

Determining the nature of the faint X-ray source population near the Galactic Centre

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We present results of a multi-wavelength program to study the faint discrete X-ray source population discovered by Chandra in the Galactic Centre (GC). From IR imaging obtained with the VLT we identify candidate K-band counterparts to 75% of the X-ray sources in our sample. By combining follow-up VLT K-band spectroscopy of a subset of these candidate counterparts with the magnitude limits of our photometric survey, we suggest that only a small percentage of the sources are HMXBs, while the majority are likely to be canonical LMXBs and CVs at the distance of the GC. In addition, we present our discovery of highly structured small-scale (5-15'') extinction towards the Galactic Centre. This is the finest-scale extinction study of the Galactic Centre to date. Finally, from these VLT observations we are able to place constraints on the stellar counterpart to the “bursting pulsar” GRO J1744-28.

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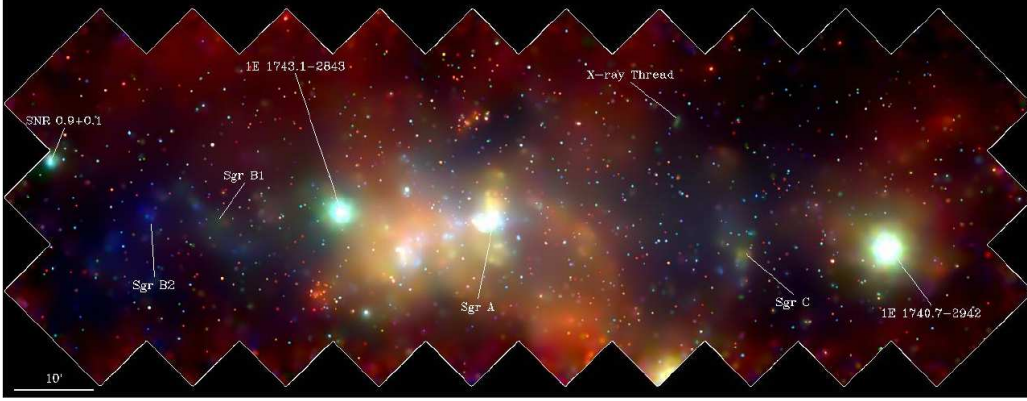


Figure 1: Full *Chandra* ACIS-I mosaic of the Galactic Centre (Wang *et al.* 2002).

1. The *Chandra* Galactic Centre Survey

In July 2001 Wang *et al.* (2002) performed an imaging survey with *Chandra*/ACIS-I of the central $0.8 \times 2^\circ$ of the Galactic Centre (GC), revealing a large population of previously undiscovered discrete weak sources with X-ray luminosities of $10^{32} - 10^{35} \text{ erg s}^{-1}$ (Figure 1). The nature of these ~ 800 newly detected sources, which may contribute $\sim 10\%$ of the total X-ray emission of the GC, is as yet unknown. In contrast to the populations of faint AGN discovered from recent deep X-ray imaging out of the Galactic plane, our calculations suggest that the extragalactic contribution to the hard point source population over the entire Wang *et al.* survey is $\leq 10\%$, consistent with the $\log(N)$ - $\log(S)$ function derived from the *Chandra* Deep Field data (*e.g.* Brandt *et al.* 2001). The harder ($\geq 3 \text{ keV}$) X-ray sources (for which the softer X-rays have been absorbed by the interstellar medium) are likely to be at the distance of the GC, while the softer sources are likely to be foreground X-ray active stars or cataclysmic variables (CVs) within a few kpc of the Sun. The distribution of X-ray colours suggests that only a small fraction of the *Chandra* sources are foreground objects. The combined spectrum of the discrete sources shows emission lines characteristic of accreting systems such as CVs and X-ray binaries (XRBs). These hard, weak X-ray sources in the GC are therefore most likely a population of XRBs; candidate classes include quiescent black hole binaries or quiescent low-mass XRBs, CVs, and high-mass wind-accreting neutron star binaries (WNSs).

2. VLT Observations

The first step in determining the nature of this population is to identify counterparts to the X-ray sources. Achievement of our goals requires astrometric accuracy and high angular resolution to overcome the confusion limit of the crowded GC. We used ISAAC on the VLT to obtain high-resolution *JHK* images in order to identify a statistically significant number of counterparts to the X-ray sources on the basis of the *Chandra* astrometry. We imaged 26 fields within the *Chandra* survey region, containing a total of 79 X-ray sources. The average extinction towards the GC is $K \sim 2-3$. Therefore with our images, which have a magnitude limit of $K=20$, we will detect

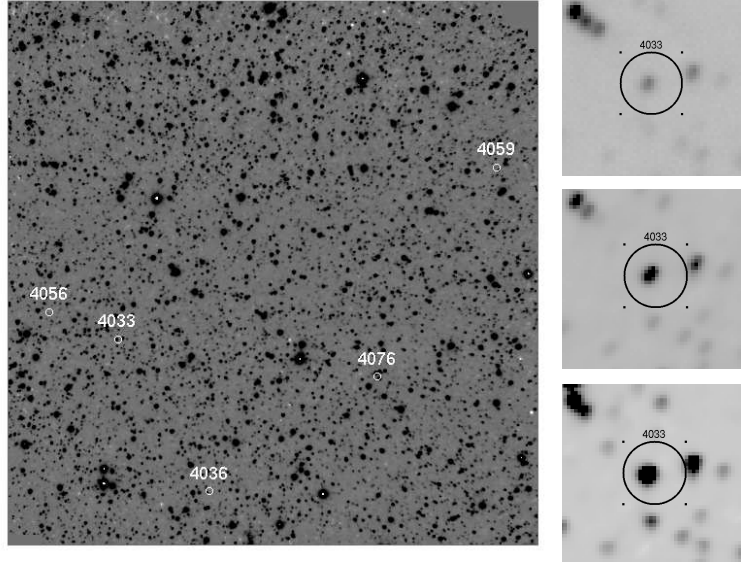


Figure 2: Left: an example ISAAC K_s -band field (2.5 arcmin^2), showing the positions of 5 *Chandra* X-ray sources. Right: Zoom-in view ($8'' \times 8''$) of the $1.3''$ error circle of one of the *Chandra* sources in this field, overlaid on the J (top), H (middle), and K_s (bottom) ISAAC images.

any XRBs with *early-type* (O, B, A) or *evolved* mass donors, all of which would have intrinsic K magnitudes ≤ 17 at 8.5 kpc.

After analyzing the photometric data (Bandyopadhyay *et al.* 2005), we selected 28 candidate counterparts (magnitudes $K \sim 12-17$) for follow-up K -band spectroscopy, to search for the characteristic accretion signatures, such as Brackett γ emission, that would denote the identity of true X-ray source counterparts. The long slit spectra were obtained with ISAAC in service mode between April-September 2005, using a $1''$ slit width ($R=450$).

3. Results: Imaging

For 65% of the X-ray sources in our VLT fields, there are 1-2 resolved K -band sources within the $1''$ *Chandra* error circle (Figure 2); only a small number of X-ray sources have more than two potential counterparts. Over 50% of the *Chandra* sources have no potential J -band counterparts, and only a few of the potential IR counterparts have colours consistent with unreddened foreground stars (Figure 3). This is consistent with the expectation that the majority of the detected X-ray sources are heavily absorbed and thus are at or beyond the GC.

The magnitude and colour distribution of the identified candidate counterparts is redder than expected for WNS systems. For an average GC extinction of $A_K \sim 2-3$, the peak of the expected reddened K magnitude distribution for the WNSs is $\sim 16-17$. The peak of the observed reddened K magnitudes for the potential counterparts is $\sim 14-15$, with an $(H-K)$ colour of $\sim 1-2$, as expected for later-type stars. However, some potential counterparts do have colours consistent with early-type stars.

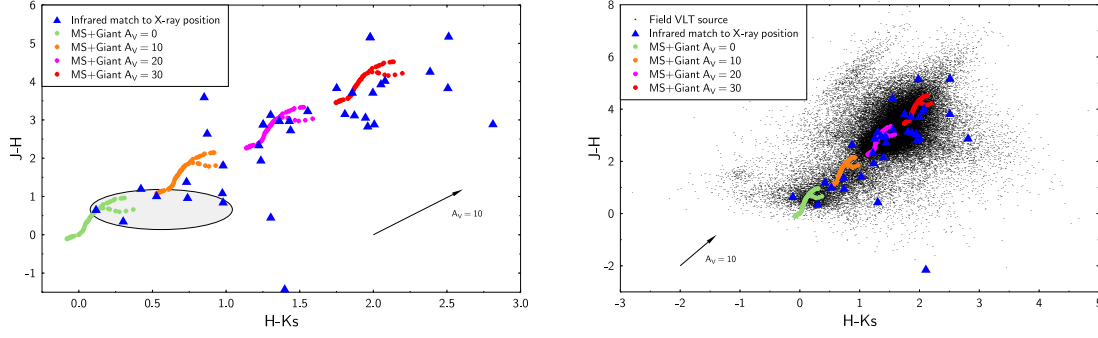


Figure 3: *Left:* Colour-colour diagram of astrometrically-selected candidate IR counterparts to the *Chandra* sources. The shaded oval indicates where unreddened AGN/QSOs would most likely be located. The theoretical main sequence and giant branches are indicated at visual extinctions of 0, 10, 20, 30 ($A_K/A_V = 0.11$). *Right:* Colour-colour diagram showing all sources in our VLT fields. This illustrates that the vast majority of field stars are consistent with highly reddened stars; thus most of the stars (including potential X-ray counterparts) are at the distance of the GC (or beyond).

3.1 Extinction

There are no K -band counterparts for $\sim 35\%$ of the *Chandra* sources. This is larger than the expected fraction of background AGN from the CDF estimate, though other groups have predicted larger fractions (up to 50%). However, we find that the extinction in the GC is highly structured on scales as small as $5''$ – $15''$ (corresponding to a physical scale of 0.2–0.6 pc at 8.5 kpc), even in the K -band (Gosling *et al.* 2006). Although the average extinction in the GC is $A_K \sim 2.3$, in some of the observed dust patches and lanes, this extinction can rise to levels of as much as $A_K \sim 6$.

Comparison of areas of low apparent stellar density with the colour-colour diagrams of the fields confirms that this “granularity” is due to extinction rather than to any intrinsic “clumpiness” in the underlying stellar distribution (Figure 4). These results are in agreement Schultheis *et al.* (1999), who suggested that structures in the GC stellar population distribution smaller than the resolution of their imaging ($\sim 1''$) were responsible for observed double peaks in histograms of star counts versus A_V in the GC. Our results are also consistent with the finding of Nishiyama *et al.* (2006) that the IR extinction varies between different lines of sight in regions around the GC; thus the previously assumed universality of the IR extinction law for the GC is not valid, especially on small angular scales. Therefore we need to carefully determine which X-ray sources actually have no IR counterpart down to the $K=20$ magnitude limit, and which are located in areas of locally heavy extinction.

4. Results: Spectroscopy

The primary accretion signature in the K -band which distinguishes a true X-ray counterpart from a field star is strong Brackett γ emission; this technique of identifying XRB counterparts has been verified with observations of several well-studied GC XRBs (see *e.g.* Bandyopadhyay *et al.* 1999). As these *Chandra* sources are weaker in X-rays than the previously known population of

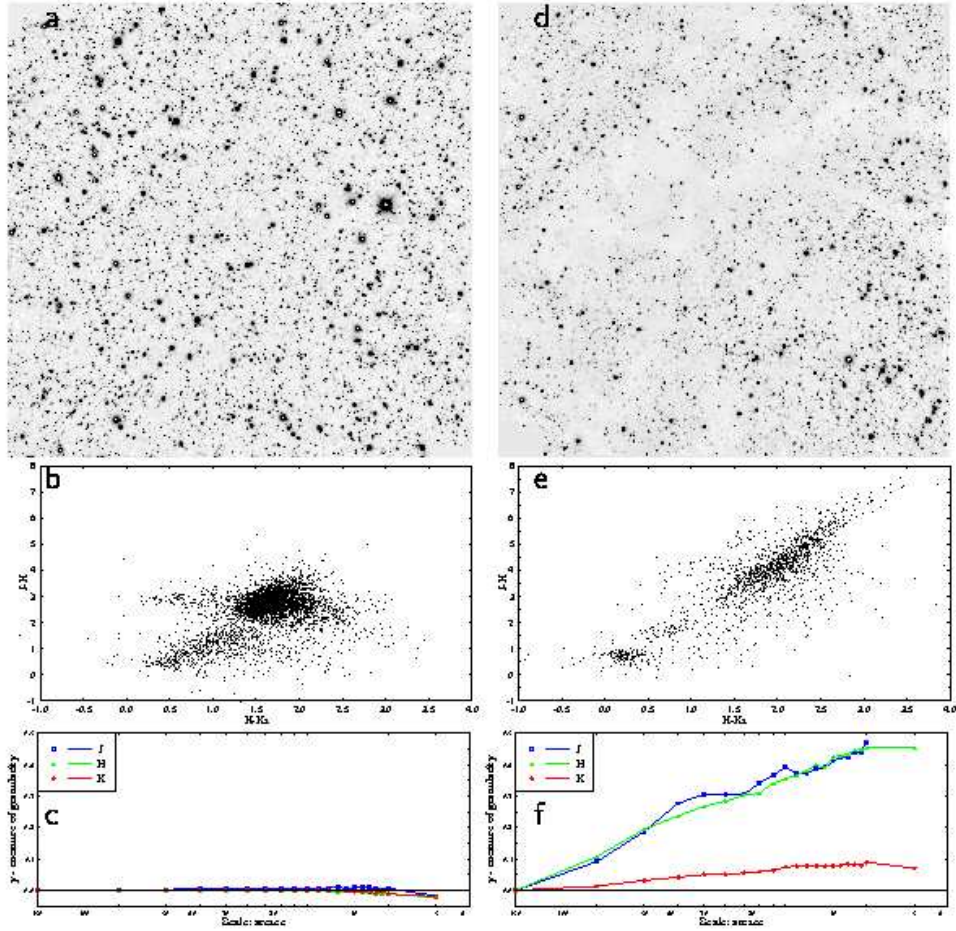


Figure 4: (a) K_S -band image of a field with no apparent structure in the stellar distribution. (b) Colour-colour diagram of the stars in the field shown in (a). There are two main loci of stars: the local population to the bottom left, and the Galactic centre population in the centre. (c) The measures of granularity for the field shown in (a). In all three bands it does not deviate from zero, as expected for a random distribution. (d) K_S -band image of a field with obvious regions of low stellar density compared to the field average. (e) Colour-colour diagram for the field shown in (d). Note, compared to the colour-colour diagram shown in (b), the locus for the GC stars is extended to high reddening. (f) The measure of granularity for the field shown in (d) shows that there is measurable structure in all three bands.

Galactic XRBs, and thus have lower accretion rates, the emission signature will likely be somewhat weaker than in the more luminous XRB population.

The spectra indicate that almost all of the candidate counterparts are K/M giant stars, identified by the strong CO absorption bands above $2\mu\text{m}$ and several metal (Ca, Na, Mg) absorption lines (Figure 5). None of the observed spectra exhibited the emission line signatures characteristic of accreting binaries. A possible explanation for this result is that the accretion signatures could be too weak to be measurable, for example if the accretion rate was low at the time of observation, or if the emission was self-absorbed by the mass donor (as was observed for the transient V404 Cyg in quiescence; Shahbaz *et al.* 1996). However, the Br γ accretion signature is clearly detected in

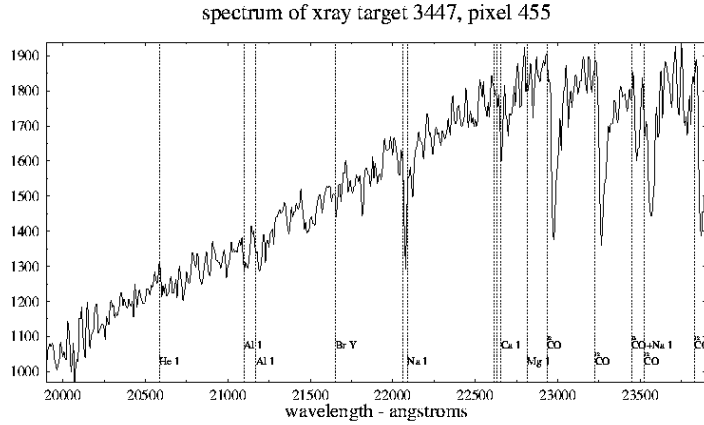


Figure 5: Example of one of the K -band spectra obtained of possible counterparts to the GC X-ray sources. From the sample of 36 targets for which spectra were obtained with ISAAC, none exhibited emission lines characteristic of accreting binaries. The spectra of the majority of the stars observed appeared to be K or M giants, with strong CO bandheads as well as other metal absorption lines.

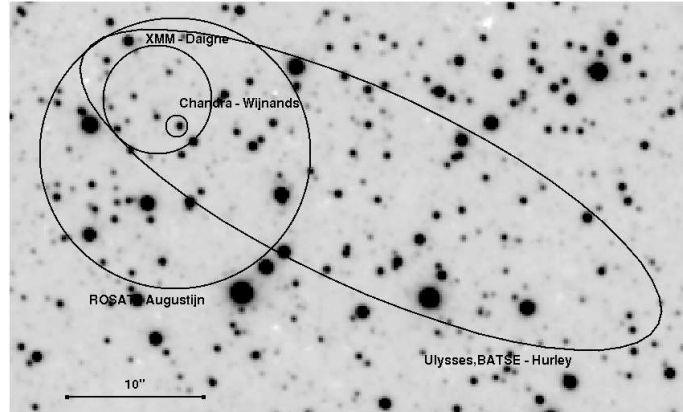


Figure 6: Position error circles for GRO J1744-28 as determined by different X-ray instruments. These are overlaid on the K_S -band image taken with the VLT.

the IR spectra of CVs, which are only weak X-ray emitters with a similar X-ray luminosity range to the *Chandra* sources (Dhillon *et al.* 1997).

A more likely explanation for the lack of observed emission in the candidate spectra is that the stars we observed are not the true counterparts to the X-ray sources. Our imaging survey had a limiting magnitude of $K=20$, so our VLT survey would detect XRBs with either early-type or evolved mass donors. Therefore it is likely that the majority of the true IR counterparts belong to a lower mass population of stars that at GC distances are fainter than the limits of our survey.

4.1 The Bursting Pulsar

Included within the *Chandra* GC survey was the X-ray source known as the “bursting pulsar”,

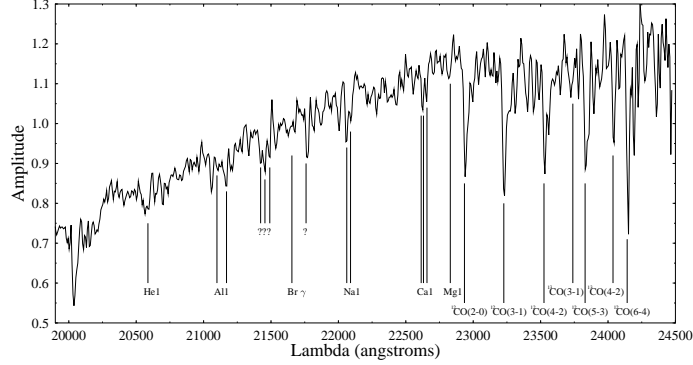


Figure 7: *K*-band spectrum of the candidate counterpart to the bursting pulsar (GRO J1744-28). The strong CO bands indicate that this star is a late-type giant. The lack of Br γ emission suggests that this star is likely not the true counterpart to the X-ray pulsar.

GRO J1744-28. This source was discovered by BATSE in 1995 and is only the second system known to have exhibited Type II bursts. The accuracy of the measured position of GRO J1744-28 has improved dramatically over the time since its discovery. The current best measurement of its position is that of Wijnands & Wang (2002) obtained with *Chandra*. With the VLT we detected one stellar source within the *Chandra* error circle (Figure 6). Its position is $R.A. = 17^{\text{h}}44^{\text{m}}33^{\text{s}}.07$, $Dec. = -28^{\circ}44'26''.89$ with a $0''.1$ error. This source was detected in all three bands with observed magnitudes of $J = 18.98 \pm 0.02$, $H = 15.68 \pm 0.01$ and $K_S = 14.43 \pm 0.01$ (the photometry was calibrated using 2MASS). The measured extinction for the source is $A_K = 1.64$, $A_H = 2.80$ and $A_J = 4.86$. This gives the prospective counterpart to GRO J1744-28 an intrinsic magnitude of $J = 14.12$, $H = 12.88$ and $K_S = 12.79$. With these magnitudes and colours, the star is likely to be an M giant.

As part of our spectroscopic program, we obtained a *K*-band spectrum of the candidate counterpart to GRO J1744-28 (Figure 7). From the absorption lines in the spectra, it appears that the potential counterpart is indeed an M type giant. There are strong ^{12}CO bandheads, some evidence of ^{13}CO bandheads, and Mg, Ca and Na absorption features. The presence of an Fe line near the $^{13}\text{CO}(3-1)$ bandhead is a feature found in M2+ III giants. No emission lines are evident.

Taking values for a typical NS and a late M III giant produces results for the dynamical and physical properties of this binary system that suggest this star is unlikely to be the true counterpart. A typical late M III has $M_c = 1.4 \pm 0.4 M_{\odot}$ and $R_c = 131.9 \pm 11.7 R_{\odot}$. Taking the extremes of NS masses from the literature, we use a typical NS of $M_x = 1.6 \pm 0.6 M_{\odot}$. Using the orbital period given by Finger *et al.* (1996) of $P_{\text{orb}} = 11.8337 \pm 0.0013$ days we find that the system has a semi-major axis of $a = 32 \pm 4 R_{\odot}$ and that the Roche lobe (RL) of the giant is $R_{\text{RL}} = 11 \pm 4 R_{\odot}$, in reasonable agreement with the values given by Finger *et al.*.

It therefore seems unlikely that this star is the true counterpart as if it was, the X-ray source would be orbiting within the envelope of the companion. It is most likely that the source observed is simply a coincidental astrometric match to the X-ray error circle, and that the true counterpart is a fainter star beyond the limits of this survey. This is highly likely due to the very high stellar

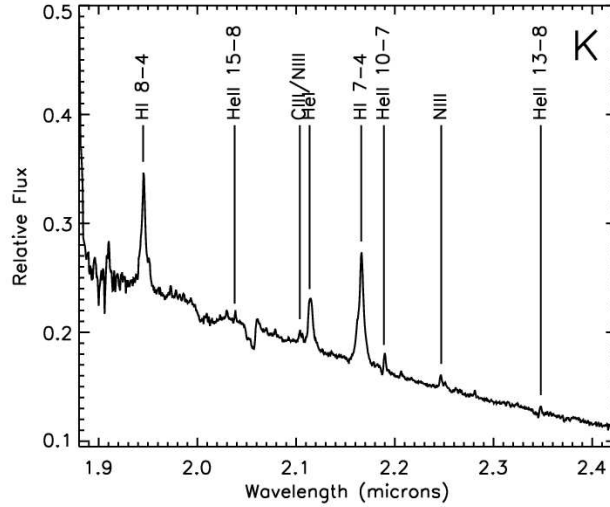


Figure 8: K-band spectrum of the first of the Galactic centre X-ray sources to have a spectroscopically identified counterpart. Emission lines that identify this star as an accreting system include Br δ (HI 8-4) and Br γ (HI 7-4).

density towards the GC, where the average stellar separation in the K_S band is $1.94''$ (Gosling *et al.* 2006).

Our survey extended to a limiting magnitude of $K_S = 20$. Taking into account the measured extinction of $A_J = 4.86$, this means that all stars of type A main sequence (MS) or earlier were detected. Therefore, if the counterpart is a MS star beyond the limits of this survey, we can place a limiting mass of $1.6M_\odot$ to the companion for a F0 V type star or lower. This also places an upper size limit of $\sim 1.5R_\odot$ for the companion. This would indicate that the X-ray emission is not powered by Roche lobe overflow, but more likely arises from low level accretion of the wind of the companion. It will be necessary to carry out deeper observations of the source to definitively identify the true counterpart, and thus the mode of accretion.

5. Conclusions

We have presented results from the search for the counterparts to the recently discovered faint X-ray sources in the GC. We found astrometric matches to the positions of $\sim 70\%$ of our X-ray targets. Photometry of these prospective counterparts and follow-up spectroscopy revealed that almost all of these candidate counterparts were late-type K/M giant stars. However, none of the spectra we obtained with the VLT showed the characteristics emission signatures expected in accreting binaries.

By combining our spectroscopic results with those of Mikles *et al.* (2006), who have one confirmed spectroscopic counterpart to a *Chandra* GC source from a sample of six targets (Figure 8), we are able to draw some preliminary conclusions about the nature of the X-ray source population. A small proportion, perhaps $\sim 3\%$, may be HMXBs/WNS. The remaining majority are likely to be canonical LMXBs and CVs with late-type main-sequence mass donors with K magnitudes ≥ 21 at 8.5 kpc.

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