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Exploring the Nature of Weak Chandra Sources near the Galactic Centre

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Abstract. We present results from the first near-IR imaging of the weak X-ray sources discovered in the *Chandra*/ACIS-I survey (Wang *et al.* 2002) towards the Galactic Centre (GC). These ~ 800 discrete sources, which contribute significantly to the GC X-ray emission, represent an important and previously unknown population within the Galaxy. From our VLT observations we will identify likely IR counterparts to a sample of the hardest sources, which are most likely X-ray binaries. With these data we can place constraints on the nature of the discrete weak X-ray source population of the GC.

Keywords: Accretion - Stars: binaries - Stars: X-rays - Stars: infrared

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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 $10^{32} - 10^{35} \text{ erg s}^{-1}$. 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 (Figure 1) 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).

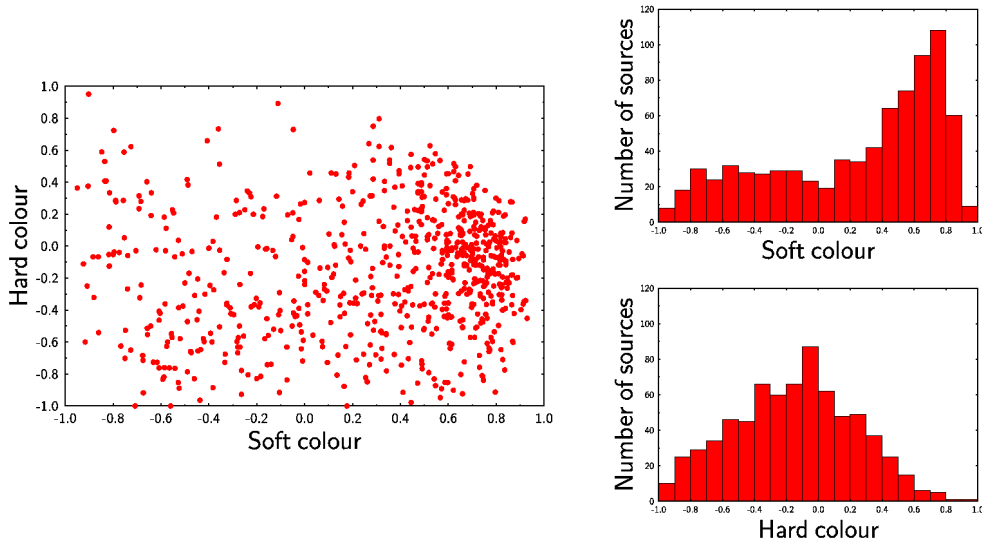


FIGURE 1. Characteristics of the X-ray source population detected in the *Chandra* mosaic. Left panel: colour-colour diagram; right panel: histogram of the number of soft and hard X-ray sources in the GC field. Soft colour is defined using the 1-3 and 3-5 keV bands, and hard colour using the 3-5 and 5-8 keV bands. The distribution of X-ray colours suggests that only a small fraction of the *Chandra* sources are foreground objects.

WHAT ARE THESE POINT SOURCES?

Pfahl *et al.* (2002) have considered in detail the likely nature of these *Chandra* sources and concluded on the basis of binary population synthesis (BPS) models that many, if not the majority, of these systems are WNSs. Depending on the mass of the companions, the WNSs may belong to the “missing” population of wind-accreting Be/X-ray transients in quiescence or the progenitors of intermediate-mass X-ray binaries (IMXBs; $3 \leq M/M_{\odot} \leq 7$). The existence of tens of thousands of quiescent Be/XRBs in the Galaxy has been predicted since the early 1980s (Rappaport & van den Heuvel 1982; Meurs & van den Heuvel 1989), while it has only recently been recognized that IMXBs may constitute a very important class of XRBs that had not been considered before (King & Ritter 1999; Podsiadlowski & Rappaport 2000). The Wang *et al.* *Chandra* survey may contain as many as 10% of the entire Galactic population of WNSs. In addition to the WNSs, Pfahl *et al.* estimate that a small fraction of the *Chandra* sources could be CVs or transient low-mass XRBs/black-hole binaries.

OUR VLT IMAGING PROGRAM

The first step in determining the nature of this population is to identify counterparts to the X-ray sources. The successful achievement of our goals requires astrometric accuracy and high angular resolution to overcome the confusion limit of the crowded GC. The 2MASS survey is severely confusion limited in the GC and is of insufficient depth

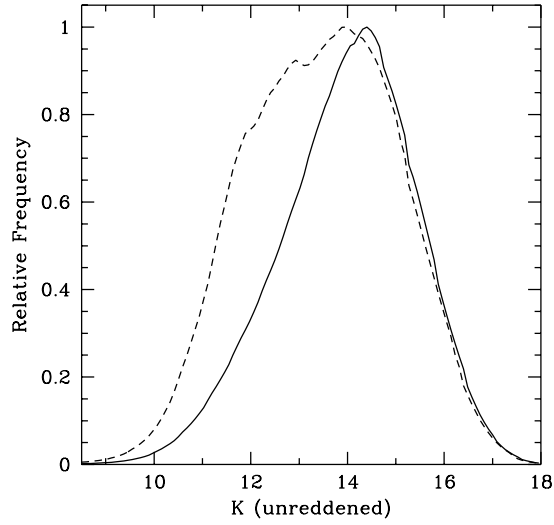


FIGURE 2. Distributions of intrinsic K magnitudes for the mass donors in WNS XRBs for two WNS formation models (Pfahl *et al.* 2002). The main difference between the two models is the relative proportion of binaries with intermediate- (solid line) and high-mass (dashed line) companions.

($K=14.3$) to detect the majority of the expected counterparts. We therefore constructed a survey program using the ISAAC IR camera 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 85 X-ray sources. In constructing our VLT program, we preferentially selected for hard X-ray sources from the *Chandra* survey, as the soft sources are most likely to be foreground. Of the hardest sources we selected those detected with an $S/N \geq 3$ and which were imaged in the central area of the ACIS-I field (due to the off-axis characteristics of the *Chandra* PSF, greater astrometric accuracy can be obtained for sources in the central regions of the field).

For the early-type donors of the WNSs, we would expect intrinsic magnitudes of $K=11-16$, with the peak of the magnitude distribution at $K \sim 14$ (Figure 2); these are therefore readily distinguishable from the majority of late-type donors expected for black hole X-ray transients which generally have $K \geq 16$ in quiescence. The average extinction towards the GC is $K \sim 3$; therefore with our images, which have a magnitude limit of $K=20$, we should detect most of the WNSs.

RESULTS: IR MAGNITUDES AND COLOURS

For 65% of the X-ray sources in our VLT fields, there are one or two resolved K -band sources within the $1''$ *Chandra* error circle; only a small number of X-ray sources have more than two potential counterparts (Figure 3). 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 4). This is consistent with

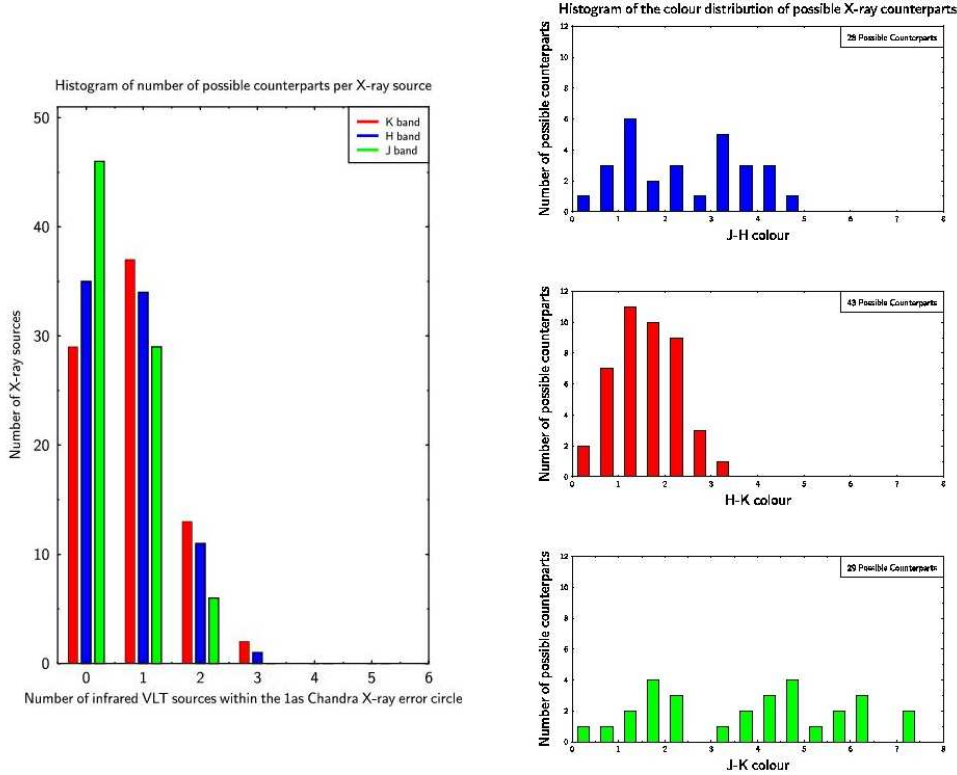


FIGURE 3. Left panel: histogram of the number of candidate IR counterparts per *Chandra* source within a 1'' X-ray error circle. Right panel: distribution of IR colours of potential counterparts.

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 (see Figures 3 and 4). 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.

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 note that the extinction in the GC is extremely variable, even in the K -band. This is evident from visual inspection of our VLT data, which clearly show areas of heavier than average extinction in the form of dust patches and lanes. 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.

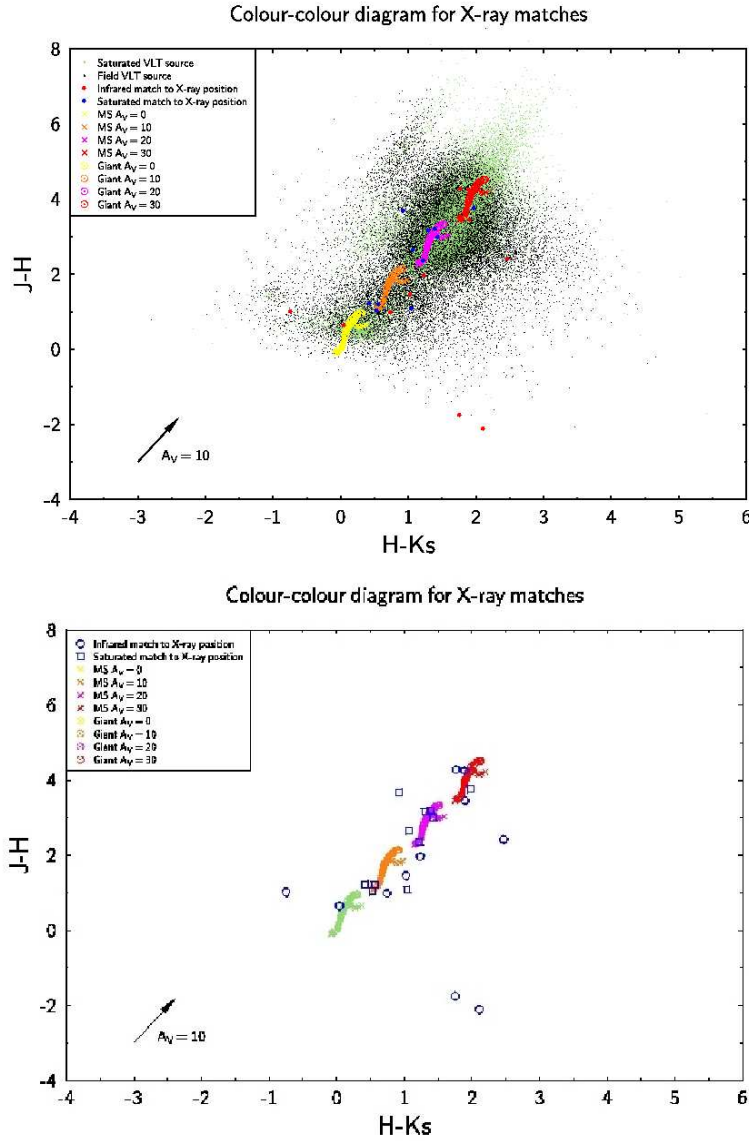


FIGURE 4. Top panel: colour-colour diagram showing all stars in our VLT fields. Bottom panel: colour-colour diagram of all potential IR counterparts to the *Chandra* sources for which we have full three-colour information. The theoretical main sequence and giant branch are indicated at visual extinctions of 0, 10, 20, 30. The IR colour-colour diagram illustrates that vast majority of field stars are consistent with highly reddened main sequence stars; thus most of the stars (including potential X-ray counterparts) are at the distance of the GC (or beyond).

THE PROGRAM CONTINUES: IR SPECTROSCOPY

We have selected 36 of the best candidate counterparts for follow-up IR spectroscopy (candidate magnitudes $K \sim 12-17$); the goal of these observations will be to identify the X-ray source counterparts via detection of accretion signatures. 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 Galactic XRBs, and thus have lower accretion rates, the emission signature will likely be somewhat weaker than in the more luminous XRB population. However, the Brackett γ accretion signature is clearly detected in the IR spectra of CVs, which are only weak X-ray emitters with a similar X-ray luminosity range to the *Chandra* sources (see e.g. Dhillon *et al.* 1997 for IR emission signatures in CVs). Therefore we expect the spectroscopic identification to be definitive even for these low-luminosity X-ray sources. For our brighter targets ($K=12-14$) the spectra we obtain will allow us not only to identify the counterpart via its emission signature but also to spectrally classify the mass donors if absorption features are detected, a crucial step in determining the nature of this new accreting binary population.

Identifying IR counterparts to these newly discovered X-ray sources provides a unique opportunity to obtain a census of the various populations of accreting binaries in the GC and may ultimately allow a determination of each system's physical properties. As this *Chandra* survey may contain 1% of the entire population of accreting binary systems in the Milky Way, our results will have important implications for our understanding of XRBs in the Galaxy, including their formation, evolutionary history, and physical characteristics. The results of this observational program will represent an important "calibration" point for BPS codes so that they can be more reliably applied to the study of other types of XRBs that have evolved from massive stars, including ultraluminous X-ray sources (ULXs) in external galaxies. Finally, the combination of the imaging data and our spectroscopic follow-up will allow us to identify the nature of an entirely new population of X-ray emitters within our Galaxy.

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