

Exploring a New Population of Compact Objects: X-ray and IR Observations of the Galactic Centre

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Abstract. I describe the IR and X-ray observational campaign we have undertaken for the purpose of determining the nature of the faint discrete X-ray source population discovered by Chandra in the Galactic Center (GC). Data obtained for this project includes a deep Chandra survey of the Galactic Bulge; deep, high resolution IR imaging from VLT/ISAAC, CTIO/ISPI, and the UKIDSS Galactic Plane Survey (GPS); and IR spectroscopy from VLT/ISAAC and IRTF/SpeX. By cross-correlating the GC X-ray imaging from Chandra with our IR surveys, we identify candidate counterparts to the X-ray sources via astrometry. Using a detailed IR extinction map, we are deriving magnitudes and colors for all the candidates. Having thus established a target list, we will use the multi-object IR spectrograph FLAMINGOS-2 on Gemini-South to carry out a spectroscopic survey of the candidate counterparts, to search for emission line signatures which are a hallmark of accreting binaries. By determining the nature of these X-ray sources, this FLAMINGOS-2 Galactic Center Survey will have a dramatic impact on our knowledge of the Galactic accreting binary population.

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INTRODUCTION

The unprecedented sensitivity and angular resolution of *Chandra* has been utilized by Wang *et al.* (2002; hereafter W02 [15]) and Munro *et al.* (2003; hereafter M03 [10]) to investigate the X-ray source population of the Galactic Center (GC). The W02 ACIS-I survey of the central $0.8^\circ \times 2^\circ$ of the GC revealed a population of ~ 800 previously undiscovered discrete weak sources with X-ray luminosities of $10^{32} - 10^{35} \text{ erg s}^{-1}$. M03 imaged the central 40 pc^2 (at 8 kpc) around Sgr A*, finding an additional ~ 2300 discrete point sources down to a limiting flux of 10^{31} erg/s . More recently, a deeper *Chandra* survey of the central $\sim 1^\circ$ around Sgr A* has been obtained; the combination of all of these surveys has revealed a total of $>10,000$ discrete sources (Figure 1; Munro *et al.* 2008, hereafter M08 [12]). The harder ($\geq 3 \text{ keV}$) X-ray sources are likely to be at the distance of the GC, while the softer sources are likely to be foreground X-ray active stars or CVs within a few kpc of the Sun. Some individual sources have been identified as X-ray transients, high-mass stars, LMXBs, and CVs. However, the nature of the majority of these newly detected sources is as yet unknown.



FIGURE 1. ACIS-I mosaic of the GC, combining the surveys of W02, M03, and M08, as well as additional archival *Chandra* data in the region [12]. Red is 1-3 keV, green is 3-5 keV, and blue is 5-8 keV.

X-RAY/IR CROSS-CORRELATION

We have undertaken an IR and X-ray observational campaign to determine the nature of the faint discrete X-ray source population discovered by *Chandra* in the GC. We have begun by cross-correlating the source catalog of Muno *et al.* (2006; hereafter M06 [11]) with *JHK* images of 26 selected $2.5''^2$ regions obtained with ISAAC on the VLT to identify candidate IR counterparts to the X-ray sources [2].

Our original search for the counterparts to the GC X-ray sources used positions obtained through private communication with the authors of the W02 survey. However, M06 re-analyzed the data and produced a significant refinement of the astrometry of the W02 data; thus the positions reported for $\sim 50\%$ of the X-ray sources in the finalized M06 catalog showed a shift of $\sim 0.5 - 1''$ from the positions we used for our original cross-correlation analysis. This astrometric shift has a substantial impact on the identification of candidate IR counterparts, since the average stellar separation in our VLT fields is $1.94''$ in *K*-band [5]. In addition, the revised M06 analysis revealed that a larger number of X-ray sources were detected in the original *Chandra* survey than had been previously cataloged. As a result, our VLT imaging survey covers 130 X-ray sources, compared to the 77 X-ray sources originally reported in Bandyopadhyay *et al.* [2].

Comparing the colours and magnitudes of the candidate counterparts to the general field populations (Figure 2), we find no clearly significant difference between the magnitude distribution of candidate counterparts and those of the field population, aside a slight over-abundance of more local, bright, blue candidate counterparts (see especially the left-hand panel of Figure 2). The colours indicate that the majority of potential counterparts are located at or beyond GC distances ($A_v \geq 10 - 30$), with a smaller number consistent with a foreground stellar population. 30.8% (40) of the X-ray sources that lie within the area covered by our VLT observations do not have detections within the X-ray error circle in any of the three IR bands. 58.5% (76) of the X-ray sources had zero candidate counterpart detections in the *J*-band, compared to 48.5% (63) for the *H*-band and only 36.2% (47) for the *K_S*-band.

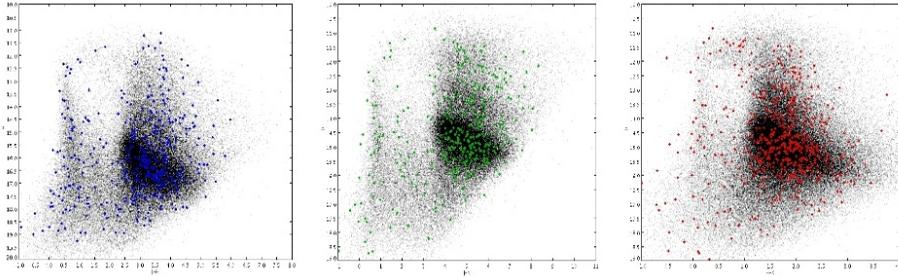


FIGURE 2. Colour-magnitude diagrams of the candidate counterparts to the X-ray sources (*coloured points*) and the field stars from the VLT Nuclear Bulge observations (*black points*). *Left, blue:* $H \nu J-H$; *middle, green:* $K_S \nu J-K_S$; and *right, red:* $K_S \nu H-K_S$. The large extension towards high values of colour (*right* in each panel) indicates that there is a significant amount of near-IR extinction.

To examine the significance of these numbers of “non-matches”, we performed a Monte Carlo test. We added a random $0''-30''$ shift to the position of each X-ray source, re-ran the matching of the X-ray and IR data, and recorded the number of candidate counterparts identified for the match; we performed this test 10,000 times, having different random shifts in the X-ray position for each trial.

The Monte Carlo test revealed that, given randomized X-ray positions, the expected fraction of X-ray sources that would have no IR counterparts across all three bands is $41.6 \pm 4.3\%$ (1σ error). For the actual positions, 30.8% of X-ray sources had no candidate IR counterpart, which is 2.5σ lower. Similarly for J , H and K_S -bands considered individually, the Monte Carlo simulation revealed that the fraction of X-ray sources for which there would be no matches if the X-ray sources are randomly scattered across the fields are $64.8 \pm 4.1\%$, $58.3 \pm 4.3\%$ and $47.5 \pm 4.4\%$ respectively. The numbers of “non-matches” for the *true* X-ray positions are thus *lower* than would be expected from random at the 1.5σ , 2.3σ and 2.6σ levels for J , H and K_S respectively. This result indicates that even with the extremely high IR source density in the GC, with the corrected and accurate X-ray astrometry we are now finding significantly *more* X-ray/IR matches than would be expected from chance coincidence.

EXTINCTION

From our analysis of the VLT images, we find that the IR extinction in the GC can vary on scales as small as $5''$ (0.2-0.6 pc at 8 kpc; [5]). Some areas show little evidence of this “granularity”, while others are highly structured. The relationship of extinction to wavelength in the IR is a power law with slope α [7]; the “canonical” value for α is ~ 2 [14, 13]. In contrast, for the GC we find a mean value of $\alpha = 2.64 \pm 0.52$; and furthermore, along any given line of sight to the GC α varies substantially, ranging from $\sim 1.8-3.6$ [6]. We find that the “universal” IR extinction law is *not* universal in the GC. Therefore to obtain reddening-corrected stellar photometry in the GC, a local value for the JHK extinction (on scales $< 20''$) must be measured and applied.

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 [1]. With this technique, using SpeX on IRTF we conclusively identified a heavily-reddened early-type star as the IR counterpart to the GC source “Edd-1” (CXOGC J174536.1-285638; [8, 9]). However, for an additional 16 candidate counterparts for which we obtained K -band spectra with ISAAC, we did not detect Br- γ emission. A possible explanation is that the accretion signatures could be too weak to be measureable, for example if the accretion rate was low at the time of observation, or if the emission was self-absorbed by the mass donor. However, a more likely explanation 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 spectroscopic data would only detect XRBs with either early-type (as in “Edd-1”) or evolved mass donors. Therefore it is likely that the majority of the true IR counterparts belong to a lower mass population of stars which includes the mass donors of CVs and LMXBs (as has been suggested by [3, 4], and other authors); at GC distances, these counterparts are fainter than the limits of our survey.

FUTURE WORK

Cross-correlation of our IR imaging of the GC with the *Chandra* surveys will produce a large number of IR candidate counterparts to the X-ray sources. Due to the extremely high stellar density in the Nuclear Bulge, many of these astrometric “matches” are likely to be chance superpositions, as indicated by our initial spectroscopic data. With thousands of candidate counterparts, traditional long-slit single-target spectroscopy would be a prohibitively inefficient method by which to identify true counterparts. Thus we will need to follow-up with multi-object IR spectroscopy to find the true matches: this is the work which will be performed with the FLAMINGOS-2 Galactic Center Survey.

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