FIFTY M31 BLACK HOLE CANDIDATES IDENTIFIED BY CHANDRA AND XMM-NEwTON

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ABSTRACT

Over approximately the last five years, we have identified ~35 black hole candidates (BHCs) in M31 from their X-ray spectra. Our BHCs exhibited 0.3–10 keV spectra consistent with the X-ray binary (XB) hard state at luminosities that are above the upper limit for neutron star (NS) XBs. When our BHC spectra were modeled with a disk blackbody + blackbody model for comparison with bright NS XBs, we found that the BHCs inhabited a different parameter space than the NS XBs. However, BH XBs may also exhibit a thermally dominated (TD) state that has never been seen in NS XBs; this TD state is most often observed in X-ray transients. We examined the ~50 X-ray transients in our Chandra survey of M31 and found 13 with spectra suitable for analysis. We also examined two BHCs outside the field of view of our survey in the globular clusters B045 and B375. We have 42 strong BHCs and 8 plausible BHCs that may benefit from further observation. Of our 15 BHCs in globular clusters, 12 differ from NS spectra by >5σ. Due to improvements in our analysis, we have upgraded 10 previously identified plausible BHs to strong BHs. The mean maximum duty cycle of the 33 X-ray transients within 6’ of M31* is 0.13; we estimate that >40% of the XBs in this region contain BH accretors. Remarkably, we estimate that BHs contribute >90% of those XBs >10^{38} erg s^{-1}.

Key words: stars: black holes – X-rays: binaries – X-rays: general

Online-only material: color figure

1. INTRODUCTION

In recent years, we have identified a number of black hole candidates (BHCs) in M31 from their X-ray spectra from XMM-Newton or Chandra using various techniques to exclude active galactic nuclei (AGNs) that may be spectrally similar (Barnard et al. 2008, 2011a, 2011b, 2012, 2013b, 2014a, 2014b; Barnard & Kolb 2009). We have recently discovered a method of quantifying the strength of our BHC identifications (Barnard et al. 2013b, 2014b) that involves using a double thermal emission model (disk blackbody + blackbody) to compare our BHC spectra with the spectra of bright Galactic neutron star (NS) X-ray binaries (XBs).

The Galactic NS low-mass X-ray binaries (LMXBs) were long thought to be separated into the highly luminous Z sources and the lower-luminosity atoll sources; the Z sources were further split into those that resembled Cygnus X-2 and those that resembled Scorpius X-1 (Hasinger & van der Klis 1989). Muno et al. (2002) showed that the two populations exhibited dramatically different variabilities, with Z-source luminosities varying by a factor of a few while their spectra evolved over timescales of a few days; and atoll-source luminosities varied by one to two orders of magnitude during spectral evolution over several months.

However, three recent Galactic X-ray transients have exhibited the full range of NS LMXB behavior, going from Cyg-like to Sco-like then to atoll behavior as their luminosities decreased: XTE J1701−462 (Homan et al. 2007), IGR J17480-2446 (e.g., Chakraborty et al. 2011), and MAXI J00556−332 (e.g., Sugizaki et al. 2013). Therefore, it is clear that NS LMXB behavior is governed by the accretion rate (which translates into luminosity).

Lin et al. (2009) examined ~900 RXTE observations of XTE J1701−462, carefully subdividing each observation so that they could study the spectral evolution in detail. They fitted each of the thousands of spectra with a double thermal model (disk blackbody + blackbody) that they developed when they examined the spectral evolution of two transient atoll LMXBs (Lin et al. 2007). They found that their double thermal model was successful except for two types of spectra: hard-state spectra, which are exhibited by NS and BH LMXBs at relatively low Eddington fractions and dominated by Comptonization (van der Klis 1994), and spectra from the Z-source “horizontal branch” (Hasinger & van der Klis 1989), which required a Comptonized component in addition to the two thermal components. Lin et al. (2012) also obtained very similar results from their analysis of the Sco-like Z source GX17+2. The work of Lin et al. (2007, 2009, 2012) covers the full range of NS LMXB behavior, which they modeled in a consistent way. Furthermore, Lin et al. (2010) successfully applied their model to Beppo-SAX and Suzaku spectra of the persistently bright NS XB 4U 1705−44; the energy ranges were 1–150 keV and 1.2–40 keV, respectively, meaning that the usefulness of the double thermal model is not confined to the RXTE pass band.

The hard state is observed in BH and NS LMXBs (van der Klis 1994) only at luminosities of L < 0.1L_{Edd}, where L_{Edd} is the Eddington luminosity (Gladdstone et al. 2007; Tang et al. 2011). We have identified 36 BHs that exhibit apparent hard-state spectra at 0.3–10 keV luminosities, too high for NS LMXBs (L_{bol} > 3 \times 10^{37} erg s^{-1}), see Barnard et al. 2013b, 2014a, and references within). When we plotted disk blackbody temperature versus 0.1–10 keV disk blackbody luminosity for our BHs, we found that none of our BHs resided in the region occupied by NS LMXBs (gleaned from the analysis of thousands of spectra by Lin et al. 2007, 2009, 2012), although some were consistent within 3σ (Barnard et al. 2013b, 2014a). We classified those BHs > 3σ away from the NS LMXB region as strong BHs and those within 3σ as plausible BHs; for some BHs, the double thermal model was unconstrained, and we labeled these as plausible BHs as well.
BH XBs also exhibit a thermally dominated state that is never seen in NS XBs (Done & Gierliński 2003). The thermally dominated state is most often observed in X-ray transients, where $\sim 1$ keV disk blackbody emission contributes $>75\%$ of the $2-20$ keV flux (Remillard & McClintock 2006). We have been monitoring the central region of M31 for the last 13 yr, averaging $\sim 1$ observation per month, and we have a total of 175 Chandra observations, including our monitoring survey, deeper observations of M31*, and public data from other programs. We have identified $\sim 50$ transient X-ray sources in our Chandra observations (Barnard et al. 2014a).

In this work, we examine those M31 transients with spectra consistent with the thermally dominated state and compare double thermal fits to these spectra with the NS LMXBs in order to expand our BHC sample. We apply an improved BHC classification method to all of our BHCs with the hope of upgrading some of the plausible BHCs to strong BHCs.

We also examine two BHCs in globular clusters (GCs) outside of the area monitored by our Chandra survey. The first is located in the GC B045 (also known as Bo 45), following the naming convention of the Revised Bologna Catalogue v3.4 (Galleti et al. 2004, 2006, 2007, 2009). Barnard et al. (2008) identified the X-ray source as a BHC because its hard spectrum and high variability indicated that it was in the canonical BH hard state, but the $0.3-10$ keV luminosity exceeded the Eddington limit for a $1.4 M_\odot$ NS. The second BHC resides in the GC B375 (Bo 375) and was identified as a BHC by Di Stefano et al. (2002). In Barnard et al. (2008), we mistakenly said that the spectrum (well described by a $0.90 \pm 0.10$ keV blackbody and a power law with photon index $1.73 \pm 0.18$) was typical of a bright NS XB; however, bright NS XBs fitted with such models yield considerably higher blackbody temperatures (e.g., $\sim 2$ keV for Sco X-1, Barnard et al. 2003a).

2. OBSERVATIONS AND DATA ANALYSIS

An overview of our survey of 528 M31 X-ray sources in 174 Chandra observations is presented in Barnard et al. (2014a). We refer the reader to that paper for the details of the analysis. In this work, we concentrated on the 112 ACIS observations in our survey because there is no way to extract reliable spectra from the 62 HRC observations. For some BHCs, we also examined XMM-Newton observations following the procedures outlined in Barnard et al. (2013b). Chandra observations were analyzed with CIAO v4.5, while XMM-Newton observations were analyzed with SAS ver. 13.0; X-ray spectra were modeled with XSPEC v12.8.

The Chandra observations are susceptible to pileup (two or more photons arriving in the same detection cell within a particular exposure). Piled-up events can either result in a single photon with an energy equivalent to the sum of the energies of the two real events, or the event can be rejected because it doesn’t look real (see e.g., Davis 2001). To estimate the degree of pileup, we created a natively binned image of each X-ray source with no filtration and found the highest number of counts in a $3 \times 3$ pixel area (the size of a Chandra ACIS detection cell). From this, we obtained the number of counts per frame, $n$. The pileup fraction, $f_p$, is then given by $f_p \simeq n/2 - (1/12) \times n^2$ according to ACIS documentation.

For this study, we only considered transients with $>200$ counts in their X-ray spectra for at least one observation. We refer to these X-ray sources by the source number in our catalog (S1–S528; Barnard et al. 2014a). We have already highlighted BHCs that appear to exhibit hard-state spectra at luminosities that are too high for NS LMXBs; our new sample exhibits spectra consistent with a disk blackbody with inner disk temperature $kT_{DBB} \lesssim 1$ keV.

We estimated the duty cycle of each transient in two ways. The first of these was to assess the percentage of observations where the target was detected at $>3\sigma$ significance. Since the roll angle was unconstrained, each observation only contained a subset of all the X-ray sources; hence, we only considered observations where the transient could be observed when making this estimate of the duty cycle (DC1). The second duty cycle estimate was made by comparing the duration of the outburst with the total observing time. To do this, we measured the time between the last observation before the outburst was detected at $>3\sigma$ to the first observation in which the transient detection goes below $3\sigma$; this estimate of the duty cycle (DC2) is an upper limit.

For each object in our sample, we identify the observation that provides the highest-quality BHC spectrum; this can be a Chandra ACIS observation (ObsID 303–14198) or an XMM-Newton observation (ObsID 0112570101–072960401). For XMM-Newton observations, we only analyzed the pn data. We fitted a double thermal model to the best spectrum for each object (WABS*(DISKBB+BB) in XSPEC); if the fit was unconstrained, then we classified the object as a plausible BHC unless the spectrum was too soft to be a NS LMXB (e.g., with no emission above 2 keV). We also fitted more traditional models to these spectra: absorbed power law, absorbed disk blackbody, and absorbed disk blackbody + power law to represent the hard, thermal, and steep power-law states, respectively (Remillard & McClintock 2006).

We estimated the uncertainties in each fit by generating 1000 spectra from the best-fit model using the XSPEC command fakeit; random variations were introduced to each simulated spectrum that were governed by the statistical properties of the original spectrum. We found the best fit for each simulated spectrum and ranked the values of each parameter from lowest to highest; the $1\sigma$ uncertainties were obtained from the 16th and 84th percentiles.

For the best double thermal fit to each spectrum, we examined the temperature and $2-10$ keV luminosity for each component. Each spectrum was assessed according to three criteria, following Barnard et al. (2013b, 2014b). The minimum disk blackbody temperature, $kT_{DBB}$, for NS LMXBs depends on the luminosity: $1.0 \text{ keV}/1.2 \text{ keV}$ for luminosities below/above $2 \times 10^{37} \text{ erg s}^{-1}$, respectively; the minimum NS LMXB blackbody temperature, $kT_{BB}$, is $\sim 1.5 \text{ keV}$; and finally, the disk blackbody contribution to the $2-10 \text{ keV}$ spectrum, $f_{DBB}$, is $>45\%$ for NS LMXBs. For our BHC spectra, we expect $kT_{DBB}$, $kT_{BB}$ and $f_{DBB}$ to be substantially lower than these minima; a cooler disk blackbody naturally leads to a smaller contribution to the $2-10 \text{ keV}$ luminosity.

For parameters that are below the NS minimum, we calculate the probability that the observed value is consistent with a NS LMXB: $P_{DBB} = \text{erfc}(1.0-kT_{DBB}/\sigma/2^{0.5})$ or $P_{DBB} = \text{erfc}((1.2-kT_{DBB})/\sigma/2^{0.5})$ depending on $L_{DBB}$ (see above); $P_{BB} = \text{erfc}((1.5-kT_{BB})/\sigma/2^{0.5})$; $P_{f} = \text{erfc}(0.45-f_{DBB}/\sigma/2^{0.5})$. The probability that the BHC is consistent with being a NS LMXB, $P_{NS}$, is then $P_{DBB} \times P_{BB} \times P_{f}$. If a parameter exceeds the NS LMXB threshold, then the probability of that parameter being consistent with a NS LMXB is 0. We assign a Rank to the BHC based on the probability of being consistent with a NS LMXB: $\text{Rank} = -\log(P_{NS})$. A Rank $>2.6$ indicates $>3\sigma$ deviation from a NS spectrum, while a Rank $>6.2$ indicates a $>5\sigma$ deviation. This approach to identifying strong BHCs is an improvement upon the one used in Barnard et al. (2013b).
therefore, we applied this analysis to our BHCs previously identified by their hard-state spectra.

3. RESULTS
3.1. Basic Properties of the BHCs
In addition to the 35 BHCs discussed in Barnard et al. (2013b), we obtained usable spectra from 13 X-ray transients from our 13 year Chandra monitoring campaign; these include two ultraluminous X-ray sources (ULXs) that exhibited 0.3–10 keV luminosities >2 × 10^{39} erg s^{-1} (Kaur et al. 2012; Nooraei et al. 2012; Middleton et al. 2013; Barnard et al. 2013a). The other ∼40 transients in our Chandra survey had insufficient counts in their spectra. With the addition of XB045 and XB375, which lie outside the Chandra survey, our sample contains a total of 50 BHCs. In Table 1, we present a summary of our Chandra results for 48 BHCs (XB045 and XB375 were not included in our Chandra survey). This table is described in the following three paragraphs.

For each source (named following Barnard et al. 2014a), we provide its identity in previous papers; BH1–BH35 are
BHCs that were analyzed in Barnard et al. (2013a), T1–T9 are transients discussed in Barnard et al. (2012), and T13 was discovered later (Barnard et al. 2014b). U1 and U2 are ultraluminous transients (Barnard et al. 2012, 2013b), and B128 is a GC BHC identified in Barnard et al. (2014a). We also provide the angular distance from M31*.

We then present the maximum and minimum 0.3–10 keV luminosities observed in our Chandra observations of that source, along with the photon index from the best-fit power-law model. Thermally dominated spectra are indicated by $\Gamma > 3$. If a source produced fewer than 200 photons during either of these observations, then we assumed the mean $\Gamma$ for all observations of that source with $> 200$ counts; these values are indicated by $\star$. If we were unable to fit a hard-state spectra for a given source, we assume $\Gamma = 1.7$ for the minimum luminosity.

Finally, we present the timing properties of each source. First, we give the number of outbursts, if any; persistently bright X-ray sources are indicated with “P.” If the number of outbursts is unclear, we simply say the source has many. Next are the two estimates of the duty cycle, DC1 and DC2; these are only provided for the transients. Finally, we provide the $\chi^2$/dof from best fitting a constant intensity to the light curve (taken from Table 1 of Barnard et al. 2014a) to indicate the level of variability.

### 3.2. Fitting Canonical BH Models

We summarize our modeling of the BHC spectra with canonical BH models (hard state, thermally dominated state, steep power-law state; Remillard & McClintock 2006) in Table 2. All three states consist of thermal and Comptonization emission components; however, the hard state is dominated by the Comptonized component and may be approximated by a power law for lower-quality spectra while the thermally dominated state may be approximated by a disk blackbody. For BHs in the steep power-law states, the photon index of the Comptonized component is $\approx 2.4$ (Remillard & McClintock 2006). For each source, we first give the observation that best supports our case for a BH accretor. We then compare the $\chi^2$ values for three spectral models (WABS*DISKBB; WABS*POWERLAW; WABS*[DISKBB + POWERLAW]): $\Delta 1$ shows the difference in $\chi^2$ between the disk blackbody model and the power-law model while $\Delta 2$ shows the difference between the power-law model and disk blackbody + power-law model. Next, we show the possible states, with our preferred model indicated in boldface. Finally, we give the best-fit parameters: absorption, temperature and luminosity of the disk blackbody component (if applicable), photon index and luminosity of the power law component (if applicable), and $\chi^2$/dof for our preferred model.

In most cases, the preferred model is the one with the lowest $\chi^2$/dof. However, if there is no significant difference between the fits, then we consider whether the BHC is persistent or transient. We favor a hard state for a persistent source and a thermally dominated state for a transient. Furthermore, a hard state is preferred to a steep power-law state if the disk temperature is higher and $\Gamma$ is lower than expected for the steep power-law state. S179, S300, S345, S415, and S487 have sufficiently good spectra to constrain the thermal components in the hard-state spectra.

We see examples of BHCs consistent with all three canonical states. S151, S287, S386, and S396 are consistent with the steep power-law state, but have $\Gamma > 3$ and are therefore particularly soft; also, we found $\Gamma = 2.6 \pm 0.4$ for B045, meaning that it could be very soft as well. B375 appears to be rather hot and rather hard for the SPL, but is consistent within uncertainties; the simple power-law model does not yield an acceptable fit.

### 3.3. Fitting Double Thermal Models

Table 3 summarizes our results. We first give the source number of each BHC in our survey paper (S1–S528; Barnard et al. 2014a). Then we present the temperature and 2–10 keV luminosity for the disk blackbody and blackbody components, respectively, along with the fractional contribution of the disk blackbody to the 2–10 keV emission. Luminosities are normalized to $10^{37}$ erg s$^{-1}$ and assume a distance of 780 kpc (Stanek & Garnavich 1998). These data are followed by the BHC Rank (i.e., $-\log(L_{2-10}$ keV)) and the class of the BHC: strong (S) or plausible (P). Finally, we present any comments. Globular clusters are indicated with “G” and the GC name in parentheses, following the Revised Bologna Catalog v3.4 (Galleti et al. 2004, 2006, 2007, 2009); transients are indicated by “T” and include ULXs labeled “U”; “P > S” shows that the BHC was previously classified as a plausible BH in Barnard et al. (2013b); and “Soft” indicates a spectrum with little flux above $\sim 2$ keV. Sources where the disk blackbody + blackbody model was unconstrained are indicated by dots.

We find that 42 BHCs exhibited a Rank $> 2.6$ and differed from the NS LMXB spectra by $> 3\sigma$; these are classed as strong BHCs and include 10 systems that have been promoted from plausible BHC classification (Barnard et al. 2013b). Previously, we considered each criterion separately, but now we combine the probabilities for each criterion into one. Furthermore, 36 BHCs exhibited Rank $> 6.2$, with a $> 5\sigma$ difference from NS LMXB spectra.

Figure 1 shows $kT_{DBB}$ versus $L_{DBB}$ for 46 BHCs; the double thermal model was unconstrained for 4 BHCs. Circles represent persistent X-ray sources, triangles represent transients, and red symbols indicate BHCs in globular clusters. None of our BHCs had best fits inside the NS LMXB region of $kT_{DBB}$ versus $L_{DBB}$ parameter space, although some BHCs were consistent within $3\sigma$. We see a natural systematic correlation between temperature and 2–10 keV luminosity: lower temperature emitters contribute...
less to the 2–10 keV flux. The transients tended towards lower temperatures than the persistent sources; this is consistent with the transients exhibiting thermally dominated states rather than hard states (Remillard & McClintock 2006). Of the 15 GC BHCs in our sample, 14 differ from NS LMXB spectra at confidence levels >3σ (2 transients, 11 persistent X-ray sources), and 12 differ from NS LMXBS spectra at >5σ confidence levels. These GC BHCs are particularly interesting because there are no confirmed GC BH XBs in our Galaxy, and there are no known persistent GC BHCs anywhere outside M31.

3.3.1. Comparison with a Bright NS XB in M31

RX J0042.6+4115 is usually the brightest X-ray source in M31 (0.3–10 keV luminosity ~5–6 × 10^{38} erg s^{-1}), and was classified as a Z source (NS LMXB) after exhibiting an apparently tri-modal color–intensity diagram (Barnard et al. 2006).
The highest-quality spectrum for RX J0042.6+4115 came

from the 2002 January 6 XMM-Newton observation 0112570101 (PI: M. Watson). The total exposure time was \( \sim \)60 ks, and we ignored the first 10 ks due to an unstable background. The resulting spectrum contained \( \sim \)30,000 net source counts. During this observation, RX J0042.6+4115 appears to have been in a Cyg-like horizontal branch state (Barnard et al. 2003b). We were unable to obtain successful fits to the spectrum with a double thermal emission model. This is expected, since Lin et al (2009,
2012) required a disk blackbody + blackbody + Comptonization emission model for the horizontal branch. This model was able to successfully describe the RX J0042.6+4115 spectrum with parameters consistent with Lin et al. (2009): $kT_{\text{DBB}} \sim 1.9$ keV, $kT_{\text{BB}} \sim 2.5$ keV, and $\Gamma \sim 2.4$, $x^2/\text{dof} = 738/705$. However, we were unable to constrain the parameters despite the high quality of the data; this is probably because the blackbody component peaks at $\sim 3$ kT, i.e., $\sim 7$ keV, near the upper limit to the XMM-Newton energy band.

3.4. Estimating the BH Population within 6' of M31*

In Barnard et al. (2014a), we found that the number of sources consistent with AGNs in our Chandra survey of sources within 20' of M31* was well below the number predicted from the 0.5–10 keV AGN flux distribution obtained by Georgakakis et al. (2008). However, when we restricted our sample to those within 6' of M31*, we saw a surplus. Hence, the observed deficit is dominated by instrumental effects. With this in mind, we decided to estimate the BH contribution to the X-ray population within 6' of M31* from the duty cycles of transients within this region.

Our survey contains 216 X-ray sources within 6' of M31*, of which 126 are probably XBs; 66 are consistent with AGNs; and 22 are known stars, novae, etc. The 0.3–10 keV detection limit is $\sim 10^{35}$ erg s$^{-1}$, although it is not complete at this level. The 126 probable XBs include 33 X-ray transients. We found 34 of our BHCs in this region, 20 persistent, and 14 transient. To date, we have no information on the accretors in the other 19 transients; they could contain BHs or NS.

We estimated the maximum duty cycle for the unclassified transients from the intervals when transient was not detected at the 3$\sigma$ level (i.e., like DC2 for our transient BHCs in Table 1). The mean maximum duty cycle for transients $> 10^{35}$ erg s$^{-1}$ was 0.13; this would suggest a total of 254 transients within 6' of M31*, 108 of those containing BHs. As a result, we expect $>40\%$ of XBs within 6' of M31 to contain BHs. Assuming the median duty cycle for the transients within 6' of M31* (0.07) yielded essentially the same results. The BH fraction would be higher if the actual duty cycle was smaller or if some of the unclassified transients contain BHs.

Similarly, we observed 24 probable XBs that exceeded $10^{38}$ erg s$^{-1}$ in the 0.3–10 keV band; 20 of these were BHCs. This sample included 11 transients (10 BH transients), with a mean maximum duty cycle of 0.09. These findings suggest that $>90\%$ of sources that exceed $10^{38}$ erg s$^{-1}$ within 6' of M31* contain BHs. By contrast, the majority of Milky Way (MW) XBs $> 10^{38}$ erg s$^{-1}$ are NS XBs (Grimm et al. 2002).

The 2007 MW X-ray binary catalog (Liu et al. 2007) contains 103 X-ray transients, of which 83 are classified with NS or BH accretors. BHCs represent $\sim 50\%$ of the total MW transient population with known accretors, but $\sim 70\%$ of transients with known distances and luminosities $> 10^{37}$ erg s$^{-1}$. We found that 31 of the 33 transients within 6' of M31 exceeded $10^{37}$ erg s$^{-1}$ at some point during our 13 yr survey; if $\sim 70\%$ of these transients contain BHCs, then $>60\%$ of the XBs within 6' of M31* could contain BHCs.

4. DISCUSSION

In this work, we expand upon Barnard et al. (2013b), where we compared the spectra of 35 BHCs with the full range of NS spectra. Lin et al. (2009) have applied a double thermal emission model to a transient Z source that exhibited all types of NS LMXB behavior; this model gave good fits except for hard-state spectra and horizontal branch spectra (where a Comptonized component is required, which dominates hard-state spectra). Lin et al. (2007) first presented this model as an NS analog to the BH thermally dominated state; the main strength of the model when applied to the two original transients was that luminosity followed $t^4$ for both thermal components (Lin et al. 2007). However, the temporal and spectral evolution of high-inclination LMXBs indicates a substantial extended Comptonized component in LMXBs throughout the luminosity range (Church & Balucinska-Church 2004 and references within). Nevertheless, the work of Lin et al. (2007, 2009, 2012) has been extremely useful because it allows us to examine the gamut of NS LMXB behavior in a single parameter space.

BH LMXBs exhibit a thermally dominated state that has never been observed in NS LMXBs; this state is usually observed in X-ray transients (Remillard & McClintock 2006). We examined $\sim 50$ X-ray transients identified in our Chandra survey (Barnard et al. 2014a) and found 13 suitable for spectral fitting. The remaining transients are possible BHs, but may also contain NS accretors; further observations may clarify the identities of these systems. We used an improved method for comparing our BH spectra with NS LMXB spectra for these 13 transients, our 35 original BHCs, and the GC BHCs B045 and B375 for a total of 50 BHCs. We found that 42 exhibited spectra that differed from the NS spectra at a $> 3\sigma$ level and 36 that differed at a $>5\sigma$ level; these were all classed as strong BHs except for S330, which exhibited a luminosity consistent with a NS XB hard state. The spectrum of S117 was unable to constrain the double thermal model, but was too soft to be a NS XB, and S117 is also considered a strong BH. The remaining sources were classed as plausible BHs; 10 BH that were previously identified as plausible in Barnard et al. (2013b) were promoted to strong BHs. We expected hard state and thermally dominated BHs to be inconsistent with NS spectra. However, we also found some steep power-law spectra that were inconsistent with NS spectra; these were particularly soft, with $\Gamma \gtrsim 3$. We certainly do not infer that all BH spectra should be separable from NS spectra.

Using this method, we may identify BHs in many galaxies, including our own. The known Galactic BH LMXBs are all transient or turned on recently (see Remillard & McClintock 2006, and references within). This is because they were identified with a method that requires observations of optical emission lines in the donor spectrum; however, the optical emission of persistently bright X-ray sources is dominated by reprocessed X-rays from the disk (van Paradijs & McClintock 1994). Our X-ray method has no such biases and may reveal further BHs in the known Galactic LMXB population.

We also examined a bright M31 XB ($> 10^{38}$ erg s$^{-1}$) that is expected to contain a NS accretor (S209 Barnard et al. 2014a). A double thermal model fit yielded parameters consistent with the NS systems studied by Lin et al. (2007, 2009, 2012). Hence, the observed differences between our BHs and the Galactic NS XBs studied by Lin et al. (2007, 2009, 2012) is not due to differences between the RXTE, Chandra, and XMM-Newton observatories.

We have identified 126 probable X-ray binaries within 6' of M31* (Barnard et al. 2014a), 34 of which are BHs; 33 of these systems are transient, including 14 BHs. The mean maximum duty cycle of the transient systems was 0.13, suggesting that $>40\%$ of XBs within 6' of M31* contain BHs. However, our results suggest that BH XBs contribute 90% of...
XBs exceeding $10^{38}$ erg s$^{-1}$ in this region. This result provides further substantial difference in the evolution histories of M31 and the MW, since the majority of MW X-ray sources exceeding $10^{38}$ erg s$^{-1}$ are NS XB (Grimm et al. 2002). We already know that M31 contains ~30 times many bright GC X-ray sources ($>10^{37}$ erg s$^{-1}$) as the MW (Barnard et al. 2014a), and could contain ~4–5 times as many XB overall (Stiele et al. 2011; Barnard et al. 2014a).

We thank the anonymous referee for useful suggestions that considerably improved this paper. This research has made use of data obtained from the Chandra satellite, and software provided by the Chandra X-Ray Center (CXC). We also include analysis of data from XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA member states and the U.S. (NASA). We are very grateful to Norbert Schartel and the XMM-Newton team for granting our TOO observation. R.B. is funded by Chandra grants GO2-13106X and GO1-12109X, along with HST grants GO-11833 and GO-12014.

Facilities: CXO (ACIS), XMM-Newton (pn)

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