Near-infrared/optical identification of five low-luminosity X-ray pulsators

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ABSTRACT

We present the identification of the most likely near-infrared (NIR)/optical counterparts of five low-luminosity X-ray pulsators (AX J1700.1−4157, AX J1740.1−2847, AX J1749.2−2725, AX J1820.5−1434 and AX J1832.3−0840) which have long pulse periods (>150 s). The X-ray properties of these systems suggest that they are likely members of persistent high-mass X-ray binaries or intermediate polars (IPs). Using our Chandra observations, we detected the most likely counterparts of three sources (excluding AX J1820.5−1434 and AX J1832.3−0840) in their European Southern Observatory-New Technology Telescope (ESO-NTT) NIR observations, and a possible counterpart for AX J1820.5−1434 and AX J1832.3−0840 in the Two Micron All Sky Survey and Digitized Sky Survey observations, respectively. We also performed the X-ray timing and spectral analysis for all the sources using our XMM–Newton observations, which further helped us to constrain the nature of these systems. Our multi-wavelength observations suggest that AX J1749.2−2725 and AX J1820.5−1434 most likely harbour accreting neutron stars, while AX J1700.1−4157, AX J1740.1−2847 and AX J1832.3−0840 could be IPs.

Key words: binaries: close – stars: neutron – novae, cataclysmic variables – pulsars: general – white dwarfs – X-rays: binaries.

1 INTRODUCTION

During the last decade, a number of Galactic subluminous X-ray pulsators ($L_X \sim 10^{34}–10^{35}$ erg s$^{-1}$) have been discovered with pulse periods ranging from a few seconds to over a thousand seconds. Most of these pulsators are discovered during Galactic plane surveys performed using various X-ray telescopes, e.g. BeppoSAX, ASCA, RXTE, and are found to harbour a variety of source-types like anomalous X-ray pulsars (isolated slowly rotating neutron stars; e.g. Torii et al. 1998), accreting magnetized white dwarfs [i.e. intermediate polars (IPs); e.g. Misaki et al. 1996] and neutron stars accreting from high-mass companions (i.e. mostly Be/X-ray binaries; e.g. Hullman, in’t Zand & Heise (1998)). A majority of these systems are transient in nature, but there are several persistent systems also emitting at such low luminosities. Among these persistent systems, there remains a group of sources whose nature has not been determined yet. The X-ray properties of most of these persistent systems suggest that they could be neutron stars accreting from a high-mass star or accreting white dwarf systems. Furthermore, in some cases, the possibility of a system in which a neutron star accretes from a low-mass star also cannot be excluded (Lin et al. 2002).

Most of the known Be/X-ray binaries are transient in nature and this behaviour is usually associated with their highly eccentric orbits (Okazaki & Negueruela 2001). A subclass of Be/X-ray binaries characterized by persistent, low-luminosity X-ray emission and slowly rotating pulsars has recently been proposed by Reig & Roche (1999). The neutron star in these systems is assumed to be orbiting its companion Be star in a relatively wide and a circular orbit, hence accreting from the low-density outer regions of the circumstellar envelope. Pfahl et al. (2002) has proposed a possible scenario for the formation of these wide orbit (>30 d) and low-eccentricity (<0.2) high-mass X-ray binaries, suggesting that these systems could have formed in a supernova explosion, accompanied with a very small kick ($\lesssim 50$ km s$^{-1}$) to the neutron star. If true, this growing class of persistent Be/X-ray binaries would help us to explore a different type of supernova explosion.

This paper is a part of our ongoing project to find the true nature of low-luminosity X-ray pulsators. In our previous paper, we reported...
the identification of NIR counterparts of two low-luminosity X-ray pulsators – SAX J1324.4–6200 and SAX J1452.8–4959 using the Chandra and the XMM–Newton observations (Kaur et al. 2009).

It was suggested that SAX J1324.4–6200 is likely a high mass X-ray binary (HMXB) pulsar, while no firm conclusion about the nature of SAX J1452.8–4959 could be drawn. In this paper, we report on the identification of the most likely counterparts of additional five low-luminosity X-ray pulsators – AX J1700.1–4157, AX J1740.1–2847, AX J1749.2–2725, AX J1820.5–1434 and AX J1832.3–0840. These sources were discovered from the Galactic plane observations made in 1995–1999 using the ASCA satellite (Sugizaki et al. 2001). The basic physical parameters with which these sources were discovered are listed in Table 1.

2 X-RAY OBSERVATIONS

We carried out X-ray observations of the five X-ray pulsators listed in Table 1 using the European Photon Imaging Camera (EPIC) aboard the XMM–Newton satellite and the Advanced CCD Imaging Spectrometer (ACIS) aboard the Chandra satellite.

2.1 XMM–Newton

The X-ray pulsators were observed for 7–32 ks each using the EPIC instruments on the XMM–Newton satellite. The observation details are summarized in Table 2. During our observations, both the EPIC-MOS and pn cameras (Turner et al. 2001; Strüder et al. 2001) were operated in the Full Frame mode and with the medium filter. The EPIC data was processed using the XMM–Newton Science Analysis System (SAS version 7.1.0).1

Investigation of the full-field count rate of X-ray pulsators revealed no time intervals of enhanced background in any of the observations and so all the data were used. For each observation, only one X-ray source was found inside the error circle from the ASCA observations. The detection of pulsations in all of them (see Section 3) further confirmed their identity. We used the task EDETECT_CHAIN to find the exact position of the X-ray sources (see Table 2) in their combined EPIC-MOS and pn image. The error circle on the position of each X-ray source is adopted as a quadratic sum of the bore sight error of the XMM–Newton telescope2 and the statistical error given by the task EDETECT_CHAIN and is ∼2.0 arcsec for all the targets.

2.2 Chandra

The X-ray pulsators were observed for ∼1 ks each using the ACIS-I instrument on the Chandra satellite in the FAINT mode. The details of these observations are summarized in Table 2. We processed the ACIS-I event 2 files using the standard software packages CIAO 4.03 and CALDB 3.4.2.4 The task WAVEDETECT was used to find the exact position of the targets in the ACIS-I images and are listed in Table 2. The error circle on the position is adopted as a quadratic sum of

1 See http://xmm2.esac.esa.int/sas/
2 See http://xmm2.esac.esa.int/docs/documents/CAL-TN-0018.pdf.
3 Chandra Interactive Analysis of Observations (CIAO), http://cxc.harvard.edu/ciao.
4 Chandra Calibration Data base (CALDB), http://cxc.harvard.edu/caldb/.
the bore sight error of the Chandra telescope5 (0.6 arcsec; Aldcroft et al. 2000), 1σ \( \sigma_{\text{WAVDETECT}} \) errors and a contribution that depends on the number of detected counts (van den Berg et al. 2004) and is found to be \( \sim 0.64 \text{ arcsec} \) for all the sources.

## 3 X-RAY TIMING ANALYSIS

The XMM–Newton EPIC-MOS and pn observations are used for the timing analysis of our targets. The X-ray events were extracted in a circular region of radius 30 arcsec centred on the position of the X-ray source in their EPIC-MOS and pn images, with a time resolution of 0.1 s. Similarly, the background X-ray events were extracted for each source from a source-free region on the same CCD. The event times were then transformed to barycentric times using the Chandra position of the X-ray source and the JPL-DE405 ephemeris using the task BARYCOR in SAS. The background was subtracted to generate the background corrected light curves separately for EPIC-MOS and pn instruments, which were then added to generate the final light curves for our timing analysis.

We searched for the spin period in the light curves using the task POWSPEC in FTOOLS6 and refined it further using the task EFSEARCH. The pulse periods thus detected for all pulsators are listed in Table 3 except for AX J1820.5–1434. We phase connected the pulsations for AX J1820.5–1434, using EPIC-pn observations, by cross-correlating each single profile with a standard profile obtained by folding the entire data set. This method gave us a pulse period of AX J1820.5–1434 with a much better accuracy, \( P_1 = 153.24 \pm 0.02 \) s (listed in Table 3). The errors on the pulse periods are calculated at the 68 per cent confidence level. Given the short baseline of all the observations, it was not possible to measure the spin-period derivative (\( \dot{P} \)) for all the sources with a phase coherent technique. However, we fitted the previous (see Table 1) and the new measured values of the spin period (see Table 3) with a linear relation and determined the spin-period derivative of AX J1820.5–1434 to be \( (3.00 \pm 0.14) \times 10^{-9} \) s s\(^{-1} \) and an upper limit for the remaining sources (see Table 3). Assuming an orbital velocity of the pulsating component to be \( \sim 300 \text{ km s}^{-1} \), the difference in pulse period (\( \Delta P_1 \)) measured in different orbital phases would be \( \sim \dot{P}_1 /1000 \). However, in case of AX J1820.5–1434, the measured \( \Delta P_1 \) is 0.98 s (\( \sim \dot{P}_1 /1000 \)) indicates that the measured period derivative is significantly more than that caused by the orbital motion.

The obtained X-ray light curves are folded in one single profile to measure the pulse fractional amplitude defined as \( \frac{F_{\text{max}}}{F_{\text{max}} + F_{\text{min}}} \) where \( F_{\text{max}} \) and \( F_{\text{min}} \) are the maximum and minimum flux (or counts) in a pulse profile. The pulse profiles of all the sources thus obtained are shown together in Fig. 1 where the pulse profile of SAX J1324.4–6200 is taken from Kaur et al. (2009) for comparison. Out of the six sources listed in Table 3, four sources clearly showed single peak profiles, while AX J1740.1–2847 and AX J1832.3–0840 showed double peak profiles.

## 4 X-RAY SPECTRAL ANALYSIS

Using the XMM–Newton data, we also performed spectral analysis of our targets. We used the same extraction region for both these instruments as were used for the timing analysis reported in Section 3. The SAS tool XMSELECT was used to extract both the source and the background spectra and XSPEC (version 12.0.0) was used for the spectral fitting. The resulting spectra were rebinned to have minimum of 20 counts per bin.

We fitted a variety of single component models to the spectra. The X-ray spectra of most of our sources could be fitted well using the absorbed power law and the blackbody models. For all pulsars, the values of the measured fit parameters using these two models are given in Table 4. The absorbed as well as the unabsorbed fluxes for the fitted models in 2–10 keV energy band are also given in the same table. Fig. 2 shows the best-fitting power-law model to the X-ray spectra of our targets, except for AX J1832.3–0840, where the blackbody model fit is shown. For all the sources, the thin thermal plasma model (mekal; Mewe et al. 1995) gave a poor fit while the bremsstrahlung model with a partial absorption component gave an acceptable fit only for AX J1832.3–0840 with a reduced \( \chi^2 \) of 1.1 for 1250 degrees of freedom. The parameters obtained from this fit are as follows: bremsstrahlung temperature, \( kT = 29.4^{+10.8}_{-6.0} \) keV, interstellar absorption, \( N_H = 0.81 \pm 0.05 \text{ cm}^{-2} \), partial absorption, \( N_{HI} = 6.2^{+10.9}_{-0.8} \text{ cm}^{-2} \), and the partial covering fraction = 0.68 ± 0.02. The detection of an Fe emission lines is marked as ‘y’ in Table 4 and the further details are given in Table 5. In the case when no Fe emission line is detected, an upper limit on Fe 6.4 keV line flux is given in Table 5. This was calculated by fixing the line centre at 6.4 keV and line width at 0.1 keV in the spectrum and fitting a Gaussian to the line. The parameters of Fe lines reported in Table 5 are measured using the power-law model fit to the spectra except for AX J1832.3–0840, for which blackbody model fit is used. Using the observed X-ray flux, we have also estimated the X-ray luminosity of our targets at a distance of 1 kpc (typical for IPs) and 8 kpc (typical for X-ray binaries) and these are listed in Table 4.

## 5 INFRARED OBSERVATIONS AND DATA ANALYSIS

We retrieved near-infrared (NIR) observations of three sources – AX J1700.1–4157, AX J1740.1–2847 and AX J1749.2–2725 from the European Southern Observatory-New Technology Telescope (ESO-NTT) archive and the details are summarized in Table 6. These observations were made in NIR J, H, K\(_s\) filters with a NIR imager and spectrograph called Son-of-ISAAC (SOFI). The instrument was set up in large imaging mode with a pixel scale of 0.29 arcsec and a field of view (FOV) of 5 x 5 arcmin\(^2\) for AX J1700.1–4157 and AX J1740.1–2847, while in small imaging mode with a pixel scale of 0.14 arcsec and a FOV of 2.5 x 2.5 arcmin\(^2\) for AX J1749.2–2725. During these observations, the seeing varied from

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5 See http://cxc.harvard.edu/cal/ASPECT/celmon.
6 http://heasarc.gsfc.nasa.gov/docs/software/ftools/ftools_menu.html
Figure 1. Pulse profiles of the X-ray pulsators from their XMM–Newton observations. The pulse profile of SAX J1324.4–6200 from Kaur et al. (2009) is also included for comparison.

Table 4. The X-ray spectral parameters of our pulsators, measured using the XMM–Newton observations.

| Power law | AX J1700.1–4157 | AX J1740.1–2847 | AX J1749.2–2725 | AX J1820.5–1434 | AX J1832.3–0840 |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| N_H (×10^{22} cm^{-2}) | 0.52^{+0.16}_{-0.12} | 1.0 ± 0.2 | 13.2^{+4.1}_{-3.5} | 8.4^{+2.8}_{-1.0} | 0.99 ± 0.05 |
| Γ | 0.56^{+0.13}_{-0.11} | 0.5 ± 0.1 | 1.5^{+0.6}_{-0.5} | 1.41^{+0.43}_{-0.16} | 0.83 ± 0.03 |
| F_{X,abs} (×10^{-12} erg s^{-1} cm^{-2}) | 3.7 ± 1.2 | 3.4 ± 0.8 | 1.1 ± 1.7 | 1.6 ± 1.2 | 7.1 ± 0.5 |
| F_{X,unabs} (×10^{-12} erg s^{-1} cm^{-2}) | 3.8 ± 1.2 | 3.5 ± 0.8 | 2.2 ± 3.0 | 2.5 ± 0.7 | 7.5 ± 0.5 |
| Fe line | y | y | – | – | y |
| χ^2/ν | 1.1/245 | 1.0/205 | 1.1/55 | 1.0/115 | 1.4/1250 |
| L_X at 1 kpc (×10^{32} erg s^{-1}) | 4.4 ± 1.4 | 4.0 ± 1.0 | 1.3 ± 2.0 | 1.9 ± 1.4 | 8.5 ± 0.6 |
| L_X at 8 kpc (×10^{32} erg s^{-1}) | 2.8 ± 0.9 | 2.6 ± 0.6 | 0.9 ± 1.3 | 1.2 ± 0.9 | 5.4 ± 0.4 |

Blackbody

| Power law | AX J1700.1–4157 | AX J1740.1–2847 | AX J1749.2–2725 | AX J1820.5–1434 | AX J1832.3–0840 |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| N_H (×10^{22} cm^{-2}) | < 0.064 | 0.2 ± 0.1 | 7.6^{+3.0}_{-2.3} | 4.6^{+1.1}_{-0.9} | 0.23 ± 0.02 |
| kT (keV) | 1.93^{+0.12}_{-0.12} | 2.4 ± 0.1 | 2.1^{+0.4}_{-0.3} | 1.92^{+0.17}_{-0.15} | 1.90 ± 0.03 |
| F_{X,abs} (×10^{-12} erg s^{-1} cm^{-2}) | 3.3 ± 0.2 | 3.2 ± 0.4 | 1.1 ± 0.2 | 1.6 ± 0.1 | 6.8 ± 0.1 |
| F_{X,unabs} (×10^{-12} erg s^{-1} cm^{-2}) | 3.3 ± 0.2 | 3.3 ± 0.4 | 1.5 ± 0.3 | 1.9 ± 0.1 | 6.9 ± 0.1 |
| Fe line | y | y | – | – | y |
| χ^2/ν | 1.0/245 | 0.9/205 | 1.2/55 | 0.9/115 | 1.1/1250 |
| L_X at 1 kpc (×10^{32} erg s^{-1}) | 3.9 ± 0.2 | 3.7 ± 0.5 | 1.3 ± 0.2 | 1.9 ± 0.1 | 8.1 ± 0.1 |
| L_X at 8 kpc (×10^{32} erg s^{-1}) | 2.5 ± 0.2 | 2.3 ± 0.3 | 0.8 ± 0.2 | 1.2 ± 0.1 | 5.2 ± 0.1 |

Note. For all the sources, the observed fluxes (F_{X,obs}), unabsorbed fluxes (F_{X,unabs}) and the X-ray luminosities (L_X) are measured in the energy band 2–10 keV. The sources in which we detected the Fe emission lines are marked as ‘y’.
Figure 2. The XMM–Newton EPIC-MOS and pn spectra of X-ray pulsators fitted with an absorbed power-law model except for AX J1832.3−0840, where an absorbed blackbody model fit is shown. The EPIC-pn, MOS1 and MOS2 data points are represented by open triangles (blue colour), filled circles (red colour) and open circles (black colour), respectively. A closer view of the X-ray spectrum of AX J1832.3−0840 from 5–8 keV is also provided to have a better look at different Fe emission lines.

Images were acquired in the auto-jitter mode in which a number of single frames (NDIT) having exposure times of detector integrator time (DIT) seconds were acquired at different positions and then co-averaged to generate an output image.

The data reduction is done using the standard routines in IRAF.7 A master sky-frame is first constructed by median stacking all the images. IRAF is distributed by the National Optical Astronomy Observatories, USA.

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7 IRAF is distributed by the National Optical Astronomy Observatories, USA.
frames of a source for each filter, which is then subtracted from all the images to generate sky-subtracted frames. These images are then flat-fielded, aligned and average stacked to obtain the final images. The astrometry and calibration of the final frames is performed using the Two Micron All Sky Survey (2MASS) observations which gave an (absolute) position uncertainty of ~0.2 arcsec for our observations.

6 IDENTIFICATION OF NIR/OPTICAL COUNTERPARTS

We searched for the NIR counterparts of the X-ray sources in their ESO-NTT or 2MASS observations using the position measurement from the Chandra observations. The NIR $K_s$ waveband images of our targets along with their Chandra images are shown in Fig. 3. The black circles in this figure represent the XMM–Newton error circles on the position and the white circles represent the Chandra error circles except for AX J1820.5–1434 where the XMM–Newton error circle (see larger one) is also shown in white colour for clarity. As can be seen in this figure, we have very likely identified the NIR counterparts of AX J1700.1–4157, AX J1740.1–2847 and AX J1749.2–2725 in the ESO-NTT observations. For the remaining two sources, AX J1820.5–1434 and AX J1832.3–0840, a bright and a faint NIR counterpart, respectively, is found in the 2MASS observations. The sources identified in the 2MASS observations could be a combination of a few nearby stars, hence we do not claim detection of optical counterparts for these three sources. Out of the remaining two sources (AX J1820.5–1434 and AX J1832.3–0840) for which we did not have the ESO-NTT observations, we could only identify a possible optical counterpart for AX J1832.3–0840 in the DSS observations with magnitudes $R = 19.58$ mag and $B = 21.13$ mag, coincident with its Chandra position (see Fig. 4). In the absence of any high-resolution observations of this source, we consider this faint optical star as its possible counterpart.

Using the neutral hydrogen column density ($N_H$) measured from the absorbed power-law model fit to the X-ray spectra of our targets (Table 4), we calculated the extinction towards them in the $J$, $H$ and $K_s$ wavebands following Predehl & Schmitt (1995) and Fitzpatrick (1999), and hence calculated the dereddened magnitudes (see Table 8). Here, we assume that the companion star experiences the same $N_H$ as observed for the X-ray source (i.e. no local absorption) which also allows us to put an upper limit on the extinction towards these sources.

On the basis of the extinction-free magnitudes and assuming that the sources are in our Galaxy (see Kaur et al. 2009 for the details about this method), we tentatively suggest that the NIR counterpart of AX J1700.1–4157, AX J1740.1–2847 and AX J1749.2–2725 to be a low-mass star while of AX J1749.2–2725 to be a high-mass star. The only source for which we did not have the ESO-NTT observations clearly showed that the optical counterparts found for AX J1700.1–4157, AX J1740.1–2847 and AX J1749.2–2725 are a combination of a few nearby stars, hence we do not claim detection of optical counterparts for these three sources. Out of the remaining two sources (AX J1820.5–1434 and AX J1832.3–0840) for which we did not have the ESO-NTT observations, we could only identify a possible optical counterpart for AX J1832.3–0840 in the DSS observations with magnitudes $R = 19.58$ mag and $B = 21.13$ mag, coincident with its Chandra position (see Fig. 4). In the absence of any high-resolution observations of this source, we consider this faint optical star as its possible counterpart.

We also searched for the optical counterparts of our sources in the Digitized Sky Survey (DSS)8 observations. For four of our sources, we identified a possible counterpart in the DSS observations, while no optical counterpart is identified for AX J1820.5–1434. However, our ESO-NTT observations clearly showed that the optical counterparts found for AX J1700.1–4157, AX J1740.1–2847 and AX J1749.2–2725 are a combination of a few nearby stars, hence we do not claim detection of optical counterparts for these three sources.

Table 5. Properties of the Fe emission lines detected in the X-ray spectrum of our targets using a power-law model except for AX J1832.3–0840, for which blackbody model fit is used.

| Object         | Fe 6.40 keV (fluorescent) | Fe 6.67 keV (He-like) | Fe 6.97 keV (H-like) |
|----------------|---------------------------|-----------------------|----------------------|
|                | Centre (keV) | Width (keV) | EW (eV) | Centre (keV) | Width (keV) | EW (eV) | Centre (keV) | Width (keV) | EW (eV) |
| AX J1700.1–4157 | –            | –          | –      | 6.69 ± 0.08 | 0.17 ± 0.09 | 580     | –            | –          | –      |
| AX J1740.1–2847  | 6.5 ± 0.1    | 0.3 ± 0.1  | 998    | –          | –          | –       | –            | –          | –      |
| AX J1749.2–2725  | 6.4 (frozen) | 0.1 (frozen) | < 88   | –          | –          | –       | –            | –          | –      |
| AX J1820.5–1434  | 6.4 (frozen) | 0.1 (frozen) | < 82   | –          | –          | –       | –            | –          | –      |
| AX J1832.3–0840  | 6.39 ± 0.03  | <0.07      | 50     | 6.67 ± 0.02 | <0.06      | 825     | 6.96 ± 0.03  | 0.06 ± 0.04 | 736   |

Note. An upper limit on EW of the Fe 6.4 keV line is given in case of non-detection of any Fe emission line in the X-ray spectrum.

Table 6. Log of the NIR observations obtained using 3.52-m ESO-NTT.

| Source         | Date (UT) | Program ID         | DIT | NDIT | Nframes | DIT | NDIT | Nframes | DIT | NDIT | Nframes |
|----------------|-----------|--------------------|-----|------|---------|-----|------|---------|-----|------|---------|
| AX J1700.1–4157| 2001 March 20 | 66.D-0440(B)       | 3   | 5    | 4       | 3   | 5    | 4       | 3   | 5    | 6       |
| AX J1740.1–2847| 2002 June 18  | 69.D-0339(A)       | 3   | 20   | 5       | 3   | 20   | 5       | 3   | 20   | 5       |
| AX J1749.2–2725| 2001 March 20  | 66.D-0440(B)       | 3   | 5    | 4       | 3   | 5    | 4       | 3   | 5    | 6       |

Note. NDIT represents the number of single frames, having exposure times of detector integrator time (DIT) seconds and are used to generate an output image having exposure time equal to one DIT. The number of output frames are represented by Nframes.
their spectra (shown with ‘open circles with dot inside’ in Fig. 5), while the other sources did not have any signature of it (shown with ‘filled squares’ in the same figure). The physical reason behind this interesting relation remains to be investigated.

7 DISCUSSION

In this paper, we aimed to find the possible counterparts of five low-luminosity X-ray pulsators and tentatively identify their nature. To achieve this goal, we obtained Chandra observations to measure the position of these sources with a subarc second accuracy, which helped us to find their counterparts in the NIR/optical observations. We also obtained XMM–Newton observations of these sources to study their X-ray pulsations, pulse profiles and spectral parameters. With the help of our XMM–Newton observations, we have determined spin-period derivative of AX J1820.5−1434 but only upper limits for the other sources. Our sources are likely neutron star binaries (with a high-mass or a low-mass companion) or accreting white dwarfs.

Most of the known slow X-ray pulsars are found among HMXBs except a very few which have low-mass companions. The known slow \((P_s > 0.1 \text{ s})\) X-ray pulsars with low-mass companions are Her X-1, 4U 1626−67, GRO 1744−28, 4U 1822−37 and GX 1+4 (Bildsten et al. 1997; Jonker & van der Klis 2001). Four of these low mass X-ray binary (LMXB) pulsars have spin periods between 0.5−10 s, while only GX 1+4 has a spin period of 140 s but also a red giant star as its companion. However, the spin period of X-ray pulsars containing high-mass companions are observed up to thousands of seconds (Bildsten et al. 1997). The X-ray pulsars (both in LMXBs and HMXBs) usually display a hard X-ray spectrum well fitted with a power-law index, \(\Gamma \sim 1.0\), or with a blackbody model of temperature, \(kT \sim 2\text{ keV}\). Sometimes, their X-ray spectrum is also characterized by a strong neutral Fe emission line at 6.4 keV and very rarely by ionized Fe lines at 6.7 and 6.9 keV (Ebisawa et al. 1996). These sources show both spin-up and spin-down behaviour on time-scales from a few days to a few years (Bildsten et al. 1997). The fastest spin-period derivative observed among neutron star binary pulsars is \(\sim 10^{-2} \text{ s}^{-1}\) for GX 1+4 (Elsner et al. 1985). On the other hand, IPs (a subclass of white dwarf binary systems; Warner 2003) have been observed with spin periods in the range of a few hundred seconds to a few thousand seconds (Kuulkers et al. 2006). The observed X-ray spectra of most of these systems are well fitted with a thin plasma or bremsstrahlung model with temperatures of \(\sim 1–30\text{ keV}\) and characterized by strong Fe emission lines at 6.4, 6.7 and 6.9 keV (Ezuka & Ishida 1999). In most of them, the X-ray spectrum also fits well with a power-law index, \(\Gamma \leq 1.0\) (Hong et al. 2009). Most of the white dwarfs in IPs spin-up with a typical spin-period derivative of \(10^{-11} \text{ s}^{-1}\) except a few of them which spin-down. The largest spin-period derivative observed in these systems is \(1.1 \times 10^{-10} \text{ s}^{-1}\) (Mason 1997).

**AX J1700.1−4157.** It has a pulse period of 714 s, and was discovered from ASCA observations performed on 1997 September 16 with a hard X-ray spectrum (\(\Gamma \sim 0.7\); Torii et al. 1999). It is unlikely a LMXB pulsar due to its large pulse period. The timing and spectral parameters measured from our observations are consistent with the previous observations reported by Torii et al. (1999). However, we detected a strong Fe emission line at 6.7 keV with an equivalent width (EW) of 580 eV during our observations, for which an upper limit of 1150 eV was given by Torii et al. (1999). From our NIR observations, we estimate a low-mass star to be the counterpart of this source which in combination with the detection of Fe emission line would favour an IP nature of this source.

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**Figure 3.** Left-hand panels: the ESO-NTT NIR \(K_s\) waveband image of AX J1700.1−4157, AX J1740.1−2847, AX J1749.2−2725 and 2MASS \(K_s\) waveband image of AX J1820.5−1434 and AX J1832.2−0840. Right-hand panels: the Chandra ACIS-I images of the same sources. The black and the white circles represent error circles on their position obtained from their XMM–Newton and the Chandra observations, respectively, except for the NIR observations of AX J1820.5−1434 for which larger white circle represents the error circle obtained from the XMM–Newton observations.

We also found a possible tentative relation between the pulse period and the measured \(N_H\) of these sources. Although we have only six sources (including SAX J1324.4−6200 from Kaur et al. 2009), it seems that these sources tend to form two separate groups – having large spin period (>700 s) and a small \(N_H\) (< 10^{22} \text{ cm}^{-2}) and vice versa, shown in Fig. 5. Our analysis also showed that the sources with large pulse periods have strong Fe emission line in...
Table 7. The observed $J$, $H$ and $K_s$ magnitudes of the most likely NIR counterparts of the X-ray pulsators.

| Star         | RA (hh:mm:ss) | Dec. (°′ ′″) | $J$ (mag)  | $H$ (mag)  | $K_s$ (mag) |
|--------------|---------------|--------------|------------|------------|-------------|
| AX J1700.1−4157 | 17:00:04.35   | −41:58:05.5  | 17.07 ± 0.04 | 17.04 ± 0.05 | 17.38 ± 0.13 |
| AX J1740.1−2847 | 17:40:09.14  | −28:47:25.7  | 16.16 ± 0.03 | 15.76 ± 0.07 | 15.57 ± 0.10 |
| AX J1749.2−2725 | 17:49:12.41  | −27:25:38.3  | Not detected | 16.89 ± 0.07 | 15.15 ± 0.02 |
| AX J1820.5−1434 | 18:20:30.10  | −14:34:22.9  | 15.41 ± 0.15 | 13.25 ± 0.07 | 11.75 ± 0.04 |
| AX J1832.3−0840 | 18:32:19.39  | −08:40:30.5  | 17.11 ± 0.23 | 16.22 ± 0.21 | 16.06 ± 0.34 |

Note. The RA and Dec. of these sources measured from their NIR observations are also given. The position of these sources is measured with an uncertainty of ~0.2 arcsec.

AX J1832.3−0840$^a$ is also detected in the Digitized Sky Survey (DSS) observations with magnitudes, $R = 19.58$ and $B = 21.13$ mag.

Table 8. Neutral hydrogen column density and the dereddened magnitudes of X-ray pulsators in $J$, $H$ and $K_s$ wavebands.

| Object         | $N_H$ ($\times 10^{22}$ cm$^{-2}$) | $N_H^\perp$ ($\times 10^{22}$ cm$^{-2}$) | $J$ (mag)  | $H$ (mag)  | $K_s$ (mag) |
|----------------|-----------------------------------|----------------------------------------|------------|------------|-------------|
| AX J1700.1−4157 | 0.5                                | 1.8                                    | 16.26 ± 0.04 | 16.54 ± 0.05 | 17.04 ± 0.13 |
| AX J1740.1−2847 | 1.1                                | 0.9                                    | 14.45 ± 0.03 | 14.71 ± 0.07 | 14.86 ± 0.10 |
| AX J1749.2−2725 | 13.2                               | 1.5                                    | Not detected | 4.25 ± 0.07  | 6.58 ± 0.02 |
| AX J1820.5−1434 | 8.4                                | 1.8                                    | 2.38 ± 0.15  | 5.21 ± 0.07  | 6.29 ± 0.04 |
| AX J1832.3−0840 | 1.0                                | 1.8                                    | 15.57 ± 0.23 | 15.27 ± 0.21 | 15.42 ± 0.34 |

Note. For AX J1749.2−2725 and AX J1820.5−1434, the measured $N_H$ is much greater than the Galactic $N_H^\perp$. $N_H$, neutral hydrogen column density measured using power-law model fit to the X-ray spectrum; $N_H^\perp$, neutral hydrogen column density in the direction of the given source from Dickey & Lockman (1990).

Figure 4. Left-hand panel: 2MASS $K_s$ waveband image of AX J1832.3−0840. Right-hand panel: DSS image of the same source in the optical $R$ waveband.

**AX J1740.1−2847.** It was discovered with a pulse period of 729 ± 14 s from observations performed on 1998 September 7–8 using ASCA and with a hard X-ray spectrum ($\Gamma^\perp \sim 0.7$; Sakano et al. 2000). The large pulse period of this source makes it unlikely to be a LMXB pulsar. The timing and spectral parameters measured from our observations are consistent with the previous measurement except that we detected a strong Fe 6.4 keV line in the X-ray spectrum with an EW of 998 eV which was not detected during the ASCA observations and an upper limit of 500 eV was given on its EW (Sakano et al. 2000). With the given NIR magnitudes, we suggest a low-mass star to be the possible counterpart of this source, favouring an IP interpretation.

**AX J1749.2−2725.** Discovered with a pulse period of 220.38 ± 0.20 s during the ASCA observations performed on 1995 March 26, AX J1749.2−2725 was detected with the X-ray spectrum having a power-law index of 1.0 (Torii et al. 1998). During our observations, AX J1749.2−2725 was detected with similar timing and spectral parameters as were reported by Torii et al. (1998). No Fe emission line was detected in the X-ray spectrum during the previous as well as the present observations. From our NIR observations, we infer a high-mass star as a possible counterpart which favours a HMXB pulsar nature for this source.

**AX J1820.5−1434.** It was detected with a pulse period of 152.26 ± 0.04 s from the ASCA observations made on 1997 April 8–12 and with a hard X-ray spectrum ($\Gamma^\perp \sim 0.9$; Kinugasa et al. 1998). The observed timing and spectral parameters from our observations are consistent with those reported by Kinugasa et al. (1998). The accurate spin-period measurement from our observations, in combination with the previous spin-period measurement (Table 1) resulted in a spin-period derivative determination of this...
source of \((3.00 \pm 0.14) \times 10^{-9}\) s\(^{-1}\). The largest spin-period derivative measured in IPs is \(1.1 \times 10^{-10}\) s\(^{-1}\) (Mason 1997). Thus, this source is unlikely a white dwarf system. Although we identified a bright NIR counterpart of this source in the 2MASS observations, we caution against drawing any conclusions on the basis of it since it could be a combination of a few nearby stars overlapped. The high spin-down rate of this source favours a neutron star nature, but we cannot distinguish between a low-mass or a high-mass X-ray binary.

**AX J1832.3–0840.** It has a pulse period of 1550 s, and was discovered during observations performed on 1997 October 11 using ASCA, with a hard X-ray spectrum \((\Gamma \sim 0.8;\) Sugizaki et al. 2000). During these observations, a strong 6.7 keV Fe emission line was detected in the X-ray spectrum and the spectrum was also satisfactorily fitted with a thermal equilibrium plasma model (Raymond & Smith 1977). During our observations, we measured the similar timing and the spectral parameters with respect to the previous observations. However, we detected three Fe emission lines in the X-ray spectrum of this source (see Fig. 2), which are typically seen in IPs. Our X-ray spectrum satisfactorily fitted with a bremsstrahlung model of temperature \(\sim 30\) keV, which is common among IPs and is rare among X-ray pulsars. We identified a faint counterpart of this source in the DSS as well as 2MASS observations, which indicate a low-mass star as its counterpart. Therefore, we suggest this source to be likely an IP.

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