Quiescent NIR and optical counterparts to candidate black hole X-ray binaries

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ABSTRACT

We present near-infrared and optical imaging of 15 candidate black hole X-ray binaries. In addition to quiescent observations for all sources, we also observed two of these sources (IGR J17451–3022 and XTE J1818–245) in outburst. We detect the quiescent counterpart for 12 out of 15 sources, and for the remaining 3, we report limiting magnitudes. The magnitudes of the detected counterparts range between $K_s = 17.59$ and $K_s = 22.29$ mag. We provide (limits on) the absolute magnitudes and finding charts of all sources. Of these 12 detections in quiescence, 7 detections represent the first quiescent reported values (for MAXI J1543–564, XTE J1726–476, IGR J17451–3022, XTE J1818–245, MAXI J1828–249, MAXI J1836–194, Swift J1910.2–0546), and 2 detections show fainter counterparts to XTE J1752–223 and XTE J2012+381 than previously reported. We used theoretical arguments and observed trends, for instance between the outburst and quiescent X-ray luminosity and orbital period $P_{\text{orb}}$ to derive an expected trend between $\Delta K_s$ and $P_{\text{orb}}$ of $\Delta K_s \propto \log P_{\text{orb}}^{0.565}$. Comparing this to observations, we find a different behaviour. We discuss possible explanations for this result.

Key words: stars: black holes – infrared: stars – X-rays: individual: XTE J1818 –245

1 INTRODUCTION

An X-ray binary (XRB) is defined as a system in which a neutron star (NS) or a black hole (BH) is accreting matter from its companion star. These systems can be classified according to the mass of the donor star, where we find high-mass X-ray binaries (HMXBs) and low-mass X-ray binaries (LMXBs). HMXBs are accreting mass through stellar winds or Roche lobe overflow from a massive star ($M \geq 10 M_\odot$) with typical spectral types of O and B for main-sequence stars. The donor companion for LMXBs is typically of K-M spectral type low-mass star and has $M \leq 1 M_\odot$, which transfers mass by Roche lobe overflow (Charles & Coe 2003). XRBs with spectral type A-F donor stars have also been identified, commonly referred to as intermediate-mass XRBs (IMXBs; Pfahl, Rappaport & Podsiedlowski 2003). These are thought to be the progenitors of some LMXBs (Podsiadlowski, Rappaport & Pfahl 2002).

Whether an XRB is a (semi) persistent source or shows outburst – quiescence cycles depends on the mass transfer rate and the orbital period $P_{\text{orb}}$ (King, Kolb & Burderi 1996). Persistent sources typically have X-ray luminosities from 1 to 100 per cent of the Eddington limit, causing the accretion disc to dominate the optical spectrum, hiding the companion star in most cases, except a few giant star mass donors (e.g. Jonker et al. 2005; Steeghs et al. 2013). On the other hand, X-ray transients (XRTs) are characterized by episodic outbursts caused by mass transfer instabilities in the accretion disc (Dubus, Hameury & Lasota 2001); between these outbursts, they decay back to the quiescent state ($L_X < 10^{33}$ erg s$^{-1}$; e.g. Garcia et al. 1998; Lasota 2000; Jonker 2008; Guillot et al. 2009; Plotkin, Gallo & Jonker 2013; Bernardini et al. 2016; Mata Sánchez et al. 2017), where the optical detection of the donor star is often, though not always (e.g. Torres et al. 2015), possible. This gives the opportunity to perform radial velocity measurements that allows us to study the orbital period evolution and to measure dynamically the
mass of the compact accretor (Casares & Jonker 2014). The latter is the best way to determine its nature since BH and NS systems display similar outburst properties such as hysteresis patterns in their hardness-intensity diagrams (Muñoz-Darias et al. 2014), though the X-ray timing properties do show differences between NS and BH accretors (see for instance the overview of Lewin & van der Klis 2010). It is also possible to use the radio properties as BHs are more radio-loud than NSs (Fender & Kuulkers 2001; Fender, Gallo & Jonker 2003).

XRTs are often first detected at X-ray wavelengths in outburst thanks to all-sky X-ray monitoring programmes, for instance through the RXTE satellite before 2012 (Bradt, Rothschild & Swank 1993), INTEGRAL (Kuulkers et al. 2007), Neil Gehrels Swift Observatory (Krimm et al. 2013), and MAXI (Matsuoka et al. 2009) missions. Until today, we have 19 dynamically confirmed Galactic stellar-mass BHs (Casares & Jonker 2014 and references therein, Mata Sánchez et al. 2015, Tetarenko et al. 2016b), where 18 of these are in L/IMXBs and one in an HMXB (Cyg X-1, Orosz et al. 2011b). There is a concentration towards the Galactic bulge and plane in the spatial distribution of these sources (i.e. $340° < l < 20°$ and $|b| < 10°$, e.g. Jonker & Nelemans 2004). Around 50 per cent of these, 19 sources are located within about 4.5 kpc from the Sun, which indicates that the dynamical mass measurements are challenging observationally due to the faintness of the mass donor stars, in part due to the sometimes high interstellar extinction towards sources located in the plane/bulge regions. Additionally, about 40 black hole X-ray binary (BHXB) candidates are known, which even though they do not have an estimate for their mass, present similar outburst properties to already classified BHXBs (see Belloni, Motta & Muñoz-Darias 2011 for a review). The number of BHXB candidates grows at an approximate rate of 2 objects per year (Corral-Santana et al. 2016).

As mentioned before, the quiescent state of XRTs is the ideal starting point to perform dynamical studies of these binary systems. The more dynamically confirmed black holes are known, the more information we have about the mass distribution of BHs in our Galaxy. This is important for understanding the physics of supernova explosions, the equation of state of nuclear matter (Casares, Jonker & Israeliian 2017) and the survival of interacting binaries, including those that might eventually merge and produce bursts of gravitational wave radiation (e.g. Abbott et al. 2016a,b). The mass distribution of BHs is expected to be smooth (Fryer & Kalogera 2001); however, observations have shown a gap between NSs and BHs in the range of $2–5 M_\odot$ ( Özel et al. 2010; Farr et al. 2011). The existence of the gap is still under debate. Some argue that the observed distribution may be biased by selection effects (i.e. Özel et al. 2010) and biases in the mass measurement procedure. For instance, Kreidberg et al. (2012) claim that there might be a systematic trend in the inclination angle determinations that lead to an underestimate of the inclination, and thus, an overestimate of the BH mass (see also van Gruzensen et al. 2017). Others state that the gap is real and could shed light on supernovae explosion models (i.e. Belczynski et al. 2012; Fryer et al. 2012). With Gaia (Gaia Collaboration et al. 2016), we will be able to obtain accurate distances and proper motions for several XRBs, necessary to determine BH natal kicks (e.g. van Paradis & White 1995; Jonker & Nelemans 2004; Miller-Jones et al. 2009; Reid et al. 2011, 2014; Repetto & Nelemans 2015; Mandel 2016) and hence, constrain the formation and evolution of BHXBs.

In this paper, we report the quiescent magnitudes, or upper limits, of the counterparts to 15 BHXB candidates in the near-infrared (NIR) and optical bands. For seven of them our measurements are the first reported to date. We provide also outburst magnitudes for two of these 15 sources (XTE J1818–245 and IGR J17451–3022); moreover, we detected for the first time the counterpart for IGR J17451–3022. We describe our sample in Section 2, the observations in Section 3 and the data reduction and analysis in Section 4. Our results are presented in Section 5 and discussed in Section 6, and we end with the conclusions of our work in Section 7. We report values taken from literature as found in the original work, i.e. if uncertainties were originally not given, we report the value without uncertainties (this includes points without error bars in our plots).

2 Sample

Our sample consists of 15 BHXB candidates (see Table 1 for discovery dates, coordinates, and distances). With the exception of MAXI J1957+032 and MAXI J1807+132, the sources can be found in either the BlackCAT (Corral-Santana et al. 2016) or WATCHDOG (Tetarenko et al. 2016a) catalogues for BHXB candidates. Both MAXI J1957+032 and MAXI J1807+132 are NS candidates (Ravi 2017; Shidatsu et al. 2017a) reported after we had observed them; however, their spectral features are also consistent with them being BH XRTs as no type I X-ray bursts or pulsation have been observed (Mata Sánchez et al. 2017; Muñoz-Darias et al. 2017; Shidatsu et al. 2017b). Thirteen sources are located at latitudes $|b| < 7°$, whereas MAXI J1957+032 is at $b \sim 13°$ and MAXI J1807+132 is at $b \sim 15°$. All 15 sources are observed during quiescence: 7 sources in the $K_s$ band (XTE J2012+381, XTE J1752–223, Swift J174510.8–262411, MAXI J1828–249, MAXI J1836–194, MAXI J1957+032, and XTE J1856+053), XTE J1726–476 in the $J$ and $K_s$ bands, MAXI J1543–564 in the $H$ and $K_s$ bands, MAXI J1807+132 in the $i$ band, Swift 1910.2–0546 in the $K_s$, $r$, $i$ bands and two sources (XTE J1650–500 and Swift J1539.2–6227) in the $g$, $r$, $i$, $z$, $J$, $H$, $K_s$ bands. XTE J1818–245 and IGR J17451–3022 are observed both in quiescence and in outburst, both in the $K_s$ band (see Table 2).

3 Observations

We obtained NIR and optical observations for this project using five different telescopes. To acquire $JHK_s$-band images, we used the William Herschel Telescope with the Long-slit Intermediate Resolution Infrared Spectrograph (WHT/LIRIS), the Keck I Telescope on Mauna Kea with the Multi-Object Spectrometer for Infra-Red Exploration (Keck/MOSFIRE, McLean et al. 2010, 2012), the Walter Baade Magellan Telescope with the Persson’s Auxiliary Nasmyth Infrared Camera (Magellan/PANIC, Martini et al. 2004), and the Very Large Telescope Unit 4 with the High Acuity Wide field $K$-band Imager (VLT/HAWK-I, Pirard et al. 2004). To obtain the optical ($r$, $i$, $z$, $J$, $H$, $K_s$) using the Gamma-Ray Burst Optical/Near-Infrared Detector (MP1/GROND, Greiner et al. 2008) at the MPI/ESO 2.2 m telescope at the ESO La Silla Observatory.

LIRIS has a pixel scale of 0.25 arcsec pixel$^{-1}$ and a field of view of $4.27$ arcsec $\times 4.27$ arcsec; MOSFIRE provides a pixel scale of 0.18 arcsec pixel$^{-1}$ and a field of view of $6.1$ arcmin $\times 6.1$ arcmin; and PANIC has a pixel scale of 0.125 arcsec pixel$^{-1}$ and a field of view of $2.0$ arcmin $\times 2.0$ arcmin. HAWK-I provides a pixel scale of 0.106 arcsec pixel$^{-1}$ and a field of view of $7.5$ arcmin $\times$
7.7 arcmin ACAM has a pixel scale of 0.25 arcsec pixel$^{-1}$ and a circular field of view with a diameter of 8.0 arcmin. GROND provides a pixel scale in the optical(NIR) channel of 0.158 arcsec circular field of view with a diameter of 8.0 arcmin and GROND done with 48 pointings of 10 s, dithered only for the J1818 observation with WHT/ACAM was done with 6 different pointings × 2 of 5.4 arcmin.

**References:**

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*The coordinates for the counterpart that we identified are RA = 17:45:06.65, Dec. = −30:22:43.67.*

## 4 DATA REDUCTION AND ANALYSIS

**4.1 Reduction**

For the images taken with GROND, the data reduction was done with the standard tools and methods described in Krühler et al. (2008). The PANIC data were processed with IRAF scripts implemented by Martin et al. (2004) for the reduction of data from that instrument. These procedures included dark and flat-field correction as well as sky subtraction. In the data reduction process, the raw frames were first dark subtracted. Master flat-fields were built by combining twilight flat-field frames scaled by the mode and these were applied to the target images. A sky image was made by masking out stars from each set of dithered target frames and was subtracted from the associated set of frames. Finally, a single target image was obtained by average combining the sky-subtracted images.

The LIRIS, ACAM, MOSFIRE, and HAWK-I data were reduced by median combining the observations without correcting for the offsets introduced by the dithering, which then is subtracted from the individual data frames. After this, THELI detects sources in the images using SExtractor (Bertin & Arnouts 1996) and obtains astrometric solutions with SCAMP (Bertin 2006). The astrometric

| BHXB | Discovery date | RA J2000 (dd:mm:ss) | Dec. J2000 (dd:mm:ss) | 3σ positional uncertainty (arcsec) | Galactic latitude $l$ (°) | Galactic longitude $b$ (°) | Distance (kpc) |
|------|----------------|---------------------|---------------------|-----------------------------------|--------------------------|---------------------------|-------------|
| Swift J1539.2−6227 | 2008 Nov 24$^{a}$ | 15:39:12.0 | −62:28:02.3 | 0.5$^{a}$ | 321.0 | −5.6 | − |
| MAXI J1543−564 | 2011 May 8$^{b,c}$ | 15:43:17.3 | −56:24:48.4 | 0.8$^{d}$ | 325.1 | −1.1 | − |
| XTE J1650−500 | 2001 Sep 5$^{e}$ | 16:50:01.0 | −49:57:43.6 | 0.6$^{f}$ | 336.7 | −3.4 | 2.6 ± 0.7$^{ad}$ |
| XTE J1726−476 | 2005 Oct 4$^{d}$ | 17:26:49.3 | −47:38:24.9 | 1.1$^{g}$ | 342.2 | −6.9 | − |
| IGR J17451−3022 | 2014 Aug 22$^{d}$ | 17:45:06.7 | −30:22:43.3 | 0.8$^{a}$ | 358.7 | −0.6 | − |
| Swift J174510.8−262411 | 2012 Sep 16$^{e}$ | 17:45:10.8 | −26:24:12.7 | 1.7$^{e}$ | 2.1 | 1.4 | $<0.01$ |
| XTE J1752−223 | 2009 Oct 23$^{f}$ | 17:52:15.0 | 09:51:35.9 | 0.0008$^{g}$ | 1.6431 | 2.1413 | 6 ± 2$^{df}$ |
| MAXI J1807+1332 | 2013 Mar 15$^{b}$ | 18:08:07.6 | +13:15:04.6 | 2.3$^{e}$ | 40.1 | 15.5 | − |
| XTE J1818−245 | 2005 Aug 12$^{e}$ | 18:18:24.4 | −24:32:18.0 | 1.3$^{e}$ | 1.7 | −4.2 | − |
| MAXI J1828−249 | 2013 Oct 15$^{b}$ | 18:28:58.1 | −25:01:45.9 | 4.0$^{b}$ | 8.1 | −6.5 | − |
| MAXI J1836−194 | 2011 Aug 29$^{f}$ | 18:35:43.4 | −19:19:10.5 | 0.2$^{g}$ | 13.9 | −5.3 | 7 ± 3$^{df}$ |
| XTE J1855+053 | 1996 Sep 17$^{f}$ | 18:55:42.9 | +05:18:34.3 | 0.3$^{a}$ | 38.2 | 1.2 | − |
| Swift J1910−0546 | 2012 May 31$^{m}$ | 19:10:22.8 | −05:47:56.4 | 1.3$^{a}$ | 29.9 | −6.8 | − |
| MAXI J1957+032 | 2015 May 11$^{l}$ | 19:57:39.1 | +03:26:04.7 | 0.9$^{ab}$ | 43.6 | −12.8 | ~6$^{ab}$ |
| XTE J2012+381 | 1998 May 24$^{a}$ | 20:12:37.7 | +38:11:01.2 | 1.2$^{a}$ | 75.4 | 2.2 | − |

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- Russell et al. (2014),
- Mata Sánchez et al. (2017).

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2 ESO programme 099.A-9025(A), PI: A. Rau.


Table 2. Observing log of the BHXB candidates discussed in this paper. All of the sources are observed in quiescence. An (+) marks sources also observed in outburst.

| BHXB candidate | Instrument | Date observed | On source time (s) | 1σ WCS uncertainty (mas) | Photometric zero-point (mag) | Limiting magnitude (mag) | Filter | Average seeing (arcsec) |
|----------------|------------|---------------|--------------------|--------------------------|-----------------------------|--------------------------|--------|-------------------------|
| Swift J1539.2−6227 | GROND | 2017 Sep 15 | 372 ± 20 | 25.61 ± 0.06 | <19.6 | g | 2.2 |
| MAXI J1543−564 | HAWK-I | 2018 Apr 10 | 480 ± 15 | 24.32 ± 0.05 | <18.9 | i | 1.8 |
| XTE J1650−500 | GROND | 2017 Sep 14 | 420 ± 20 | 27.31 ± 0.16 | <23.2 | H | 0.5 |
| XTE J1726−476 | PANIC | 2006 Aug 3 | 900 ± 10 | 25.03 ± 0.24 | <20.7 | J | 0.7 |
| IGR J17451−3022 | LIRIS | 2015 Apr 9* | 375 ± 20 | 25.38 ± 0.26 | <17.9 | K_s | 0.6 |
| Swift J174510.8−26241 | LIRIS | 2017 Apr 13 | 450 ± 10 | 24.41 ± 0.08 | <17.7 | K_s | 0.8 |
| XTE J1752−223 | LIRIS | 2017 Apr 13 | 1600 ± 10 | 24.80 ± 0.05 | <19.0 | K_s | 0.9 |
| MAXI J1807+132 | ACAM | 2017 Jul 11 | 1800 ± 20 | 25.88 ± 0.05 | <24.4 | i | 1.3 |
| XTE J1818−245 | PANIC | 2005 Sep 12* | 450 ± 20 | 25.39 ± 0.01 | <19.3 | K_s | 0.5 |
| Swift J1910.2−0546 | ACAM | 2015 Jul 19 | 600 ± 10 | 26.25 ± 0.01 | <22.4 | i | 1.1 |
| MAXI J1957+032 | MOSFIRE | 2017 Jun 15 | 436 ± 10 | 27.51 ± 0.29 | <22.2 | K_s | 1.1 |
| XTE J2012+381 | MOSFIRE | 2017 Apr 13 | 291 ± 20 | 27.63 ± 0.13 | <23.3 | K_s | 0.9 |

Note. *Observation in outburst. †Uncertainty with respect to the reference catalog. The first value is a statistical uncertainty, given by the STARLINK GAIA tool, while the second value is a systematic uncertainty, and corresponds to the astrometric accuracy of the reference catalog (20 mas for UCAC4 and 15 mas for 2MASS). ‡Photometric zero-point derived from the data with respect to the 2MASS catalogue, or VVV when possible, (for all the NIR sources), and the Pan-STARRS 1 catalogue (for the optical sources). §Limiting magnitude close to the position of the BHXB.

4.2 Astrometry

To improve the accuracy of the global astrometric solution of the coadded images, we used the STARLINK tool GAIA, fitting at least five star positions from the 2 Micron All Sky Survey (2MASS; Skrutskie et al. 2006) or from the fourth US Naval Observatory CCD Astrograph Catalog (UCAC4; Zacharias et al. 2013) in order to build a local astrometric solution around the position of the sources. The rms errors of these fits are indicated in Table 2 as WCS (World Coordinate System) uncertainties, where the intrinsic systematic error of the catalogue with respect to the International Celestial Reference System (ICRS) is also listed (15 mas for 2MASS and 20 mas for UCAC4).

4.3 Photometry

For seven sources (Swift J1910.2−0546, XTE J1726−476, MAXI J1807+132, XTE J1752−223, MAXI J1543−564, Swift J1539.2−6227, and XTE J1650−500), we used SEXTRACTOR for the source detection and photometry, making sure that each detection was more than 3σ above the local background. We performed aperture photometry to determine instrumental magnitudes. We determined the full width at half-maximum of point-like objects in each image with the STARLINK tool GAIA and we used it as the aperture size. We performed point spread function (PSF) photometry for the eight remaining images using the DAOPHOT package in IRAF to determine the photometric zero-point with respect to the reference catalog. The first value is a statistical uncertainty, given by the STARLINK GAIA tool, while the second value is a systematic uncertainty, and corresponds to the astrometric accuracy of the reference catalog (20 mas for UCAC4 and 15 mas for 2MASS). Photometric zero-point derived from the data with respect to the 2MASS catalogue, or VVV when possible, (for all the NIR sources), and the Pan-STARRS 1 catalogue (for the optical sources). Limiting magnitude close to the position of the BHXB.

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5 RESULTS

5.1 Sources observed in outburst

5.1.1 IGR J17451−3022

This source was discovered by INTEGRAL/JEM-X on 2014 August 22 (Chenevez et al. 2014). Suzaku observations done in 2014 September revealed eclipses in the light curve of IGR J17451−3022 (Jaisawal et al. 2015), from which they estimated a $P_{\text{orb}}$ of $\sim 6.3$ h. We performed an NIR observation of IGR J17451−3022 during its outburst and detected two sources (labelled A and B in Fig. 1a) in the 99.7% per cent confidence radius around the X-ray position. The source returned to quiescence in 2015 May (Bahramian et al. 2015). We observed it for a second time using the same telescope and instrument and filter on 2016 March 28 and detected again the same two sources (see Fig. 1b) in the 99.7% per cent confidence radius around the X-ray position. The source returned to quiescence in 2015 May (Bahramian et al. 2015).

5.2 Sources observed in quiescence

5.2.1 Swift J1539.2−6227

Swift J1539.2−6227 was discovered on 2008 November 24 by Swift/BAT (Krimm et al. 2008). UV/optical observations made a month later revealed a counterpart with magnitudes of $u^m v = 18.07 \pm 0.03$ and $uvw2 = 17.96 \pm 0.04$ (Krimm et al. 2009), which continued until at least until 2009 March (Torres et al. 2009a). The optical spectrum of the counterpart revealed no Balmer lines, nor evidence for HeII 4686 Å or Bowen blend emission (Torres et al. 2009a). We observed this source with GROND and did not detect the counterpart down to limiting magnitudes of $g > 16.0$, $r > 16.1$, $i > 17.0$, $z > 17.9$, $J > 18.9$, $H > 16.8$, and $K_s > 17.6$ (see Table 3).

5.2.2 MAXI J1543−564

Negoro et al. (2011a) discovered this source on 2011 May 8. UV/optical observations with Swift revealed no counterpart to this source down to limiting magnitudes of $V > 19.47$ and $U > 20.85$ (Kennea et al. 2011a), which is consistent with the large absorption column towards this source. Russell et al. (2011) detected a possible counterpart with a magnitude of $i = 19.5$. Two days after the outburst was reported, Rau et al. (2011b) detected the same optical counterpart (called source A) with GROND, and reported outburst magnitudes of $g > 22.8$, $r > 20.7$, $i > 19.4 \pm 0.1$, $z > 18.7 \pm 0.1$, $J > 17.1 \pm 0.2$, $H = 16.8 \pm 0.2$, and $K_s = 17.0 \pm 0.2$. Additionally, Rau et al. (2011b) reported the detection of two other
Figure 1. Finder charts of the two XRBs for which the outburst counterpart has not been identified until now, so we have to rely on their Chandra X-ray localisation for the identification of the counterpart in quiescence. **Upper panel:** LIRIS \(K_s\)-band image of IGR J17451\(-30\) in (a) outburst and (b) quiescence. As no counterparts were reported previously for IGR J17451\(-30\), we analysed the two sources (labelled A and B) inside the 99.7 per cent confidence region around the Chandra X-ray position (Chakrabarty et al. 2014), and using differential photometry, determined that the likely counterpart is source B as that source is fainter in quiescence than in outburst. **Bottom panel:** HAWK-I \(K_s\)-band image of MAXI J1543-564, where we indicate the sources identified by Rau et al. (2011b) and label them in the same way as they did, with the difference that they identified one source B, whereas we detect two sources in this position (B1 and B2). These two sources are consistent with the position of the likely counterpart, according to a Chandra localization of the X-ray source (Chakrabarty, Jonker & Markwardt 2011).

Sources, called sources B and C, with magnitudes \(z' \sim 20.7\) and \(z' \sim 20.5\), respectively. No measurements in the \(JHK_s\) bands are reported, as they are strongly affected by the blending of sources A, B, and C. A Chandra localization of MAXI J1543-564 (Chakrabarty et al. 2011) showed that the optical source detected by Russell et al. (2011) and Rau et al. (2011b) was not likely the counterpart but instead, the source identified as source B by Rau et al. (2011b) is a better candidate counterpart. We observe this source with HAWK-I and detect two sources inside the 3\(\sigma\) confidence radius around the position of source B from Rau et al. (2011b) in both \(H\) and \(K_s\) bands (see Fig. 1c). We label the sources B1 and B2 and estimate magnitudes of \(H = 20.5 \pm 0.2\) and \(K_s = 20.68 \pm 0.16\) for B1 and \(H = 21.7 \pm 0.2\) and \(K_s = 21.8 \pm 0.2\) for B2. Further observations are required in order to determine which one is the true counterpart (if any).

5.2.3 XTE J1650\(-500\)

This XRT was discovered on 2001 September 5 by RXTE and optical observations revealed a counterpart with \(V = 17\) (Castro-Tirado et al. 2001). A month later, with observations from ESO NTT, NIR/optical magnitudes were derived (Curran, Chatty & Zurita...
5.2.5 Swift J174510.8

et al. 2012) and was observed with GROND 1 d after (Rau et al. 2012b), where they found a candidate counterpart with an apparent magnitude of $i \sim 17.59 \pm 0.07$. We observed this source 5 yr after its outburst and detect the counterpart in the NIR (see Fig. A1b) with a magnitude of $K_s = 18.63\pm0.15$ (see Table 3) with a position consistent with that reported in Rau et al. (2012b). Muñoz-Darias et al. (2013) estimated a distance of $d > 7$ kpc (see Table 1) and with $N_H = 1.70\pm0.04\times10^{22}$ cm$^{-2}$ (Tomskick, DelSanto & Belloni 2012), we get an extinction of $A_K = 0.918$, which we use to estimate a limiting absolute magnitude of $M_K > 3.4$. This would make the donor star a KOV star or later (Tokunaga 2000; Drilling & Landolt 2000), consistent with the hydrogen emission lines detected by de Ugarte Postigo et al. (2012).

5.2.6 XTE J1752−223

This source was discovered on 2009 October 23 (Markwardt et al. 2009) and later confirmed to be a strong accreting BH candidate (Nakahira et al. 2010; Muñoz-Darias et al. 2010; Shaposhnikov et al. 2010; Curran et al. 2011). An optical counterpart was identified by Torres et al. (2009b), later confirmed by optical spectra and an NIR detection (Torres et al. 2009c) with a magnitude of $K_s = 15.83\pm0.01$. Approximately 9 months after the outburst, Russell et al. (2010) reported optical and NIR quiescent magnitudes for the counterpart of $V = 21.2\pm0.3$ and $K_s = 17.1\pm0.1$, respectively. However, Ratti et al. (2012) showed that the source had not yet reached the quiescent state at the point in time related to the observations of Russell et al. (2010), as they did not detect the source 10 months later down to a limiting magnitude of $i > 24.77$, making the difference between the source brightness in outburst and in quiescence at least 8 mag. We obtained NIR observations of this source 6 yr after its outburst and did not detect any source at the position of the outburst counterpart, down to a limiting magnitude of $K_s > 19.6$. This is 2.5 mag fainter than reported before by Russell et al. (2010). With a distance of $d = 6\pm2$ kpc, derived by Ratti et al. (2012) (see Table 1), and using $N_H = 4.5\times10^{21}$ cm$^{-2}$ (Dickey & Lockman 1990), we get an extinction of $A_K = 0.243$, which results in a limiting absolute magnitude of $M_K > 5.3$, which means that the donor star is a main-sequence star with spectral type M0 or later (Drilling & Landolt 2000; Tokunaga 2000). This is consistent with the constraints on the spectral type given in Ratti et al. (2012) and with the hydrogen emission lines found in the spectra by Torres et al. (2009c).

5.2.7 MAXI J1807 +132

MAXI J1807+132 was discovered on 2017 March 13 by MAXI/GSC (Negoro et al. 2017). A UV/optical counterpart was detected soon after by Kennea et al. (2017b) and Denisenko (2017), who reported magnitudes of $B = 18.3\pm0.2$ and $V = 17.82$, respectively. Furthermore, Denisenko (2017) reported the quiescent magnitude of this optical counterpart as $r = 21.19\pm0.09$ and $i = 21.38\pm0.04$ from PanSTARRS-1 archival images. Spectroscopy taken with GTC/OSIRIS revealed spectral features consistent with that of an LMXB (Muñoz-Darias et al. 2017; Shibatsu et al. 2017b). Tachihana et al. (2017) detected in the optical a decay in magnitude of $−0.4$ mag d$^{-1}$, which coincided with a decay in the X-ray magnitude of $i \sim 17.8$ and $J \sim 16.5\pm0.5$, which was then spectroscopically confirmed by de Ugarte Postigo et al. (2012). Subsequent optical observations were performed by Hynes et al. (2012) and Russell et al. (2012); the former did not detect the counterpart, whereas the latter detected the source previously identified by Rau et al. (2012b), this time with a magnitude of $i = 17.59\pm0.07$. We observed this source 5 yr after its outburst and detect the counterpart in the NIR (see Fig. A1b) with a magnitude of $K_s = 18.63\pm0.15$ (see Table 3) with a position consistent with that reported in Rau et al. (2012b). Muñoz-Darias et al. (2013) estimated a distance of $d > 7$ kpc (see Table 1) and with $N_H = 1.70\pm0.04\times10^{22}$ cm$^{-2}$ (Tomskick, DelSanto & Belloni 2012), we get an extinction of $A_K = 0.918$, which we use to estimate a limiting absolute magnitude of $M_K > 3.4$. This would make the donor star a KOV star or later (Tokunaga 2000; Drilling & Landolt 2000), consistent with the hydrogen emission lines detected by de Ugarte Postigo et al. (2012).

Figure 2. Magnitude difference of 18 stars inside a radius of $\sim 40$ arcsec around the Chandra X-ray position of IGR J17451−3022, between its outburst and quiescence images. The blue line indicates the average of all the differences and the pink line indicates the standard deviation of the distribution. Note how source B (red symbol) is clearly an outlier.

Heras 2012): $V = 17.1 \pm 0.2$, $R = 16.9 \pm 0.4$, $I = 16.14 \pm 0.13$, $J = 15.33 \pm 0.11$, $H = 15.18 \pm 0.11$, and $K_s = 15.14 \pm 0.13$ mag. It was observed $\sim 10$ months later (2002 August 10) in the optical with the Magellanic telescope, and the counterpart was detected in quiescence, with magnitudes of $R \sim 22$ and $V \sim 24$ (Garcia & Wilkes 2002). We observed this source with GROND and did not detect the counterpart down to limiting magnitudes of $R > 20.5$, $i > 19.4$, $z > 18.5$, $J > 18.4$, $H > 16.8$, and $K_s > 17.8$ (see Table 3), resulting in an outburst amplitude of $> 2$ mag in the $JHK_s$ bands. With a distance of $d = 2.6 \pm 0.7$ kpc given by Homan et al. (2006) and $N_H = 0.5 \pm 0.1 \times 10^{22}$ cm$^{-2}$ (Mininni, Fabian & Miller 2004), we calculate an extinction of $A_K = 0.270$, which gives a limiting absolute magnitude of $M_K > 5.4$, making the donor star an M0V spectral type or later.

5.2.4 XTE J1726−476

XTE J1726−476 was discovered with RXTE by Levine, Lin & Remillard (2005b) on 2005 October 4. Optical $I$-band observations revealed a counterpart with $I = 17.42 \pm 0.11$ mag days after the outburst start (Maitra et al. 2005). Additionally, Steeghs et al. (2005b) observed XTE J1726−476 in the NIR and detected the counterpart with $K_s = 18.05$. We observed this source in quiescence in both $J$ and $K_s$ bands (see Table 3). Our observation in the $K_s$ band yielded a non-detection down to a limiting magnitude of $K_s > 17.9$, whereas in the $J$ band we just detect a faint candidate counterpart with $J = 21.0 \pm 0.3$ (see Fig. A1a).

5.2.5 Swift J174510.8−262411

This XRT went into outburst on 2012 September 16 (Cummings et al. 2012) and was observed with GROND 1 d after (Rau et al. 2012b), where they found a candidate counterpart with an apparent
Table 3. Outburst and quiescent magnitudes.

| BHXB candidate | Time after discovery | Outburst | Reference | Time after discovery | Quiescent |
|----------------|----------------------|----------|-----------|----------------------|-----------|
| Swift J1539.2−6227 | 1 month | \( uuw2 = 18.07 \pm 0.03 \) | Krimm et al. (2009) | 10.8 yr | \( g' > 19.6 \) |
| MAXI J1543−564 | 12 d | \( \dot{z} \sim 20.7 \) | Rau et al. (2011b) | 7 yr | \( H = 20.5 \pm 0.2 \) |
| XTE J1650−500 | 1 month | \( V = 17.1 \pm 0.2 \) | Curran et al. (2012) | 16 yr | \( g > 20.3 \) |
| XTE J1726−476 | 6 d | \( I = 17.42 \pm 0.11 \) | Maitra et al. (2005) | 10 months | \( J = 21.0 \pm 0.3 \) |
| IGR J17451−3022 | 8 months | \( K_s = 18.85 \pm 0.01 \) | Steeghs et al. (2005b) | 10 months | \( K_s > 17.9 \) |
| Swift J174510.8−262411 | 1 d | \( \dot{J} - 16.5 \pm 0.5 \) | Rau et al. (2012b) | 4.5 yr | \( K_s = 18.5 \pm 1.0 \) |
| XTE J1752−223 | 3 d | \( K_s = 15.00 \pm 0.01 \) | Kennea et al. (2017b) | 6.5 yr | \( K_s = 19.6 \) |
| MAXI J1807+132 | 14 d | \( B = 18.3 \pm 0.2 \) | Kennea et al. (2017b) | 8 months | \( K_s = 19.9 \pm 0.2 \) |
| XTE J1818−245 | 1 month | \( K_s = 16.18 \pm 0.02 \) | Kennea et al. (2017b) | 3.6 yr | \( K_s = 20.4 \pm 0.09 \) |
| MAXI J1828−249 | 3 d | \( K_s = 17.2 \pm 0.0 \) | Rau et al. (2012a) | 6 yr | \( K_s = 20.9 \pm 0.3 \) |
| MAXI J1836−194 | 1 d | \( K_s = 14.00 \pm 0.07 \) | Rau, Greiner & Sudilovsky (2011c) | 10 months | \( K_s = 16.1 \pm 0.3 \) |
| XTE J1856+053 | 17 d\(^a\) | \( K_s = 18.28 \pm 0.05 \) | Torres et al. (2007) | 10 yr\(^a\) | \( K_s = 20.9 \pm 0.2 \) |
| Swift J1910.2−0546 | 1 d | \( i' = 15.7 \pm 0.1 \) | Rau et al. (2012a) | 3 yr | \( i' = 23.4 \pm 0.07 \) |
| MAXI J1957+032 | 4 d | \( J = 19.75 \pm 0.14 \) | Rau et al. (2015) | 2 yr | \( K_s = 22.9 \pm 0.15 \) |
| XTE J2012+381 | 8 d | \( K = 16.2 \pm 0.1 \) | Callanan et al. (1998) | 9 yr | \( K_s = 20.8 \pm 0.22 \) |

Note. \(^a\)Time after the second outburst was detected. All the values in quiescence are calculated in this paper, with the exception of the magnitude for MAXI J1807+132, which is from the PanSTARRS 1 catalogue. The magnitudes are in the AB system, unless indicated otherwise (conversion between the Vega and AB systems was done following Blanton & Roweis 2007, i.e. \( J_{AB} = J_{VEGA} + 0.91 \), \( H_{AB} = H_{VEGA} + 1.39 \), \( K_{AB} = K_{VEGA} + 1.85 \)).

(Armas Padilla et al. 2017). Furthermore, after the X-ray fading phase of MAXI J1807+132, the optical counterpart varied its magnitude from \( r = 20.76 \pm 0.07 \) to \( r = 19.34 \pm 0.02 \) in a 5-d interval (Kong et al. 2017). We observed this X-ray source in the J band (see Fig. A1c) 4 months after its outburst started, and detected the optical counterpart reported by Kennea et al. (2017b) with an magnitude of \( i' = 20.26 \pm 0.05 \). This is 2.3 mag brighter than the archival magnitude from PanSTARRS-1, which implies that the source had not fully returned to quiescence yet at the time of our observations.

5.2.8 MAXI J1828−249

Nakahira et al. (2013) discovered MAXI J1828−249 in a soft state on 2013 October 15. An uncatalogued UV point source was detected with Swift as a possible counterpart, with a magnitude of

\[
uvw2 = 18.64 \pm 0.04 \pm 0.03
\]

(with 0.04 and 0.03 being statistical and systematic uncertainties, respectively, Kennea et al. 2013). Follow-up observations by Rau, Tanga & Greiner (2013) detected a counterpart at \( H = 16.9 \pm 0.1 \) and \( K_s = 17.2 \pm 0.2 \). A month later, another NIR observation (D’Avanzo et al. 2013) revealed fading of this counterpart, with a magnitude of \( H = 18.7 \pm 0.1 \), which implies that this source is the counterpart. We detect this source in our NIR observations with \( K_s = 20.8 \pm 0.09 \) (see Table 3), 3.6 mag fainter than in outburst (see Fig. A1d).

5.2.9 MAXI J1836−194

MAXI J1836-194 was first detected on 2011 August 29 by MAXI/GSC and Swift/BAT, as a hard X-ray transient (Negoro et al. 2011b). Swift observations revealed an optical counterpart with a magnitude of \( V = 16.22 \pm 0.04 \) (Kennea et al. 2011b). GROND observations detected the optical counterpart with magnitudes of

\[
g = 16.21 \pm 0.05, \ r' = 15.92 \pm 0.05, \ i' = 15.53 \pm 0.01, \ z' = 15.09 \pm 0.05, \ J = 14.77 \pm 0.05, \ H = 14.34 \pm 0.05, \ \text{and} \ K_s = 14.00 \pm 0.07 \text{ mag} \ (\text{Rau et al. 2011c}).
\]

This XRB has a face-on accretion disc with an inclination between 4° and 15°, and a lower
limit on the compact object mass of 1.9 $M_\odot$ (Russell et al. 2014). Six years after the first discovery outburst, we just detect the NIR counterpart at the position given by Kennea et al. (2011b), with a magnitude of $K_s = 20.9 \pm 0.3$ (see Fig. A1e). This source has an estimated distance of $d = 7 \pm 3$ kpc (Russell et al. 2014, see Table 1) and an $N_H = 2.0 \pm 0.4 \times 10^{21}$ cm$^{-2}$ (Kennea et al. 2011b), which results in an extinction of $A_{K} = 0.108$ and an absolute magnitude of $M_K > 6.5$. This would make the donor star a M2 main-sequence star or later (Drilling & Landolt 2000; Tokunaga 2000).

5.2.10 XTE J1856+053

This BHXB candidate was discovered on 1996 September 17 (Marshall et al. 1996), with a new outburst observed 9 yr later on 2007 February 28 (Levine & Remillard 2007). It seems that the source was already in outburst around 2007 February 22 (Krimm et al. 2007). Days after the 2007 outburst detection, NIR observations were performed and yielded a counterpart with an apparent magnitude of $K_s = 18.28 \pm 0.05$ (Torres et al. 2007) that had faded 2 months after the outburst to $K_s = 19.7 \pm 0.1$. In 2015, a new outburst from XTE J1856+053 was detected by MAXI/GSC (Suzuki et al. 2015; Negoro et al. 2015b) and Swift/XRT (Sanna et al. 2015). Two years later, we observed this source in the NIR (see Fig. A1f). We detect the same counterpart reported by Torres et al. (2007), this time with a magnitude of $K_s = 20.09 \pm 0.26$, which is consistent at the $1 \sigma$ level with the quiescent value reported in 2007 (see Table 4).

5.2.11 Swift J1910.2−0546

An outburst from Swift 1910.2−0546 was discovered on 2012 May 31 (Usui et al. 2012). Optical/NIR observations made 1 d after by Rau et al. (2012a) revealed a counterpart with $g = 16.1 \pm 0.1$, $r = 15.7 \pm 0.1$, $i = 15.6 \pm 0.1$, $z = 15.3 \pm 0.1$, $J = 15.5 \pm 0.1$, $H = 15.5 \pm 0.1$, and $K_s = 15.6 \pm 0.1$ mag. That same day, Cenko & Ofek (2012) also detected this counterpart at $R = 16.11$. The optical spectra reported by Charles, Cornelisse & Casares (2012) are typical of an LMXB. In our $K_s$-band observations (see Fig. A1g), we detect the quiescent counterpart with an apparent magnitude of $K_s = 20.43 \pm 0.11$, while in our optical observations, the counterpart detected with an apparent magnitude of $r' = 23.46 \pm 0.07$ and $i' = 22.18 \pm 0.04$.

5.2.12 MAXI J1957+032

Discovered on 2015 May 11 (Cherepashchuk et al. 2015; Negoro et al. 2015a), MAXI J1957+032 was classified as an LMXB (Munoz-Darias et al. 2017). Subsequent optical and NIR observations revealed a candidate counterpart with magnitudes $r = 20.03 \pm 0.14$ and $J = 19.75 \pm 0.14$ (Rau et al. 2015). In the $K_s$ band there was no detection, down to a limiting magnitude of $K_s > 19.0$. A day later the source had faded to $r' = 21.36 \pm 0.14$, and since this quick decay was similar to the one observed in X-rays (Molkov et al. 2015), it is most likely that the NIR source is the counterpart. This source seemed to have brightened approximately 1 mag when observed in the optical some months later (Guver et al. 2015), coinciding with a new outburst from MAXI J1957+032 (Sugimoto et al. 2015). Optical spectra were taken (Buckley et al. 2016), which turned out to be featureless. This is consistent with a high-inclination compact system, where the optical spectra have almost undetectable emission lines (Baglio et al. 2016). MAXI J1957+032 shows short duration outbursts (<5 d) and it has a high recurrence rate (4 in 16 months). Mata Sánchez et al. (2017) found not only that the optical spectra is consistent with MAXI J1957+032 being a short-period LMXB but also that the short duration and short recurrence time of the outburst are reminiscent of an accreting millisecond X-ray pulsar. We detect an NIR source (see Fig. A1h), at the position indicated by Rau et al. (2015), with $K_s = 22.29 \pm 0.15$ mag. Using the distance estimate of $d \sim 6$ kpc and the column density $N_H = 1.7 \times 10^{21}$ cm$^{-2}$ from Mata Sánchez et al. (2017) (see Table 1), we get an extinction of $A_{K_s} = 0.091$, and thus, an absolute magnitude of $M_K > 8.3$, making it consistent with an M6 main-sequence star or later (Tokunaga 2000; Drilling & Landolt 2000).

5.2.13 XTE J2012+381

This source went into outburst on 1998 May 24 (Remillard et al. 1998). A radio source was identified as a possible counterpart
which Shahbaz & Kuulkers (1998) (see Table A1). Since many of the amplitudes smaller. As already mentioned in Miller-Jones et al. (2011b) P luminous than a system with shorter orb, the secondary star is larger and hence, more luminous than a system with shorter orb, making the outburst amplitude smaller. As already mentioned in Miller-Jones et al. (2011b) and Revnivtsev, Zolotukhin & Meshcheryakov (2012), the inclination i is an important parameter as well. We searched the literature and found i for 6 of these 8 sources (see Table A1) and plot \( \Delta V \) versus i and \( P_{\text{orb}} \) in Fig. 4(a). We also include other sources for which \( \Delta V \), i, and \( P_{\text{orb}} \) have become available since the work of Shahbaz & Kuulkers (1998) (see Table A1). Since many of the sources analysed are known to have had multiple outbursts (e.g. XTE J1550-564, GX 339-4, GS 2023+338), we take the brightest outburst magnitude and the faintest quiescent magnitude reported. The latter is because there are sources like A 0620-00 whose mean brightness varies even while in quiescence (‘active’ and ‘passive’ states; Cantrell et al. 2008). However, note that the outburst amplitudes are probably lower limits, to account for the fact that one may have missed the peak magnitude in the sparsely sampled outbursts and that there could be a brightness variation in quiescence.

For 10 of the 15 sources that we observed we have outburst and quiescent magnitudes in the \( K_s \) band (see Table 3), allowing us to derive a lower limit on the outburst amplitude \( \Delta K_s \). As with the optical data, we complement our data with that available in the literature. We plot \( \Delta K_s \) versus i and \( P_{\text{orb}} \) and show the results in Fig. 4(b). We performed a 3D least squares plane fit (see Fig. A2) for both data sets and obtained

\[
\Delta V = (-2.63 \pm 1.01) \log P_{\text{orb}} + (0.03 \pm 0.03)i + (7.82 \pm 1.94)
\]

with \( \chi^2 = 16.73 \) and residuals plotted in Fig. A2(c), and

\[
\Delta K_s = (-1.32 \pm 0.99) \log P_{\text{orb}} - (0.04 \pm 0.03)i + (6.89 \pm 2.16)
\]

(1)To calculate \( \chi^2 \) we assigned to the data points without reported uncertainties, the mean uncertainty of \( P_{\text{orb}}, i, \Delta V, \) or \( \Delta K_s \) within their respective data sets.
predicted correlation between $\Delta V$ and $P_{\text{orb}}$ may suffer from low number statistics themselves implying that the distribution between 0 and 17.5 per cent and 30.5 per cent (based on selecting 1000 different samples of 8 elements from a simulation of 100 systems with a flat distribution between 0 and 17.5 per cent and 30.5 per cent) was probably caused by small number statistics.

In order to try and assess the influence that the low number of sources involved in the work of Shahbaz & Kuulkers (1998) (and also to a lesser extent in the work presented here), we determine the probability of randomly selecting 8 systems and finding a correlation between $\Delta V$ and $P_{\text{orb}}$. We find that it ranges between 17.5 per cent and 30.5 per cent (based on selecting 1000 different samples of 8 elements from a simulation of 100 systems with a flat distribution between 0 and $P_{\text{orb}} < 12$ and $0 < \Delta V < 10$). We conclude that the correlation reported by Shahbaz & Kuulkers (1998) was probably caused by small number statistics.

We do note that some of the observational correlations used above to determine the expected relation between $P_{\text{orb}}$, $i$, and $\Delta V$ ($\Delta K_i$) may suffer from low number statistics themselves implying that the predicted correlation between $\Delta V$ and $P_{\text{orb}}$ itself is uncertain.

7 CONCLUSIONS

We observed 15 BHXB candidates in quiescence in the NIR and optical in order to investigate which of these sources would be promising targets for BH mass determinations. We detected 2 with $K_i < 20$ (AB magnitude) out of our sample, which depending on their $P_{\text{orb}}$, may allow for time-resolved spectroscopic observations to be taken with 8–10 m class telescopes. Such measurements for fainter systems will have to await the arrival of larger or space-based telescopes. Of our 15 observed sources, XTE J1818-245 and IGR J17451-3022 were observed in quiescence and in outburst, while the other 13 were observed only in quiescence. XTE J1818-245 presents an outburst–quiescence magnitude difference of about $\sim 4$ mag in the $K_s$ band. IGR J17451-3022 was analysed with differential photometry, as it was not clear which, if any, of the two sources inside the 99.7 per cent confidence radius around it is the counterpart. One source has a magnitude change consistent in direction with the fading in the X-rays. However, the outburst–quiescence magnitude difference is small. It is conceivable that this is due to the fact that the system has a high inclination, so the projected surface area of the disc is small. Out of the 13 sources observed only in quiescence, we detect NIR and optical counterparts for ten of them, while for the remaining three sources we report the limiting magnitudes. Of the ten sources with detected quiescent counterparts, we present measurements for the first time for five of them, and in contrast, two of them had previously published quiescent magnitudes that we update now with fainter magnitudes, showing that these BHXBs had not yet reached their quiescent states at the epoch of the observations reported in the literature before. We analysed the $K_s$-band and V-band outburst amplitudes with respect to $P_{\text{orb}}$ and $i$ of the system for sources in our sample and for BHXBs for which we could find published values of $\Delta K_s$, $\Delta V$, $P_{\text{orb}}$, and $i$. We find best fits to the data although the fits are not formally acceptable, showing that probably additional parameters to $P_{\text{orb}}$ and $i$ are important (e.g. emission from a jet, energy generation on the disc, light contribution from the donor star). Using theoretical arguments and observed relations, we further derive a correlation between $\Delta V$ and $P_{\text{orb}}$ of $\Delta V \propto \log P_{\text{orb}}^{0.565}$; however, such a correlation also provides no good fit to the data, probably due to the observed relations being affected by low number statistics, which could make our derived correlation less certain, and reinforcing the idea that additional parameters to $P_{\text{orb}}$ and $i$ should be considered.

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APPENDIX: QUIESCENT DETECTIONS
Table A1. BHXBs with values of outburst and quiescence magnitudes, orbital periods and inclination angles, represented graphically in Figs 4(a) and (b). The well-known BHXB GRS 1915+105 is not included in this table, as it has never been observed in quiescence.

| BHXB             | Filter | AB Magnitudes Outburst (mag) | Quiescence (mag) | Orbital period (h) | Inclination angle (°) |
|------------------|--------|------------------------------|------------------|-------------------|----------------------|
| Swift J1357.2−0933 | Ks     | 17.4 ± 0.1^f                | 20.09 ± 0.05^f   | 2.8 ± 0.3^f       | ~90°                 |
| XTE J1118+480    | Ks     | 12.64 ± 0.09^b              | 18.45±           | 4.078414 ± 0.000005^f | 68 ≤ i ≤ 79°             |
| SXJ 1819.3−2525  | Ks     | 14.4 ± 0.3^d                | 14.68 ± 0.05^m   | 67.6152 ± 0.002^i  | 72.3 ± 4.1^aw           |
| XTE J1550−564    | Ks     | 13.91 ± 0.09^d              | 18.00 ± 0.04^a   | 37.0088 ± 0.0001^u | 75 ± 4^a               |
| GRO J1655−40     | Ks     | 14.25^r                     | 15.12^r          | 62.920 ± 0.003^f   | 69 ± 2^ab              |
| GS 2023+338      | Ks     | 12.45 ± 0.03^f              | 14.39 ± 0.05^m   | 155.311 ± 0.002^a  | 67 ± 3^ac              |
| GX 339−4         | Ks     | 12.41 ± 0.01^g              | 15.2 ± 0.3^r     | 42.20 ± 0.001^v    | 37 ≤ i ≤ 78°             |
| IGR J17451−3022‡ | Ks     | 17.39 ± 0.16^b              | 17.59 ± 0.14^e   | 6.284 ± 0.001^w    | 71 ≤ i ≤ 76^ad           |
| MAXI J1836−194‡  | Ks     | 14.00 ± 0.07^i              | 20.9 ± 0.3^b     | <4.9^f            | 4 ≤ i ≤ 15^s             |
| XTE J1650−500‡   | Ks     | 15.14 ± 0.13^j              | >17.8^h          | 7.60 ± 0.02^c     | >47°                  |
| GRO J0422+32^*   | V      | 13.2 ± 0.1                  | 22.4 ± 0.3       | 5.09 ± 0.01       | 10 ≤ i ≤ 50^me           |
| A 0620−00^*      | V      | 11.22                       | 18.32            | 7.7235 ± 0.0001   | 54.1 ± 1.1^ef          |
| GRS 1009−45^*    | V      | 13.8 ± 0.3                  | 21.67 ± 0.25     | 6.86 ± 0.12       | 37 ≤ i ≤ 80^ge           |
| GRS 1124−68*     | V      | 13.52                       | 20.35            | 10.3825392 ± 0.0000744 | 39 ≤ i ≤ 65^ah           |
| H 1705−250^*     | V      | 15.8 ± 0.5                  | 21.5 ± 0.1       | 12.51 ± 0.03      | 48 ≤ i ≤ 80^me           |
| GS 2000+25^+     | V      | 16.42                       | 25.22            | 8.26              | 54 ≤ i ≤ 60^pg           |
| GRO J1655−40^+   | V      | 14.02                       | 17.2±            | 62.920 ± 0.003^f  | 69 ± 2^at              |
| GS 2023+338^+    | V      | 11^e                        | 18.44 ± 0.02     | 155.311 ± 0.002^a | 67^±ac                |
| 4U 1543−475      | V      | 14.76 ± 0.02^mu             | 19.67 ± 0.06^mu  | 42.20 ± 0.001^v   | 37 ≤ i ≤ 78^ge           |
| SAX J1819.3−2525 | V      | 8.8^w                       | 13.96 ± 0.02^as  | 67.6152 ± 0.0002^s | 72.3 ± 4.1^ac           |
| XTE J1118+480    | V      | 13.0 ± 0.3^aw               | 19.6^f           | 4.078414 ± 0.000006^f | 68 ≤ i ≤ 79°             |
| XTE J1550−564    | V      | 16.6^m                      | 22.0 ± 0.4^mu    | 37.0088 ± 0.0001^u | 75 ± 4^e               |
| GS 1534−64       | V      | 16.9^m                      | 21.5^mv          | 61.068 ± 0.002^mv | ≤79^me                |
| XTE J1859−226    | V      | 15.3 ± 0.1^ext              | 23.3 ± 0.1^ext   | 6.58^u            | ≤70^pp                |

Ref: ^a=Rau, Greiner & Filgas (2011a), ^b=Taranova & Shenavrin (2001), ^c=Chaty et al. (2003), ^d=Curran & Chaty (2013), ^e=Buxton, Bailyn & Maitra (2005), ^f=Garner et al. (2015), ^g=Chaty et al. (2002), ^h=This work, ^i=Rau et al. (2011c), ^j=Curran et al. (2012), ^k=Shahbaz et al. (2013), ^l=Gelino et al. (2006), ^m=MacDonald et al. (2014), ^n=Orosz et al. (2011a), ^o=Greene, Bailyn & Oroz (2001), ^p=Zarita et al. (2004), ^q=Coral-Santana et al. (2013b), ^r=Torres et al. (2004), ^s=Coral-Santana et al. (2011), ^t=van der Hooft et al. (1998), ^u=Casares, Charles & Naylor (1992), ^v=Heida et al. (2017), ^w=Jaisawal et al. (2015), ^x=Russell et al. (2014), ^y=Orosz et al. (2004), ^z=Khargaria et al. (2013), ^aa=MacDonald et al. (2014), ^ab=Beer & Podsidiakowski (2002), ^ac=Khargaria, Froning & Robinson (2010), ^ad=Zdziarski et al. (2016), ^ae=Webb et al. (2000), ^af=van Gurtenen et al. (2017), ^ag=Shahbaz et al. (1996), ^ah=Gelino, Harrison & McNamara (2001), ^ai=Remillard et al. (1996), ^aj=Ioannou et al. (2004), ^ak=Beer & Podsidiakowski (2002), ^al=Kimura et al. (2016), ^am=Buxton et al. (2012), ^an=Kosenkov & Velединa (2018), ^ao=Blissett et al. (1983), ^ap=Orosz et al. (1998), ^aq=Orosz (2003), ^ar=Orosz et al. (2001), ^as=MacDonald et al. (2014), ^at=Torres et al. (2002), ^au=Orosz et al. (2002), ^av=Kita et al. (1990), ^aw=Casares et al. (2009), ^ax=Zarita et al. (2002) and ^ay=Coral-Santana et al. (2013a). ^z=Sources in our sample. ^m=Magnitudes and orbital periods are taken from Shahbaz & Kuulkers (1998) and references therein, unless indicated otherwise.
Figure A1. Finder charts of the XRBs with a quiescent counterpart detected. These sources have a known position for the counterpart in outburst. All images are in the NIR $K_s$ band, unless indicated otherwise. The position of the detected counterparts is indicated in every image. For image (i), we also indicate the other star identified by Hynes et al. (1999) and label it A.
Figure A2. (a) 3D least squares plane fit to the $V$-band outburst amplitude versus the logarithm of the orbital period $P_{\text{orb}}$ and the inclination angle $i$ (for references see Table A1); adapted from Shahbaz & Kuulkers (1998). (b) Same as for panel (a) but now for the $K_s$-band amplitude. Residuals of the fit for (c) $\Delta V$ and (d) $\Delta K_s$.

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