12 YEARS OF X-RAY VARIABILITY IN M31 GLOBULAR CLUSTERS, INCLUDING 8 BLACK HOLE CANDIDATES, AS SEEN BY CHANDRA

R. Barnard1, M. Garcia1, and S. S. Murray2
1 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge MA 02138, USA
2 Department of Physics and Astronomy, Johns Hopkins University, 366 Bloomberg Center, 3400 N. Charles Street, Baltimore, MD 21218, USA

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ABSTRACT

We examined 134 Chandra observations of the population of X-ray sources associated with globular clusters (GCs) in the central region of M31. These are expected to be X-ray binary systems (XBs), consisting of a neutron star or black hole accreting material from a close companion. We created long-term light curves for these sources, correcting for background, interstellar absorption, and instrumental effects. We tested for variability by examining the goodness of fit for the best-fit constant intensity. We also created structure functions (SFs) for every object in our sample, the first time this technique has been applied to XBs. We found significant variability in 28 out of 34 GCs and GC candidates; the other 6 sources had 0.3–10 keV luminosities fainter than \( \sim 2 \times 10^{36} \text{ erg s}^{-1} \), limiting our ability to detect similar variability. The SFs of XBs with 0.3–10 keV luminosities \( \sim 2\times10^{36} \text{ erg s}^{-1} \) generally showed considerably more variability than the published ensemble SF of active galactic nuclei (AGNs). Our brightest XBs were mostly consistent with the AGN SF; however, their 2–10 keV fluxes could be matched by \(< 1 \text{ AGN per square degree. These encouraging results suggest that examining the long-term light curves of other X-ray sources in the field may provide an important distinction between X-ray binaries and background galaxies, as the X-ray emission spectra from these two classes of X-ray sources are similar. Additionally, we identify 3 new black hole candidates (BHCs) using additional XMM-Newton data, bringing the total number of 31 GC BHCs to 9, with 8 covered in this survey.

Key words: black hole physics – globular clusters: general – globular clusters: individual – X-rays: binaries – X-rays: general

Online-only material: color figures, extended figures

1. INTRODUCTION

When studying the X-ray populations of external galaxies, globular cluster X-ray sources are of particular interest, because they are most probably low-mass X-ray binaries (LMXBs), rather than, e.g., background galaxies, supernova remnants, or high-mass X-ray binaries (HMXBs). Globular clusters contain \( \sim 10\% \) of the Galactic LMXB population (14 out of \( \sim 150 \)), but are thought to contain only 0.1\% of the mass; hence the LMXB density is \( \sim 100 \) times higher in globular clusters (GCs) than elsewhere (see the comprehensive review by Verbunt & Lewin 2006, and references within). Indeed, it has been speculated that all LMXBs were born in globular clusters (see, e.g., D’Antona et al. 2007, and references within).

M31 is the nearest neighboring spiral galaxy, at \( \sim 780 \) kpc (Stanek & Garnavich 1998), and is a favored target of many X-ray telescopes. Hence, its GC X-ray sources have been particularly well studied. X-ray surveys of M31 include those made with Einstein (Trinchieri & Fabbiano 1991), ROSAT (Supper et al. 1997, 2001), XMM-Newton (Trudolyubov & Friedhorsky 2004; Shaw Greening et al. 2009; Stiele et al. 2011), and Chandra (Kong et al. 2002; Di Stefano et al. 2002; Williams et al. 2004).

Di Stefano et al. (2002) conducted a GC survey of M31 with Chandra, covering \( \sim 2560 \) arcmin\(^2\). They found 30 GC X-ray sources, 15 of which were new discoveries. They found that the M31 GC X-ray population was systematically more luminous than the Milky Way (MW) population; 10 M31 GC X-ray sources in their survey exceeded \( 10^{37} \) erg s\(^{-1}\), versus 1 of the 11 MW GC X-ray sources surveyed by ROSAT (Verbunt et al. 1995).

Recently, Peacock et al. (2010) conducted a survey of X-ray sources in the 2XMMi catalog (Watson et al. 2009) that included all publicly available XMM-Newton observations of M31, searching for associations with GCs; the observations cover \( \sim 80\% \) of the GCs in M31. They found 41 GC associations in the 2XMMi catalog, and 4 transient X-ray sources observed by either ROSAT or Chandra, for a total of 45 GC LMXBs.

We have been monitoring the central region of M31 with Chandra for the last \( \sim 12 \) years, averaging \( \sim 1 \) observation per month, looking for X-ray transients; we exclude periods where M31 is too close to the Sun to be observed. These observations have no fixed roll angle, and the combined field may be approximated by a circle with a \( \sim 20' \) radius. The earlier Chandra surveys included long-term variability studies: Kong et al. (2002) found 204 X-ray sources in the central 17' \( \times \) 17' region, detecting variability in \( \sim 50\% \) of the sources over 8 ACIS-I observations between 1999 October and 2001 June; Williams et al. (2004) examined 2.5 years of HRC data, and found at least 25\% of 166 sources to be significantly variable.

In this work we present a variability survey of all X-ray sources in our Chandra observations that are associated with objects in the Revised Bologna Catalog of M31 globular clusters (RBC V.4; Galleti et al. 2004, 2006, 2007, 2009). This includes 30 out of 45 GC X-ray sources identified by Peacock et al. (2010); the other 7 RBC associations in our survey include 4 GC candidates, 2 background galaxies (active galactic nuclei, AGNs), and 1 star. We compare the variability of these X-ray sources with the ensemble variability for active galaxies found by Vagnetti et al. (2011).
It has long been known that AGNs may vary by a factor of 2–3 on timescales of months to years, with the amplitude of variation inversely proportional to the luminosity (see, e.g., Marshall et al. 1981; Nandra et al. 1997, and references within). However, it has been known for exceptional AGNs to flare up by an order of magnitude (e.g., Tananbaum et al. 1978).

Recently Vagnetti et al. (2011) studied the ensemble variability over timescales of hours to years of AGNs in the serendipitous source catalogs from *XMM-Newton* (Watson et al. 2009) and *Swift* (Puccetti et al. 2011); their sample covered redshifts $\sim 0.2–4.5$, and 0.5–4.5 keV luminosities $\sim 10^{33}–10^{46}$ erg s$^{-1}$. They included 412 AGNs from the *XMM-Newton* catalog and 27 AGNs from the *Swift* catalog; all of these AGNs were sampled at least twice. They used a structure function (SF) to estimate the mean intensity deviation for data separated by time $\tau$:

$$SF(\tau) \equiv \sqrt{\frac{\pi}{2}} \left( |\log f_X(t + \tau) - \log f_X(t)|^2 - \sigma_n^2 \right), \quad (1)$$

where $\sigma_n$ is the photon noise and $f_X$ is the X-ray flux. They grouped the SF into logarithmic bins with width 0.5; each bin in the range $\log(\tau) = 1.0–3.0$ contained more than 100 measurements.

Vagnetti et al. (2011) found that SF increased from $\sim 0.1$ to $\sim 0.2$ as $\tau$ ranged over 0.1–1000 days in the rest frame of the AGN. SF $\sim 0.15$ for $\tau = 30$ days, suggesting that typical AGNs would vary by $\sim 25\%–75\%$ between our observations. They also investigated the well-observed anticorrelation between intensity variability ($I_{var}$) and luminosity, expressed in the form $I_{var} \propto L_X^{0.3}$ in the literature for timescales of days to tens of days. They measured $k$ for AGNs grouped logarithmically over $\log L_X = 43.5–45.5$ for two values of $\tau$: 1 day and 100 days. They find $k = 0.42 \pm 0.03$ for $\tau = 1$ day and $k = 0.21 \pm 0.07$ for $\tau = 100$ days.

Vagnetti et al. (2011) measured the average values of $\sigma_n^2$ for the *XMM-Newton* and *Swift* samples to be 0.031 and 0.163, respectively. When they used these values to calculate the SFs for each sample, the two SFs were consistent; if SF($\tau$) $\propto \tau^{-b}$, then $b = 0.10 \pm 0.01$ for the *XMM-Newton* SF and $b = 0.07 \pm 0.04$ for the *Swift* SF.

We have created structure functions for each of our targets from their 0.5–4.5 keV fluxes. The goal was to ascertain whether we may distinguish between XBs and AGNs from their variability alone; this is important because XBs and AGNs often exhibit similar spectra.

Our analysis of the full data set has allowed us to identify seven black hole candidates associated with globular clusters; four were previously published (Barnard et al. 2011a), and three are new to this work. We identified one more GC black hole candidate in this region in earlier work (Barnard & Kolb 2009), and one away from the bulge (Barnard et al. 2008). They were all identified from their X-ray properties, as they exhibited characteristic low-state emission spectra at luminosities that exceeded the limit for a neutron star accretor; other neutron star emission models were rejected (see Barnard et al. 2011a, for the most complete justification of this method).

We describe the data analysis in the next section, followed by a presentation of our results, then a discussion of our findings and conclusions.

2. OBSERVATIONS AND DATA REDUCTION

We have analyzed 89 ACIS observations and 45 HRC observations, in order to discern the variability of X-ray sources associated with GCs in this region. The merged ACIS image was registered to the Field 5 B-band image from the Local Group Survey (LGS) observations of M31 (Massey et al. 2006) with *iraf* software, using 27 X-ray bright GCs. After refining the GC positions in the *Chandra* and LGS B-band images with *imcentroid*, we found the sky coordinates of the new positions with *x2sky*, then registered the X-ray positions to the LGS B-band image using *ccmap*. The mean rms uncertainty in position due to registration was $0.11'$ in R.A. and $0.09'$ in Decl.

We obtained 0.3–7.0 keV light curves and spectra from circular source and background regions for each source. The background region was the same size as the source region, and at a similar off-axis angle. The extraction radius varied between sources, because larger off-axis angles resulted in larger point spread functions.

For ACIS observations, we obtained corresponding response matrices and ancillary response files. Source spectra with >200 net source counts were freely fitted with absorbed power-law models. For GCs with multiple freely fitted spectra, we obtained the best-fit constant values for absorption ($N_H$) and photon index ($\Gamma$). For observations with <200 net source photons, we fixed $N_H$ and $\Gamma$ to the best-fit values; if a particular GC had no freely fitted spectra, then we assumed $N_H = 7 \times 10^{20}$ H atoms cm$^{-2}$, and $\Gamma = 1.7$. We obtained luminosities for faint sources by determining the unabsorbed 0.3–10 keV luminosity equivalent to 1 count s$^{-1}$; multiplying the source luminosity by this conversion factor gave the source luminosity, after correcting for the exposure, vignetting, and background.

For HRC observations, we included only PI channels 48–293, thereby reducing the instrumental background. We used the WebPIMMS tool to find the unabsorbed luminosity equivalent to 1 count s$^{-1}$, assuming the same emission model as for the ACIS observations with <200 photons. We created a 1 keV exposure map for each observation, and compared the exposure within the source region with that of an identical on-axis region, in order to estimate the necessary exposure correction. We multiplied the background-subtracted, corrected source intensity by the conversion to get the 0.3–10 keV luminosity.

We created long-term 0.3–10 keV light curves for each source, using the luminosities obtained from each observation as described above. We only included observations with net source counts $\geq 0$ after background subtraction. We fitted each long-term light curve with a line of constant intensity, in order to ascertain the source variability. If the null hypothesis probability for the best fit to a light curve was <0.003, then the variability of that light curve had a significance $>3\sigma$, and we classified the target as variable; the null hypothesis probability determines the likelihood that observed deviations from the model are due to random fluctuations in the data.

Luminosity uncertainties for freely fitted spectra were estimated with XSPEC by calculating a range of fluxes obtained by varying the emission parameters; the uncertainties for the faint spectra are derived directly from intensity uncertainties using the relevant fixed model.

We derived SFs from the 0.5–4.5 keV fluxes of each observation of every target by assuming a power-law spectrum with the same photon index as for the HRC and faint ACIS observations; an M31 X-ray source with a 0.3–10 keV unabsorbed luminosity of $1.0 \times 10^{37}$ erg s$^{-1}$ and $\Gamma = 1.7$ has a 0.5–4.5 keV flux of $0.8 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$. 


The merged observations cover an approximately circular region with 20′ radius. We detected 430 X-ray sources in this region, and found 428 globular clusters from the RBC. Therefore, we expect chance coincidences of X-ray sources within 1″ of the GC centers for 0.12 out of 428 GCs.

Shifting the declination of each source by ±5″ resulted in no coincidences within 1″ of a RBC object; shifting the R.A. by −5″ also resulted in no coincidences; however, shifting the R.A. by +5″ resulted in two matches within 1″ of an RBC object. Expanding the search radius from 1″ to 2″ provided one additional match each for offsets ±5″ in declination. Hence we expect 0–2 false matches.

We found 37 X-ray sources to be coincident with M31 GCs, as classified by the RBC. X-ray positional uncertainties include uncertainties in the centroid on the X-ray image, uncertainties in the registration (0.′′11 for R.A. and 0.′′09 for Decl.), and 0.′′25 uncertainty in the LGS position.

In Table 1 we present the positions and identifications of each X-ray source that we associate with a member of the RBC V.4. We provide the latest classifications of the optical counterparts, gleaned from Caldwell et al. (2009); our sample
includes 1 star and 2 galaxies, as well as 30 confirmed old GCs and 4 GC candidates. We also show the distance between the X-ray source and its optical counterpart, and the uncertainties in R.A. and Decl.: X-ray sources with no good centroid solution are indicated by “...” Eight of our targets are far off-axis (~11–20”) and also X-ray faint. We estimated the positional uncertainties for these targets by binning the merged image by a factor 9 in x and y, then running ICENTROID on this binned image.

Table 2 details the X-ray properties of each target. We first give the number of Chandra observations with ≥0 net source counts. We then show the line-of-sight absorption and photon index used for the model used to convert from intensity to luminosity for all HRC observations, and for ACIS observations with <200 net source photons. We finally give the best-fit 0.3–10 keV unabsorbed luminosity and \( \chi^2/\text{dof} \) for the best-fit line of constant intensity. The light curves of the variable sources are presented in Figure 1.

### 3.1. Variability Analysis

We found significant X-ray variability in 28 of the 34 GCs and GC candidates; the remaining 6 sources had 0.3–10 keV luminosities \(<2\times10^{36} \text{ erg s}^{-1}\). The two AGNs in our survey, B042D and B044D, were rather faint (<2 \times 10^{36} \text{ erg s}^{-1}), but both exhibited variability at >3σ significance.

In Figure 2 we present a histogram showing the number of pairs of observation with a given separation \( \tau \) for XB144, the target with the most observations. The histogram is binned logarithmically, with a width of 0.2. Each bin averages tens or hundreds of observation pairs. We provide the structure functions for each target in Figure 3.

We note that SF(τ) becomes imaginary if the observed variability is smaller than the noise. Such behavior manifests as SF(τ) = 0. Both AGNs have mostly imaginary SFs; however, both show significant variability over timescales of a few thousand days; this variability is consistent with the ensemble AGN SF created by Vagnetti et al. (2011).

The SFs of the brightest X-ray binaries (0.3–10 keV luminosity \( \geq 5\times10^{37} \text{ erg s}^{-1} \)) are also generally consistent with the ensemble AGN SF, or even less variable, despite the relatively high signal to noise. This result is in keeping with the observed behavior of Galactic X-ray binaries; Muno et al. (2002) showed that the brightest X-ray binaries (i.e., Z-sources) vary by a
factor of a few, while the fainter binaries (atoll sources) can vary by 1 or 2 orders of magnitude. However, these bright X-ray sources have 2–10 keV fluxes greater than nearly all AGNs; the 2–10 keV log $N$–log $S$ plot for AGNs calculated by Moretti et al. (2003) leads us to expect <1 AGN per square degree with comparable fluxes.

Our most encouraging result is that most of the fainter X-ray sources have SFs showing substantially more variability than the ensemble AGN SF over most timescales. This is an important distinction to make, since X-ray binary and AGN emission spectra are often very similar.

Unlike the other bright X-ray sources, the SF for XB158 shows considerably more variability than the ensemble AGN SF over all timescales. XB158 is a high-inclination X-ray binary that exhibits periodic intensity dips on a ∼10,000 s period (Trudolyubov et al. 2002) and also disk precession (Barnard et al. 2006); it is further discussed in Section 3.3.

### 3.2. Eight Black Hole Candidates

We have previously identified six black hole candidates (BHCs) in the observed region, based on their exhibition of
characteristic low-state emission spectra at luminosities that are too high for neutron star systems (Barnard & Kolb 2009; Barnard et al. 2011a, 2011b). Five of these systems are associated with GCs, and four of those are persistently bright, which is unexpected given that much of the theoretical work to date models these systems as transients (see Barnard et al. 2011a, for an overview of the literature on the topic of black holes in globular clusters).

Low-state emission spectra are characterized by a dominant power-law component with $\Gamma < 2$, contributing $\gtrsim 90\%$ of the flux (McClintock & Remillard 2006), and are seen in all LMXBs, whether they contain black holes or neutron stars (van der Klis 1994). However, it has become apparent that the low state is confined to luminosities $\lesssim 10^3$ Eddington (Gladstone et al. 2007; Tang et al. 2011). Hence X-ray binaries that exhibit low-state spectra at luminosities significantly higher than $3 \times 10^{37}$ erg s$^{-1}$ are likely to contain black hole accretors.

However, a good fit with $\Gamma < 2$ is not sufficient by itself to identify a BHC; we must first reject competing emission models. In particular, we must reject a disk blackbody-dominated spectrum (representing the thermally-dominated black hole state), a blackbody + power-law model that represents high-luminosity emission in neutron starXBs, and a disk blackbody + steep power-law ($\Gamma > 2.4$) model to represent the BH steep power-law state.

The Terzan 5 X-ray transient IGR J17480−2446 exhibited an unusually impressive range of properties: Z-source and atoll behavior, as well as thermonuclear X-ray bursts and 11 Hz pulsations; Chakraborty et al. (2011) conducted detailed spectral analysis of the outburst, using data from $\sim 40$ daily RXTE observations. They found that the spectra were all well described by a simple emission model (blackbody + power law + Gaussian emission line). The blackbody component contributed $\sim 30$–$50\%$ of the $3$–$15$ keV flux, with $kT = 1.4$–$2.1$ keV for the most part and $3.7$ keV for the first observation; $\Gamma = 2.1$–$3.0$; the unabsorbed $3$–$15$ keV flux was $2.58$–$17.94 \times 10^{39}$ erg cm$^{-2}$ s$^{-1}$ (Chakraborty et al. 2011).

We estimated the unabsorbed luminosity and blackbody contribution to each spectrum in the $0.3$–$10$ keV band for IGR J17480−2446, from the best-fit parameters, and assuming a distance of $5.5$ kpc. We assumed that the power-law component extended down to $0.3$ keV; alternative models where the seed photon energy for the Comptonized component matched the inner disk temperature were rejected by the XMM-Newton spectrum of our M31 black hole candidate RX J0042.3+4115 in the steep power-law state (Barnard et al. 2011b). We found that the blackbody contributed $7$–$13\%$ of the unabsorbed $0.3$–$10$ keV luminosity of $1.8$–$33 \times 10^{37}$ erg s$^{-1}$. IGR J17480−2446 appears not to have been in the low state at any time during the outburst.

We note that Lin et al. (2007) devised an alternative model to describe two other neutron star X-ray transients, Aql X-1 and 4U 1608−52; traditional emission models (thermal + inverse-Comptonized emission) all yielded good fits for spectra with $>10^9$ net source counts, but the authors raised objections to various aspects of the spectral evolution of the transient outbursts. They preferred a disk blackbody + blackbody emission model at high luminosities, with a Comptonized component necessary at lower luminosities. In this scenario, the neutron star transient evolution closely follows black hole transient evolution, with an extra blackbody component from either the neutron star itself or the boundary layer between the disk and neutron star surface.

However, their model contradicts a large body of work based on observations of Galactic neutron star XB. Plenty of evidence exists for an extended X-ray emission region in the high-inclination, "dipping" X-ray binaries (radius $\sim 20,000$–$700,000$ obtained from ingress of photoelectric absorption dips; see Church & Balucinska-Church 2004, and references within). Furthermore, broadened emission lines in Chandra observations of Cygnus X-2 suggest a hot, dense corona of up to $\sim 100,000$ km (Schulz et al. 2009). Nevertheless, we applied the double-thermal emission model to our BHC spectra for completeness; the Comptonized component should not be required at such high X-ray luminosities according to Lin et al. (2007).

We examined the light curves and spectral histories of all our targets, searching for further BHCs. We found a total of 8 GC LMXBs that apparently exhibited high-luminosity low states; we refer to the X-ray source associated with GC labeled in the RBC V.4 as Bnn and XBnn. In addition to the known BHCs XB082, XB144, XB153, XB163, and XB185 (Barnard & Kolb 2009; Barnard et al. 2011a), we have identified XB086, XB135, and XB148 as new BHCs. We present the light curves and spectral histories ($\Gamma$ versus time) for the 8 BHCs in Figure 4. The best-fit blackbody + power-law emission models for XB082, XB144, XB153, XB163, and XB185 are presented in Barnard & Kolb (2009) and Barnard et al. (2011a); they clearly demonstrate the low-state nature of the emission.

In the following spectral analysis, uncertainties in best-fit parameters and luminosities for XB086, XB135, and XB148 are quoted at the 90% confidence level, corresponding to $\sim 1.6\sigma$.

### 3.2.1. XB086

XB086 exhibited $\Gamma = 1.4$ at $0.3$–$10$ keV luminosities $\sim 6$–$10 \times 10^{37}$ erg s$^{-1}$. Furthermore, it exhibited spectral variability $\sim 1600$ days into the observations; $\Gamma$ changed from 2.0 to 1.5 accompanied by a luminosity decrease from $1.1 \times 10^{38}$ to $7.5 \times 10^{37}$ erg s$^{-1}$. This variation may indicate a state change from, e.g., the steep power-law state to the low state. We note that XB086 apparently exhibited two different spectral states at very similar luminosities; hysteresis in the state transitions of black hole binaries where the transition from high state to low state is at a lower luminosity than the transition from low state to high state is well known (see, e.g., Maccarone 2003).

None of the ACIS spectra were of sufficient quality to discriminate between spectral states, so we obtained a spectrum

![Figure 2. Histogram showing the number of observations with separation $\tau$ for B144, which is the GC that was observed most often. (A color version of this figure is available in the online journal.)](image-url)
Figure 3. Structure functions for each of the variable X-ray sources, created from 0.5 to 4.5 keV fluxes for comparison with Vagnetti et al. (2011); the dashed line represents their ensemble AGN structure function. The dotted line shows $\sigma^2_n$ for each bin for reference, since the noise component has already been subtracted from $\text{SF}(\tau)$. We provide the name of the X-ray source at the top of each panel, along with the best-fit constant luminosity. The $y$-axis is scaled to the SF, and high values for the noise may be excluded.

(An extended, color version of this figure is available in the online journal.)

for XB086 from the 2002 January 6 XMM-Newton observation (ObsID 0112570101). This spectrum rejected a disk blackbody model ($kT_{\text{BB}} = 1.7$ keV, $\chi^2$/dof = 284/155), but a power-law model provided a good fit ($\Gamma = 1.48 \pm 0.05$, $\chi^2$/dof = 155/154).

Adding a blackbody to the power law resulted in a slightly improved fit ($kT = 0.9 \pm 0.3$ keV, $\Gamma = 1.47 \pm 0.18$, $\chi^2$/dof = 141/152); the blackbody component contributed $\sim 12\%$ of the 0.3–10 keV luminosity ($\sim 6 \times 10^{37}$ erg s$^{-1}$). The Terzan 5 NS transient exhibited $kT \sim 2.0$ and $\Gamma \sim 2.3$ at similar luminosities (Chakraborty et al. 2011); these parameters differ by $>5\sigma$. Figure 5 shows the best-fit two-component model to the unfolded spectrum, multiplied by channel energy; it is representative of the BH low state, and inconsistent with a high-luminosity NS XB. This spectrum contained $\sim 9000$ net source counts.
Figure 4. Long-term 0.3–10 keV light curves of black hole candidates, along with the best-fit photon index, \( \Gamma \), for each ACIS observation; for observations with \(<200\) net source counts \( \Gamma \) is fixed to the mean \( \Gamma \) for bright observations. Luminosity uncertainties are quoted at the 1\( \sigma \) level, while \( \Gamma \) uncertainties are at the 90\% confidence level.

(An extended, color version of this figure is available in the online journal.)

Figure 5. Unfolded XMM-Newton pn spectrum for XB086, assuming the best-fit absorbed blackbody + power-law model; the flux of each channel is multiplied by the energy. The power-law component has similar \( \Gamma \) to the simple power-law fit.

(A color version of this figure is available in the online journal.)

Fitting a blackbody + disk blackbody model to B086 resulted in a \( 1.50^{+0.14}_{-0.14} \) keV blackbody and an inner disk temperature of \( 0.66 \pm 0.08 \); the blackbody component contributed 64\% of the unabsorbed flux. The inner disk temperature obtained for XB086 is \( >5\sigma \) below the minimum temperatures observed by Lin et al. (2007); furthermore, Lin et al. (2007) never observed blackbody contributions \( >50\% \) in any of their transient spectra. Therefore, the B086 spectrum is quite unlike any of the spectra observed by Lin et al. (2007).

We conclude that XB086 was in a low state; \( N_{\text{H}} = 1.06 \pm 0.15 \times 10^{21} \) atoms cm\(^{-2}\), and the unabsorbed 0.3–10 keV luminosity was \( 6.4 \pm 0.2 \times 10^{37} \) erg s\(^{-1}\) (90\% confidence limits). This result supports our BHC classification from the ACIS observations.

3.2.2. XB135

XB135 exhibited \( \Gamma \sim 1.6 \) at incredibly high luminosities: \( \sim 4-6 \times 10^{38} \) erg s\(^{-1}\) during the Chandra observations. The highest quality spectrum (ObsID 14198) had a \( \sim 40 \) ks exposure time and a count rate \( \sim 0.2 \) counts s\(^{-1}\). This high intensity would result in significant pile-up if XB135 were on-axis; however, it is near the edge of the field of view, and the photons are distributed over a large number of pixels. Indeed, no pixel accumulated more than 19 photons over 40 ks and hence pile-up was not an issue.

The ObsID 14198 0.3–7.0 keV XB135 emission spectrum was well described by an absorbed power law (\( \Gamma = 1.72 \pm 0.08 \), \( \chi^2/\text{dof} = 205/221 \)), a disk blackbody (\( kT_{\text{in}} = 1.63 \pm 0.08 \) keV, \( \leq 0.13 \)), and a simple power law (\( \Gamma \)).
\( \chi^2/\text{dof} = 197/221 \), or a blackbody + power-law model \((kT = 0.7 \pm 0.2 \text{ keV}, \Gamma = 1.5 \pm 0.4, \chi^2/\text{dof} = 187/219)\).

We have previously published analysis of an XMM-Newton observation of XB135 (Barnard et al. 2008). It was well described by a power-law emission model \((\Gamma = 1.56 \pm 0.03, \chi^2/\text{dof} = 467/435)\), but the fit was significantly improved by adding a thermal component \((kT = 0.8 \pm 0.2, \Gamma = 1.54 \pm 0.14, \chi^2/\text{dof} = 413/433)\); the thermal component contributed 11 \pm 5\% of the flux. A disk blackbody-dominated model was rejected. We present the best-fit blackbody + power-law emission model to the pn spectrum in Figure 6; this spectrum contains \(\sim 15,000\) net source counts.

The Terzan 5 transient exhibited \(kT = 1.64^{+0.05}_{-0.07} \text{ keV} \) and \(\Gamma = 2.76^{+0.06}_{-0.08}\) at its peak flux (Chakraborty et al. 2011); these are extremely different from the observed parameters for B135. Fitting a blackbody + disk blackbody model resulted in a \(1.8^{+0.3}_{-0.2} \text{ keV}\) blackbody contributing 49\% of the 0.3–10 keV unabsorbed luminosity \((3.7 \times 10^{38} \text{ erg s}^{-1})\); the inner disk temperature was 1.0 \pm 0.2 keV. Such a low disk temperature is consistent only with the lowest luminosities of the NS transients measured by Lin et al. (2007), and the blackbody contribution is too large. We conclude that this B135 spectrum is unlike either model for NS high states, and most likely represents a low-state BH XB.

The inferred mass for XB135 is very large, at least 33 \(M_\odot\) from the XMM-Newton observation, and possibly \(> 50 M_\odot\) if XB135 was also in the low-state during the ACIS observations. Such a massive black hole could have been formed from a metal-poor high-mass star, so that little mass was lost in stellar winds during the aging process (Belczynski et al. 2010; Mapelli et al. 2010), or could have been formed by stellar mergers in the cluster core (Miller & Hamilton 2002).

### 3.2.3. XB148

XB148 exhibited a hard emission spectrum \((\Gamma \sim 1.5)\) up to a 0.3–10 keV luminosity of \(8 \times 10^{37} \text{ erg s}^{-1}\). Unfortunately, none of the ACIS spectra suggesting high-luminosity low states were of sufficient quality to discriminate between emission models.

A 2008 January 27 XMM-Newton observation of XB148 (ObsID 0505720501) with \(\sim 2000\) net source counts yielded a 0.3–10 keV spectrum that was well described by a power law \((\Gamma = 1.80 \pm 0.15, \chi^2/\text{dof} = 96/115)\) or a disk blackbody \((kT_{\text{in}} = 1.14 \pm 0.15, \chi^2/\text{dof} = 125/116)\); these results are consistent with a black hole low state or high state. Fitting a blackbody + power-law model resulted in \(kT = 0.4 \text{ keV}\), unexpectedly low for a neutron star system; we present this best fit to the unfolded spectrum times channel energy in Figure 7.

The Terzan 5 transient exhibited \(kT = 1.4–3.7\) (Chakraborty et al. 2011), for 0.3–10 keV luminosities \(2.5–33.7 \times 10^{37} \text{ erg s}^{-1}\); \(> 5\sigma\) higher than for XB148; similarly, \(\Gamma\) for XB148 is \(> 4\sigma\) lower than the range observed by Chakraborty et al. (2011). Fitting a blackbody + disk blackbody model yielded \(kT = 3.5 \text{ keV}\), with unconstrained uncertainties, contributing 42\% of the unrealistic 0.3–10 keV luminosity \((1.3 \times 10^{39} \text{ erg s}^{-1})\); the inner disk temperature is 0.80 \pm 0.10, 3\sigma below the lowest temperature measured by Lin et al. (2007).

These results are supportive of the classification of XB148 as a black hole candidate. Assuming a power-law model yields \(N_H = 1.5 \pm 0.4 \times 10^{21} \text{ atoms cm}^{-2}\), giving an unabsorbed 0.3–10 keV luminosity of 4.7 \pm 0.5 \times 10^{37} \text{ erg s}^{-1}\); hence, we cannot rule out a particularly massive \((\sim 28 M_\odot)\) neutron star accretor in its low state.

### 3.2.4. Properties of the Host Clusters

We now consider the properties of the GCs hosting our BHCs. In particular, we examine the masses, ages, and metallicities of these clusters; these values were obtained from Caldwell et al. (2011), who also ranked the 379 M31 GCs in their study by mass and by metallicity. We list these properties in Table 3.

In Barnard et al. (2011a) we concluded that particularly massive or metal-rich GCs could contain bright X-ray sources (and hence BHCs) as well as those GCs that are both massive and metal-rich. The GCs containing our three new BHCs are more massive than \(> 80\%\) of the GCs surveyed by Caldwell et al. (2011); however, two of them (B086 and B135) are in the lowest quartile for metallicity, with \([\text{Fe/H}] = -1.82\). We note that the low metallicity for B135 is in keeping with the...
have shown that while BH masses are limited to ∼86 $M_\odot$ for metallicities ∼1% solar.

### 3.3. The Dipping, Precessing X-Ray Binary XB158 and Related Systems

XB158 (a.k.a. Bo 158) is a high-inclination XB that experiences periodic intensity dips on the orbital period (Trudolyubov et al. 2002); the original study used light curves folded on the 10.017 s (2.8 hr) period, and Trudolyubov et al. (2002) concluded that the dip depth varied with luminosity. However, detailed analysis of the original XMM-Newton observations, along with proprietary observations, revealed that the dips appeared in some observations but not in others (Barnard et al. 2006). This behavior occurs in systems with low mass ratios (short periods) because the outer edge of the accretion disk reaches the 3:1 resonance, causing additional tidal torques from the secondary that lead to elongation and precession of the disk (see, e.g., Osaki 1989; Whitehurst & King 1991; Ogilvie & Dubus 2001).

XB158 is located at a high off-axis angle from the focus of the observations, and was only observed in 19 ACIS observations; it was observed in all of the HRC observations thanks to the larger field of view. The 0.3–10 keV luminosity was extremely variable, ranging over ∼4 $\times$ 10$^{37}$ erg s$^{-1}$, with the best-fit line of constant intensity yielding $\chi^2$/dof = 3030/63 for ACIS and HRC observations.

We note that the high-quality XMM-Newton spectra of XB158 require a two-component emission model consisting of, e.g., a black body + power law (Barnard et al. 2006); however, the Chandra spectra were well described by a power law with best-fit constant $\Gamma = 0.59 \pm 0.17$.

We propose that the observed fluctuation between high and low luminosities may be caused by varying accretion rates over the disk precession cycle. Using proprietary three-dimensional smoothed particle hydrodynamics code, we estimated the disk precession period to be ∼29 orbital periods, or ∼81 hr (Barnard et al. 2006). The cadence of these observations is not well suited for testing such a period; however the similar minima and maxima are suggestive of some sort of super-orbital cycle.

We note that the HRC luminosities for XB158 may be misleading, since we are approximating a two-component spectrum with a single power law, and the HRC responses to each component may be different from the ACIS responses. However, it is encouraging to see that ACIS and HRC observations made at similar times produced consistent luminosities. Even if the normalization of the HRC light curve is incorrect, the variability reflects the intensity variation of the source, suggesting that the luminosity of XB158 really is rapidly and systematically variable.

We may expect GC XBs to have systematically shorter periods than XBs outside GCs because the probability of collisions with other stars in the GC is high, and these interactions shorten the orbital periods. Hence, even binaries with mass ratios >0.3 may have sufficiently short periods to experience the tidal resonances that produce precessing disks.

The 0.3–10 keV light curve of XB146 looks similar to that of XB158, in that it also fluctuates between fairly consistent minima and maxima; however, it is observed in 131 out of 134 observations, and appears to be more structured. The best-fit line of constant intensity yields $\chi^2$/dof = 3614/130, as the 0.3–10 keV luminosity fluctuates between ∼10$^{37}$ and ∼5 $\times$ 10$^{37}$ erg s$^{-1}$, with the occasional outlier. We therefore suggest that XB146, and other X-ray sources exhibiting similar behavior, are XBs with precessing accretion disks. Unfortunately, this is not easily verified unless they are viewed close to edge-on.

### 3.4. X-Ray Transients

Four X-ray sources in our sample are considered transient, in that they vary in 0.3–10 keV luminosity by a factor >100 between observations where they are detected, and are fainter than the detection limit in other observations. Two types of XB behavior lead to transient X-ray sources. LMXBs may exhibit transient behavior due to instabilities in the disk; the disks accumulate matter during a long quiescent phase, and burn a large portion of the accreted material during outbursts. Long-period HMXBs with eccentric orbits may also be X-ray transients, if accretion occurs only in a limited phase range near periastron.

Three of the transients are associated with a GC or candidate and are expected to be LMXBs due to the ages of the GC populations; this includes XB163, which we have identified as a black hole candidate, as previously discussed.

XB128 varied by a factor >500 over 47 observations, peaking at a 0.3–10 keV luminosity ∼5 $\times$ 10$^{37}$ erg s$^{-1}$. The best spectrum for XB128 was from Chandra observation 4682 (2004 May 23), yielding 157 net source counts; it was well described by a power law with $\Gamma = 1.5^{+0.9}_{-0.7}$, a disk blackbody with $kT = 1.6^{+0.9}_{-0.4}$ keV, or a two-component model consisting of a ∼1 keV blackbody and a power law with $\Gamma \sim 2$; this spectrum is consistent with a neutron star or black hole primary.

XPB-in7 varied by a factor >100 over 103 observations. The peak luminosity of XPB-in7 was in Chandra observation 8183 (2007 January 14), with 227 net counts; however, we were unable to obtain an acceptable fit from any of our spectral models. Since the peak luminosity was only 1.7 $\times$ 10$^{37}$ erg s$^{-1}$, we would be unable to determine the nature of the accreter in any case. We note that PB-in7 is only a GC candidate, and further insight into the nature of the host may help interpret the nature of XPB-in7.

XSK059A is coincident with a likely compact GC, in a region rich in H II (N. Caldwell 2012, private communication). As such, it may be an HMXB associated with the H II instead of an LMXB associated with the GC. XSK059A varied by a factor ∼300 between Chandra observations, exhibiting long quiescent intervals punctuated with many outbursts. The light curve is consistent with 8 outbursts $\geq 10^{37}$ erg s$^{-1}$ separated by 1–6 cycles of ∼120 days, with the outbursts lasting up to ∼90 days; we indicate these bursts in Figure 1 with downward arrows. However, these outbursts are not present in every cycle.
Such behavior may be explained by an HMXB with variable mass-loss rate from the secondary.

4. DISCUSSION AND CONCLUSIONS

We have analyzed the long-term light curves of globular cluster X-ray sources using 134 Chandra observations taken over ~12 years; these X-ray sources are likely LMXBs. Our sample was drawn from the Revised Bologna Catalog V.4. D’Antona, F., Teodorescu, A., & Ventura P. 2007, in AIP Conf. Ser. 924, The Multicolored Landscape of Compact Objects and Their Explosive Origins, ed. T. di Salvo, G. L. Israel, L. Piersant, L. Burderi, G. Matt, A. Tornambe, & M. T. Menna (Melville, NY: AIP), 649

We created structure functions from the 0.3–10 keV fluxes of our variable sources, for comparison with the ensemble AGN SF created by Vagnetti et al. (2011). The lower luminosity XBs exhibited SFs that generally showed substantially more variability than the AGN SF over most timescales. The higher luminosity XBs had SFs generally indicating similar, or lesser, variability than the ensemble AGN SF; however, the 2–10 keV fluxes for these systems were higher than almost all AGNs. This discrimination is important, since the emission spectra of XBs and AGNs are often similar.

We have identified a total of 9 black hole candidates in M31 GCs, of which 8 are covered by this survey; 7 BHCs were identified in these data (4 reported in Barnard et al. 2011, and 3 new to this work), using our well-established method of seeking low-state emission spectra at luminosities that conspicuously exceed the limit for neutron star binaries. We have identified apparent super-orbital variability in XB158, which is a short-period system with a precessing disk.

We will be creating SFs for the remaining ~400 X-ray sources in our field, and expect to identify ≥100 new X-ray binaries.

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Facility: CXO (ACIS, HRC)

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