarding its form and content.

## TABLE 10
### SOURCE COUNTS, HARDNESS RATIOS, COLOR-COLOR VALUES, AND VARIABILITY: OBSERVATION 5

| MID (1) | B Band (2) | S1 Band (3) | S2 Band (4) | S Band (5) | H Band (6) | Sc Band (7) | He Band (8) | HR (9) | C21 (10) | C32 (11) | BB (12) | K-S (13) | Signif. (14) | log $L_X$ (15) |
|---------|------------|-------------|-------------|------------|------------|-------------|-------------|--------|----------|----------|---------|----------|-------------|----------------|
| 1.............. | ≤16.3      | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤37.5 |
| 2.............. | 11.7 ± 5.2 | 0.9 ± 2.7  | 8.3 ± 4.3  | 9.2 ± 4.6  | 2.5 ± 3.4  | 9.6 ± 4.4  | 3.0 ± 3.6  | -0.66 ± 0.15 | -0.53 ± 0.38 | 0.46 ± 0.56 | N | N | 0.5 | 37.3 |
| 3.............. | ≤10.1      | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤37.2 |
| 4.............. | ≤2.0       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤36.5 |
| 5.............. | ≤1.7       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤36.4 |
| 6.............. | ≤5.4       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤36.9 |
| 7.............. | ≤8.0       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤37.1 |
| 8.............. | ≤14.7      | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤37.3 |
| 9.............. | 302.9 ± 18.8 | 83.9 ± 10.4 | 182.5 ± 14.6 | 266.5 ± 17.5 | 36.5 ± 7.5 | 237.5 ± 16.5 | 54.7 ± 8.9 | -0.68 ± 0.03 | -0.15 ± 0.05 | 0.75 ± 0.06 | N | N | 2.9 | 38.7 |
| 10...........  | ≤3.0       | ...        | ...         | ...        | ...        | ...         | ...         | ...      | ...      | ...      | ...      | ...      | ...         | ≤36.7 |

**Notes.**—Col. (1): Master ID. Cols. (2)–(8): Net counts in each of the seven energy bands (see Table 3 for definitions of these bands). Col. (9): Hardness ratio. Cols. (10)–(11): Color values; errors are given as 1σ. Cols. (12)–(13): Short-term variability, where (BB) indicate Bayesian block analysis and (K-S) indicates the Kolmogorov-Smirnov test. In both columns (N) indicates nonvariable in all observations, (V) variable in at least one observation, (P) possible variability in at least one observation. Col. (14): Significance of the change in $L_X$ between the previous observation and the current observation (eq. [2]). Col. (15): log $L_X$ (0.3–8.0 keV). Upper limit values of net B and $L_X$ are at the 68% confidence level. Table 10 is published in its entirety in the electronic edition of the Astrophysical Journal Supplement. A portion is shown here for guidance regarding its form and content.
### TABLE 11
**Properties of Optical Sources that Are Correlated with an X-Ray Point Source**

| Master ID | $V$-I | $B-V$ | $V-R$ | $V$ | Master ID | $V$-I | $B-V$ | $V-R$ | $V$ |
|-----------|-------|-------|-------|-----|-----------|-------|-------|-------|-----|
| 41................. | 21.148 ± 0.008 | 20.297 ± 0.010 | 0.851 ± 0.013 | ... | ... | ... | ... | ... | 
| 42................. | 21.880 ± 0.011 | 20.753 ± 0.012 | 1.127 ± 0.016 | 1.074 | 0.519 | 1.590 | 889 ± 7 | 0.307 | 1.31 |
| 43................. | 22.569 ± 0.022 | 21.307 ± 0.021 | 1.262 ± 0.030 | ... | ... | ... | ... | ... | 
| 44................. | 20.059 ± 0.004 | 19.007 ± 0.004 | 1.052 ± 0.006 | 1.240 | 0.77 ± 4 | 0.380 | 1.59 | 1, 4 |
| 45................. | 22.923 ± 0.032 | 22.094 ± 0.043 | 0.829 ± 0.054 | ... | ... | ... | ... | ... | 
| 46................. | 21.006 ± 0.010 | 19.877 ± 0.012 | 1.129 ± 0.016 | ... | ... | 1.260 | 1071 ± 18 | 0.146 | 0.54 |
| 47................. | 21.517 ± 0.013 | 20.334 ± 0.013 | 1.183 ± 0.018 | ... | ... | 1.310 | 1258 ± 38 | 0.174 | 0.67 |
| 48................. | 21.567 ± 0.025 | 20.702 ± 0.038 | 0.865 ± 0.045 | ... | ... | ... | ... | ... | 
| 49................. | 21.796 ± 0.013 | 20.765 ± 0.015 | 1.031 ± 0.020 | ... | ... | 1.260 | 546 ± 45 | 0.373 | 0.38 |
| 50................. | 21.180 | ... | ... | 0.988 | 0.560 | 1.550 | 1048 ± 4 | 0.380 | 1.07 |

**Background Objects**

| Master ID | $V$-I | $B-V$ | $V-R$ | $V$ |
|-----------|-------|-------|-------|-----|
| 31................. | 22.322 ± 0.060 | 21.751 ± 0.087 | 0.571 ± 0.106 | ... |
| 32................. | 23.396 ± 0.057 | 23.902 ± 0.388 | 1.494 ± 0.599 | ... |
| 33................. | 24.068 ± 0.274 | 22.775 ± 0.269 | 1.293 ± 0.384 | ... |
| 34................. | 23.482 ± 0.129 | 21.969 ± 0.107 | 1.513 ± 0.168 | ... |

**Note:**—The sources in the top section of the table have been confirmed as globular clusters, while those in the bottom section of the table have all been identified as background objects.

**References:**—(1) Bergond et al. 2006; (2) Puzia et al. 2004; (3) Pierce et al. 2006; (4) Kundu & Whitmore 2001, confirmed GCs; (5) Kundu & Whitmore 2001, background objects; (6) Rhode & Zepf 2004.

### TABLE 12
**Properties of Optical Sources Classified as Excluded Matches**

| Master ID | $V$-I | $B-V$ | $V-R$ | $V$ |
|-----------|-------|-------|-------|-----|
| 28................. | 23.213 ± 0.030 | 21.984 ± 6 | 1.229 ± 0.042 | ... |
| 29................. | 22.041 ± 0.014 | 20.931 ± 6 | 1.110 ± 0.020 | ... |
| 30................. | 25.379 ± 0.450 | 24.040 ± 6 | 1.339 ± 0.567 | ... |
| 41................. | 21.573 ± 0.012 | 20.474 ± 6 | 1.099 ± 0.019 | ... |
| 42................. | 23.782 ± 0.063 | 22.629 ± 6 | 1.153 ± 0.099 | ... |
| 43................. | 22.236 ± 0.050 | 22.105 ± 6 | 1.121 ± 0.076 | ... |
| 44................. | 24.061 ± 0.068 | 23.545 ± 6 | 0.516 ± 0.110 | ... |
| 45................. | 22.319 ± 0.077 | 21.253 ± 6 | 1.066 ± 0.118 | ... |
| 46................. | 21.102 ± 0.039 | 19.939 ± 6 | 1.163 ± 0.060 | ... |
| 47................. | 22.066 ± 0.027 | 21.336 ± 6 | 0.730 ± 0.046 | ... |

**Background Objects**

| Master ID | $V$-I | $B-V$ | $V-R$ | $V$ |
|-----------|-------|-------|-------|-----|
| 25................. | 25.714 ± 0.384 | 23.482 ± 6 | 2.232 ± 0.416 | ... |
| 26................. | 25.389 ± 0.324 | 24.637 ± 6 | 0.752 ± 0.606 | ... |
| 44................. | 25.060 ± 0.289 | 23.191 ± 6 | 1.869 ± 0.335 | ... |
| 45................. | 24.790 ± 0.264 | 23.367 ± 6 | 1.423 ± 0.351 | ... |
| 53................. | 24.132 ± 0.271 | 22.981 ± 6 | 1.151 ± 0.388 | ... |
| 54................. | 24.652 ± 0.472 | 23.622 ± 6 | 1.030 ± 0.704 | ... |
| 55................. | 24.742 ± 0.332 | 23.314 ± 6 | 1.428 ± 0.428 | ... |
| 56................. | 24.571 ± 0.373 | 23.416 ± 6 | 1.155 ± 0.520 | ... |
| 57................. | 24.382 ± 0.259 | 22.841 ± 6 | 1.541 ± 0.346 | ... |
| 58................. | 25.931 ± 0.933 | 25.401 ± 6 | 0.530 ± 1.854 | ... |
| 59................. | 24.419 ± 0.323 | 22.953 ± 6 | 1.466 ± 0.413 | ... |
| 60................. | 25.969 ± 1.380 | 22.659 ± 6 | 3.310 ± 1.396 | ... |
| 61................. | 25.756 ± 0.899 | 23.636 ± 6 | 2.120 ± 0.968 | ... |

**Notes:**—Excluded matches are sources detected within 0.6°–3° of an X-ray point source. The sources in the top section of the table have been confirmed as globular clusters, while those in the bottom section of the table have all been identified as background objects.

**References:**—(1) Bergond et al. 2006; (2) Puzia et al. 2004; (3) Pierce et al. 2006; (4) Kundu & Whitmore 2001, confirmed GCs; (5) Kundu & Whitmore 2001, background objects; (6) Rhode & Zepf 2004.
co-added observation, with the overlap region and $D_{25}$ ellipse overlaid, is presented in the main image, with source regions also indicated. The smaller images present the central region of the galaxy, where the dense population of sources can be more clearly seen. Of these 132 sources, based on the hard-band ChaMP+CDF log $N$–log $S$ relation (Kim et al. 2007b), $\sim$36 sources detected in the co-added observation are expected to be objects not associated with NGC 3379. Within the $D_{25}$ ellipse of the galaxy it is expected that $\sim$17 of these sources are background objects. In Figure 4 the number of expected background objects is indicated in the X-ray source number density profile of the galaxy.

The X-ray luminosity of the sources detected within NGC 3379 ranges from $6 \times 10^{35}$ erg s$^{-1}$ (with 3 $\sigma$ upper limit $\leq 4 \times 10^{36}$ erg s$^{-1}$) up to $2 \times 10^{39}$ erg s$^{-1}$, where the brightest source, 70, is the only ULX detected within this system. The properties of this source from the first two observations have been reported.
in Fabbiano et al. (2006), and the full analysis of the five individual pointings of the ULX will be presented in the forthcoming paper, L. Angelini et al. (2008, in preparation). The $L_X$ distribution of all of the detected X-ray sources within NGC 3379 is shown in Figure 10, where the GC associations are also indicated.

In this figure the main histogram presents the calculated $L_X$ values from all sources (with 1 $\sigma$ upper limits from the co-added observation provided for sources only detected in a single observation). The bottom left histogram presents these same sources, but for those with $S/N < 3$, 3 $\sigma$ upper limits are shown; these upper limit values are then presented separately in the bottom right histogram. From the main figure it can be seen that the GC–LMXB sources appear to predominantly lie at the high X-ray luminosity end of this distribution. The properties of these 10 GC–LMXB sources and their implications for understanding LMXB evolution in galaxies are presented and discussed in detail in the companion paper, Fabbiano et al. (2007). Also from this figure it can be seen that the majority of sources detected in this observation lie in the luminosity range of $5 \times 10^{36} - 5 \times 10^{37}$ erg s$^{-1}$, with a mode luminosity of $\sim 6 \times 10^{36}$ erg s$^{-1}$ and with source incompleteness beginning to affect the source distribution at $\sim 5 \times 10^{36}$ erg s$^{-1}$. From the histogram including 3 $\sigma$ upper

**Fig. Set 8.**—HR-$L_X$ plots for each source detected in more than one individual observation. Each individual observation is labeled, and the co-added observation is indicated by the solid box. The hardness ratios are defined to be $HR = H - S / H + S$, where $H$ is the number of counts in the hard band (2.0–8.0 keV) and $S$ is the number of counts in the soft band (0.5–2.0 keV). [See the electronic edition of the Supplement for all Figs. 8.1–8.77.]
limit values, this mode value rises to $1 \times 10^{37}$ erg s$^{-1}$, with source incompleteness beginning to affect the source distribution at $\sim 8 \times 10^{36}$ erg s$^{-1}$.

In the forthcoming paper D.-W. Kim et al. (2008, in preparation), the X-ray luminosity function (XLF) of NGC 3379 will be investigated, and a correction to allow for source incompleteness will be applied. Some preliminary results, investigating the XLF of NGC 3379, have been reported in Kim et al. (2006), where sources down to a 90% completeness limit of $L_X = 1 \times 10^{37}$ erg s$^{-1}$ from the first two observations have been detected. From the even greater sensitivity afforded to us by combining the five separate pointings, we can investigate the XLF down to the X-ray luminosity range of normal Galactic LMXBs. Previously, this has only been possible for the nearby radio galaxy Centaurus A (NGC 512), where the XLF has been measured down to $\sim 2 \times 10^{36}$ erg s$^{-1}$ (Kraft et al. 2001; Voss & Gilfanov 2006). With our greater sensitivity, we can compare our results to these studies, allowing us to investigate the shape of the low-luminosity LMXB XLF, although it should be noted that NGC 3379 is a much more "normal" galaxy than Centaurus A.

In addition to the X-ray point sources that have been presented in this catalog, the optical sources within NGC 3379 have also...
been identified. These were detected in a WFPC2 HST observation, where 70 confirmed globular clusters have been identified. From these 70 sources, 9 GC–LMXB, with separations <0.6″, have been detected, with one further GC–LMXB connection found outside the HST FOV.

GC–LMXB associations within this galaxy were previously reported by Kundu et al. (2002), where correlations between the same WFPC2 data used here and the archival Chandra observation were used to search for associations. This archival observation is much shorter than the deep data set presented here, providing a typical source detection threshold of $\frac{S}{N} < 3$, $\frac{3}{\sigma}$ upper limit values have been used in place of $L_X$. The bottom right image presents these upper limit values only. The shading for these two figures is the same as described for the main histogram.

4.2. X-Ray Colors

Figure 11 presents the LMXB population color-color diagram, based on the photometry of the co-added observation. In the top panel color-color values are plotted, with the sources divided into luminosity bins, with symbols of each bin indicated by the labeling in the panel. Variability is also indicated; variable sources are shown in blue, non-variable source are indicated in green, and sources for which variability has not been determined are shown in cyan. In the lower panel the error values for each of the sources are presented. In both of the panels, the grid indicates the predicted locations of the sources at redshift $z = 0$ with various photon indices (0 ≤ $\Gamma_{ph} ≤ 4$, top to bottom) and absorption column densities ($10^{20} \leq N_H \leq 10^{22} \text{ cm}^{-2}$, right to left).

Figure 11.— Color-color diagram of the X-ray point sources detected in the co-added observation. In the top panel color-color values are plotted, with the sources divided into luminosity bins, with symbols of each bin indicated by the labeling in the panel. Variability is also indicated; variable sources are shown in blue, non-variable source are indicated in green, and sources for which variability has not been determined are shown in cyan. In the lower panel the error values for each of the sources are presented. In both of the panels, the grid indicates the predicted locations of the sources at redshift $z = 0$ with various photon indices (0 ≤ $\Gamma_{ph} ≤ 4$, top to bottom) and absorption column densities ($10^{20} \leq N_H \leq 10^{22} \text{ cm}^{-2}$, right to left).
shown in blue, nonvariable sources in green, and sources with undetermined variability in cyan.

From the color-color diagram presented in Figure 11, it can be seen that most of the well-defined colors lie within the area of a typical LMXB spectrum of $\Gamma = 1.5 - 2.0$, with no intrinsic absorption (e.g., Irwin et al. 2003; Fabbiano 2006). However, there also appears to be a population of sources that have much harder spectra, again with either no intrinsic absorption, or sources with a possible soft excess, albeit with colors that are not as well defined. This subpopulation can also be seen in the $L_X$-HR population plot presented in the top panel of Figure 12, where a significant number of sources have higher hardness ratios than one would expect from LMXB sources.

This subpopulation was investigated by identifying sources with HR values $>0.2$, resulting in a selection of 10 sources, 4 of which lie within the $D_{25}$ ellipse of the galaxy. The HR and color values of these objects are presented in Figure 13, where red indicates sources that lie within the $D_{25}$ ellipse, and black marks those that lie outside of this region. Alongside these plots, an image indicating the spatial distribution of these objects is also presented. These plots indicate that these hard sources have $C_{21}$ values similar to the majority of the LMXB population, but have lower $C_{32}$ values, indicating that these sources not only have large hardness ratios but also exhibit spectral hardness in their color values.

Because many of these objects have $L_X \leq 10^{37}$ erg s$^{-1}$, the sources were stacked to ensure that these harder values are not a consequence of the low counts in the individual sources. From this stacked photometry, a $C_{21}$ value of $-0.53 (-0.61 \rightarrow -0.41)$ and $C_{32}$ value of $-0.23 (-0.28 \rightarrow -0.18)$ was derived, with a hardness ratio of 0.41 (0.36–0.46). These values indicate that these sources are truly hard objects and, from looking at their spatial distribution (bottom right panel in Fig. 13), it is clear that they are located throughout the galaxy, which suggests that, coupled with their HR and color values, most of these sources are likely to be objects not associated with NGC 3379, possibly absorbed background AGN. This result is consistent with the number of sources that are expected to be background objects (36) from the hard-band ChaMP+CDF log $N$–log $S$ relation.

However, if we compare the color-color plot in Figure 13 to the one presented in Figure 11, it can be seen that some of the harder sources, with no intrinsic absorption (or a soft excess component) from the whole population plot are not selected with the HR $> 0.2$ cut that has been imposed. From the $L_X$-HR population plot in Figure 12, it is clear that there is a continuum of HR values for the sources within NGC 3379, rather than a distinct separation of different classes. We therefore impose a lower HR value cut of 0, in an attempt to further identify the population of hard sources within the galaxy identified in Figure 11.

Extending this cut down to HR $> 0$ increases the subpopulation of harder sources to 17, all of which exhibit colors indicating that they are sources with hard spectra and no intrinsic absorption. However, five of these extra sources lie within the $D_{25}$ ellipse, with only two external to this region. This centrally concentrated distribution of objects indicates that it is likely that some of these additional sources are associated with the galaxy, and are not AGNs. Such an effect is unsurprising, as it is not unusual for different classes of sources to have regions of overlap in color-color diagrams (Prestwich et al. 2003). As a consequence of this confusion, we use the HR $> 0.2$ cut to identify 10 sources that are likely to be absorbed background AGNs, but also note that there are a further seven sources within this galaxy that, while exhibiting lower HR values, also exhibit spectral
hardness in their color values. We suggest here that, due to their centrally concentrated distribution, it is likely that these sources are associated with NGC 3379, although we do not rule out the possibility that some of these objects could be background AGNs.

4.3. Source Variability

One characteristic of compact accretion sources such as LMXBs is variability, and as a result of the monitoring nature of the observing campaign we have been able to search for this variability, both in the long-term regime and also over short-term baselines, where changes over hours and days have been identified. One of the specific aims of our monitoring campaign has been to identify transient candidate sources, as it has been suggested that field LMXBs are expected to be transients (Piro & Bildsten 2002; King 2002), and low-luminosity ultracompact binaries in GCs are also expected to be transient in nature (Bildsten & Deloye 2004). In a forthcoming paper (N. J. Brassington et al. 2008, in preparation), we investigate the subpopulation of transient candidates that has been discovered in NGC 3379.

Our data represent the most complete variability study for an extragalactic LMXB population (see Fabbiano 2006; Xu et al. 2005), investigating both long- and short-term behavior. In the case of the long-term variability, sources have been separated into four different classifications; nonvariable and variable sources, and also transient candidates (TC) or possible transients candidates (PTC). These latter two definitions have been applied to sources that either appear or disappear, or are only detected for a limited amount of contiguous time during the observations, with a lower bound ratio of greater than 10 between the on-state and the off-state for TCs, or a lower bound ratio between 5 and 10 for the PTCs (see § 2.4 for a full discussion of this definition). The 11 sources that were investigated for transient behavior are presented in Table 13, where both the ratio and the lower bound ratio, calculated from Bayesian modeling, are presented, along with each source’s variability classification. From this table it can be seen that many of these sources appear to be strong TCs from their ratio alone, but when one allows for the uncertainties from their source and background counts, they can only be classified as variable sources. Including the uncertainties when

![Image of the variability study results](image-url)
determining TCs is particularly important when dealing with sources with low S/N values, as is the case here for a number of sources in this catalog.

Out of the 132 sources, 56 (42%) of the sources within NGC 3379 have been defined as variable sources. A further five sources are TCs, and 3 are PTCs, with 44 sources found to be nonvarying in intensity over the five observations. The remaining 24 sources have insufficient data to investigate their long-term variability. These, alongside the number of sources exhibiting short-term variability, are summarized in Table 1, where these two variability parameters have been cross-correlated, to indicate the number of sources exhibiting both long- and short-term variations, although the majority of these sources do not have sufficient counts in each observation to determine their short-term variability. The numbers in this table indicate the number of sources from the whole observation; values in parentheses represent the sources within the D25 ellipse.

From this table it can be seen that, for the sources with a defined short-term variability measure, both long-term variable and nonvariable sources have a variety of short-term behavior. For the transient candidates, both classes of sources have a few sources with determined short-term variability, but all the sources that do have short-term measures have also been found to exhibit short-term variability. Also, as an additional point, nearly all of the TCs and PTCs found within NGC 3379 reside within the D25 ellipse of the galaxy, with only one confirmed TC, source 128, external to this region, indicating that they are likely LMXBs associated with NGC 3379.

In addition to the $L_X$ variability, spectral variations have also been investigated. These are presented in Figure Sets 8 and 9, which show $L_X$-HR and color–color plots for each source. From these figures it is clear that the majority of sources within NGC 3379 are variable, and that their distribution follows the total source distribution. There is a variety of different spectral variations within this population, similar to spectral variability behavior discussed in McClintock & Remillard (2006), with a significant number of sources emitting harder spectra as $L_X$ increases (e.g., sources 25 and 99). Conversely, sources exhibiting spectral softening with increasing $L_X$ are also present within the galaxy (e.g., sources 81 and 119), as well as sources that show little to no spectral variation with increasing luminosity (e.g., sources 86 and 121), and sources that show no discernible pattern at all (e.g., sources 62 and 98). A more detailed discussion of the spectral variability of the X-ray sources presented in this catalog will be the subject of a forthcoming paper.

5. Conclusions

We have presented a source catalog and variability atlas resulting from our deep monitoring observations of the nearby elliptical NGC 3379 with Chandra ACIS-S. Our results can be summarized as follows:

1. 132 X-ray point sources have been detected within NGC 3379, ranging in luminosity from $6 \times 10^{35}$ erg s$^{-1}$ (with $3 \sigma$ upper limit $\leq 4 \times 10^{35}$ erg s$^{-1}$) to $\sim 2 \times 10^{39}$ erg s$^{-1}$, with 98 of these sources residing within the D25 ellipse of the galaxy.

2. Only one ULX has been identified within this galaxy, with a galactocentric radius of 6.7$''$, and a peak luminosity of $L_X \sim 3 \times 10^{39}$ erg s$^{-1}$.

3. Ten globular clusters have been identified to be coincident with X-ray sources, all of which lie within the D25 ellipse of the galaxy. These GC–LMXB associations tend to have high X-ray luminosities, with three of these sources exhibiting $L_X > 1 \times 10^{38}$ erg s$^{-1}$.

4. From source photometry, it has been determined that the majority of sources with well-constrained colors have values that are consistent with a typical LMXB spectrum of $\Gamma = 1.5–2.0$, with no intrinsic absorption.

5. A subpopulation of 10 sources has been found to exhibit very hard spectra. These objects are distributed uniformly in the sky, and it is expected that most of these sources are absorbed background AGNs.

6. 64 sources, 48% of the X-ray source population, have been found to exhibit some type of long-term variability, which clearly identifies them as accreting compact objects. Five of these variable sources have been identified as transient candidates, with a further three identified as possible transients.

7. Spectral variability analysis has revealed that the sources within NGC 3379 exhibit a range of variability patterns, where both high/soft-low/hard and low/soft-high/hard spectral transitions have been observed, as well as sources that vary in luminosity but exhibit no spectral variation, indicating that there are many different source classes within this galaxy.

In addition to this catalog paper, our companion paper (Fabbiano et al. 2007) discusses the dearth of low-luminosity GC–LMXBs within this galaxy. Further highlights from the X-ray binary

| TABLE 13 | RATIO VALUES OF POTENTIAL TRANSIENT CANDIDATES |
|---|---|---|---|
| Master ID | Mode Ratio | Lower Bound Ratio | Variability |
| 25 | 161.39 | 43.48 | TC |
| 50 | 6.83 | 5.87 | PTC |
| 53 | 11.40 | 4.20 | V |
| 85 | 30.19 | 9.00 | PTC |
| 89 | 18.39 | 16.42 | TC |
| 91 | 8.49 | 4.75 | V |
| 92 | 7.44 | 3.15 | V |
| 94 | 19.21 | 13.18 | TC |
| 100 | 20.21 | 14.05 | TC |
| 115 | 12.88 | 6.84 | PTC |
| 128 | 85.09 | 50.69 | TC |

Notes.—The 11 sources that were identified as potential transients candidates. Mode ratios and lower bound ratios were derived from Bayesian modeling; see § 2.4 for more details. Sources were determined to be transient candidates (TC) if the lower bound >10, possible transient candidates (PTC) if the lower bound >5, and variable (V) if lower than 5.

| TABLE 14 | SUMMARY OF LONG-TERM AND SHORT-TERM SOURCE VARIABILITY |
|---|---|---|---|---|---|
| Short-Term Variability | N | V | TC | PTC | U | Total |
| Long-Term Variability |
| N | 2 (2) | 8 (7) | 0 (0) | 0 (0) | 0 (0) | 10 (9) |
| V | 2 (2) | 3 (2) | 2 (1) | 0 (0) | 0 (0) | 7 (5) |
| P | 3 (3) | 4 (4) | 0 (0) | 0 (0) | 0 (0) | 7 (7) |
| U | 37 (27) | 41 (30) | 3 (3) | 3 (3) | 24 (14) | 108 (77) |
| Total | 44 (34) | 56 (43) | 5 (4) | 3 (3) | 24 (14) | 132 (98) |

Notes.—Long-term variability definitions: (N) nonvariable; (V) variable; (TC) transient candidate; (PTC) possible transient candidate; (U) unable to determine variability as all individual observations were upper limits. Short-term variability definitions: (N) nonvariable in all five observation; (V) variable in at least one observation; (P) possible variability in at least one observation (see § 2.4 for full definition); (U) too few counts in all five observations to determine variability. Values in parentheses indicate the number of sources within the D25 ellipse.
population of NGC 3379 will also be presented in N. J. Brassington et al. (2008, in preparation), where the properties of the transient population will be presented.

Other forthcoming papers will also present the properties of the ULX, the X-ray luminosity function, and the diffuse emission of the galaxy, as well as the properties of the nuclear source and the intensity and spectral variability of the luminous X-ray binary population. The results from this deep observation will then be compared to the X-ray source catalog of the old, GC-rich elliptical galaxy NGC 4278, which has also recently been the subject of a deep Chandra observation.

We thank the CXC DS and SDS teams for their efforts in reducing the data and developing the software used for the reduction (SDP) and analysis (CIAO). We would also like to thank the anonymous referee for helpful comments which have improved this paper. This work was supported by Chandra G0 grant G06-7079A (PI: Fabbiano) and subcontract G06-7079B (PI: Kalogera). We acknowledge partial support from NASA contract NAS8-39073 (CXC). A. Z. acknowledges support from NASA LTSA grant NAG 05-13056. S. P. acknowledges partial financial support from the Italian Space Agency ASI (Agenzia Spaziale Italiana) through grant ASI-INAF 1/023/05/0.

APPENDIX A

BAYESIAN ESTIMATIONS OF SOURCE UPPER LIMITS AND HR VALUES

In order to obtain accurate estimates of the source intensities and their hardness ratios, we use a method based on the Bayesian estimation of the true source intensity in the presence of background, and effective area variations (Park et al. 2006). This method is based on the posterior predictive probability distribution of the source intensity, given the number of observed counts (source plus background), and an estimate of the local background (van Dyk et al. 2001). The advantage of this method is that it takes into account the Poisson nature of the source and the background, allowing a more accurate decomposition of the net source intensity. This is particularly important for sources very close to the detection limit; in these cases the classical method (e.g., assuming Gaussian errors, or even the simplified version of the Gehrels approximation) may give zero or negative counts. However, our method overcomes these problems and can provide the full probability distribution of the source intensities. The raw source and background counts (divided by the background to source area ratio), used to determine the HR and color values from Bayesian estimations, are presented in Table 15.

For sources very close to the detection limit, we can obtain the mode of the distribution which, although lower than the average background, might well be above zero. In those cases we can also estimate the upper 68% quantile of the distribution, which would correspond to the 68% confidence level on the source intensity (a similar method, which however does not model the Poisson probability distribution of the background counts, is presented in Kraft et al. 1991). In Figure 14 we present the posterior probability distributions for hypothetical sources with 10 observed counts and estimated background of 6, 8, and 10 counts. None of these cases is a formal “detection” (i.e., flux intensity at least 3 \sigma above the background) in the classical method; however, from these distributions we can recover the source intensity, and even in the most extreme case (10 background counts) we can estimate the upper confidence bound on the source intensity.

---

We acknowledge partial support from NASA contract NAS8-7079A (PI: Fabbiano) and subcontract G06-7079B (PI: Kalogera).

This work was supported by Chandra G0 grant G06-7079A (PI: Fabbiano) and subcontract G06-7079B (PI: Kalogera). We acknowledge partial financial support from the Italian Space Agency ASI (Agenzia Spaziale Italiana) through grant ASI-INAF 1/023/05/0.

---

12 We note, however, that the significance of the source flux has a different meaning from the significance of the detection, which strongly depends on the detection process; a more detailed description of these nuanced terms will be presented in D. van Dyk et al. (2008, in preparation).

### Table 15

| Master ID | Net B Counts (1) | B Band Src (3) | B Band Bkg (4) | S1 Band Src (5) | S1 Band Bkg (6) | S2 Band Src (7) | S2 Band Bkg (8) | H Band Src (9) | H Band Bkg (10) | Be Band Src (11) | Be Band Bkg (12) | Sc Band Src (13) | Sc Band Bkg (14) | Hc Band Src (15) | Hc Band Bkg (16) |
|-----------|------------------|---------------|--------------|----------------|----------------|----------------|----------------|---------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 1.......... | 58.9             | 82            | 23.1         | 20             | 5.8            | 42             | 5.6            | 20            | 11.7          | 77             | 19.4          | 52             | 6.3            | 25             | 13.1           |
| 2.......... | 36.2             | 57            | 20.8         | 6              | 4.5            | 29             | 6.0            | 22            | 10.3          | 56             | 17.9          | 31             | 6.2            | 25             | 11.6           |
| 3.......... | 28.9             | 52            | 23.1         | 13             | 5.7            | 21             | 5.9            | 18            | 11.5          | 45             | 19.3          | 23             | 6.5            | 22             | 12.9           |
| 4.......... | 1.8              | 6             | 4.2          | 1              | 1.1            | 1              | 1.1            | 4             | 2.0           | 6              | 3.5           | 2              | 1.2            | 4              | 2.3            |
| 5.......... | 4.6              | 6             | 1.4          | 0              | 0.3            | 3              | 0.4            | 3             | 0.7           | 6              | 1.2           | 2              | 0.4            | 4              | 0.8            |
| 6.......... |                 |               |              |               |               |               |               |               |               |                 |               |                 |               |                 |               |
| 7.......... |                 |               |              |               |               |               |               |               |               |                 |               |                 |               |                 |               |
| 8.......... |                 |               |              |               |               |               |               |               |               |                 |               |                 |               |                 |               |
| 9.......... |                 |               |              |               |               |               |               |               |               |                 |               |                 |               |                 |               |
| 10......... | 27.9             | 49            | 21.1         | 7              | 5.5            | 9              | 5.5            | 33            | 10.1          | 45             | 17.6          | 8              | 6.3            | 37             | 11.4           |

Notes.—Col. (1): Master ID. Col. (2): Net broadband counts. Cols. (3), (5), (7), (9), (11), (13), and (15): Raw source counts in each of the seven energy bands (see Table 3 for definitions of these bands). Cols. (4), (6), (8), (10), (12), (14), and (16): Background counts in each of the seven energy bands. In some instances background counts are very low. For these sources, standard aperture photometry results in negative net counts, so instead the source cell determined by wavdetect has been used. This results in a large area ratio between the background and source regions, and therefore a low background count value is derived. Table 15 is published in its entirety in the electronic edition of the Astrophysical Journal Supplement. A portion is shown here for guidance regarding its form and content.
Fig. 14.—Posterior probability distributions for hypothetical sources with 10 observed counts and background counts of 6, 8, and 10, based on Bayesian estimations of the “real” source’s intensity.

REFERENCES

Angelini, L., Loewenstein, M., & Mushotzky, R. F. 2001, ApJ, 557, L35
Bergond, G., Zepf, S. E., Romanowsky, A. J., Sharples, R. M., & Rhodes, K. L. 2006, A&A, 448, 155
Bildsten, L., & Deloye, C. J. 2004, ApJ, 607, L119
Cappellari, M., et al. 2006, MNRAS, 366, 1126
David, L. P., Jones, C., Forman, W., & Murray, S. S. 2005, ApJ, 635, 1053
Fabbiano, G. 2006, ARA&A, 44, 323
Fabbiano, G., et al. 2006, ApJ, 650, 879
———. 2007, preprint (arXiv:0710.5126)
Freeman, P. E., Kashyap, V., Rosner, R., & Lamb, D. Q. 2002, ApJS, 138, 185
Gehrels, N. 1986, ApJ, 303, 336
Giacconi, R. 1974, in X-ray Astronomy, ed. R. Giacconi & H. Gursky (Dordrecht: Reidel), 155
Gilfanov, M. 2004, MNRAS, 349, 146
Grindlay, J. E. 1984, Adv. Space Res., 3, 19
Harris, W. E. 1991, ARA&A, 29, 543
Irwin, J. 2006, MNRAS, 371, 1903
Irwin, J., Athey, A., & Bregman, J. 2003, ApJ, 587, 356
Kenter, A., et al. 2005, ApJS, 161, 9
Kim, D.-W., & Fabbiano, G. 2004, ApJ, 611, 846
Kim, D.-W., Wilkes, B., Green, P., et al. 2004a, ApJ, 600, 59
Kim, D.-W., et al. 2004b, ApJS, 150, 19
———. 2006, ApJ, 652, 1090
Kim, M., et al. 2007a, ApJS, 169, 401
———. 2007b, ApJ, 659, 29
King, A. R. 2002, MNRAS, 335, L13
Kraft, R. P., Burrows, D. N., & Nousek, J. A. 1991, ApJ, 374, 344
Kraft, R. P., et al. 2001, ApJ, 560, 675
Kundu, A., Maccarone, T. J., & Zepf, S. E. 2002, ApJ, 574, L5
Kundu, A., & Whitmore, B. C. 2001, AJ, 121, 2950
McClintock, J. E., & Remillard, R. A. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press
Park, T., Kashyap, V., Siemiginowska, A., van Dyk, D., Zezas, A., Heinke, C., & Wargelin, B. 2006, ApJ, 652, 610
Pierce, M., et al. 2006, MNRAS, 366, 1253
Piro, A. L., & Bildsten, L. 2002, ApJ, 571, L103
Prestwich, A. H., Irwin, J. A., Kilgard, R. E., Krauss, M. I., Zezas, A., Primini, F., Kaaret, P., & Boroson, B. 2003, ApJ, 595, 719
Puzia, T. H., et al. 2004, A&A, 415, 123
Rhode, K. L., & Zept, S. E. 2004, AJ, 127, 302
Scargle, J. D. 1998, ApJ, 504, 405
Sivakoff, G. R., Jordán, A., Juett, A. M., Sarazin, C. L., & Irwin, J. A. 2007a, preprint (arXiv:0712.3052)
Sivakoff, G. R., et al. 2007b, ApJ, 660, 1246
Terlevich, A. I., & Forbes, D. A. 2002, MNRAS, 330, 547
Tonry, J., et al. 2001, ApJ, 546, 681
van Dyk, D., et al. 2001, ApJ, 548, 224
Verbunt, F., & van den Heuvel, E. P. J. 1995, in X-ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 457
Voss, R., & Gilfanov, M. 2006, A&A, 447, 71
Weisskopf, M. C., Tananbaum, H. D., Van Speybroeck, L. P., & O’Dell, S. L. 2000, Proc. SPIE, 4012, 2
White, R. E. III, Sarazin, C. L., & Kulkarni, S. R. 2002, ApJ, 571, L23
Williams, B. F., et al. 2008, ApJ, 680, 1120
Xu, Y., Xu, H., Zhang, Z., Kundu, A., Wang, Y., & Wu, X.-P. 2005, ApJ, 631, 809
Zezas, A, Fabbiano, G., Rots, A. H., & Murray, S. S. 2002, ApJ, 577, 710