Chandra X-ray and Gemini near-infrared observations of the eclipsing millisecond pulsar SWIFT J1749.4-2807 in quiescence

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ABSTRACT

We report on Chandra X-ray and Gemini–North near-infrared K-band observations of the eclipsing accretion–powered millisecond X-ray pulsar SWIFT J1749.4–2807 in quiescence. Using the Chandra observation we derive a source position of Right Ascension: 17:49:31.73 and Declination: -28:08:05.08. The position is accurate to 0.′′6 (90 per cent confidence). We find one source at a magnitude \( K = 18.44 \pm 0.03 \) with a position fully consistent with the accurate Chandra X-ray localisation and a second source at \( K = 19.2 \pm 0.1 \) that falls close to the edge of the error circle in the deep K-band images. The presence of a few weaker sources as suggested by previous \( H \)-band observations presented in the literature cannot be ruled out. There is marginal evidence that the brighter of these two sources is variable. Follow-up spectroscopy of this potential counterpart will show if this source is the true counterpart to SWIFT J1749.4–2807. If so, barring the presence of complicating effects such as heating of the mass-donor star, it would allow for the mass of the neutron star to be measured through the measurement of periodic radial velocity variations.

Key words: binaries — X-rays: binaries — X-rays:individual:SWIFT J1749.4–2807 — stars: neutron
and the neutron star, $q$. Alternatively, this $q$ can be determined from the rotational broadening of the stellar absorption lines ($v \sin i$). This $v \sin i$ combined with $K_2$ gives $q$ via $\frac{v \sin i}{K_2} = \left(1 + q\right)^{-1} \frac{0.3}{0.8} \frac{a_{\text{rot}}}{c}$ (e.g., see Horne et al. 1986). The system inclination can be determined through modelling of the multi-colour optical lightcurves or, in systems with favorable viewing angles such as SWIFT J1749.4–2807 the X-ray eclipse duration can be used to accurately determine the inclination (Horne 1985). As the inclination is constrained by the geometry (Chanan et al. 1976), mass measurements in eclipsing systems are independent of the modelling that lies behind inclinations derived from ellipsoidal variations. In most cases the system has to be in quiescence such that the accretion continuum is suppressed permitting the detection of photospheric absorption features from the mass donor. These absorption features allow one to estimate the mass of the companion to SWIFT J1749.4–2807. Throughout this paper we use the ephemeris of SWIFT J1749.4–2807 given by Altamirano et al. (2011).

Recently, it was discovered that the transient SWIFT J1749.4–2807 found in 2006 (Schady et al. 2006) exhibits pulsations at 518 Hz (Altamirano et al. 2011). Furthermore, the X-ray light curve shows eclipses at the 8.8 hr orbital period (Markwardt & Strohmayer 2010). For the companion star to fill its Roche lobe in the 8.8 hours orbit its mean density would imply a spectral type of a G3 V–G5 V star if the companion is close to the lower main-sequence. Thus, this source holds the promise of allowing for a model-independent neutron star mass determination. From a type I X-ray burst the upper limit to the distance to this source has been determined to be 6.7±1.3 kpc (Wijnands et al. 2009).

The observed interstellar hydrogen column density $N_H$ towards the source is $\approx 3 \times 10^{22}$ cm$^{-2}$ (Ferrigno et al. 2011). As it implies about 17 magnitudes of extinction in the $V$-band (Predehl & Schmitt 1995) it precludes the search of an optical counterpart. Given that the extinction in the $K$-band is only $\approx 11\%$ of that in the $V$-band (Cardelli et al. 1989) it allows for the detection of a near-infrared counterpart. D’Avanzo et al. (2011) searched for a near-infrared counterpart in the T.6 Swift error circle in the $H$-band. Given the crowded field, the relatively large uncertainty on the Swift X-ray position and the deep observations, D’Avanzo et al. (2011) found more than 40 potential counterparts.

In this Paper we report on a Chandra observation of SWIFT J1749.4–2807 in quiescence. This observation provides an accurate localisation. Using this accurate position we investigate our deep Gemini $K$-band observations obtained under excellent natural seeing conditions for the presence of a counterpart to SWIFT J1749.4–2807. Throughout this paper we use the ephemeris of SWIFT J1749.4–2807 given by Altamirano et al. (2011).

![Figure 1. Zoom-in around the Chandra ACIS-S3 position of SWIFT J1749.4–2807 (indicated with the small red circle with a radius of 0.6′). The blue circle indicates the Swift (D’Avanzo et al. 2011) position and the magenta circles represent the XMM-Newton positions of SWIFT J1749.4–2807 given by Wijnands et al. (2009) (XMM 1) and Degenaar et al. (2012) (XMM 2).](image)
cally 0.6″ at 90 per cent confidence. We tried to reduce this boresight uncertainty by investigating if one of the other detected X-ray sources can be safely associated with a source with a well known position but this was not the case.

We have extracted source counts from a circular region of 2″ radius centered on the source position. Similarly, we have used a circular region with a radius of 50″ on a source–free region of the CCD to extract background counts. A point–source aperture correction was applied to the auxiliary response file of the source. The net, background subtracted, detected source count rate is 2.9±10−13 counts s−1. In total after correcting for the number of expected background photons, 61 source photons have been detected in the energy range between 0.3–7 keV. The number of background photons in the same area in 0.3–7 keV was less than 1.

Using xspec version 12.6.0q (Arnaud 1996) we have fitted the spectra of SWIFT J1749.4–2807 using Cash statistics (Cash 1979) modified to account for the subtraction of background counts, the so called W–statistics.

Given that we only detected a low number of counts we decided to fix the N_H to 3×1022 cm−2 in our spectral fits, consistent with the values determined by Ferrigno et al. (2011) and Degenaar et al. (2012). We have used an absorbed powerlaw model fit function to describe the data (the model pegpwrlw in xspec). We visually inspected a plot of the count rate as a function of heliocentric time to search for the presence of the eclipse. The Chandra observed count rate is consistent with zero at the predicted heliocentric time of the eclipse. The eclipse duration is consistent with the duration determined by Markwardt & Strohmayer (2010) when the source was in outburst. To account for the fact that the source is eclipsed during 2 ksec (Markwardt & Strohmayer 2010), which is about 8 per cent of the total exposure time, we decrease the effective exposure by 2 ksec when calculating the source flux. We find a best–fit power law index of 0.6±0.4 which gives an unabsorbed X-ray flux of (0.8±0.1)×10−13 erg cm−2 s−1 in the 0.3–7 keV band and 1.4×10−13 erg cm−2 s−1 in the 0.5–10 keV band.

2.2 Gemini near–infrared observations

K-band imaging of the field containing SWIFT J1749.4–2807 was performed with the Gemini–North telescope on the nights of June 15 and 20, 2012 under observing program GN-2012A-Q-67. The Near Infrared Imaging and Spectrometer (NIRI; Hodapp et al. 2003) instrument was used with the f/14 camera to yield a field of view of 51″×51″ with a plate scale of 0.05 pixel−1.

The field of SWIFT J1749.4–2807 is crowded and care was taken to avoid as much as possible image artifacts due to saturated stars. In particular, we exclude from the NIRI FOV the K ∼ 8.6 star 2MASS J17493218–2807563. Therefore, we both rotated the instrument 45 degrees and used a (p,q,z=0)-dithering pattern. Integration times were 10 s in other to mitigate saturation effects from other bright stars in the field of view. Thus the observing sequences consisted of a 5–point dither pattern with offset steps p of 0, 10, -5, 5 and 15″ and we added three 10 s exposures at each dither position. This pattern was repeated twenty one times yielding a total of 52.5 min on source. The image quality varied during the observations due to the weather conditions. We measure a point–spread function full–width at half maximum (FWHM) between 0″.22–0″.36 and 0″.23–0″.58 with a median value of 0″.29±0″.03 and 0″.40±0″.07 on June 15 and 20, respectively.

The data were processed using both python scripts and IRAF tasks developed and provided by the Gemini Observatory. Note that sky frames were not subtracted from the data. The observed field is too crowded to allow us to build a useful sky frame from the dithered images and there were no nearby regions on the sky suitable to measure the local sky background.

For the analysis, we generated images by stacking all the reduced frames using imcoadd. In this way we obtained for the night of June 15 seven combined images of 150 s on source each. We also combined the images with seeing <0″.31 of the first night into one average image. The night of June 20 was of less good image quality (see above) and a single combined frame was build totalling 1770 s on source.

We improved the astrometry of the best–seeing frame using the position of six 2MASS stars that were well separated from other stars and which did not saturate the Gemini NIRI detector. A fit of pixel scale in x and y, and orientation provide an root–mean–square (rms) uncertainty of 0″.03 for a pixel scale of 0″.05 per pixel in x and y and an orientation of 44.9°.

In Fig. 2 we show the finding chart of the field of SWIFT J1749.4–2807 using the best seeing image of June 15. Overplotted is the 90 per cent confidence error circle on the Chandra X–ray position of the source. A clear source is detected near the centre of the error circle (star 1) and towards the south–east corner just outside the formal 90 per cent confidence error circle, lies another fainter potential candidate counterpart (star 2).

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1 see http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/manual/

2 IRAF is distributed by the National Optical Astronomy Observatories.
We performed aperture photometry on the images using DAOPHOT in IRAF to compute the instrumental magnitudes for the objects of interest. Absolute flux calibration of the images was obtained selecting isolated stars with magnitudes reported in the UKIDSS-DR6 Galactic Plane Survey (UGPS; Lucas et al. 2008). Both the NIRI and the UKIDSS photometric systems are close representations of the Mauna Kea Observatory (MKO) standard system. Differential photometry was obtained on each of the averaged images to derive the flux variability of the sources as a function of time. The photometric results given here are with respect to the star UGPS J176971.32–288889.6 ($K = 14.551 \pm 0.022$). The scatter in the light curves build for this UGPS star using other bright and isolated comparison stars shows that the differential photometry is accurate to $\lesssim 1$ per cent.

Photometry of the two candidate counterparts on the combined best seeing image of June 15, 2012, yields a magnitude of $K_1 = 18.44 \pm 0.03$ and $K_2 = 19.20 \pm 0.06$ for star 1 and star 2, respectively. The magnitude during the observation on June 20, 2012 is $K_1 = 18.75 \pm 0.07$ and $K_2 = 19.3 \pm 0.1$ mag. So, with an average magnitude of $K_1 = 18.44 \pm 0.03$ on June 15, and $K_1 = 18.75 \pm 0.07$ on June 20, 2012, there is evidence at the 4 $\sigma$ level that this source is variable.

3 DISCUSSION

Using Chandra we obtained a 24.4 ksec exposure of the eclipsing msec pulsar Swift J1749.4–2807 in quiescence. We detected the source at an unabsorbed flux of $2 \times 10^{-13}$ erg $^{-1}$ cm$^{-2}$ s$^{-1}$ in the 0.5–10 keV band and we provide a position accurate to $\pm 6$ at 90 per cent confidence. At a distance upper limit of 6.7$\pm$1.3 kpc (Wijnands et al. 2009), this flux corresponds to an X-ray luminosity of $1 \times 10^{34}$ erg s$^{-1}$ in the 0.5–10 keV band. Owing to the uncertainty in the high hydrogen column density towards the source this number is uncertain, but the value is consistent with that found before from XMM-Newton observations in quiescence (Wijnands et al. 2009; Degenaar et al. 2011). The derived quiescent X-ray luminosity is also in agreement with the rough correlation between quiescent X-ray luminosity and the orbital period, although the source is on the bright end of the observed correlation (a plot highlighting this correlation can be found in Rea et al. 2011). The best-fit power law index of the X-ray spectrum is $0.6 \pm 0.4$, which is steep for quiescent neutron stars, however, the uncertainty on this number is currently such that it could be made consistent with more canonical values of 1.5–2 particularly if $N_H$ is somewhat higher than the $3 \times 10^{22}$ cm$^{-2}$ that was used in the fit (see for instance the powerlaw fit in Degenaar et al. 2012).

In addition to the Chandra observation, we obtained Gemini $K$-band images under excellent natural seeing conditions of the field of Swift J1749.4–2807. The position of one point source is consistent with the X-ray location and a second is bordering the Chandra error circle. There is marginal evidence for the brighter of the two to be variable. The observed interstellar hydrogen column density, $N_H$, towards Swift J1749.4–2807 is $\approx 3 \times 10^{22}$ cm$^{-2}$ (Ferrigno et al. 2011). This yields an extinction in the $K$-band of 1.9 mag (Cardelli et al. 1989). However, as $A_K/(E(B-V)) = R_V$ is known to be closer to 2.5 than 3.1 for fields towards the bulge (Nataf et al. 2012) this implies that $A_K$ would be 1.7 mag for $R_V=2.5$.

For the companion star to fill its Roche lobe in the 8.8 hours orbit its mean density would imply a spectral type of a G3 V–G5 V star if the companion is close to the lower main-sequence. Note that the spectral type of G5 V that we derive here is consistent with the broad mass range for the companion star (0.45–0.8 $M_\odot$) that is derived by Markwardt & Strohmayer (2010) and Altamirano et al. (2011) as the mass donors in LMXBs and CVs are often undermassive for their spectral type (Knigge et al. 2011). For a G5 V donor star, the absolute magnitude in the $V$– and in the $K$-band is $M_V = 5.1$ and $M_K = 3.5$, respectively (see Cox 2000 and Tokunaga 2000 respectively). At a distance upper limit of 6.7 kpc the distance modulus, DM, is 14.1. Allowing for 1.7 magnitudes of extinction in the $K$-band will mean that the companion star has an apparent magnitude of $m_K = DM + 1.7 + M_K$ yielding $m_K = 19.3$ for the G5 V star. The observed $K$ band magnitude of $\sim 18.6$ is consistent with this if the source is more nearby than the 6.7 kpc upper limit (i.e. the source has to be at $\sim 5$ kpc) and/or if the extinction in the $K$-band is lower than 1.7 magnitudes. The latter can be the case if part of the observed $N_H$ is due to ionised material for instance material local to the source.

Previous to our work, D’Avanzo et al. (2011) obtained $H$-band adaptive optics observations with the Very Large Telescope. Of the 41 sources that those authors detected inside the error circle of the Swift X-ray position, five fall inside the Chandra error circle; six if we include our source 2. Two of these six sources coincide with the position of the two potential counterparts that we found. In Table 1 we list the properties found by D’Avanzo et al. (2011) for these six sources.

Our star 1 at RA: 17:49:31.73 Dec: -28:08:05.09 would correspond to source number 8 in table 2 of D’Avanzo et al. (2011) (see Table 1). Our star 2 which is at RA: 17:49:31.768 Dec: -28:08:05.41 would correspond to their entry number 24. The other four sources inside the Chandra error circle are not significantly detected in our Gemini data, although there is some evidence for additional flux to the south of star 1, which could be caused by either source 25 or source 27, or by both sources together.

The extinction towards Swift J1749.4–2807 in the $H$-band is $\sim 1.2$ mag more than that in the $K$-band. The $(H-K)_0$ colour of A–M5 stars is between 0 and 0.3 mag (Tokunaga 2000). Therefore, the magnitudes of the two sources that we find should be, at most, 1.5 magnitude brighter than the $H$-band magnitudes reported in D’Avanzo et al. (2011) for these two sources. However, comparing our observed $K$ band magnitudes with the $H$-band magnitudes reported by D’Avanzo et al. (2011) (see Table 1) we see that the observed $H-K$ colour is approximately 2.4 magnitudes for star 1 and 2.8 magnitudes for star 2. We investigated the potential reason for this peculiar colour by comparing our magnitudes as well as the $H$-band magnitudes derived by D’Avanzo et al. (2011) with the magnitudes of 2MASS and UKIDSS stars in the images. The $H$-band magnitude of the star at RA: 17:49:31.88 Dec: -28:08:03.3 reported by D’Avanzo et al. (2011) (entry number 1 in their paper) is 16.26, however it has $H=15.01 \pm 0.05$ according to the UKIDDS database, this is nearly 1.3 magnitudes brighter. In addition, we looked up the $H$ and $K$ magnitudes reported

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The magnitudes for source 1 on the night of June 15, 2012 (near phase 0.77) and June 20, 2012 (near phase 0.36) are overplotted, showing that the observed variability has the right sign given that the source is brighter near phase 0.77 than near phase 0.36. For smaller mass ratios the peak-to-peak amplitude increases, which given that the two data points lie above and below the curves, could hint at a more extreme mass ratio. Such a mass ratio could be accommodated by a neutron star more massive than 1.4 M⊙ and a mass donor star under-massive for its spectral type. Furthermore, if light from a residual accretion disc is present it will reduce the apparent amplitude of the ellipsoidal modulations. Thus, adding a significant amount of light of an accretion disc to the model can only be made in agreement with the two data points for a (very) small mass ratio q. Potentially, if the neutron star heats the companion star one can find variations due to changes in the aspect of the companion star (see for instance Homer et al. 2001; Burderi et al. 2003; Jonker et al. 2008; D’Avanzo et al. 2009). However, such variations would possibly be larger than the ellipsoidal variations and they would produce a bright K-band magnitude at orbital phase of 0.5 and this is not seen in the current data (see Figure 3). Given that the orbital period of SWIFT J1749.4–2807 is larger than that of the accretion powered millisecond pulsars where this effect has been found before, the amplitude of the effect will be reduced. Finally, flickering often observed in optical and near-infrared light of X-ray binaries in quiescence due to for instance short-term variations of the accretion disc can also explain the observed variability (e.g. see Reynolds et al. 2008; Cantrell et al. 2010).

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