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Demonstrating the likely neutron star nature of five M31 globular cluster sources with *Swift*-NuSTAR spectroscopy

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ABSTRACT

We present the results of a joint *Swift*-NuSTAR spectroscopy campaign on M31. We focus on the five brightest globular cluster X-ray sources in our fields. Two of these had previously been argued to be black hole candidates on the basis of apparent hard-state spectra at luminosities above those for which neutron stars are in hard states. We show that these two sources are likely to be Z-sources (i.e. low magnetic field neutron stars accreting near their Eddington limits), or perhaps bright atoll sources (low magnetic field neutron stars which are just a bit fainter than this level) on the basis of simultaneous *Swift* and NuSTAR spectra which cover a broader range of energies. These new observations reveal spectral curvature above 6–8 keV that would be hard to detect without the broader energy coverage the NuSTAR data provide relative to *Chandra* and *XMM–Newton*. We show that the other three sources are also likely to be bright neutron star X-ray binaries, rather than black hole X-ray binaries. We discuss why it should already have been realized that it was unlikely that these objects were black holes on the basis of their being persistent sources, and we re-examine past work which suggested that tidal capture products would be persistently bright X-ray emitters. We discuss how this problem is likely due to neglecting disc winds in older work that predict which systems will be persistent and which will be transient.

Key words: globular clusters: general – galaxies: individual: M 31 – X-rays: binaries.

1 INTRODUCTION

It has long been known that there are more X-ray binaries per unit stellar mass in globular clusters than in field stellar populations (Clark 1975). The process by which X-ray binaries form in globular clusters is different from X-ray binary formation processes in low

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density field star populations. In globular clusters, close binaries are formed through interactions between stars, be they tidal captures (Fabian, Pringle & Rees 1975), exchange encounters (Hills 1976), or direct collisions (Verbunt & Hut 1987). As a result, the orbital period distributions of the systems may be quite different from one another.

Whether black holes exist in globular clusters is a topic of great importance for understanding the dynamical evolution of clusters (e.g. Sippel & Hurley 2013; Heggie & Giersz 2014; Morscher et al. 2015), and the formation of gravitational wave sources. Black holes in globular clusters are likely to have a different mass distribution than those in field X-ray binaries, extending up to higher masses, because the black holes in field X-ray binaries form predominantly through common envelope evolution (e.g. van den Heuvel 1983), while the black holes in cluster X-ray binaries may have formed in from single stars, or wide binary progenitors, and then entered binaries through tidal capture (Fabian et al. 1975) or exchange interactions (Hills 1976). One can compare, for example, the expected distribution of black hole masses from single star evolution (Fryer & Kalogera 2001) with the observed distribution from X-ray binaries (Özel et al. 2010; Farr et al. 2011). The observed black holes are lighter than the distribution predicted in the case of single star evolution, lending credence to the idea that common envelopes lead to lower black hole masses. There have also been suggestions that heavier black holes may also form at low metallicity (e.g. Linden et al. 2010; Mapelli et al. 2010), and many globular clusters are significantly more metal-poor than the typical star in the Galactic field. The overall level of X-ray emission, and the luminosities of the brightest individual X-ray sources are highest in the most metal-poor star-forming galaxies (Basu-Zych et al. 2013; Brorby, Kaaret & Prestwich 2014) indicating that the metallicity must affect either the masses of the compact objects, or the number of close binaries with compact objects. These claims had also appeared to be supported by the reports of $\sim$30 $M_\odot$ black holes in two low-metallicty galaxies, in the binaries IC 10 X-1 and NGC 300 X-1 (Prestwich et al. 2007; Crowther et al. 2010). The mass estimates for both of these objects have recently been called into question because the phasing of the X-ray eclipses relative to the radial velocity curves indicate that the radial velocity curves are not tracing the orbits of the donor stars (Binder et al. 2015; Laycock, Cappallo & Moro 2015a; Laycock, Maccarone & Christodoulou 2015b).

There are a few more reasons why identifying stellar mass black hole X-ray binaries in globular clusters is of major astrophysical importance. These objects are unlikely to survive in the same globular clusters that contain intermediate-mass black holes (IMBH; Leigh et al. 2014); instead, dynamical friction should cause them to sink to the centre of the cluster, where the IMBH will split the binaries. Additionally, stellar mass black holes in globular clusters represent an extreme case that can be used to test theories of space–times with more than four dimensions in which Hawking radiation might be far more efficient than in a space–time described by standard general relativity (Emparan, Fabbri & Kaloper 2002; Psaltis 2007); globular clusters give excellent ‘clocks’ for proving that the black hole in question is quite old, so stellar mass black holes in globular clusters give the strongest available constraints on this problem (Gnedin et al. 2009).

It has been suggested that the black hole X-ray binaries that form via tidal capture should be persistent X-ray sources, while those that form via exchange interactions might be predominantly transient sources (Kalogera, King & Rasio 2004). We define the boundary between persistent and transient sources here to be sources which are unaffected and affected, respectively, by the ionization instability in their accretion discs – i.e. persistent sources accrete rapidly enough that their outer accretion discs are ionized at all times, while transient sources are sources which have low enough accretion rates that they spend most of their times in states where the outer disc is neutral, and hence they are subject to this instability (e.g. Cannizzo, Wheeler & Ghosh 1985; Cannizzo, Chen & Livio 1995; King, Kolb & Burderi 1996). In practice, this should be associated with variations of a factor of $\sim 10^4$ or more in luminosity, but given the long outbursts of sources with long orbital periods (see e.g. Truss & Done 2006), there may be objects which appear to be persistent over the lifetime of X-ray astronomy, but which are undergoing such outburst cycles. The basis for the suggestion that tidal capture sources would be persistent comes from King et al. (1996), where it was shown that black hole X-ray binaries with orbital periods of a few to ten hours would typically have mass transfer rates that would make them persistent sources. Barnard et al. (2008) use this as part of the argument for why it is reasonable to find many persistent objects at luminosities of 10^{38} erg s^{-1} in M31 globular clusters, and to associate them with black hole accretors. On the other hand, persistent black holes are not seen in substantial numbers in the Galactic field populations. The known black hole X-ray binaries in this period range are predominantly transient sources – only one strong candidate black hole X-ray binary with a low-mass donor star is persistent – 4U 1957+11 (Gomez, Mason & Robinson 2015) – and even that object is not a dynamically confirmed black hole.

For quite some time, it was thought that globular clusters would not contain stellar mass black holes in substantial numbers. Spitzer (1969) had shown that dynamical decoupling would result based on a criterion involving a critical combination of the fraction of the cluster's mass, and the ratio of the masses of the heavy objects to the masses of the light objects. This criterion would be satisfied for black holes in most old star clusters. This then leads to a combination of effects that should eject a large numbers of the black holes – dynamical evaporation and ejection in three body encounters being the two most important (Kulkarni, Hut & Mcmillan 1993; Sigurdsson & Hernquist 1993). Additionally, the gravitational radiation rocket effect (Redmount & Rees 1989) could also eject a large fraction of any black holes that merge.

Additional discussion, both in the 1970's and in the past 15 yr, has concerned the possibility of finding IMBH in globular clusters. In recent years, searches have been partially motivated by placing globular clusters on the $M_{\rm BH}$–σ relation for galaxies (Ferrarese & Merritt 2000; Gebhardt et al. 2000) and finding that, if the nature of the systems is the same, they should host IMBH; and partly by numerical calculations that suggest that either mergers of stellar mass black holes (Miller & Hamilton 2002) or mergers of massive stars (Portegies Zwart & McMillan 2002) could lead to the production of IMBH in globular clusters. Concrete observational evidence has continued to be lacking. Dynamical studies have, in some cases, shown evidence for increasing mass-to-light ratios in the centres of globular clusters (e.g. Newell, Da Costa & Norris 1976; Gerssen et al. 2002; Noyola, Gebhardt & Bergmann 2008). Dynamics theory has argued that mass segregation should place an excess of stellar remnants in the centres of globular clusters (Illingworth & King 1977; Baumgardt et al. 2003). Proper motion studies of Omega Cen to date have not shown a need for an IMBH (van der Marel & Anderson 2010; Watkins et al. 2013). Searches for accretion signatures, both in X-rays (Grindlay et al. 2001; Haggard et al. 2013) and in radio (e.g. Maccarone 2004; Strader et al. 2012a) have yielded only upper limits, which in some cases are below the estimates from dynamical studies.

On the other hand, over the past decade, the evidence for globular clusters with stellar mass black holes has mounted. The first evidence was seen from extremely bright, strongly variable sources in galaxies within 20 Mpc (Maccarone et al. 2007; Brassington et al. 2008), followed by observations of 'ultrasoft' spectra (White & Marshall 1984) from moderately variable sources in NGC 4472 (Maccarone et al. 2011). More recently, flat spectrum radio sources have been detected in the cores of many Milky Way clusters at luminosities in excess of what is expected from neutron star X-ray binaries (Strader et al. 2012b; Chomiuk et al. 2013).

In this paper, we use joint *Swift*-NuSTAR spectra of several bright X-ray sources in M31 globular clusters to help determine whether they are accreting black holes or accreting neutron stars. The sources are selected on the basis of being bright globular cluster X-ray sources which are in our NuSTAR fields and are sufficiently isolated as to allow straightforward spectroscopy. Two of these have already been claimed to be globular cluster black holes (Barnard et al. 2011) on the basis of fits to spectra taken by *Chandra* and *XMM–Newton*. In this paper, we find that the spectra of both of those sources, as well as those of two other bright globular cluster X-ray sources in M31, are much better fit by models typically used to fit the spectra of neutron stars than models typically used to fit the spectra of black holes. We also discuss in this paper possible reasons why the prediction made in Kalogera et al. (2004) that tidal capture products should be persistent sources is at odds with observations of other Galactic black hole X-ray binaries in a similar orbital period range.

2 SPECTRAL STATE PHENOMENOLOGY

Accreting compact objects typically show a few key spectral states in which substantial amounts of time are spent. Historically, the nomenclature for these sources has been different for black holes and neutron stars, but in recent years, terminology has begun to converge for the lower luminosity, more stable source states.

The first indications of spectral state dichotomy were discovered by Tananbaum et al. (1972), who found, in Cygnus X-1, that the radio emission turned off as the X-ray spectrum went from being dominated by hard X-rays to being dominated by soft X-rays. Hard states are well modelled by thermal Comptonization in an optically thin, geometrically thick hot flow (Thorne & Price 1975). These states are always seen at low luminosities (in the 'low/hard states', typically seen below 2 per cent of the Eddington limit – Maccarone 2003), and are often seen at higher luminosities at the starts of transient outbursts, due to a hysteresis effect seen in black holes (Miyamoto et al. 1995) and found to show analogous behaviour in neutron stars (Maccarone & Coppi 2003) and even in accreting white dwarfs (Wheatley, Mauche & Mattei 2003). In the accreting neutron stars, it was once common to refer to such states as island states, following Hasinger & van der Klis (1989), but in recent years, the term 'hard state' has been applied to both black hole and neutron star accretion flows.

X-ray binaries also often exhibit states well explained by standard accretion disc models (e.g. Shakura & Sunyaev 1973; Davis et al. 2005), in which the emission is thermal with gravitational energy release balanced by radiation. These states are dominated by soft X-rays, and are often called soft states. Neutron stars with similar accretion rates will typically show more complicated spectra, presumably because there is emission from both the accretion disc and the boundary layer (i.e. the region near the surface of the star where the excess rotational energy of the inflow is dissipated) – see e.g. White & Marshall (1984). With high signal-to-noise ratio, it is often necessary to use two components to model 'soft-state' neutron star spectra. The spectra of neutron stars in such states tend to peak at higher temperatures than the spectra of black holes, but they still show strong curvature above 10 keV, rather than power law spectra, and the difference in temperature is likely to be due primarily to the $M^{-1/4}$ temperature dependence for accretion discs at a constant Eddington fraction which extend in to the innermost stable circular orbit.

Bright neutron stars often behave as "Z-sources", so named because as they vary, they evolve through a colour-colour diagram along a path that is shaped roughly like the letter "Z" (Hasinger & van der Klis 1989). The spectral shapes for these sources are not much different from those of the soft-state sources. They can generally be well modelled by low temperature, moderate optical depth thermal Comptonization models when the count rates are low, and often require two quasi-thermal components when observed at high signal-to-noise ratio. The brightest atoll sources – i.e. the brightest 'soft state' neutron stars – have spectra that are quite difficult to distinguish from the Z-source spectra (e.g. Di Salvo et al. 2002; Gierliński & Done 2002), and there is even one source, XTE J1701−462, which transitions between the atoll and Z behaviours, but which does not show any dramatic difference between Z-source and bright atoll source spectra (Lin, Remillard & Homan 2009). The Z-sources are generally a bit more strongly variable than the brightest atoll sources (e.g. van der Klis 1995), but this distinction is not something of which we can take advantage when working with sources in M31 due to the relatively low count rates.

Extremely bright black hole accretion discs, as well as black hole accretion discs observed during the transition between the hard state and the soft state, show different modes of behaviour (Miyamoto et al. 1991; Homan et al. 2001). The brightest accretors probably have radiation pressure-dominated discs (Shakura & Sunyaev 1973), and can be moderately well modelled as steep power laws and are sometimes called steep power-law states (McClintock & Remillard 2006). These states are relatively uncommon and short-lived in most systems. They are seen fairly often in GRS 1915+105, but that object is typically near the Eddington limit, and on the basis of its luminosity alone, it would be classified as a black hole without much debate, now that its distance is well established (Reid et al. 2014).[1]

3 OBSERVATIONS

We make use of data sets obtained from *Swift* and NuSTAR. Both the NuSTAR data and the *Swift* data have been extracted with 45 arcsec apertures around the already-known source positions (Galetti et al. 2004; Peacock et al. 2010). The names, positions and magnitudes of the clusters are given in Table 1. There do exist higher signal-to-noise archival *XMM* and *Chandra* data for these sources, but we

[1] There is now an ultraluminous X-ray source, M82 X-2, which has been established to have a neutron star primary on the basis of pulsations (Bachetti et al. 2014). This source shows a spectrum harder than that which is seen from black hole candidates at similar luminosities, and shows pulsations, both of which distinguish it from bright black hole X-ray binaries fairly clearly. Its existence does suggest more caution on characterizing sources solely based on luminosity, but it is quite phenomenologically different from black holes accreting above the neutron star Eddington limit, and the magnetic collimation that causes the pulsations to appear also probably allows the apparent luminosity from M82 X-2 to exceed the Eddington limit by such a large factor.

Table 1. The positions, SDSS magnitudes, and SDSS colours of the clusters, as taken from Peacock et al. (2010).

Name	RA	Dec.	g	$u-g$	$g-r$	$r-i$
Bo 153	00:43:10.61	+41:14:51.4	16.69	1.81	0.80	0.44
Bo 185	00:43:37.28	+41:14:43.5	16.04	1.69	0.77	0.39
Bo 225	00:44:29.56	+41:21:35.7	14.59	1.74	0.77	0.40
Bo 375	00:45:45.56	+41:39:42.3	18.04	1.69	0.78	0.35
SKC182C	00:45:27.32	+41:32:54.1	19.78	0.63	1.27	0.62

prefer the quasi-simultaneous *Swift* data over the *Chandra/XMM* data, because the systematic uncertainties that may be induced due to source variability are hard to quantify and likely are more important than the increased statistical errors from the *Swift* data. The data are grouped to a minimum of 1 count per bin to avoid some poorly understood statistical problems. In the plots, further rebinning is done to help make the figures clearer, but these binnings are not used for spectral fitting. Source-free background regions near the sources are used for creating background spectra for both instruments, and response matrices are generated with the standard tools for both satellites. For NuSTAR, Focal Plane Module A and Focal Plane Module B data are combined, and an averaged response matrix is produced.

We have three NuSTAR observations which were used for this project. These are listed in Table 2.

4 CLASSIFICATION OF COMPACT OBJECT CLASS BASED ON X-RAY DATA

The gold standard for identifying black holes has traditionally been demonstration that the mass of the accretor exceeds the maximum mass for a neutron star under equations of state allowed by both general relativity and laboratory experiments on dense matter (Kalogera & Baym 1996). The masses are typically estimated using a combination of radial velocity curves, and some estimate of the binary inclination angle (McClintock & Remillard 1986; Casares & Jonker 2014). In many cases, however, the distance, extinction and/or crowding make it difficult or impossible to make a measurement of an object's radial velocity curve. Additionally, some sources are persistently bright, making it impossible to estimate their inclination angles from ellipsoidal modulations.

A variety of tests exists for showing that an accreting object is a neutron star rather than a black hole. The two most prominent are detection of pulsations (Giacconi et al. 1971) and detection of Type I X-ray bursts (first seen by Grindlay et al. 1976, but first associated with thermonuclear fusion on a neutron star by Maraschi & Cavaliere 1977 – see also Woosley & Taam 1976). These phenomena can be used for nearby sources in crowded or reddened regions, but typically do not provide sufficiently strong signals to be detected in extragalactic binaries, even in M31. Additionally, the absence of bursts or pulsations is rather difficult to use as strong evidence in favour of a black hole. There may be accretion regimes in which Type I bursts would be expected if the object is a neutron star (e.g. Remillard et al. 2006) such that strong indirect evidence would be provided.

At the same time, a phenomenology exists for demonstrating that an object is a black hole rather than a neutron star, given more and better X-ray data. The origins of the ideas used date back to the 1980's, and have been fleshed out to the extent that they have reached fairly wide acceptance, if not a total consensus. White & Marshall (1984) suggested that the presence of an ultrasoft component in a spectrum could be an indicator of a black hole rather than neutron star accretor. This suggestion has stood up well over time. Gradually, it has been found that high/soft state black holes are well modelled by a series of optically thick annuli with temperatures that decrease outwards. The disc blackbody model (DISKBB in XSPEC – Mitsuda et al. 1984) provides an excellent phenomenological description of the data. There do exist more models which treat the radiative transfer and relativistic effects in the disc in greater detail (e.g. Davis et al. 2005) and have been used to estimate the inner disc radii in order to make estimates of the spin of accreting black holes (Zhang, Cui & Chen 1997, for an early attempt; Shafee et al. 2006). The newer disc models provide much more precise parameter estimation, but typically do not fit the data any better, and for the purposes of this paper, in which we merely aim to classify the type of source spectrum, the higher level of complication in using such models is not justified.

The spectra of neutron stars are considerably more complex, and there is less consensus about the correct models for describing the real physics of the systems (see e.g. White, Stellar & Parmar 1988; Mitsuda et al. 1989; Church & Balucińska-Church 1995). In this paper, we will use a simple thermal Comptonization model within XSPEC (COMPTT – Titarchuk 1994). This model has been shown to provide good spectral fits to bright accreting neutron stars in the past (e.g. Lavagetto et al. 2008).[2] These sources typically fit to relatively high optical depths ($\tau \sim 10$) and low-temperature Comptonization ($k_{\rm B}T \sim 3$ keV) models, with low-temperature seed photon distributions.

Additionally, state transitions from soft states to hard states occur at a fairly uniform 2 per cent of the Eddington luminosity (Maccarone 2003; Kalemci et al. 2013).[3] Thus, if a distance to a source is known, the state transition luminosity can be used as an estimator of the compact object mass, which is sufficient to distinguish between neutron stars of ≈1.4–2.0 $M_\odot$ and black holes of 5–10 $M_\odot$. Some hysteresis effects are seen in black hole systems (Miyamoto et al. 1995) which are generally quite similar to those seen in neutron star systems (Maccarone & Coppi 2003), but the high-luminosity hysteretic hard states are generally quite short lived, and so are improbable to catch in a single snapshot, and can be ruled out with monitoring observations. Based on an earlier understanding of black hole/neutron star phenomenology, Barret, McClintock & Grindlay (1996) proposed that observing a source to have a hard X-ray (i.e. >20 keV) luminosity above 10^{37} erg s^{-1} was evidence that a source is a black hole.

[2] We are not particularly concerned with extracting detailed information about the spectra of the sources studied in this paper, given that Galactic and Magellanic Cloud sources will be better for that purpose. We are primarily interested in understanding which sources are black holes and which are neutron stars. We are thus concerned only about classification and hence choose a model with relatively few free parameters and which can parametrize the data well, rather than a model which is physically well motivated.

[3] Dunn et al. (2010) suggested that there was as much spread in the soft-to-hard state transition luminosities as in the hard-to-soft state transition luminosities, but those claims were based entirely on including a set of objects without known black hole masses or distances, and assuming them to be at distances of 5 kpc (closer than the Galactic Center distance), and to have masses of 10 $M_\odot$ (larger than the typical 8 $M_\odot$ value for other stellar mass black holes from Özel et al. 2010; Farr et al. 2011) The combination of these assumption systematically drives down the state transition luminosities for the poorly studied sources, creating a substantial amount of scatter which does not exist for the well-studied sources.

Table 2. The observations used for this project. The columns are: (1) the host globular cluster name (2) the observation ID number for the NuSTAR data (3) the dates for the NuSTAR observation (4) the total NuSTAR exposure time in seconds (5) the *Swift* observation ID number(s) (6) the date(s) for the *Swift* observations and (7) the total *Swift* exposure time in seconds. There are two *Swift* observations for Bo 153 and Bo 185, and three *Swift* observations for Bo 225.

Source	NuSTAR ObsID	NuSTAR dates	NuSTAR exposure	*Swift* obsID	*Swift* dates	*Swift* exposure
Bo 153	50026001002	2015 February 6–8	106386	0008000700(1,2)	2015 February 6,8	17016
Bo 185	50026001002	2015 February 6–8	106386	0008000700(1,2)	2015 February 6,8	17016
Bo 225	50026002001	2015 February 8–11	108939	0008084600(1–3)	2015 February 8–11	22996
Bo 375	50026003003	2015 March 8–11	104370	00080847003	2015 March 8–9	17311
SK182C	50026003003	2015 March 8–11	104370	00080847003	2015 March 8–9	17311

Single epoch X-ray spectroscopy can often separate out black holes from neutron stars, as well. In low/hard states, the spectra can often be quite difficult to differentiate from one another, but neutron stars often show cutoffs at somewhat lower energies than do black holes. In softer states, the differences are much more pronounced. The neutron stars have two quasi-thermal components – the disc and the boundary layer – while black holes have only a disc. Additionally, the characteristic temperatures of the neutron stars' discs are higher than those of the black holes because of the $M^{-1/4}$ scaling of inner disc temperatures. The combination of these factors makes the neutron stars have harder spectra in their soft states than do soft state black holes.

5 AN INTRODUCTION TO OUR STATISTICAL METHODOLOGY

We use some methodology for fitting and testing the spectral models which is non-standard for X-ray spectroscopy, but which have been used widely in other contexts, and is well developed. We use the CSTAT option within XSPEC 12.8, following Cash (1979). This statistic returns a likelihood function which is maximized for the best-fitting value for a particular model, but does not yield, in a straightforward manner, a goodness of fit. We use the *Swift* data from 0.5–6.0 keV and the NuSTAR date from 4–20 keV. These bands are chosen because they are well calibrated and have high ratios of source to background photons for the sources we study here. All source fluxes are reported by taking the unabsorbed model and integrating between 0.5 and 20 keV.

We then note that the most likely problem with a fit is that the curvature of the spectral model will be different from the curvature of the data. This will lead to maximal differences between cumulative number of counts in the data and the model, folded through the response matrix, at the edges of the distribution. Such a difference between data and model is identified most readily in an Anderson–Darling (1952) test. XSPEC has a routine for computing the Anderson–Darling parameter as a test statistic, which we use. We can then use the Monte Carlo GOODNESS command in XSPEC to estimate the null hypothesis probability, by running a set of simulations and determining how often the simulations give fits with a better Anderson–Darling statistic than the model. We use 10 000 simulations with the GOODNESS command to estimate the null hypothesis probabilities.

We note that we rely on fits to time-integrated spectra for this work, rather than examining the source variability. In principle, the source variability could provide very strong constraints on the nature of the sources, but the number of counts here is insufficient for such an analysis. E.g., we have approximately 15 per cent statistical uncertainties on hardness ratios between 6–10 and 10–20 keV in integrations with about 100 ksec of good time, while Smale, Homan & Kuulkers (2003) show that the deviations from the mean in that pair of bands is about 25 per cent; we thus do not have the data quality we need to see if the colours follow a Z-track for the sources.

6 INDIVIDUAL SOURCES

For all sources for which we have good NuSTAR spectra, we attempt to fit three different spectral models: a power law, a disc blackbody, and a Comptonized blackbody (COMPTT). In nearly every case, we consider absorption with the Galactic value, and absorption which may float freely; when a statistically acceptable fit is given without allowing the absorption to float freely, we know already that the model cannot be rejected, and we do not consider further the variable absorption case. Given the low redshift of M31, we do not treat Galactic absorption and intrinsic absorption as separate components, but rather treat them as a single component with a summed absorption column. We take the Galactic absorption to the M31 fields to be 10^{21} cm^{-2} (Kalberla et al. 2005). The results of the different spectral fits are given in Table 3.

6.1 Bo 153

Bo 153 was suggested by Barnard et al. (2011) to be a strong candidate for being a globular cluster black hole on the basis of appearing to fit well to a low/hard state spectrum while being at a luminosity (varying in the range from 0.8–2.4$\times 10^{38}$ erg s^{-1} in the 0.3–10.0 keV band) above which neutron stars do not show low hard states. With NuSTAR, the single power-law model gives an unacceptable fit - - clearly the data show more curvature than a single power law allows. Disc blackbody model with free temperature and column density produces a fit which is marginally statistically acceptable, but which requires an unphysically small inner disc radius (i.e. much less than a Schwarzschild radius), unphysically large temperatures (i.e. $>$ 2 keV), and no Galactic column density. When the model is forced to have an inner disc radius of 30 km, the fit is no longer statistically acceptable. The COMPTT model provides a fit which is statistically acceptable, and which has parameters in line with typical Z sources and typical bright atoll sources. The flux from the COMPTT model, correcting for absorption, is 1.7×10^{-12} erg s^{-1} cm^{-2}, corresponding to a luminosity of 1.2×10^{38} erg s^{-1} for a distance of 784 kpc (Stanek & Garnavich 1998), which is also a typical value for a Z source. Figures are presented for the power-law fit – Fig. 1, the disc blackbody fit – Fig. 2, and the thermal Comptonization model fit – Fig. 3. These figures are representative of the results for all the sources, so we do not present figures for the fits to the other sources.

Table 3. The table of spectral fits for the five sources. The first column gives the source names. The second column gives the different models used: PLA – power law with frozen $N_{\rm H}$ and frozen Γ; PLB – power law with frozen $N_{\rm H}$, but free Γ; PLC – power law with both parameters free; DBBA – disc blackbody model with frozen $N_{\rm H}$ but free normalization and temperature; DBBB – disc blackbody with frozen $N_{\rm H}$, frozen normalization to 0.1 (consistent with 30 km inner radius at M31 distance for a face-on disc) and free temperature; DBBC – disc blackbody with all parameters free; COMPTT, where only a single model is fitted, which has frozen $N_{\rm H}$, and seed photon temperature frozen to 0.1 keV; DBBPL – disc blackbody plus power law with all parameters free; DBBCMPT – disc blackbody plus COMPTT with frozen $N_{\rm H}$ and frozen seed photon temperature of 0.1 keV. The third column gives the $N_{\rm H}$ used for the fit in $\rm cm^{-2}$. The fourth column gives Γ, the spectral index for the power-law spectra, defined such that the differential number of photons as a function of energy, $\frac{dN}{dE}$ scales as $E^{-\Gamma}$. The fifth column gives the inner disc temperature from the DISKBB model. The sixth column gives the electron temperature in the corona for the COMPTT model. The seventh column gives the inner disc radius in km for the DISKBB model, assuming a face-on disc and no colour correction. The eighth column gives the optical depth of the thermal Comptonization model. The ninth column gives the value of the Cash statistic and the number of degrees of freedom for the fit. The tenth column gives the logarithm of the Anderson–Darling statistic. The eleventh column gives the fraction of the simulations made using GOODNESS that were statistically as bad as the model fit. Where no simulations were as bad as the model fit, $<10^{-4}$ is placed in this column.

Source	Model	$N_{\rm H}$	Γ	$kT_{\rm in}$	$kT_{\rm e}$	$R_{\rm in}$	τ	Cstat/dof	AD	Null prob
Bo 153	PLA	10^{21}	1.7					639/616	−3.84	$<10^{-4}$
Bo 153	PLB	10^{21}	1.8 ± 0.1					618/615	−3.85	$<10^{-4}$
Bo 153	PLC	$4.2^{+1.5}_{-1.0} \times 10^{21}$	2.1 ± 0.1					567/614	−4.77	$<10^{-4}$
Bo 153	DBBA	10^{21}		$2.29^{+0.12}_{-0.11}$		4		518/615	−4.86	$<10^{-4}$
Bo 153	DBBB	10^{21}		1.04 ± 0.01		30		1510/616	−2.64	$<10^{-4}$
Bo 153	DBBC	≈ 0.0		$2.27^{+0.12}_{-0.11}$		4		518/614	−5.40	0.004
Bo 153	COMPTT	10^{21}			2.2 ± 0.2		8.6 ± 0.8	506/614	−7.21	0.41
Bo 185	PLA	10^{21}	1.7					599/502	−3.39	$<10^{-4}$
Bo 185	PLB	10^{21}	1.8 ± 0.1					593/501	−3.41	$<10^{-4}$
Bo 185	PLC	$7.1^{+1.4}_{-1.2} \times 10^{21}$	2.2 ± 0.1					527/500	−4.79	0.0006
Bo 185	DBBA	10^{21}		$2.43^{+0.15}_{-0.14}$		3		485/502	−5.88	$<10^{-4}$
Bo 185	DBBB	10^{21}		0.97 ± 0.01		30		1559/502	−2.35	$<10^{-4}$
Bo 185	DBBC	≈ 0.0		2.51 ± 0.15		2		479/500	−6.58	0.15
Bo 185	COMPTT	10^{21}			2.1 ± 0.2		$9.8^{+1.1}_{-1.3}$	481/500	−6.75	0.80
Bo 225	PLA	10^{21}	1.7					602/603	−4.60	$<10^{-4}$
Bo 225	PLB	10^{21}	1.9 ± 0.1					556/602	−4.70	$<10^{-4}$
Bo 225	PLC	$3.0^{+0.7}_{-0.6} \times 10^{21}$	2.1 ± 0.1					531/601	−5.46	0.0003
Bo 225	DBBA	10^{21}		$2.32^{+0.13}_{-0.12}$		3		660/602	−3.84	$<10^{-4}$
Bo 225	DBBB	10^{21}		0.97 ± 0.01		30		1714/603	−2.32	$<10^{-4}$
Bo 225	DBBC	≈ 0.0		$2.40^{+0.13}_{-0.12}$		3		614/602	−4.17	$<10^{-4}$
Bo 225	COMPTT	10^{21}			$3.1^{+0.5}_{-0.4}$		6.2 ± 0.7	519/601	−7.10	0.31
Bo 375	PLA	10^{21}	1.7					2897/848	−3.35	$<10^{-4}$
Bo 375	PLB	10^{21}	2.0 ± 0.0					2273/847	−3.37	$<10^{-4}$
Bo 375	PLC	$5.7^{+0.4}_{-0.2} \times 10^{21}$	2.5 ± 0.0					1544/846	−4.30	$<10^{-4}$
Bo 375	DBBA	10^{21}		1.86 ± 0.03		13		937/847	−5.40	$<10^{-4}$
Bo 375	DBBB	10^{21}		1.47 ± 0.01		30		1644/848	−4.92	$<10^{-4}$
Bo 375	DBBC	≈ 0.0		1.93 ± 0.03		12		847/846	−6.15	$<10^{-4}$
Bo 375	COMPTT	10^{21}			1.7 ± 0.1		$10.3^{+0.4}_{-0.3}$	849/846	−7.15	0.0001
Bo 375	DBBPL	$1.5 \pm 0.7 \times 10^{21}$	2.3 ± 0.1	$1.88^{+0.08}_{-0.07}$		12		795/844	−8.05	0.035
Bo 375	DBBCMPT	10^{21}		$1.54^{+0.31}_{-0.33}$	$2.3^{+2.6}_{-0.4}$	16	$8.4^{+3.7}_{-4.4}$	792/844	−8.73	0.32
SK182C	PLA	10^{21}	1.7					408/441	−7.16	0.78
SK182C	PLB	10^{21}	1.7 ± 0.1					408/440	−7.02	0.69
SK182C	PLC	$2.3^{+1.4}_{-1.2} \times 10^{21}$	1.8 ± 0.1					404/439	−6.94	0.93
SK182C	DBBA	10^{21}		$3.11^{+0.41}_{-0.34}$		1		465/440	−3.34	$<10^{-4}$
SK182C	DBBB	10^{21}		0.75 ± 0.02		30		997/404	−1.32	$<10^{-4}$
SK182C	DBBC	≈ 0.0		$3.24^{+0.43}_{-0.36}$		1		452/439	−3.55	$<10^{-4}$
SK182C	COMPTT	10^{21}			$45.1^{+1839.7}_{-45.1}$		$1.1^{+4.1}_{-1.1}$	408/439	−7.06	0.92

6.2 Bo 185

The results for this source are quite similar to those for Bo 153. This source was also claimed by Barnard et al. (2011) to be a strong globular cluster black hole candidate on the ground of being a bright hard state object. Like for Bo 153, we find that the power-law model fits are not statistically acceptable, and that the statistically acceptable disc blackbody model fits have unphysically small inner disc radii and unphysically large temperatures. We find that the thermal Comptonization model gives a fit that is typical of Z-sources and bright atoll sources. The flux from the model, correcting for absorption, is 1.0×10^{-12} erg $\rm s^{-1}/cm^{-2}$, corresponding to a luminosity of 7.3×10^{37} erg $\rm s^{-1}$, which is, again, typical for Z-sources and bright atoll sources.

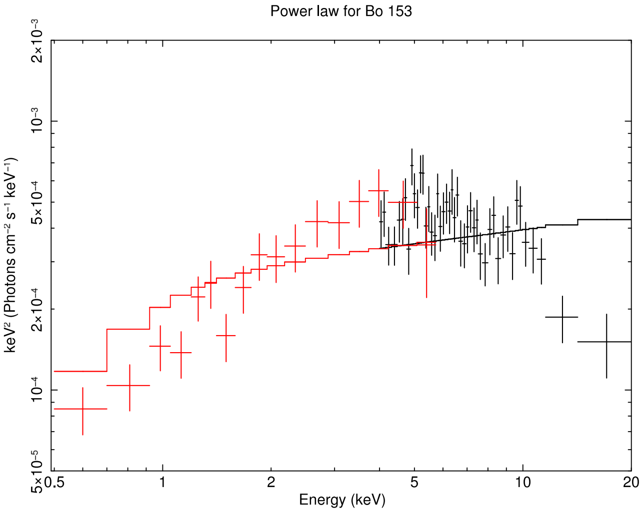

Figure 1. The best-fitting power-law model with absorption frozen to 10^{21} cm^{-2} for Bo 153's X-ray spectrum. The data are plotted after rebinning either until a signal to noise of 5 is reached, or 100 bins have been used, but the input spectra grouped to one count per bin have been used. From the plot, it is clear that the data have a greater level of curvature than the model does. The *Swift* data, and the model convolved through the *Swift* response function are in red while the NuSTAR data and the model convolved through NuSTAR's response function are in black.

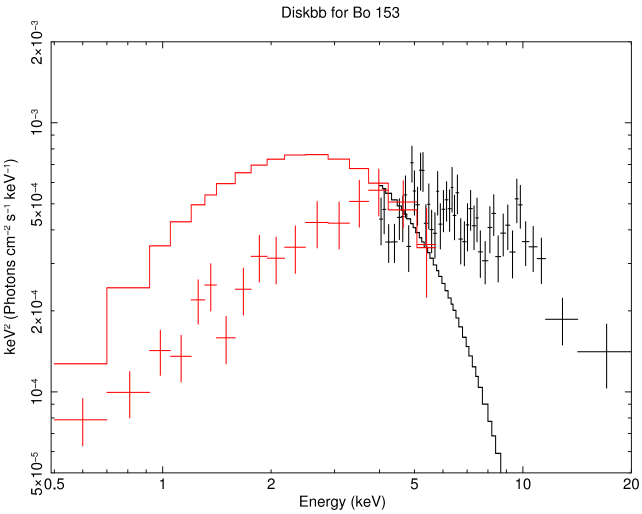

Figure 2. The best-fitting disc blackbody model with absorption frozen to 10^{21} cm^{-2} for Bo 153's X-ray spectrum, and the normalization frozen to a physically plausible value. The data are plotted after rebinning either until a signal to noise of 5 is reached, or 100 bins have been used, but the input spectra grouped to one count per bin have been used. That the real spectrum is harder than any reasonable disc model is obvious from the plot. The *Swift* data, and the model convolved through the *Swift* response function are in red while the NuSTAR data and the model convolved through NuSTAR's response function are in black.

6.3 Bo 225

An additional bright X-ray source in M31 is Bo 225. This object is less well studied than the two previously discussed sources and has not been claimed in the past to be a black hole candidate. The only model that fits this source well is the COMPTT model. This source, then, we may have run into the limitations of using such a simple thermal Comptonization model, and the data may be justifying a slightly high level of complexity. None the less, this model is clearly the best of the group we have tried. The flux from the unabsorbed COMPTT model is 1.3×10^{-12} erg s^{-1}/cm^{-2}, corresponding to a luminosity of 9×10^{37} erg s^{-1}. The combination of the luminosity of the source, and the fact that COMPTT provides both a statistically acceptable fit and reasonable parameter values, indicates that the source can be confidently identified as a Z-source or a bright atoll source.

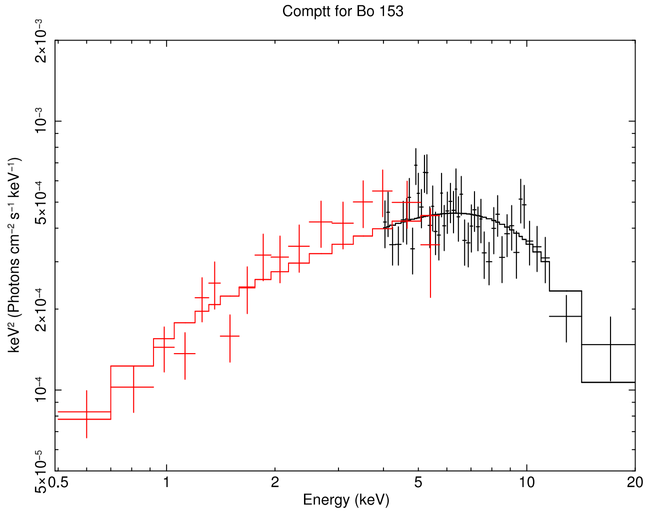

Figure 3. The best-fitting thermal Comptonization model with absorption frozen to 10^{21} cm^{-2} for Bo 153's X-ray spectrum. The data are plotted after rebinning either until a signal to noise of 5 is reached, or 100 bins have been used, but the input spectra grouped to one count per bin have been used. The model can be seen to be a good description of the data. The *Swift* data, and the model convolved through the *Swift* response function are in red while the NuSTAR data and the model convolved through NuSTAR's response function are in black. It is clear that the model not only provides a good statistical fit to the data, but also matches the curvature of the data.

6.4 Bo 375

Bo 375 has also been observed with NuSTAR and *Swift*. This is a bright source which has been previously classified as a neutron star (Barnard et al 2008). For this source, none of the models with a single continuum component provides a good fit to the data. The data can be well fitted with a model consisting of a disc blackbody plus a Comptonized blackbody, which is one of the models often used to fit Z-sources and bright atoll sources (null hypothesis probability of 0.31) and marginally well fitted by a disc blackbody plus power-law model (null hypothesis probability of 0.03). The inner disc radius for the disc blackbody plus power-law model is unphysically small (12 km), so this model is additionally disfavoured. The flux from the disc blackbody plus Comptonized blackbody model, correcting for absorption, is 8.1×10^{-12} erg s^{-1}/cm^{-2}, corresponding to a luminosity of 6×10^{38} erg s^{-1} for a distance of 784 kpc. This value is slightly above the Eddington luminosity for a 1.4 $M_{\odot}$ neutron star. This value is slightly above the highest luminosity seen from Sco X-1 of 4.5×10^{38} erg s^{-1} (Barnard, Church & Balucińska-Church 2003), which is robust given the geometric parallax distance (Bradshaw, Fomalant & Geldzahler 1999), but the discrepancy can be explained if the neutron star in Bo 375 is a bit more massive than the neutron star in Sco X-1, or if the neutron star in Bo 375 is accreting hydrogen-poor gas. Given that ultracompact X-ray binaries represent a substantial fraction of the X-ray binaries in Milky

Way globular clusters (Stella, Priedhorsky & White 1987; Dieball et al. 2005; Zurek et al. 2009), this latter interpretation would not be surprising.

Barnard et al. (2008) had previously found with *XMM–Newton* data that a single power law could not fit the spectrum of that source, suggesting that it is a neutron star. We thus favour a neutron star interpretation for the data, as it is consistent with both our analysis and that of Barnard et al. (2008).

6.5 SK182C

SK182C is located in the same field of view as Bo 375, and hence is included in the same observations. This source is fainter than the others, so our ability to rule out models is somewhat diminished. For this source, we find both the power-law and COMPTT models to be statistically acceptable and to have reasonable parameter values.

The flux from the model, correcting for absorption, is 7.6×10^{-13} erg s^{-1}/cm^{-2}, corresponding to a luminosity of 5×10^{37} erg s^{-1} at the distance to M31. For the spectra we analyse here, we find that either a low hard state black hole model or a neutron star model could fit well to the data. The disc blackbody models are all statistically unacceptable. Given that the source is at about 5 per cent of the Eddington luminosity for an 8 $M_{\odot}$ black hole, and that black holes at such a luminosity are usually in soft states unless they are caught in the rise of a transient outburst (Maccarone 2003; Kalemci et al. 2013), the black hole interpretation is disfavoured for this source, but not as strongly as for the other sources in the sample. This source also has no previous identification as either a black hole or a neutron star.

7 DISCUSSION

These results cast doubt on many of the other claims of globular cluster black holes in M31 globular clusters. Many of these are based on the same methodology as the claims for Bo 153 and Bo 185. The results also illustrate the importance of having a broad bandpass, as from NuSTAR, for making classifications of black hole and neutron star spectra. In particular, the Z-source/bright atoll source spectral models can be seen to be relatively similar to power-law spectra, as long as most of the counts are obtained below about 10 keV where the spectra break sharply. This is, notably, where the responses of *Chandra* and *XMM–Newton* start to become poor.

Some additional support for the neutron star nature of the sources can come from looking at the Milky Way's population of persistent black hole candidates. The only dynamically confirmed black hole candidate which is persistent is Cygnus X-1 (Gies & Bolton 1986; Caballero-Nieves et al. 2009; Orosz et al. 2011), which spends most of its time in a hard state, but which is likely to be immune from the full ionization instability due to having a high-mass donor star, and being wind-fed so that the circularization radius of the disc is smaller than for Roche lobe overflow from a star with the same orbital period (see discussion in Smith, Heindl & Swank 2002a). Cygnus X-3 represents a similar case, although its dynamical confirmation is not clear (Szostek & Zdziarski 2008). SS 433 is even less securely a black hole, and is likely intrinsically super-Eddington but observed edge-on so that only scattered X-rays are seen (e.g. Charles et al. 2004). 4U 1957+11 is not dynamically confirmed, but appears to spend most of its time in soft states (Gomez et al. 2015).

There are two other persistent sources, 1E 1740.7−2942 and GRS 1758−258, which appear to be long X-ray periodicities (12.73 and 18.45 d, respectively), and which spend significant fractions of their time in hard states, but these objects are not dynamically confirmed black holes, they have unknown donor types (Smith, Heindl & Swank 2002b), and the periods are significantly longer than expected for tidal capture products. The persistent hard state black hole sources with low-mass donors thus may not exist at all, and are clearly, at most, a small fraction of the total source population bright enough to be detected with all-sky instruments in the Milky Way (which is a similar luminosity limit to the luminosity needed to detect a source at all in M31). There are, of course, a number of relatively steady quiescent black hole sources, which might be regarded as persistent hard state sources, but all of these which are dynamically confirmed as black holes have undergone large outbursts.

There are selection effects against dynamical confirmation of black holes in persistently bright X-ray binaries. None the less, there is only one candidate persistent black hole low-mass X-ray binary whose orbital period is short enough to be in the ~10 h range where tidal capture might work, 4U 1957+11. There are many black hole X-ray binaries with both shorter and longer orbital periods which are transients, and there are no other persistent X-ray emitters whose X-ray emission properties mark them as likely black hole accretors. As a result, it seems highly unlikely that black hole X-ray binaries that form from tidal capture are typically persistent, but it cannot be excluded that this might occasionally happen.

7.1 Disc winds and the transient problem

One of the original motivations for considering these objects to be persistent black hole binaries formed by tidal capture was that such objects had been predicted to exist. Repeated claims exist in the literature (e.g. Kalogera et al. 2004; Barnard et al. 2008) that tidal capture black hole X-ray binaries should be persistently X-ray bright. Thus, our finding that these objects in M31 are likely neutron stars gives us good cause to re-consider some of the assumptions that went into these claims. In particular, it is worth considering why it may actually be unlikely for a large population of persistent black hole X-ray binaries to exist, especially in the orbital period range expected for tidal capture products.

Standard binary evolution and disc instability theory predicts that systems with orbital periods of about 10 h, the range expected from tidal captures, should be persistent sources (King et al. 1996; Kalogera et al. 2004). However, as we describe below, this claim is not in line with phenomenology of outburst behaviour from black hole X-ray binaries, and we suggest that mass-loss in disc winds can explain the discrepancy between observation and theory.

Comparison of fig. 1 of King et al. (1996), which shows the expected mass transfer rates as a function of orbital period, and fig. 7 of Lasota (2001), which shows observed mean accretion rates as a function of orbital period indicates a clear discrepancy between the two values. King et al. (1996) find that the typical mass transfer rates in black hole X-ray binaries in that orbital period range should be 10^{-10}–10^{-9} $M_{\odot}$ yr^{-1}, while the recurrence times of X-ray transients indicate that the mass transfer rates are more typically a few times 10^{-11} $M_{\odot}$ yr^{-1}. Indeed, the discrepancy is already implicitly noted by King et al. (1996) themselves, who point out that the known low-mass X-ray binaries with black hole primaries are predominantly soft X-ray transients, rather than persistent emitters. Our finding that these persistent sources in M31 are more likely neutron stars than black holes underscores this point.

A few possible explanations exist for the paucity of persistent black hole emitters. Perhaps the simplest is to invoke a mechanism that lowers the accretion rate on to the central black hole relative to that predicted from the prescriptions for binary evolution used in

King et al. (1996). Two possible ways to change the mass accretion rates are to change the mass transfer rates by invoking alternative prescriptions for magnetic braking, and invoking non-conservative mass transfer due to disc winds. The now-good agreement between theory and data for models of evolution of cataclysmic variables (Knigge, Baraffe & Patterson 2011) casts doubt on the possibility that magnetic braking prescriptions are badly flawed, unless the donor stars in black hole X-ray binaries are considerably more bloated than those in cataclysmic variables.

Disc winds, on the other hand, show clear evidence of being present and important in X-ray binaries. If we take, for example, the best studied quiescent X-ray binary, A0620−00 we see that it has an orbital period of 7.1 h, and a donor mass of 0.4 $M_{\odot}$, meaning that its donor mass is about 0.6 times as large as that of an unevolved star filling its Roche lobe, given the well-known relationship between donor star mass and orbital period for main-sequence stars. This produces a reduction in mass transfer rate by a factor of about 3.5 – a substantial factor, but not one large enough to explain the discrepancy between the observed mean outburst fluence averaged over the best estimate of the source duty cycle and the predicted mass transfer rates.

Therefore, it appears more likely that disc winds during the outbursts of black hole X-ray binaries lead to highly non-conservative mass transfer and hence make the mean accretion rate by the compact object less than the mass-loss rate by the donor star. Three methods have been used to estimate the mass-loss due to disc winds, and all result in the finding that ~90 per cent of the mass lost by the donor star is also lost by the accretion disc. One method for making the estimate is the result above, that transient outbursts seem to have recurrence time-scales about 10 times too long, and that some objects which would be expected to be persistent are, in fact, transient. Another is that estimates can be made of the depths of absorption lines seen from the accretion discs, the opening angles of the disc winds, and the chemical composition and ionization state of the absorbing gas, and convert these to mass-loss rates in the disc wind (e.g. Neilsen, Remillard & Lee 2011). Additionally, one can estimate the mass transfer rate from the luminosity of the hotspot where the accretion stream impacts the outer accretion disc, and compare with the quiescent X-ray luminosity and with the outburst duty cycle (e.g. Froning et al. 2011).

Finally, two short-period X-ray binaries have period derivatives that cannot be well explained in the light of standard binary evolution scenarios (Gonzalez Hernandez, Rebolo & Casares 2014). If mass-loss is the cause of the latter effect, then strong mass-loss takes place even for quiescent X-ray binaries. This is at odds with prominent interpretations of recent findings that strong X-ray absorption lines are seen only when sources are in X-ray soft states (Neilsen & Lee 2009; Ponti et al. 2012). On the other hand, if the ionization state of the wind, rather than the presence of the wind, is what changes at state transitions, then the claims can be reconciled. Additionally, there are detections of single-peaked emission lines in GX 339−4 in hard states (Wu et al. 2001), and single-peaked lines from accretors are often associated with scatter broadening of lines by disc winds (e.g. Shlosman & Vitello 1993; Knigge & Drew 1996; Murray & Chiang 1996; Sim et al. 2010).

All these methods of estimating the actual accretion rates in black hole X-ray binaries, and the amount of mass-loss in their winds, suggest that mass transfer is in black hole binaries is highly non-conservative. Systems which would be persistent can then be forced into quiescent regimes because the mass-loss will reduce the central accretion rates and reduce the irradiation of the outer discs by the inner discs; additionally, just the mere loss of mass will reduce the gas density, and hence the gas temperature in the outer discs, even in the absence of irradiation. The duty cycles of bright sources are then suppressed compared to what would be expected. Importantly, in cataclysmic variables, the mass-loss rates in the wind are very small compared to mass accretion rates by the central white dwarfs (Vitello & Shlosman 1988; Knigge, Woods & Drew 1995), so disc winds should not be important for CV evolution. The same may be true for neutron star accretors. Thus, in hindsight, one should not expect a substantial population of persistent black hole X-ray binaries, even if the systems are formed by tidal capture, and persistent sources should be expected to more commonly be neutron stars, as we have found here.

At the same time, a more detailed treatment of disc winds would be well justified. In this paper, we have discussed disc winds only in the context of removing mass from the accretion disc at a constant accretion rate. A more detailed treatment of non-conservative mass transfer would also consider the angular momentum carried away by the mass lost from the accretion disc and its subsequent effects on the mass transfer rate itself. Such a treatment lies beyond the scope of this paper, but would be well justified in light of recent developments.

8 SUMMARY

We have examined five globular cluster sources at $L_X \sim 10^{38}$ erg s^{-1} in M31 with a combination of data from *Swift* and NuSTAR. We have found that in all cases, the data can be well fitted with high optical depth ($\tau \sim 3$–10), low temperature ($k_B T < 10$) keV Comptonization models, while for four of the five sources, the data argue strongly against a single power-law model fitting the data, and for all the sources, the data argue against a multitemperature blackbody disc model fitting the data. As a result, we argue that these sources are all likely to be high accretion rate neutron star X-ray binaries, although the data are not presently good enough to determine whether they are 'Z-sources' or bright atoll sources in soft states. Bolstering the idea that these are neutron stars is the dearth of black hole X-ray binaries. Because past theoretical work has argued that the accretion rates expected within a particular range of orbital periods should yield persistent black hole X-ray binaries, we have discussed how non-conservative mass transfer due to disc winds leads to a violation of the assumptions of the past work.

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REFERENCES

Anderson T. W., Darling D. A., 1952, Ann. Math. Stat., 23, 193
Bachetti M. et al., 2014, Nature, 514, 202
Barnard R., Church M. J., Balucińska-Church M., 2003, A&A, 405, 237
Barnard R. et al., 2008, ApJ, 689, 1215
Barnard R., Garcia M., Li Z., Primini F., Murray S. S., 2011, ApJ, 734, 79
Barret D., McClintock J. E., Grindlay J. E., 1996, ApJ, 473, 963
Basu-Zych A. R. et al., 2013, ApJ, 774, 152

Baumgardt H., Hut P., Makino J., McMillan S., Portegies Zwart S., 2003, ApJ, 582, L21
Binder B., Gross J., Williams B. F., Simons D., 2015, MNRAS, 451, 4471
Bradshaw C. F., Fomalant E. B., Geldzahler B. J., 1999, ApJ, 512, L121
Brassington N. J. et al., 2008, ApJS, 179, 142
Brorby M., Kaaret P., Prestwich A., 2014, MNRAS, 441, 2346
Caballero-Nieves S. et al., 2009, ApJ, 701, 1895
Cannizzo J. K., Wheeler J. C., Ghosh P., 1985, in Lamb D. Q., Patterson J., Astrophysics and Space Science Library, Vol. 113, Cataclysmic Variables and Low-Mass X-ray Binaries. Reidel, Dordrecht, p. 307
Cannizzo J. K., Chen W., Livio M., 1995, ApJ, 454, 880
Casares J., Jonker P. G., 2014, Space Sci. Rev., 183, 223
Cash W., 1979, ApJ, 228, 939
Charles P. A. et al., 2004, Rev. Mex. Astron. Astrofis. Ser. Conf., 20, 50
Chomiuk L., Strader J., Maccarone T. J., Miller-Jones J. C. A., Heinke C., Noyola E., Seth A. C., Ransom S., 2013, ApJ, 777, 69
Church M. J., Balucińska-Church M., 1995, A&A, 300, 441
Clark G. W., 1975, ApJ, 195, L143
Crowther P., Barnard R., Carpano S., Clark J. S., Dhillon V. S., Pollock A. M. T., 2010, MNRAS, 403, 41
Davis S. W., Blaes O. M., Hubeny I., Turner N. J., 2005, ApJ, 621, 372
Dieball A., Knigge C., Zurek D. R., Shara M. M., Long K. S., Charles P. A., Hannikainen D. C., van Zyl L., 2005, ApJ, 634, L105
Di Salvo T. et al., 2002, A&A. 386, 535
Dunn R. J. H., Fender R. P., Körding E. G., Belloni T., Cabanac C., 2010, MNRAS, 403, 61
Emparan R., Fabbri A., Kaloper N., 2002, J. High Energy Phys., 08, 043
Fabian A. C., Pringle J. E., Rees M. J., 1975, MNRAS, 172, 15p
Farr W. M., Sravan N., Cantrell A., Kreidberg L., Bailyn C. D., Mandel I., Kalogera V., 2011, ApJ, 741, 103
Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Froning C. S. et al., 2011, ApJ, 743, 26
Fryer C. L., Kalogera V., 2001, ApJ, 554, 548
Galetti S., Federici L., Bellazzini M., Fusi Pecci F., Macrina S., 2004, A&A, 416, 917
Gebhardt K. et al., 2000, ApJ, 539, L13
Gerssen J., van der Marel R. P., Gebhardt K., Guhathakurtha P., Peterson R. C., Pryor C., 2002, AJ, 124, 3270
Giacconi R., Gursky H., Kellogg E., Schreier E., Tananbaum H., 1971, ApJ, 167, L67
Gierliński M., Done C., 2002, MNRAS, 337, 1373
Gies D. R., Bolton C. T., 1986, ApJ, 304, 371
Gnedin O. Y., Maccarone T. J., Psaltis D., Zepf S. E., 2009, ApJ, 705, L168
Gomez S., Mason P. A., Robinson E. L., 2015, ApJ, 809, 9
Gonzalez Hernandez J. I., Rebolo R., Casares J., 2014, MNRAS, 438, L21
Grindlay J. E., Gursky H., Schnopper H., Parsignault D. R., Heise J., Brinkman A. C., Schrijver J., 1976, ApJ, 205, L127
Grindlay J. E., Heinke C., Edmonds P. D., Murray S. S., 2001, Science, 292, 2290
Haggard D., Cool A. M., Heinke C. O., van der Marel R., Cohn H. N., Lugger P. M., Anderson J., 2013, ApJ, 773, L31
Hasinger G., van der Klis M., 1989, A&A, 225, 79
Heggie D. C., Giersz M., 2014, MNRAS, 439, 2459
Hills J. G., 1976, MNRAS, 175, 1p
Homan J., Wijnands R., van der Klis M., Belloni T., van Paradijs J., Klein-Wolt M., Fender R., Méndez M., 2001, ApJS, 132, 377
Illingworth G., King I. R., 1977, ApJ, 218L, 109
Kalberla P. M. W., Burton W. B., Hartmann D., Arnal E. M., Bajaja E., Morras R. Poppel W. G. L., 2005, A&A, 440, 775
Kalemci E., Dincer T., Tomsick J. A., Buxton M. M., Bailyn C. D., Chun Y. Y., 2013, ApJ, 779, 95
Kalogera V., Baym G., 1996, ApJ, 470, L61
Kalogera V., King A. R., Rasio F. A., 2004, ApJ, 601, L171
King A. R., Kolb U., Burderi L., 1996, ApJ, 464, L127
Knigge C., Drew J. E., 1996, MNRAS, 281, 1352
Knigge C., Woods J. A., Drew J. E., 1995, MNRAS, 273, 225
Knigge C., Baraffe I., Patterson J., 2011, ApJS, 194, 28
Kulkarni S., Hut P., Mcmillan S., 1993, Nature, 364, 421
Lasota J-P., 2001, New Astron. Rev., 45, 449
Lavagetto G., Iaria R., D'Ai A., Di Salvo T., Robba N. R., 2008, A&A, 478, 181
Laycock S. G. T., Cappallo R. C., Moro M. L., 2015a, MNRAS, 446, 1399
Laycock S. G. T., Maccarone T. J., Christodoulou D. M., 2015b, MNRAS, 452, L31
Leigh N. W. C., Luetgendorf N., Geller A. M., Maccarone T. J., Heinke C., Sesana A., 2014, MNRAS, 444, 29
Lin D., Remillard R. A., Homan J., 2009, ApJ, 696, 1257
Linden T., Kalogera V., Sepinsky J. F., Prestwich A., Zezas A., Gallagher J. S., 2010, ApJ, 725, 1984
Maccarone T. J., 2003, A&A, 409, 697
Maccarone T. J., 2004, MNRAS, 351, 1049
Maccarone T. J., Coppi P. S., 2003, MNRAS, 338, 189
Maccarone T. J., Kundu A., Zepf S. E., Rhode K. L., 2007, Nature, 445, 183
Maccarone T. J., Kundu A., Zepf S. E., Rhode K. L., 2011, MNRAS, 410, 1655
McClintock J. E., Remillard R. A., 2006, in Lewin W. H. G., van der Klis M., eds, Compact Stellar Xray Sources. Cambridge Univ. Press, Cambridge
McClintock J. E., Remillard R. A., 1986, ApJ, 308, 110
Mapelli M., Ripamonti E., Zampieri L., Colpi M., Bressan A., 2010, MNRAS, 408, 234
Miller M. C., Hamilton D. P., 2002, MNRAS, 330, 232
Mitsuda K. et al., 1984, PASJ, 36, 741
Mitsuda K., Inoue H., Makamura N., Tanaka Y., 1989, PASJ, 41, 97
Miyamoto S., Kitamoto S., Hayashida K., Egoshi W., 1995, ApJ, 442, L13
Miyamoto S., Kimura K., Kitamoto S., Dotani T., Ebisawa K., 1991, ApJ, 383, 784
Morscher M., Parrabiraman B., Rodriguez C., Rasio F. A., Umbreit S., 2015, ApJ, 800, 9
Murray N., Chiang J., 1996, Nature, 382, 789
Neilsen J., Lee J. C., 2009, Nature, 458, 481
Neilsen J., Remillard R. A., Lee J. C., 2011, ApJ, 737, 69
Newell B., Da Costa G. S., Norris J., 1976, ApJ, 208L, 55
Noyola E., Gebhardt K., Bergmann M., 2008, ApJ, 676, 1008
Orosz J. A., McClintock J. E., Aufdenberg J. P., Remillard R. A., Reid M. J., Narayan R., Gou L., 2011, ApJ, 742, 84
Özel F., Psaltis D., Narayan R., McClintock J. E., 2010, ApJ, 725, 1918
Peacock M. B., Maccarone T. J., Knigge C., Kundu A., Waters C. Z., Zepf S. E., Zurek D. R., 2010, MNRAS, 402, 803
Ponti G., Fender R. P., Begelman M. C., Dunn R. J. H., Neilsen J., Coriat M., 2012, MNRAS, 422, L11
Portegies Zwart S. F., McMillan S. L. W., 2002, ApJ, 576, 899
Prestwich A. et al., 2007, ApJ, 669, L21
Psaltis D., 2007, Phys. Rev. Lett., 98, 1101
Redmount I. H., Rees M. J., 1989, Comments Astrophys., 14, 165
Reid M. J., McClintock J. E., Steiner J. F., Steeghs D., Remillard R. A., Dhawan V., Narayan R., 2014, ApJ, 796, 2
Remillard R. A., Lin D., Cooper R. L., Narayan R., 2006, ApJ, 646, 407
Shafee R., McClintock J. E., Narayan R., David S. W., Li L., Remillard R. A., 2006, ApJ, 636, L113
Shakura N. I., Sunyaev R. A., 1973, A&A, 24, 337
Shlosman I., Vitello P., 1993, ApJ, 409, 372
Sigurdsson S., Hernquist L., 1993, Nature, 364, 423
Sim S. A., Proga D., Miller L., Long K. S., Turner T. J., 2010, MNRAS, 408, 1396
Sippel A. C., Hurley J. R., 2013, MNRAS, 430, L30
Smale A. P., Homan J., Kuulkers E., 2003, ApJ, 590, 1035
Smith D. M., Heindl W. A., Swank J. H., 2002a, ApJ, 569, 362
Smith D. M., Heindl W. A., Swank J. H., 2002b, ApJ, 578, L129
Spitzer L., 1969, ApJ, 158L, 139
Stanek K. Z., Garnavich P. M., 1998, ApJ, 503, L131
Stella L., Priedhorsky W., White N. E., 1987, ApJ, 312, L17
Strader J., Chomiuk L., Maccarone T. J., Miller-Jones J. C. A., Seth A. C., 2012a, Nature, 490, 71

Strader J., Chomiuk L., Maccarone T. J., Miller-Jones J. C. A., Seth A. C., Heinke C. O., Sivakoff G. R., 2012b, ApJ, 750, L27
Szostek A., Zdziarski A. A., 2008, MNRAS, 386, 593
Tananbaum H., Gursky H., Kellogg E., Giacconi R., Jones C., 1972, ApJ, 177, L5
Thorne K. S., Price R. H., 1975, ApJ, 195, L101
Titarchuk L., 1994, ApJ, 434, 570
Truss M., Done C., 2006, MNRAS, 368, L25
van den Heuvel E., 1983, Accretion Driven Stellar X-ray Sources. Cambridge Univ. Press, Cambridge
van der Klis M., 1995, X-Ray Binaries. Cambridge Univ. Press, Cambridge
van der Marel R. P., Anderson J., 2010, ApJ, 710, 1063
Verbunt F., Hut P., 1987, in Helfand D. J., Huang J.-H., eds, Proc. IAU Symp. 125, The Origin and Evolution of Neutron Stars. Reidel, Dordrecht, p. 187
Vitello P., Shlosman I., 1988, ApJ, 327, 680
Watkins L. L., van de Ven G., den Brok M., van den Bosch R. C. E., 2013, MNRAS, 436, 2598
Wheatley P. J., Mauche C. W., Mattei J. A., 2003, MNRAS, 345, 49
White N. E., Marshall F. E., 1984, ApJ, 281, 354
White N. E., Stellar L., Parmar A. N., 1988, ApJ, 324, 363
Woosley S. E., Taam R. E., 1976, Nature, 263, 101
Wu K., Soria R., Hunstead R. W., Johnston H., 2001, MNRAS, 320, 177
Zhang S. N., Cui W., Chen W., 1997, ApJ, 482, L155
Zurek D. R., Knigge C., Maccarone T. J., Dieball A., Long K. S., 2009, ApJ, 699, 1113

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