A second black hole candidate in a M31 globular cluster is identified with XMM–Newton

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ABSTRACT

We use arguments developed in previous work to identify a second black hole candidate associated with an M31 globular cluster (GC), Bo 144, on the basis of X-ray spectral and timing properties. The 2002 XMM–Newton observation of the associated X-ray source (hereafter XBo 144) revealed behaviour that is common to all low-mass X-ray binaries (LMXBs) in the low-hard state. Studies have shown that neutron star LMXBs exhibit this behaviour at 0.01–1000 keV luminosities \( \leq 0.1 \) per cent of the Eddington limit \( (L_{\text{Edd}}) \). However, the unabsorbed 0.3–10 keV luminosity of XBo 144 was \( \sim 0.30 \) \( L_{\text{Edd}} \) for a 1.4 \( M_\odot \) neutron star, and the 0.01–1000 keV luminosity is expected to be \( \geq 3–7 \) times higher. We therefore identify XBo 144 as a black hole candidate. Furthermore, it is the second black hole candidate to be consistent with formation via tidal capture of a main sequence donor in a GC; such systems were previously thought non-existent, because the donor was thought to be disrupted during the capture process.

Key words: black hole physics – galaxies: individual: M31 – X-rays: binaries – X-rays: general.

1 INTRODUCTION

In Barnard et al. (2008), we identified the first genuine black hole candidate using our X-ray classification method, which was developed fully in Barnard et al. The X-ray source associated with the globular cluster (GC) Bo 45 (hereafter known as XBo 45) exhibited behaviour associated with all low-mass X-ray binaries (LMXBs) in the low state: hard power law emission and high rms variability (see e.g. van der Klis 1994, 1995). A recent survey of Galactic neutron star LMXBs has shown that the low state is observed at 0.01–1000 keV luminosities \( \leq 0.1L_{\text{Edd}} \) for systems that trace a diagonal transition in colour–colour space from low state to high state, and \( \leq 0.02L_{\text{Edd}} \) for systems that exhibit a vertical transition (Gladstone, Done & Gierliński 2007); \( L_{\text{Edd}} \) is the Eddington luminosity. However, XBo 45 exhibited this behaviour at a 0.3–10 keV luminosity \( \sim 120 \) per cent Eddington for a 1.4 \( M_\odot \) neutron star, hence we identified it as a black hole candidate.

XBo 45 is particularly interesting because there has been a distinct lack of black holes in GCs, and most black hole LMXBs are thought to be ejected from the cluster. The theoretical work of Kalogera, King & Rasio (2004) showed that one possible formation channel for black hole LMXBs is the tidal capture of a main sequence star; indeed, it is the most likely channel for dense clusters, such as those with collapsed cores. Kalogera et al. (2004) predicted such systems to be persistently bright, and inferred from the absence of such systems that the prospective donor is disrupted during capture. XBo 45 has appeared in all X-ray observations covering that region of sky, spanning \( \sim 30 \) years, and hence is consistent with theoretical predictions for a system formed by tidal capture.

In this paper, we use the same arguments to identify XBo 144 (r2-5 in Kong et al. 2002, \( \alpha = 00:42:59.803 \delta = 41:16:06.01 \)) as another black hole candidate. Furthermore, XBo 144 is located in a confirmed M31 GC (see the revised Bologna Catalogue V.3.5, 2008 March; Galleti et al. 2004, 2005, 2006, 2007).

We present detailed analysis of the 2002 June XMM–Newton observation of XBo 144, the deepest of four exposures made between 2000 and 2002. Results from the other observations are consistent with this one. In Section 2, we describe the observations and data reduction, then present the results of our analysis in Section 3. We discuss our findings in Section 4, and draw conclusions in Section 5.

2 OBSERVATIONS AND DATA ANALYSIS

We rebuilt the data products for the 2002 June 26 XMM–Newton observation of the central region of M31 using version 7.1 of the Science Analysis Software (SAS) suite. In order to screen for background flares, we followed the recommended procedure, finding a small flare near the start of the observation; this was removed. We then synchronized the pn and MOS light curves as described in Barnard et al. (2007).

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We extracted pn (Strüder et al. 2001) and MOS (MOS1 and MOS2; Turner et al. 2001) data from a circular source region with radius 20 arcsec, with a 20 arcsec background region at a similar off-axis angle, with no point sources and on the same CCD chip. A larger background is desirable, but was prevented by crowding. Source and background light curves were constructed from the pn and MOS data in 0.3–2.5, 2.5–10 and 0.3–10 keV bands. The light curves were background subtracted. Source and background spectra were then created, along with corresponding response matrices and ancillary response files. The pn image yielded 5542 net source photons, while the data from the two MOS cameras were combined, yielding 4893 net source photons.

3 RESULTS

3.1 Spectral analysis

The pn and combined MOS spectra were modelled simultaneously, using xspec ver 11.3. Each model consisted of an emission model, with line-of-sight absorption and a normalization constant that accounts for differences in the pn and MOS calibrations, after setting the pn normalization to 1. The parameters of the emission models were forced to be the same for the pn and MOS spectra, but free to vary. Three emission models were initially chosen: blackbody (BB), bremsstrahlung (BR) and power law (PL). The BB and BR models were characterized by $kT$, where $T$ is the temperature and $k$ is the Boltzmann constant, while PL emission is characterized by photon index, $\Gamma$. Absorption is expressed in terms of $N_H$, the equivalent absorption by neutral hydrogen.

We first modelled the XBo 144 spectra with single component emission models: BB, BR and PL. We found the pn and MOS spectra to be best fitted by the PL model, with $N_H = 8.1 \pm 1.2 \times 10^{20}$ atom cm$^{-2}$ and $\Gamma = 1.48 \pm 0.04$; all spectral models are provided in Table 1. The best-fitting model is as expected for a LMXB in its low state; however, we do not expect such behaviour at X-ray luminosities above $0.1 L_{\text{Edd}}$ in the 0.01–1000 keV band (Barnard et al. 2008). The 0.3–10 keV luminosity for our best-fitting PL model is $5.33 \pm 0.03 \times 10^{37}$ erg s$^{-1}$, which is 0.29 $L_{\text{Edd}}$ for a 1.4 $M_\odot$ neutron star, and 0.20 $L_{\text{Edd}}$ for the most massive observed neutron star (2.1 $M_\odot$; see e.g. Nice et al. 2005). This is sufficiently bright for XBo 144 to be a plausible black hole candidate.

We then modelled the XBo 144 spectra with a two component (BB+PL) emission model. The favoured BB temperature is 0.0082±0.0016 keV; this tells us that there is no BB component in the 0.3–10 keV band. In Figs 1 and 2, we compare the PL and BB+PL emission models with the 0.3–10 keV pn spectrum, unfolded from the instrumental responses; we see that the instruments are in agreement. Without the BB component, the pn and MOS spectra are in excellent agreement. We are therefore confident in our interpretation of the X-ray emission from XBo 144.

Table 1. Best fits to XBo 144 pn and MOS spectra with various emission models. BB, BR and PL emission models were used, all suffering line-of-sight absorption. For each model, we provide the absorption ($N_H / 10^{20}$ atom cm$^{-2}$), temperature (k7keV), photon index ($\Gamma$) and MOS normalization constant ($n_{\text{MOS}}$). Numbers in parentheses indicate 90 per cent confidence limits. We then provide the $\chi^2$/dof. No uncertainties were calculated for the BB model, as $\chi^2$/dof = 8.5.

| Model | $N_H$ | $kT$ | $\Gamma$ | $n_{\text{MOS}}$ | $\chi^2$/dof |
|-------|-------|-------|---------|----------------|--------------|
| BB    | 7     | 0.68  | ...     | 1.07           | 1690/199     |
| BR    | 5.3(9)| 17(14)| ...     | 1.11(4)        | 193/198      |
| PL    | 8.1(12)| 14.8(4)| 11.1(4)| 182/198        |
| BB+PL | 8.7(12)| 0.0087(9)| 14.9(4)| 11.1(4)        | 178/196      |
| PL (pn)| 8.4(16)| ...     | 1.46(6)| ...            | 105/111      |
| PL (MOS)| 7(2)  | ...     | 1.49(7)| ...            | 74/85        |

3.2 Variability studies

The combined pn+MOS, background-subtracted, 0.3–10 keV light curve of XBo 144 is shown in Fig. 3, with 400 s binning. The intensity appears to vary in the manner of low-state LMXBs; however, the uncertainties are large, and the best-fitting line of constant intensity yields $\chi^2$/dof = 630/601, i.e. the light curve is consistent with being constant. The fractional rms variability is 6±4 per cent on time-scales longer than 100 s; this is consistent with a LMXB in the low state, but adds no extra strength to our argument. Without the definite variability exhibited by XBo 45 (Barnard et al. 2008),...
the case for XBo 144 being a black hole X-ray binary is somewhat weaker, and rests on its association with the GC Bo 144.

4 DISCUSSION

The X-ray source associated with the M31 GC Bo 144, XBo 144, exhibits an emission spectrum that is characteristic of a LMXB in the low state: the 0.3–10 keV emission is described by a pure PL, with $\Gamma = 1.48 \pm 0.04$. Gladstone et al. (2007) showed that neutron star LMXBs only exhibit this behaviour at 0.01–1000 keV luminosities $\lesssim 10$ per cent of the Eddington limit; the 0.3–10 keV luminosity of XBo 144 exceeds $0.20 L_{\text{Edd}}$ for all known neutron stars (2.1 $M_\odot$ or less).

Estimating the 0.01–1000 keV luminosity of XBo 144 is not as simple as extrapolating the PL to 1000 keV. Low-state spectra are thought to be caused by unsaturated inverse Compton scattering of cool photons on hot electrons in a corona, resulting in a PL for energies lower than the electron temperature, and a Wien spectrum for higher energies (Sunyaev & Titarchuk 1980). The coronae in black hole X-ray binaries tend to have temperatures of ~100–300 keV (McClimont & Remillard 2006); hence we cannot determine the corona temperature with 0.3–10 keV data. We obtained lower limit estimates to the 0.01–1000 keV luminosity of XBo 144 by measuring the flux of a PL with $\Gamma = 1.48$ for energy ranges 0.3–100 and 0.3–300 keV. We therefore expect the 0.01–1000 keV luminosity of XBo 144 to be at least ~3–7 times higher than the observed 0.3–10 keV luminosity, i.e. $> 0.6 - 1.4 L_{\text{Edd}}$ for a neutron star with mass 2.1 $M_\odot$. Hence, we propose XBo 144 as a candidate GC black hole LMXB.

Without the strong time variability observed in XBo 45, it is possible that XBo 144 is simply an active galactic nucleus (AGN), since $\Gamma \sim 1.4$ for typical AGN. Hence, associating the X-ray source with a GC is strong evidence that it is an X-ray binary. We therefore calculated the probability of an AGN coinciding with a GC within the observed field of view. We employed the X-ray luminosity functions (XLFs) for AGN devised by Moretti et al. (2003). They created AGN XLFs in 1–2 keV and 2–10 keV bands; therefore, we calculated the absorbed 1–2 and 2–10 keV fluxes of XBo 144 (1.08 $\times 10^{-13}$ and 5.69 $\times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, respectively). From the XLFs of Moretti et al. (2003), we expect 3.8 $\pm 0.9 \times 10^{-7}$ AGN per square arcsec to exhibit 1–2 keV fluxes as bright as XBo 144, and only $8 \pm 5 \times 10^{-8}$ AGN per square arcsec to exhibit 2–10 keV fluxes as bright as XBo 144. Kong et al. (2002) found the Chandra position of XBo 144 to be 2.2 arcsec from the GC position. There are 20 GCs within the field of view of the XMM–Newton observation we are interested in; hence, the probability for a chance coincidence between a GC and an AGN as bright as Bo 144 in the 2–10 keV band within 2.2 arcsec is $2.4 \pm 1.5 \times 10^{-3}$.

The 0.3–10 keV light curve of XBo 144 is consistent with a low-state LMXB, but also is consistent with being constant. We note that XBo 144 is ~5 times fainter than XBo 45, and may be more severely limited by low photon counts. There is a remarkable similarity between the two systems: they exhibit very similar emission spectra, they are both associated with GCs and both appear to have been persistently bright over the ~30-year period of observation. We infer that XBo 144 and XBo 45 are the same class of object: black hole LMXBs, likely produced by tidal capture of a main sequence star.

We now consider the influence of metallicity on the probability of finding black hole LMXBs in GCs. Bellazzini et al. (1995) discovered a novel mechanism to promote tidal capture at higher metallicities, in addition to the previously suspected correlation between metallicity and initial mass function (IMF). They assume that for a fixed cluster density, the rate of tidal capture depends on the mass and radius of the capturing star. They find that higher metallicity stars have larger masses and radii; therefore, they expect the tidal capture rate to increase with metallicity. Furthermore, a metal-rich star will more easily fill its Roche lobe. They conclude that this effect alone could explain the observed ratio between frequencies of X-ray sources in metal-rich and metal-poor clusters, although there is no reason to exclude the effects of metallicity on the IMF.

Fan et al. (2008) have produced the most comprehensive survey of metallicities of M31 GCs yet made. They combine spectroscopically derived metallicities for 295 GCs and GC candidates with colour-derived metallicities for 209 GCs and candidates. Fan et al. (2008) found a mean $[\text{Fe/H}]$ of $-1.29 \pm 0.03$ for the combined sample, which is remarkably similar to the mean $[\text{Fe/H}]$ for the Milky Way ($-1.30 \pm 0.05$; Harris 1996, updated in 2003). In particular, $[\text{Fe/H}] = -0.6 \pm 0.2$ for Bo 144, making it ~5 times more metal rich than the mean for M31 or the Milky Way. Bo 45 also has a relatively high metallicity: $[\text{Fe/H}] = -1.1 \pm 0.3$, suggesting that it is ~60 per cent more metal rich than the mean, with possible metallicity range 80–300 per cent of the M31 mean. The high metallicity of Bo 144 and the inferred increase in tidal capture rate support the plausibility of XBo 144 being black hole LMXB.

5 CONCLUSIONS

We have identified a second black hole candidate in a M31 GC; such a system would most likely be formed by tidal capture. Kalogera et al. (2004) found tidal capture to be the dominant mechanism for LMXB formation in collapsed core GCs, or even denser clusters such as M15. A survey of Galactic clusters (Harris 1996) showed ~20 per cent of clusters to be core collapsed; therefore, we expect no more than 20 per cent of GC X-ray sources to harbour black holes. Traditional methods of identifying a black hole involve obtaining a mass function from the radial velocity curves of the donor, and are quite unsuitable for identifying black holes in GC LMXBs because the donor is near-impossible to identify. Our X-ray identification of black holes is not so hindered, but does identify only that subset of black hole LMXBs in the low state at an observed luminosity $\geq 3 \times 10^{37}$ erg s$^{-1}$. Applying our X-ray technique to other known, bright X-ray sources in GCs may reveal further candidate black hole systems.
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REFERENCES

Barnard R., Trudolyubov S., Kolb U. C., Haswell C. A., Osborne J. P., Priedhorsky W. C., 2007, A&A, 469, 875
Barnard R. et al., 2008, ApJ, 689, 1215
Bellazzini M., Pasquali A., Federici L., Ferraro F. R., Pecci F. F., 1995, ApJ, 439, 687
Fan Z., Ma J., de Grijs R., Zhou X., 2008, MNRAS, 385, 1973
Galleti S., Federici L., Bellazzini M., Fusi Pecci F., Macrina S., 2004, A&A, 416, 917
Galleti S., Bellazzini M., Federici L., Fusi Pecci F., 2005, A&A, 436, 535
Galleti S., Federici L., Bellazzini M., Buzzoni A., Fusi Pecci F., 2006, A&A, 456, 985
Galleti S., Bellazzini M., Federici L., Buzzoni A., Fusi Pecci F., 2007, A&A, 471, 127
Gladstone J., Done C., Gierliński M., 2007, MNRAS, 378, 13
Harris W. E., 1996, AJ, 112, 1487
Kalogera V., King A. R., Rasio F. A., 2004, ApJ, 601, L171
Kong A. H. K., Garcia M. R., Primini F. A., Murray S. S., 2002, ApJ, 577, 738
McClintock J. E., Remillard R. A., 2006, in Lewin W. H. G., van der Klis M., eds, Compact stellar X-ray sources, Cambridge Univ. Press, Cambridge, p. 157
Moretti A., Campana S., Lazzati D., Tagliaferri G., 2003, ApJ, 588, 696
Nice D. J., Splaver E. M., Stairs I. H., Löhmer O., Jessner A., Kramer M., Cordes J. M., 2005, ApJ, 634, 1242
Strüder L. et al., 2001, A&A, 365, L18
Sunyaev R. A., Titarchuk L. G., 1980, A&A, 86, 121
Turner M. J. L. et al., 2001, A&A, 365, L27
van der Klis M., 1994, ApJS, 92, 511
van der Klis M., 1995, X-ray Binaries. Cambridge Univ. Press, Cambridge, p. 256

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