AX J1749.1−2733 and AX J1749.2−2725 – the close pair of X-ray pulsars behind the Galactic Centre: an optical identification

D. I. Karasev, A. A. Lutovinov and R. A. Burenin

Space Research Institute, Profsoyuznaya str. 84/32, Moscow 117997, Russia

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ABSTRACT
Two faint X-ray pulsars, AX J1749.2−2725 and AX J1749.1−2733, located in the direction of the Galactic Centre, were studied in detail using data from the INTEGRAL, XMM–Newton and Chandra observatories in X-rays, the SOFI/NTT instrument in the infrared and the RTT150 telescope in the optical. X-ray positions of both sources were determined with an uncertainty better than ~1 arcsec, which allowed us to identify their infrared counterparts. From the subsequent analysis of infrared and optical data, we conclude that the counterparts of both pulsars are likely to be massive stars of B0–B3 class located behind the Galactic Centre at distances of 12–20 kpc, depending on the type, probably in the further parts of the Galactic spiral arms. In addition, we investigated the extinction law towards the Galactic bulge and found that it is significantly different from the standard one.

Key words: stars: individual: AX J1749.2−2725 – stars: individual: AX J1749.1−2733 – X-rays: binaries.

1 INTRODUCTION
The heavily obscured (N_H ~ 10^{23} cm^{-2}) X-ray source AX J1749.2−2725 was discovered by the ASCA observatory in 1995 March and localized with coordinates RA = 17^h49^m10^s, Dec. = −27°25′16″ (all coordinates here and below are given in the J2000 system) and uncertainty about 50 arcsec (Tori, Kunugasa & Katayama 1998). They also found coherent pulsations with a period of ~220.4 s and proposed that AX J1749.2−2725 is an X-ray pulsar in a high-mass X-ray binary (HMXB) system. These results and conclusions were confirmed later by Sakano, Koyama & Maeda (2002) during ASCA observations in 1998.

The other X-ray source AX J1749.1−2733, located just a few arcminutes away from AX J1749.2−2725, was discovered on 1996 September 19 by the ASCA observatory at RA = 17^h49^m10^s, Dec. = −27°33′14″ with an uncertainty of ~55 arcsec (Sakano et al. 2002). Observations of the source with the INTEGRAL observatory during the flare in 2003 September (Grebeniev & Sunyaev 2007) and with the XMM–Newton observatory in 2007 March allowed us to discover a periodicity of X-ray flux from the source with a period of ~132 s (Karasev et al. 2007). The combination of this result with results of the analysis of ASCA, XMM–Newton and SWIFT spectral data, which revealed a strong absorption, led us to the conclusion that AX J1749.1−2733 is a new X-ray pulsar in the HMXB system (Karasev, Tsygankov & Lutovinov 2008). But there has been no optical identification of these sources to date.

Using XMM–Newton data, Zurita Heras & Chaty (2008, hereafter ZC08) obtained an accurate X-ray position for AX J1749.1−2733 of RA = 17^h49^m06^s and Dec. = −27°32′32′′ with an uncertainty of 2 arcsec. Subsequent observations of this field of the sky with the ESO/NTT telescope in infrared (IR) and optical bands showed that all three relatively bright stars, suggested by Romano et al. (2007) as possible counterparts of AX J1749.1−2733, can be ruled out, but several faint stars remained. One of them (#5 in the paper of ZC08) was proposed as a companion star of possible Be-nature at a distance of >8.5 kpc.

In this Letter, we reanalysed XMM–Newton data, obtained on 2007 March 31 (Obs.ID 0510010401) during observations of AX J1749.1−2733, and found that the X-ray pulsar AX J1749.2−2725 was also significantly detected at the position RA = 17^h49^m12^s, Dec. = −27°25′37″ with an uncertainty of ~2 arcsec. Combining XMM–Newton measurements with Chandra and SOFI/NTT data, we identified IR counterparts for both X-ray sources.

2 OBSERVATIONS AND DATA ANALYSIS
We analysed data from the MOS2 camera onboard the XMM–Newton observatory, with a total exposure of ~6ks, using the standard XMM–Newton software – Science Analysis System (SAS) v7.0.0. The final timing and spectral analysis was carried out with the HEASOFT 6.4 package.

For the cross-checking of positional measurements and final conclusions about the source coordinates, we used results of the
pipeline analysis of the Chandra observatory data, obtained during observations of AX J1749.1−2733 and AX J1749.2−2725 on 2008 February 8 (Obs.ID 9013) and 2008 April 27 (Obs.ID 7504), respectively.

In order to identify optical counterparts for the studied sources, we used IR data from the SOFI instrument of the NTT telescope from the public ESO archive. Observations of AX J1749.2−2725 were performed on 2001 March 20 with a pixel scale of 0.144 arcsec and total exposures of 4 × 15, 4 × 15 and 36+5 × 15 s in J, H and Ks bands, respectively; observations of AX J1749.1−2733 were performed on 2007 April 3–4 with a pixel scale of 0.288 arcsec and total exposures of 9 × 47.3 and 383 × 5.9 s in H and Ks bands, respectively.

Additional images in the optical i band were obtained with the Russian–Turkish 1.5-m Telescope (RTT150, TUBITAK National Observatory, Antalya, Turkey). The IR and optical data were reduced and analysed using the standard packages and our own software. The photometry was performed by fitting the point spread function with the DAOPHOT III software (ESO, scisoft). The photometric solutions for SOFI/NTT images of AX J1749.1−2733 were taken from ZC08 and the solutions for AX J1749.2−2725 images were obtained using data of standard star observations from the ESO archive. The astrometric solutions of images were found using the 2MASS catalogue as a reference.

3 AX J1749.2−2725 IN X-RAYS

With XMM–NEWTON

As was mentioned above, during observations of AX J1749.1−2733 by XMM–Newton on 2007 March 31 the other X-ray pulsar AX J1749.2−2725 was detected in the same field of view. The source was identified due to X-ray pulsations with a period of ∼220 s, which were discovered earlier by the ASCA observatory (Torii et al. 1998). The periodogram of the AX J1749.2−2725 background subtracted emission, obtained by XMM–Newton/MOS2 in the 2–10 keV energy band, is shown in Fig. 1. Despite the source faintness a significant excess of the χ2-distribution near ∼220 s is clearly seen. The best-fitting value of the pulse period is equal to ∼216.86 ± 0.14 s; the uncertainty corresponds to 1σ and was determined by the bootstrap method from the analysis of a large number of simulated light curves (see Tsyganov & Lutovinov 2005 for details). The source pulse profile folded with this period is presented in Fig. 1 (bottom); it has a single-peaked shape and pulse fraction of ∼70 per cent in the 2–10 keV energy range.

The spectrum of the source can be well approximated by a power-law model with the photon index Γ = 1.41^{+0.05}_{−0.10}, modified by the photoelectric absorption with NH = 1.41^{+0.13}_{−0.26} × 10^{22} cm−2 (reduced χ2 = 0.73 for 18 d.o.f., Fig. 2). The corresponding unabsorbed source flux in the 2–10 keV energy band was ∼2.6 × 10^{−12} erg cm−2 s−1 during XMM–Newton observations, which is about an order of magnitude lower than that measured by the ASCA observatory in 1995 (Torii et al. 1998). Nevertheless, the spectrum slope and interstellar absorption are formally in a good agreement determined from these observations. This fact may be explained by the large uncertainty of the determination of spectral parameters due to the source faintness. The corresponding confidence contours for the spectral index and absorption are shown in Fig. 2 (inset). Nevertheless, the measured value of NH is significantly higher than the value of the interstellar absorption in the direction to the source (Schlegel, Finkbeiner & Davis 1998), which indicates the presence of strong intrinsic absorption in the binary system.

The comparison of our pulse period measurements with those of Torii et al. (1998) and Sakano et al. (2002) points to the acceleration of a neutron star rotation since the ASCA observations with an average rate of ˙P/P ∼ 1.3 × 10^{−3} yr−1. Using the expression for the maximum possible acceleration from Lipunov (1981), we can estimate roughly the source luminosity as LX,2−100 keV ≃ 2.1 × 10^{39} erg s−1 (here we consider LX,2−100 keV = X-ray luminosity in the 2–100 keV energy band, as bolometric). Applying a correction factor of ∼3 to make a transition from the luminosity in the 2–100 keV band to the 2–10 keV energy band (this factor was derived from the spectral analysis of a large number of X-ray pulsars in a wide range of luminosities).
4 IDENTIFICATION OF IR COUNTERPARTS FOR AX J1749.2−2725 AND AX J1749.1−2733

Coordinates of AX J1749.2−2725 and AX J1749.1−2733 were derived from XMM–Newton data using standard methods described in the SAS manual. They have statistical uncertainties of 0.7 and 0.4 arcsec, respectively. The additional systematic uncertainty of the XMM–Newton pointing direction can be as large as ±2 arcsec (http://xmm2.esac.esa.int/external/).

The standard way to minimize this systematic uncertainty is to use other X-ray sources on the same X-ray image, with clearly identified optical counterparts. The 2–10 keV image of the field of the sky near X-ray pulsars AX J1749.1−2733 and AX J1749.2−2725 can be preliminarily regarded as a system–detector astrometric error in the XMM–Newton image, which was obtained from the RCG positions, which were obtained from the pipeline data. The uncertainty in both cases is about 1 arcsec and mainly systematic. These Chandra positions coincide well with the two IR sources proposed above based on XMM–Newton data.

Thus the coordinates of the IR counterparts of AXJ1749.2−2725 and AXJ1749.1−2733 (and consequently the pulsars themselves) can be determined as (RA, Dec.) 17h49m12.5′ ± 0.25′; 27°25′39.3″ ± 0.14″, respectively. Note that the IR counterpart for AX J1749.1−2733 is different from the star suggested by ZC08. At the same time our candidate was significantly detected in every one of about 400 observations of this field by the SOFI/NTT telescope in the Ks filter with an approximately persistent magnitude.

Both proposed counterparts are not detected in optical bands. One of them, AX J1749.2−2725, is hard to observe due to a very bright nearby star to the north-east of the pulsar (Fig. 4). The i′-band image of the AX J1749.1−2733 field of the sky obtained with the RTT150 telescope is shown in Fig. 5. Magnitudes and upper limits for both IR counterparts are summarized in Table 1.

5 SPECTRAL TYPE AND DISTANCE ESTIMATIONS

In order to estimate the spectral type of these counterparts we need to measure the interstellar extinction to the Galactic Centre (GC) in the direction to these objects. Using SOFI/NTT data, we constructed the colour–magnitude diagrams (CMDs) for all stars in 1 × 2 arcmin² box fields near each of the sources (see Fig. 6 for AX J1749.2−2725). The red giant branch and, particularly, the red clump giants (RCGs) are clearly seen in this diagram because almost all of them are located approximately at the same distance, which corresponds to the distance to the GC or Galactic bulge (8.4 ± 0.4 kpc; Paczynski & Stanek 1998).

Using the observed positions of RCGs at the CMDs and their unabsorbed colours and magnitudes, we found using 2MASS IR photometry of RCGs from the Hipparcos catalogue, we estimated the interstellar extinction as $A_H = 2.1 \pm 0.1$ and $A_K = 1.42 ± 0.25$ for the fields near AX J1749.2−2725 and AX J1749.1−2733, respectively. The extinction law measured from RCG colours turns out to be $A_H/E(H−K) = 1.67 ± 0.12$ for both the fields and is different from the standard extinction law in the Galactic plane, $A_H/E(H−K) = 2.75$ (e.g. Cardelli, Clayton & Mathis 1989). A similar analysis based on the $J−K$ CMD also showed a strong difference between the measured extinction law in the AX J1749.2−2725 field, $A_J/E(J−K) = 1.29 ± 0.14$, and the standard one, $A_J/E(J−K) = 1.69$. These conclusions are in agreement with the results of Popowski (2000) and Revnivtsev, van den Berg & Burenin (2010), which demonstrated the significant difference of the extinction law in the Galactic bulge and disc.

Early-type luminous stars with magnitudes similar to that observed for the AX J1749.2−2725 counterpart would be located at the distance of the GC or larger. It is easy to show if we assume that the studied system is located at the distance of the GC and, consequently, has an extinction of $A_H \sim 2.1$. Proposing the different classes of the stars as a companion of AX J1749.2−2725, we can obtain their apparent $H$ magnitudes for the above mentioned distance and extinction. If this magnitude is higher than the observed one, then a star of such a type should be located before the GC; in the opposite case – behind it. Using the observed colour of the AX J1749.2−2725 counterpart $(H−K) \approx 1.6$, and the extinction law measured from RCG colours above, we can estimate the extinction for these stars as $A_H \approx 2.7$. A late-type star with the same observed magnitude would be located at a distance smaller than that of the GC, and the standard extinction law should be used to

![Figure 3. The XMM–Newton/MOS2 X-ray image (the 2–10 keV energy band) of the field of the sky near X-ray pulsars AX J1749.1−2733 and AX J1749.2−2725.](https://academic.oup.com/mnrasl/article-abstract/409/1/L69/1004517/AX-J1749-1-2733-and-AX-J1749-2-2725-the-close-pair/15275273)
estimate their extinction. In that case, from the observed reddening $E(H - K) > 1$ we estimate the extinction $A_H > 2.8$.

In both the cases, the extinction is larger than that measured above using RCGs in the Galactic bulge. Therefore, AX J1749.2−2725 should be located at larger distances, behind the GC. From the measured magnitudes of its counterpart, we conclude that it should be earlier than B5 if a main-sequence star is suggested. From the other side, a main-sequence star with spectral type earlier than B1–2 would be located at a distance larger than 24 kpc, i.e. outside the Galaxy (Fig. 7, top). This diagram shows the possibility of different classes of stars being the counterpart of the studied source on the assumption of an appropriate absorption law. Only stars placed on white fields of the diagram may be the counterpart of the source. If a star is placed on the cyan field, it means that: (1) it would be located before the GC, but the extinction would be higher than for the GC; (2) it would be located behind the GC, but the extinction would be lower than for the GC. Applying similar reasoning for AX J1749.1−2733, we conclude that it is also located behind the GC and the type of its counterpart should be earlier than B3 and later than B0 for the main-sequence stars (Fig. 7, bottom).

Finally, note that giants with spectral types G5–K0 could also fit the observed magnitudes and colours of the counterpart of the sources (Fig. 7). This possibility does not look very surprising taking into account a recent discovery of a new class of symbiotic X-ray sources.

### Table 1. Magnitudes of the proposed counterparts.

<table>
<thead>
<tr>
<th>Band</th>
<th>AX J1749.2−2725</th>
<th>AX J1749.1−2733</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i'$</td>
<td>$&gt;20.5$</td>
<td></td>
</tr>
<tr>
<td>$J$</td>
<td>18.58 ± 0.21</td>
<td>18.7</td>
</tr>
<tr>
<td>$H$</td>
<td>16.57 ± 0.07</td>
<td>17.43 ± 0.14</td>
</tr>
<tr>
<td>$K_s$</td>
<td>14.95 ± 0.05</td>
<td>15.18 ± 0.03</td>
</tr>
</tbody>
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**Figure 4.** SOFI/NTT $K_s$-band images of the field of the sky containing X-ray pulsars AX J1749.2−2725 (left) and AX J1749.1−2733 (right). Large solid circles show the standard (statistical plus systematic) positional uncertainty from XMM-Newton/MOS2 measurements. Small solid circles show statistical uncertainties of XMM-Newton measurements only, with the proposed systematic shift applied (shown with arrows). Dashed circles show the Chandra absolute astrometric uncertainty of the sources’ position. The position of the star, proposed by ZC08 as a counterpart for AX J1749.1−2733, is marked by the cross.

**Figure 5.** The $i'$-band image of the field of the sky near AX J1749.1−2733 obtained with the RTT150 telescope. The circle, shift arrow and cross are the same as in Fig. 4, right.

**Figure 6.** CMD obtained using SOFI/NTT data for the stars from the $1 \times 2$ arcmin$^2$ sky field near AX J1749.2−2725.
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6 SUMMARY

Based on the data of XMM–Newton and Chandra observatories we significantly improved localizations and identified IR counterparts for two X-ray pulsars, AX J1749.1−2733 and AX J1749.2−2725, located in the direction of the GC. It was shown that the extinction law towards the Galactic bulge is significantly different from the standard one. Using this result we estimated the spectral class of the counterparts for both sources and concluded that they belong to the class of HMXBs located behind the GC, presumably in one of the spiral arms (Lutovinov et al. 2005). The most likely candidates to be counterparts seem to be the B3 star at a distance of $d = 14 \pm 2.5$ kpc for AX J1749.2−2725 and the B3 star at a distance of $d = 11 \pm 3$ kpc or the B1–2 star at a distance of $d = 16 \pm 3.5$ kpc for AX J1749.1−2733. Note that these estimations of the distance for AX J1749.2−2725 are in good agreement with the ones obtained from the pulse period changes.

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