Near-infrared counterparts of three transient very faint neutron star X-ray binaries

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ABSTRACT

We present near-infrared (NIR) imaging observations of three transient neutron star X-ray binaries, SAX J1753.5–2349, SAX J1806.5–2215 and AX J1754.2–2754. All three sources are members of the class of ‘very faint’ X-ray transients which exhibit X-ray luminosities \( L_X \lesssim 10^{36} \text{ erg s}^{-1} \). The nature of this class of sources is still poorly understood. We detect NIR counterparts for all three systems and perform multi-band photometry for both SAX J1753.5–2349 and SAX J1806.5–2215, including narrow-band Br\( \gamma \) photometry for SAX J1806.5–2215. We find that SAX J1753.5–2349 is significantly redder than the field population, indicating that there may be absorption intrinsic to the system, or perhaps a jet is contributing to the infrared emission. SAX J1806.5–2215 appears to exhibit absorption in Br\( \gamma \), providing evidence for hydrogen in the system. Our observations of AX J1754.2–2754 represent the first detection of a NIR counterpart for this system. We find that none of the measured magnitudes are consistent with the expected quiescent magnitudes of these systems. Assuming that the infrared radiation is dominated by either the disc or the companion star, the observed magnitudes argue against an ultracompact nature for all three systems.

Key words: accretion, accretion discs – infrared: general – stars: neutron – X-rays: binaries – X-rays: individual: SAX J1753.5–2349 – X-rays: individual: SAX J1806.5–2215 – X-rays: individual: AX J1754.2–2754

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are binary systems in which a compact object, either a black hole (BH) or neutron star (NS), accretes matter from a low-mass star. Many LMXBs are discovered when they undergo transient outbursts, where the X-ray luminosity increases by a factor > 1000, accompanied by a large increase in optical luminosity (\( \Delta V \sim 7 \); e.g., Kuulkers 1998) for a short period (typically weeks to months) before decaying to quiescence. Although transient LMXBs exhibit high luminosities during outburst (\( L_X \sim 10^{37}–39 \) erg s\(^{-1}\)), during the last decade, a population of faint X-ray transients have emerged. Members of this class of Very Faint X-ray Transients (VFXTs) exhibit peak X-ray luminosities in the range \( 10^{34}–36 \) erg s\(^{-1}\) (e.g. Munu et al. 2005a; Wijnands et al. 2006; Degenaar & Wijnands 2009, 2010). Due to the frequent monitoring of the Galactic Centre, a large number of VFXTs have been found to lie close to this region.

The current disc instability model (DIM) which well describes the general behaviour of the outbursts in typical LMXB transients (Lasota 2001; Coriat et al. 2012) cannot immediately explain the low peak X-luminosities of VFXTs (Heinke et al. 2015; Hameury & Lasota 2016). The luminosities of these sources time-averaged accretion rate in the range \( 10^{-13}–10^{-10} M_{\odot} \text{yr}^{-1} \) (King & Wijnands 2006; Degenaar & Wijnands 2009), which can be difficult to explain in the context of binary evolution models. A number of models have emerged in an effort to characterize the observed low accretion rates and faint X-ray luminosities. It is possible that some VFXTs are wind accreting systems, similar to high-mass X-ray binary (HMXB) systems, except that the compact object is accreting from the weak stellar wind of a low-mass companion (Pfahl et al. 2002; Maccarone & Patruno 2013). An alternative model is that the compact object has a small accretion disc, indicative of an ultracom-
impact system with a short orbital period \( P_{\text{orb}} \lesssim 2\,\text{hrs} \); e.g. In’t Zand et al. 2005, 2007; Hameury & Lasota 2016) that can only accommodate a (partly) degenerate donor such as a brown or white dwarf (King & Wijnands 2006; Heinke et al. 2015). It has also been proposed that the magnetic field of a NS can inhibit accretion, resulting in the observed very faint X-ray luminosities (Heinke et al. 2009; D’Angelo & Spruit 2012; Heinke et al. 2015). Some VFXTs have been shown to have a large orbital inclination, meaning observers only see the scattered light of an intrinsically bright source (Muno et al. 2005b; Corral-Santana et al. 2013), but this scenario cannot be applied to most systems (Wijnands et al. 2006).

The nature of the donors in VFXTs can be best understood through optical/near infrared (NIR) follow-up of sources discovered in X-ray surveys. However, as most of the sources have been found so far to be close to the Galactic Centre, optical/NIR photometry is inhibited by high extinction and extremely crowded fields (Mauerhan et al. 2009). Hence, optical/NIR results have not been reported for most VFXTs as it becomes difficult to identify the correct counterpart. Despite this, there are a small number of observations of VFXTs in the optical/NIR regime. Degenaar et al. (2010) identified the optical counterpart of the bursting NS binary IRXH J173523.7–354013, revealing H\(_{\alpha}\) emission in the optical spectrum and effectively ruling out an ultracompact nature (though it must be noted that recent efforts to model ultracompact evolution have provided evidence that some ultracompact systems can potentially exhibit hydrogen in their spectra; Sengar et al. 2017). Through optical observations, M15 X-3 has been shown to contain a main sequence star in a \( \sim \) 4 hr orbit with a NS (Heinke et al. 2009; Arnason et al. 2015). In addition, XTE J1719–291, Swift J1357.2–0933, SAX J1806.5–2215 and CXOGC J174540.0–290301 have all been suggested to contain main-sequence companions from optical/NIR observations (Muno et al. 2005b; Greiner et al. 2008; Corral-Santana et al. 2013; Kaur et al. 2017).

Based on their optical/NIR properties, all of the above sources appear to be typical LMXBs, not ultracompact systems. However, owing to the small sample size, we cannot yet rule out any of the above models. We need to investigate the companion stars of many more VFXTs in order to better understand the different possible accretion regimes in these systems. Due to the typically large absorption columns in the Galactic plane, searching for counterparts at NIR wavelengths is much more effective than at optical wavelengths. In this work we present NIR photometry of three VFXTs in order to place constraints on their counterparts and investigate the nature of accretion in these systems.

1.1 SAX J1753.5–2349

SAX J1753.5–2349 (hereafter SAX1753) was discovered with the Wide Field Camera (WFC) instrument on board the BeppoSAX X-ray observatory during a single type-I burst on August 24 1996 (In’t Zand et al. 1999). Initially a ‘burst-only’ source, persistent emission (either in outburst or quiescence) was not detected for SAX1753 until the source was once more detected in outburst in 2008 by the Proportional Counter Array on board the Rossi X-ray Timing Explorer (RXTE/PCA) and the Swift/Burst Alert Telescope (BAT) (Markwardt et al. 2008), as well as the INTEGRAL imager IBIS (Cadolle Bel et al. 2008). A further X-ray burst and associated transient outburst was observed by INTEGRAL and RXTE/PCA in 2010 (Chenevez et al. 2010) and a NIR counterpart with \( K_s = 15.63 \pm 0.01 \) was identified (Torres et al. 2010).

Modelling of the broadband X-ray spectrum of SAX1753 from the 2008 outburst (which lasted > 5 months; Del Santo et al. 2009) revealed a spectrum consistent with the Compton up-scattering of soft seed photons by a hot optically thin electron plasma with an inferred temperature \( \gtrsim 24 \, \text{keV} \) (Del Santo et al. 2010). The low luminosity of SAX1753 (peaking at \( L_X \sim 10^{36} \, \text{erg}\,\text{s}^{-1} \)) suggests that the system is very compact (Del Santo et al. 2010), though its orbital period has not yet been measured and, as discussed in Section 1, there are number of alternative possible origins for the low X-ray luminosity. The compact object is known to be a neutron star from observations of thermonuclear bursts (Chakrabarty et al. 2010).

1.2 SAX J1806.5–2215

SAX J1806.5–2215 (hereafter SAX1806) was discovered by BeppoSAX/WFC through the detection of four type-I X-ray bursts observed between August 1996 and October 1997 (In’t Zand et al. 1999; Cornelisse et al. 2002b). Similar to SAX1753, SAX1806 was initially classified as a ‘burst-only’ source until faint persistent emission was revealed by the RXTE/All Sky Monitor (ASM) coinciding with the same period as the occurrence of the X-ray bursts (Cornelisse et al. 2002b).

The source remained quiescent for 12 yrs, with upper limits on the X-ray luminosity during this time estimated to be \( 0.5 – 4 \times 10^{35} \, \text{erg}\,\text{s}^{-1} \) (Campana 2009; Degenaar et al. 2011). A new outburst was detected by RXTE in February 2011 (Altamirano et al. 2011). Swift observations revealed an X-ray spectrum consistent with a power law with a hard photon index \( \Gamma \sim 1.7 – 2 \) (Degenaar et al. 2011; Kaur et al. 2012; Del Santo et al. 2012). Monitoring with Swift/BAT indicates that the source is still exhibiting low-level activity and hence has likely remained in outburst for \( \gtrsim 6 \) years. During the X-ray outburst that began in 2011, a NIR counterpart was discovered with \( K = 17.25 \pm 0.03 \) (Kaur et al. 2017).

1.3 AX J1754.2–2754

AX J1754.2–2754 (hereafter AXJ1754) was discovered in 1999 by the Advanced Satellite for Cosmology and Astrophysics (ASCA) during a survey of the Galactic Centre region (Sakano et al. 2002). A type-I X-ray burst in April 2005 revealed the compact object as a NS (Chelovekov & Grebenev 2007b). The source has been detected at a luminosity of \( L_x \sim 10^{35} \, \text{erg}\,\text{s}^{-1} \) every time it has been observed (see e.g. Jonker & Keek 2008; Degenaar et al. 2012; Maccarone et al. 2012), aside from one brief (\( \lesssim 11 \)

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1 https://swift.gsfc.nasa.gov/results/transients/weak/SAXJ1806.5-2215/
months) period of quiescence \((L_X \lesssim 5 \times 10^{32} \text{ erg s}^{-1};\)
Bassa et al. 2008\). A long observing campaign of AX1754
with Swift revealed a very soft X-ray spectrum \((\Gamma = 2.5;\)
Armas Padilla et al. 2013\).

Unlike those of SAX1753 and SAX1806, the X-ray bursts displayed by AX1754 are long (up to 15 minutes in length; Chelovekov & Grebenev 2007a; Chenevez et al. 2017\).
Intermediate-to-long duration bursts are thought to be due to the ignition of a thick layer of helium on the surface of the NS which builds up due to the low mass accretion rate (Peng et al. 2007; Cooper & Narayan 2007\).
This, coupled with the non-detection of the source at optical/NIR wavelengths (Bassa et al. 2008; Zolotukhin & Revnivtsev 2015\) suggest that AX1754 is an ultracompact X-ray binary, though no orbital period has been measured.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 Swift

We used all available Swift/X-Ray Telescope (XRT; Burrows et al. 2005\) observations of each source to construct long-term X-ray light curves in order to put the NIR observations into context. The light curves were created with the online Swift/XRT User Objects tool (Evans et al. 2009\) and grouped into 1 day bins. In the event of a non-detection, a \(3\sigma\) upper limit on the XRT count rate is calculated by the light curve generator. We also used the data from the Swift/BAT Hard X-ray Transient Monitor (Krimm et al. 2013\) to construct long term X-ray light curves in the 15-50 keV range.

Data are available online and do not require any reduction.\(^2\)

### 2.2 Near Infrared

All three sources were observed with the Near InfraRed Imager and spectrophotograph (NIRI; Hodapp et al. 2003\) on the 8.1m Gemini North telescope at Mauna Kea, Hawaii with the f/6 camera in imaging mode. The f/6 camera has a plate scale of \(0.117''\) pixel\(^{-1}\), providing a field of view of \(120'' \times 120''.\) SAX1753 was observed on the night of 2012 July 11. We obtained 34 exposures of 53s in \(H\) and 45 exposures of 56s in \(K_s\). To account for the changing sky background at NIR wavelengths, a dithering pattern was applied in each filter, with each co-added exposure consisting of 17, 3s exposures in \(H\) and 20, 2.7s exposures in \(K_s\).

\(\text{SAX1806 was observed on 2012 May 2. The source was observed in } H \text{ and } K_s \text{ broad-band filters as well as the } Br_{\gamma} \text{ narrow-band filter. We obtained 10 exposures of 39s in both } H \text{ and } Br_{\gamma}, \text{ with each co-add comprising of three, } 13s \text{ dithered exposures. 10 exposures of 12s were obtained in } K_s, \text{ with each co-add comprising of three, } 4s \text{ dithered exposures.}\)

AX1754 was observed with Gemini/NIRI on 2012 May 21. The field was observed in \(H\) and \(K_s\) broad-band filters as well as the \(Br_{\gamma}\) narrow-band filter. However, as detailed in section 3.3, we were only able to detect the counterpart in the \(K_s\)-band. We therefore choose to concentrate here on the \(K_s\)-band observations. We obtained 10 exposures of 12s, each comprising of three, 4s dithered exposures.

Data reduction for all NIRI images is performed using the IRAF (Tody 1986\) Gemini package and NIRI-specific PYTHON routines. To remove artifacts superimposed by the IR detector controller we utilized the CLEANIR script\(^3\) before correcting for non-linearity in the detector with NIRLIN.\(^4\) As there were no extended objects in the fields of view of each target, sky frames were created from the science images. For each target, a normalized flat field was created with the task NIFLAT and bad pixels identified using short dark frames. Flat-fielding and sky subtraction was performed using NIREDUCE and the final images were created with IMCOADD. From the final reduced images we obtained a signal-to-noise ratio, \(SN > 10\) for a 17th magnitude star, which agrees with the estimates made by the NIRI Integration Time Calculator (ITC).\(^5\)

To determine the astrometry, we first used SEXtractor (Bertin & Arnouts 1996\) to create source catalogs for each target field. The astrometric solution in each band was obtained with SCAMP (Bertin 2006\), using the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006\) catalog as a reference, then the projection was applied to the co-added science images using SWarp (Bertin et al. 2002\). The solution delivered an RMS error \(\sim 0.1''\) in each coordinate, indicative of the positional uncertainty.

To measure instrumental magnitudes we used the IRAF DAOPHOT routines developed for crowded-field photometry (Stetson 1987\). We determined the empirical point spread function (PSF) for each target frame using relatively isolated field stars. We identified 10 suitable PSF stars in each band for the images of SAX1753 and AX1754, and, due to extreme crowding and a large number of saturated stars, 4 suitable PSF stars in each band for the SAX1806 images. The PSF was then fit to all the stars in the frame with the task ALLSTAR to determine instrumental magnitudes. The observations were calibrated using 2MASS stars in the field. We used a total of 10 calibration stars for SAX1753, 4 for SAX1806 (due to, again, crowding and saturated stars, as well as a difference in pointing between \(H\) and \(K_s\) observations such that only 4 suitable calibration stars were present in both bands) and 6 for AX1754. For SAX1753 and SAX1806 we calibrated the frames using transformation equations of the form:

\[
h = h_0 + c_1 + c_2 X + c_3 H - K_s
\]

\[
k_s = k_s + c_4 + c_5 X + c_6 H - K_s
\]

where \(h\) \((k_s)\) is the instrumental magnitude of the calibration star in the \((H, K_s)\)-band, \(H\) \((K_s)\) is its known magnitude, \(c_1 - c_6\) are constants (representing an additive term, an extinction term and a colour term in each band), \(X\) is the airmass and \(H - K_s\) is the known NIR colour of the calibration star.

For AX1754, we were only able to detect a counterpart

\[^2\]https://swift.gsfc.nasa.gov/results/transients/

\[^3\]http://staff.gemini.edu/~astephens/niri/cleanir/cleanir.py

\[^4\]http://staff.gemini.edu/~astephens/niri/nirlin/

\[^5\]http://www.gemini.edu/sciops/instruments/integration-time-calculators/niri-itic
in the $K_s$-band. We therefore calibrated our magnitude by determining the zero-point for our observations using the 6 well-detected, isolated 2MASS stars in the field.

3 RESULTS

3.1 SAX J1753.5-2349

Fig. 1 shows the $K_s$-band NIR image of the field of SAXJ1753, as well as an archival image observed with the United Kingdom Infrared Telescope (UKIRT) as part of the UKIRT Infrared Deep Sky Survey (UKIDSS). We detect the source in the NIR image at a position of RA, Dec = 17$^{h}$53$^{m}$31$^{s}$.87, $-$23$^\circ$39$''$.14$''$.83, consistent with the position of the source determined during outburst using a Chandra observation (Chakrabarty et al. 2010) and from the NIR counterpart (Torres et al. 2010). We measure magnitudes of the NIR counterpart of $H = 18.58 \pm 0.03$ and $K_s = 17.44 \pm 0.02$, which is $\sim 2$ magnitudes fainter than during the 2010 outburst (Torres et al. 2010). Though this may indicate that the source was quiescent at the time, it is important to note that these magnitudes would have been measurable in the UKIDSS data, which has 5σ limits of $K = 18.05$, $H = 19.00$ (Lucas et al. 2008). In addition there are sources in the UKIDSS field fainter than the measured NIR magnitudes of SAXJ1753 (Lucas et al. 2008), yet SAXJ1753 is not detectable by UKIDSS. This suggests that SAXJ1753 was not in true quiescence during the time of our observations, but was still active at a low level. The X-ray light curve presented in Fig. 2 suggests that the source had reached quiescence at X-ray energies. However, there were no pointed X-ray observations at the time of the NIRI observations. We therefore investigated the long-term Swift/BAT light curve of SAXJ1753 and found that the source underwent a faint outburst in 2012 June/July that was not reported (Fig. 3). Our Gemini observations took place close to the end of the decay of this outburst, and it is likely that there was still accretion activity at this time, which would explain why we measured a magnitude above the UKIDSS limit.

We present a colour-magnitude diagram of the SAXJ1753 field in Fig. 4. Due to the long exposure times, field stars with $K_s < 12$ saturated the CCD and hence have been excluded. The NIR counterpart to SAXJ1753 appears to be significantly redder in relation to the field population for magnitudes fainter than $K_s > 19.0$. This argues that the system is not intrinsic colour index of $H - K_{	ext{int}} = 0.55 \pm 0.13$ mag.

To determine whether this intrinsic reddening is typical we match the coordinates of all field sources with $H - K_{\text{obs}} > 1$ against the field image. We find an isotropic distribution of such sources in the field, indicating that SAXJ1753 is not located in a region of high absorption (e.g. behind a dust cloud) and it is possible that there is absorption local to the system itself. It is important to note that the calculation is dependent on the determination of $N_H$, which is highly dependent on the model used to define the X-ray continuum, as well as the absorption model utilized during spectral fitting. It is also possible that, as SAXJ1753 was potentially still showing signs of accretion at the time of the NIRI observations, the intrinsically red spectrum could be due to an outflow in the form of an accretion disc wind, or to jets - which are known to exhibit optically thin (negative slope) spectra in the infrared (see e.g. Díaz Trigo et al. 2017).

If we assume that the secondary star fills its Roche lobe, then we can use the NIR magnitude from the 2010 outburst to constrain the orbital period of the system using the relation between $K$-band magnitude, $L_X$ and $P_{\text{orb}}$ derived by Revnivtsev et al. (2012). Assuming a distance of 8 kpc, a luminosity of $L_X \approx 0.02 L_{\text{Edd}}$ (for a 1.4M$_{\odot}$ NS) at the peak of the outburst (Del Santo et al. 2010) and $K = 15.63$ (Torres et al. 2010) we estimate $P_{\text{orb}} \approx 15$ h with a typical propagated uncertainty of ±4h. There are a number of assumptions in this calculation, for example we assume here that all of the NIR emission is due to reprocessed X-rays and that at the peak of the outburst there is no contribution from a jet or the companion (which may not be a reasonable assumption as discussed above). However, this estimate of $P_{\text{orb}}$ argues that the system is not ultracompact, though the only way to truly determine $P_{\text{orb}}$ is through quiescent time-series photometry or spectroscopy.

3.2 SAX J1806.5-2215

Fig. 5 shows the $K_s$-band field of SAXJ1806 as observed by Gemini/NIRI. We detect the source at a position of RA, Dec = 18$^{h}$06$^{m}$32$^{s}$.18, $-$22$^\circ$14$'$17$''$.36, within the Chandra error circle (Chakrabarty et al. 2011). We measure magnitudes of the NIR counterpart of $H = 17.94 \pm 0.06$ and $K_s = 17.22 \pm 0.02$. The measured $K_s$ magnitude is consistent with 2011 $K$-band observations of the source (Kaur et al. 2017). Fig. 6 shows the long term Swift/XRT light curve. Though it initially seems as if the X-ray count rate had decayed significantly between the observations of Kaur et al. (2017) and those of this work, the inset shows that the two NIR observations occurred at similar X-ray fluxes, consistent with the near identical NIR magnitudes observed at the two epochs. SAXJ1806 is not detected in UKIDSS, which observed the field in July 2006 when SAXJ1806 was in quiescence (Campana 2009), placing a 5σ upper limit on the quiescent magnitude of $K > 18.05$, $H > 19.00$.

It is important to note that the NIR counterpart to SAXJ1806 is located close to a diffraction spike of a nearby bright star (2MASS 18063303-2214249), which may have an effect on the measured magnitude of the target. However, an

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6 http://www.astro.caltech.edu/~jmc/2mass/v3/transformations/
NIR photometry of faint transients

Figure 1. Left: $K_s$-band NIRI image of SAX1753. Right: $K$-band image of the same field, observed on 2007 May 4 as part of the UKIDSS. In both panels, the white circle represents the 0.6″ error circle of the Chandra X-ray position of the source (Chakrabarty et al. 2010).

Figure 2. Long term Swift/XRT light curve of SAX1753, the green arrow represents the time of the observation presented by Torres et al. (2010), the red arrow indicates the time of the Gemini/NIRI observation. Black, capped arrows represent 3σ upper limits on the XRT count rate.

Figure 3. Portions of the long term Swift/BAT light curve of SAX1753. The green arrow in the left panel indicates the time of the NIR follow-up observation by Torres et al. (2010), the red arrow in the right panel indicates the time of the Gemini/NIRI observation presented in this work.

investigation of the PSF subtracted image revealed no obvious residuals at the location of the source, and the diffraction spike was still present, indicative of a clean subtraction. In addition, we measured the magnitudes of two known sources present in the diffraction spikes (UGPS J180633.87–221431.0 and UGPS J180633.67–221429.3) and found them to be consistent with measured UKIDSS magnitudes. The same stars are not located in the diffraction spikes in the archival UKIDSS images. We can therefore assume that our PSF photometry is unaffected by the presence of the diffraction spike of the bright star.

As with SAX1753, we present a colour-magnitude diagram of the source field of SAX1806 in Fig. 7. The source reddening is consistent with the majority of the field population. We also obtained observations of the source field in the Brγ narrow-band filter, which allows us to study the hydrogen emission in the system.

It is possible to identify stars with strong line emission/absorption by using a broadband photometric filter as an indicator of the continuum near the location of the spectral line (see e.g. Robertson & Jordan 1989; Panagia et al. 2000; Drew et al. 2005, for methods of finding Hα emitting stars using photometry). In the case of SAX1806, we use the $K_s$-band magnitude as an indicator of the continuum near the Brγ line. Therefore, a large ($K_s$–Brγ) colour would provide evidence of excess hydrogen emission in the system.

To construct the ($H-K_s$) vs. ($K_s$–Brγ) colour-colour diagram in Fig. 8 we utilised the instrumental magnitudes in the Brγ band, as we cannot convert Brγ instrumental magnitudes on to the standard photometric system due to the absence of photometric standard stars in this band. We
also excluded saturated stars and stars close to the edge of the CCD. The dashed line in Fig. 8 is the running median ($K_s - \Delta K_s$) colour, and represents the locus at which stars have no excess $\Delta K_s$ emission. Any sources lying significantly above/below this line can be assumed to exhibit a strong $\Delta K_s$ feature in emission/absorption.

The SAX1806 ($K_s - \Delta K_s$) colour places it well below the locus of the continuum at the same ($H - K_s$), showing a $|\Delta K_s| > 5$ times larger than the photometric uncertainty on the ($K_s - \Delta K_s$) colour of SAX1806. This is evidence that the source is exhibiting significant $\Delta K_s$ absorption.

We can attempt to place an estimate on the equivalent width of the $\Delta K_s$ line, $EW(\Delta K_s)$ utilizing the methods of De Marchi et al. (2010); Beccari et al. (2014), who derived the equivalent width of $\Delta H_\alpha$ to be related to the rectangular width, $RW$, of the $\Delta H_\alpha$ filter as $EWH\alpha = RW \times 1 - 10^{-0.4 \times \Delta H_\alpha}$, where the $\Delta H_\alpha$ excess emission is the distance $\Delta H_\alpha$ from the median. Echoing this, we estimate $EWH\alpha \sim 120\AA$, where a negative $EWH_\alpha$ in this case represents absorption (contrary to standard notation). This is an disturbingly large value - an order of magnitude stronger than is typically seen in LMXBs (see e.g. Rahoui et al. 2014).

To investigate this we create two new co-added images, one from the first 5 individual frames of the observing run and one from the second 5 frames in order to determine if the large implied EW is caused by large amplitude variability of the $\Delta K_s$ instrumental magnitude. We find that the source is not detected (to 5σ) in either of the new images, indicating that the source truly is likely to be exhibiting $\Delta K_s$ at a lower flux than is typical of the field population. Though we cannot truly determine the properties of the $\Delta K_s$ line without NIR spectroscopy, this does provide evidence that there is hydrogen present in the SAX1806 system, and therefore it is likely that it is not an ultracompact binary.

We can examine this further by applying the Revnivtsev et al. (2012) scaling relation to the measured flux values. Assuming a distance of 8kpc and $L_X \sim 0.01L_{Edd}$ (Cornelisse et al. 2002a) we estimate $P_{\text{orb}} \approx 4 \pm 1\text{h}$. We make the same assumptions here as with the $P_{\text{orb}}$ estimate for SAX1753.

This provides further evidence that SAX1806 is not an ultracompact system, as discussed above.

3.3 AX J1754.2–2754

The AXJ1754 field in the $K_s$-band is presented in Fig. 9. After using the PSF fit to subtract the nearby bright star (UGPS J175414.57–275436.0) we find a source at a level of $\sim 5\sigma$ above the background at a position of RA, Dec $= 17^h54^m14^s.47, -27^\circ54'35''.34$, well inside the Chandra error circle (Bassa et al. 2008). We therefore conclude that this source is the NIRT counterpart of AX1754, and the measured magnitude of $K_s = 18.12 \pm 0.15$ represents the first optical/NIR detection of this source. We do not detect a counterpart in the $H$-band (to a depth of $H = 20$) or $\Delta K_s$-band observations.

There is no evidence of a NIRT counterpart in the archival UKIDSS image (Fig. 9), which has a limiting magnitude of $K = 18.05$ (Lucas et al. 2008). The source was X-ray active at the time of the NIRT observations (Fig. 10), so the quiescent magnitude of this source remains unknown. Zolotukhin & Revnivtsev (2015) provided a constraint of $P_{\text{orb}} < 9\text{h}$ using the Revnivtsev et al. (2012) relations, based on an upper limit to the NIR brightness, as the source has not been detected in archival images. We can provide a more accurate estimate using the measured $K_s$-band magnitude. Adopting $L_X \sim 0.0006L_{Edd}$ for a distance of 9.2kpc (Chelovekov & Grebenev 2007a) we estimate $P_{\text{orb}} \approx 5.4 \pm 2.3\text{h}$. Though this is clearly too long for an ultracompact system, it is important to note that the calculation relies heavily on the distance measurement. Adopting the closest distance estimate calculated for AX1754 (6.6kpc; Chelovekov & Grebenev 2007a), we find $P_{\text{orb}} \approx 2.6 \pm 1.1\text{h}$, which is indicative of a much more compact binary, though probably not ultracompact. We note that we have assumed that the measured $K_s$-band magnitude is the peak value. However, it is possible that AX1754 has been brighter in the NIR over the course of its prolonged X-ray activity, implying a larger $P_{\text{orb}}$, hence making an ultracompact scenario even less likely.

4 SUMMARY AND CONCLUSIONS

We present here NIR observations of the counterparts of three VFXTs. Included in this analysis is the first ever NIR detection of AX1754. We also present analysis of two other sources, SAX1753 and SAX1806, which have only previously been studied in single NIR bands, preventing in depth discussion of NIR colour.

We identified the NIRT counterpart to SAX1753, consistent with the position of the source reported during its 2010 outburst (Torres et al. 2010). We find that the flux of the source has decayed by $\sim 2$ magnitudes in the $K_s$-band, consistent with an apparent return to quiescence in X-rays. However, we note in Section 3.1 that SAX1753 was likely not in quiescence at the time of the NIRT observations, as a source with a quiescent magnitude of $K_s = 17.44 \pm 0.02$ is detectable in UKIDSS archival images. The Swift/BAT light curves in Fig. 3 show evidence for a faint outburst close to the time of our NIRT observations, which suggests...
that the source was still exhibiting accretion activity during this time, and hence not in true quiescence.

SAX1753 appears to exhibit significant reddening in relation to the field population (Fig. 4), with an intrinsic colour index $H - K_{\text{int}} = 0.55 \pm 0.13$ mag, which is larger than typical values for main sequence companions (Cox 2000). It must be noted that this value is highly dependent on the derived $N_H$, which itself is dependent on the model chosen to constrain the X-ray spectrum. We therefore cannot definitively state that there is absorption intrinsic to the system. However, it is clear from Fig. 4 that SAX1753 is redder than the majority of other stars in the field, independent of the modelled $N_H$. Another possible origin for the unusually red colour of SAX1753 is the presence of a jet. It has been shown in a number of NS LMXBs that jets manifest in the NIR spectrum as a power law with a negative slope (Migliari et al. 2010; Baglio et al. 2016; Díaz Trigo et al. 2017) and it is possible that we are seeing a similar process in SAX1753, as the source appeared to still be accreting at the time of our observations. However, we cannot constrain any properties with just two NIR data points, and SAX1753 has never exhibited any signs of a radio jet, so it is unclear if this interpretation is correct.

We also obtained the first multi-band NIR photometry of the counterpart to SAX1806, which had previously only been observed in the $K$-band (Kaur et al. 2017). We find that the source exhibits a low $K_s - \text{Br}\gamma$ colour in relation to the rest of the field population. This suggests the presence of a Brγ absorption feature in the NIR spectrum of SAX1806 and, though the derived EW of $\sim 120$ seems rather large, is indicative of hydrogen present in the system. This, coupled with an estimate of $P_{\text{orb}} \approx 4 \pm 1$ h from the Revnivtsev et al. (2012) relations provides significant evidence against...
an ultracompact nature. We require NIR spectroscopy to confirm the absorption in the Brγ-band, and SAX1806 is bright and isolated enough to be targeted for spectroscopy with the current generation of 8m class telescopes.

We present the first ever NIR detection of AX1754, a NS system that is actively accreting most of the time and exhibits intermediate length X-ray bursts. The $K_s$-band magnitude of $18.12 \pm 0.15$, combined with the extremely low X-ray luminosity, suggests a short period system ($P_{\text{orb}} \approx 5.4 \pm 2.3$ hr), though not ultracompact in nature. The source is in close proximity to a bright star, which makes NIR photometric and spectroscopic follow up extremely difficult, and hence determining the true nature of the system becomes problematic.

We have shown in this work that the three faint NS systems presented here are likely normal LMXBs. They do not show any evidence of ultracompact behaviour, either from estimates of $P_{\text{orb}}$ or through inferring the presence of hydrogen. In addition, several other VFXTs are found to exhibit properties typical of regular LMXBs rather than ultracompact binaries (see e.g. Heinke et al. 2009; Degenaar et al. 2010). However, this does not rule out the ultracompact scenario as a way of explaining the faint outbursts of a sub-class of VFXTs, but rather suggests that there are multiple classes of sources accreting in a faint regime. It is worth noting here that the best studied sample of VFXTs is those that show long ($\gtrsim 1$ yr) outbursts (the so-called ‘quasi-persistent’ sources - two of which, SAX1806 and AX1754 are presented in this work), and the accretion regimes may be different among the shorter duration transients. We require dedicated photometric and spectroscopic observing campaigns to fully determine the nature of accretion in VFXTs, but this remains difficult at such low optical/NIR fluxes, and we will likely require the next generation of large telescopes to achieve this goal for a large number of sources.

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REFERENCES

Altamirano D., Kaur R., Degenaar N., Wijnands R., Yang Y., Armas-Padilla M., Strohmayer T., Markwardt C., 2011, The Astronomer’s Telegram, 3193

Armstr Padilla M., Degenaar N., Wijnands R., 2013, MNRAS, 434, 1586

Arnason R. M., Sivakoff G. R., Heinke C. O., Cohn H. N., Lugger P. M., 2015, ApJ, 807, 52

Baglio M. C., D’Avanzo P., Campa S., Goldoni P., Masetti N., Muñoz-Darias T., Patiño-Álvarez V., Chavushyan V., 2016, A&A, 587, A102

Bassa C. et al., 2008, The Astronomer’s Telegram, 1575

Beccari G., De Marchi G., Panagia N., Pasquini L., 2014, MNRAS, 437, 2621

Bertin E., 2006, in Gabriel C., Arviset C., Ponz D., Enrique S., eds, Astronomical Society of the Pacific Conference Series Vol. 351, Astronomical Data Analysis Software and Systems XV. p. 112

Bertin E., Arnouts S., 1996, A&AS, 117, 393

Bertin E., Meller Y., Radovich M., Missonnier G., Didelon P., Morin B., 2002, in Bohlender D. A., Durand D., Handley T. H., eds, Astronomical Society of the Pacific Conference Series Vol. 281, Astronomical Data Analysis Software and Systems XI. p. 228

Bessell M. S., Brett J. M., 1988, PASP, 100, 1134

Burrows D. N., et al., 2005, Space Sci. Rev., 120, 165

Cadolle Bel M., Kuulkers E., Chenevez J., Beckmann V., Soldi S., 2008, The Astronomer’s Telegram, 1810

Campana S., 2009, ApJ, 699, 1144

Cardelli J. A., Clayton G. C., Mathis J. S., 1989, ApJ, 345, 245

Chakrabarty D., Jonker P. G., Markwardt C. B., 2010, The Astronomer’s Telegram, 2540

Chakrabarty D., Jonker P., Markwardt C. B., 2011, The Astronomer’s Telegram, 3218

Chełołøvko I. V., Grebenev S. A., 2007a, Astronomy Letters, 33, 807

Chełołøvko I. V., Grebenev S. A., 2007b, The Astronomer’s Telegram, 1094

Chenevez J., et al., 2010, The Astronomer’s Telegram, 2505

Chenevez J., et al., 2017, The Astronomer’s Telegram, No. 10195, 195
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Figure 9. Left: $K_s$-band NIRI image of AX1754. Right: $K$-band image of the same field, observed with UKIRT on 2006 July 23 as part of the UKIDSS. In both panels, the white circle represents the 0.45" error circle of the Chandra X-ray position of the source (Bassa et al. 2008).

Figure 10. Long-term Swift/XRT light curve of AX1754, the red arrow indicates the time of the Gemini/NIRI observation. Black, capped arrows represent 3σ upper limits on the XRT count rate.

Cooper R. L., Narayan R., 2007, ApJ, 661, 468
Coriat M., Fender R. P., Dubus G., 2012, MNRAS, 424, 1991
Cornelisse R., et al., 2002a, A&A, 392, 885
Cornelisse R., Verbunt F., in’t Zand J. J. M., Kuulkers E., Heise J., 2002b, A&A, 392, 931
Corral-Santana J. M., Casares J., Muñoz-Darias T., Rodríguez-Gil P., Shahbaz T., Torres M. A. P., Zurita C., Tyndall A. A., 2013, Science, 339, 1048
Cox A. N., 2000, Allen’s astrophysical quantities
D’Angelo C. R., Spruit H. C., 2012, MNRAS, 420, 416
De Marchi G., Fanagia N., Romaniello M., 2010, ApJ, 715, 1
Degenaar N., Wijnands R., 2009, A&A, 495, 547
Degenaar N., Wijnands R., 2010, A&A, 524, A69
Degenaar N., et al., 2010, MNRAS, 404, 1591
Degenaar N., Altamirano D., Padilla M. A., Kaur R., Wijnands R., Yang Y. J., 2011, The Astronomer’s Telegram, 3202
Degenaar N., et al., 2012, A&A, 540, A22
Del Santo M., Romano P., Sidoli L., 2009, The Astronomer’s Telegram, 1975

Del Santo M., Sidoli L., Romano P., Bazzano A., Wijnands R., Degenaar N., Mereghetti S., 2010, MNRAS, 403, L89
Del Santo M., et al., 2012, The Astronomer’s Telegram, 4017
Díaz Trigo M., Migliari S., Miller-Jones J. C. A., Rahoui F., Russell D. M., Tudor V., 2017, A&A, 600, A8
Drew J. E., et al., 2005, MNRAS, 362, 753
Evans P. A., et al., 2009, MNRAS, 397, 1177
Greiner J., Sala G., Kruehler T., 2008, The Astronomer’s Telegram, 1577
Güver T., Özel F., 2009, MNRAS, 400, 2050
Hameury J.-M., Lasota J.-P., 2016, A&A, 594, A87
Heinke C. O., Cohn H. N., Lugger P. M., 2009, ApJ, 692, 584
Heinke C. O., Bahramian A., Degenaar N., Wijnands R., 2015, MNRAS, 447, 3034
Hodapp K. W., et al., 2003, PASP, 115, 1388
In’t Zand J. J. M., Heise J., Muller J. M., Bazzano A., Cocchi M., Natalucci L., Ubertini P., 1999, Nuclear Physics B Proceedings Supplements, 69, 228
Jonker P. G., Keek L., 2008, The Astronomer’s Telegram, 1643
Kaur R., Wijnands R., Heise C., Degenaar N., 2012, The Astronomer’s Telegram, 3926
Kaur R., Wijnands R., Ramble A., Cackett E. M., Kutullu R., Kaplan D., Degenaar N., 2017, MNRAS, 464, 170
King A. R., Wijnands R., 2006, MNRAS, 366, L31
Krimm H. A., et al., 2013, ApJS, 209, 14
Kuulkers E., 1998, New Astron. Rev., 42, 1
Lasota J.-P., 2001, New Astron. Rev., 45, 449
Lucas P. W., et al., 2008, MNRAS, 391, 136
Maccarone T. J., Patruno A., 2013, MNRAS, 428, 1335
Maccarone T. J., et al., 2012, The Astronomer’s Telegram, 4109
Markwardt C. B., Krimm H. A., Swank J. H., 2008, The Astronomer’s Telegram, 1799
Mauerhan J. C., Muno M. P., Morris M. R., Bauer F. E., Nishiyama S., Nagata T., 2009, ApJ, 703, 30
Migliari S., et al., 2010, ApJ, 710, 117
Muno M. P., Pfahl E., Bagannof F. K., Brandt W. N., Ghez A., Lu J., Morris M. R., 2005a, ApJ, 622, L113
Muno M. P., Lu J. R., Bagannof F. K., Brandt W. N., Garmire G. P., Ghez A. M., Hornstein S. D., Morris M. R., 2005b, ApJ, 633, 228
Panagia N., Romaniello M., Scuderi S., Kirshner R. P., 2000, ApJ, 539, 197
Pfen F., Brown E. F., Truran J. W., 2007, ApJ, 654, 1022
Pfahl E., Rappaport S., Podsiadlowski P., 2002, ApJ, 571, L37

MNRA 000, 1–10 (2015)
Rahoui F., Coriat M., Lee J. C., 2014, MNRAS, 442, 1610
Revnivtsev M. G., Zolotukhin I. Y., Meshcheryakov A. V., 2012, MNRAS, 421, 2846
Robertson T. H., Jordan T. M., 1989, AJ, 98, 1354
Sakano M., Koyama K., Murakami H., Maeda Y., Yamauchi S., 2002, ApJS, 138, 19
Sengar R., Tauris T. M., Langer N., Istrate A. G., 2017, preprint, (arXiv:1704.08260)
Skrutskie M. F., et al., 2006, AJ, 131, 1163
Stetson P. B., 1987, PASP, 99, 191
Tody D., 1986, in Crawford D. L., ed., Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 627, Instrumentation in astronomy VI, p. 731
Torres M. A. P., Jonker P. G., Steeghs D., Chanae J., 2010, The Astronomer’s Telegram, 2526
Wijnands R., et al., 2006, A&A, 449, 1117
Zolotukhin I. Y., Revnivtsev M. G., 2015, MNRAS, 446, 2418
in’t Zand J. J. M., Cumming A., van der Sluys M. V., Verbunt F., Pols O. R., 2005, A&A, 441, 675
in’t Zand J. J. M., Jonker P. G., Markwardt C. B., 2007, A&A, 465, 953

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