# Deep O/IR Survey Of Chandra Galactic Bulge Fields

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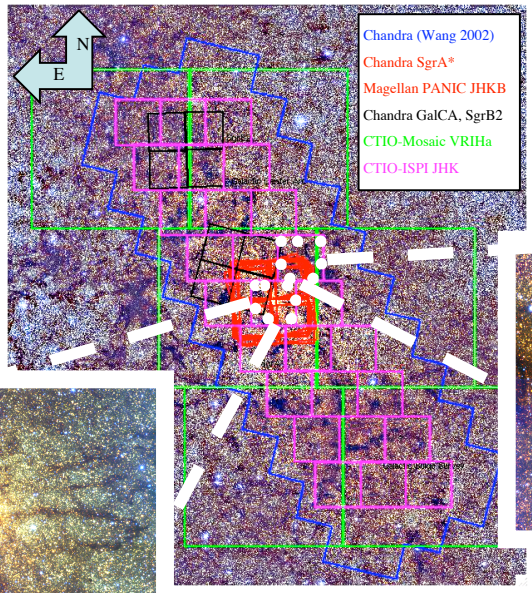
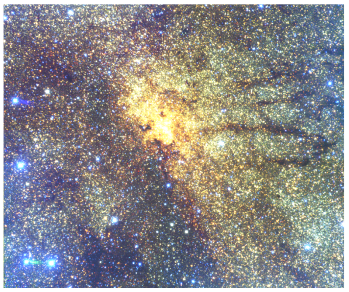
## Introduction

We are conducting near-IR and optical survey of archival Chandra fields in the Galactic Bulge, as part of the Chandra Multiwavelength Plane survey (ChaMPlane), which is an effort to measure the space density and luminosity function of all types of accreting binaries, particularly concentrating on the low luminosity populations, CVs, qLMXBs where these quantities are not known to within several orders of magnitude. The Galactic Bulge has been found to harbor several thousand X-ray point sources, which probably represent the majority of the Galaxy's X-ray binary population. These sources were found by Muno et al (2003) to be concentrated in a centrally condensed spherical "cusp" distribution centered on the Galactic Center (SgrA*). On top of the central peak which extends out a few arcmin in radius is a broader population associated with the Bulge, and discovered by Wang et al (2002). Many X-ray transients are also detected in the Bulge with Chandra and XMM.

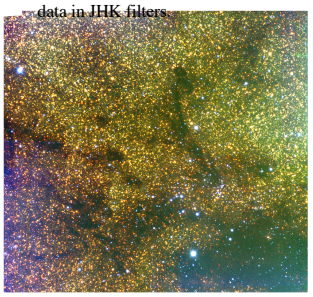
The Galactic Bulge sources are characterized by extremely hard X-ray spectra, which is in part due to the large column density toward the bulge. However spectral fitting, hardness-rations and quantile analysis suggest that a large subset of the sources are intrinsically hard, and reasonably described by a power law with photon index =0. The typical luminosities of these objects are in the range $10^{31-33}$ erg/s. The largest well studied class of objects fitting this description are high magnetic field cataclysmic variables known as Intermediate Polars (IPs). Certain high mass X-ray binaries can also produce these characteristics, in particular Be/X systems at low accretion rate. All other "obvious" explanations seem to fail, for example coronally active stars, which have soft spectra typically represented by a 1keV thermal plasma would not be detectable given the high NH ($10^{22-23}$), similarly most Neutron Star LMXBs are too soft and Black Hole binaries too faint. Although it is by no means certain that another hitherto un-encountered binary is responsible, the two hypotheses IP vs Be/X make predictions that are testable by ground based follow-up observations: High mass counterparts will be detectable in the Bulge while typical IP counterparts will not, owing to the confusion limit and faintness. These observations require IR imaging to penetrate the obscuring dust clouds, while optical imaging is needed to study the many objects lying in the foreground Galactic Plane.



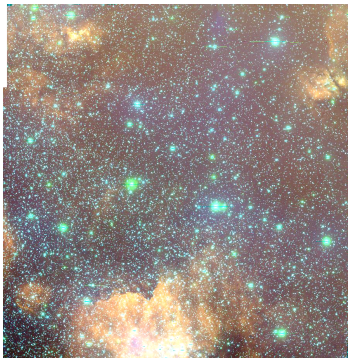

This 2MASS mosaic of 2x2 degrees shows the area coverage of our survey in X-ray, optical and IR wavebands. The 2x0.75 degree strip observed by Wang (2002) with Chandra is shown in blue. The whole Chandra area is covered by NOAO Mosaic imaging down to 24th magnitude in VRIHa. Magenta shows the extent of our IR observations to date. The two blowups are "truecolor" images made from ISPI data in JHK filters.



ISPI JHK ~10'x10', centered on SgrA*

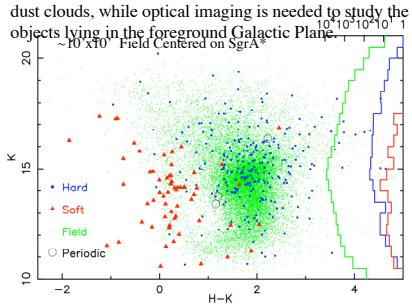


ISPI JHK ~10'x10'



Mosaic VRHa ~0.5x0.5 Degrees

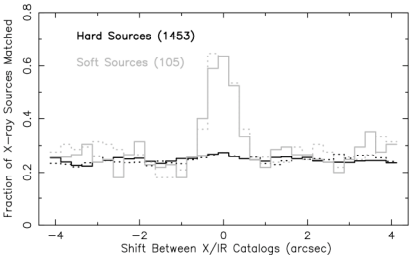
While the infrared images are crowded with stars, limiting the effective photometric depth attainable to the confusion limit at K~15, the optical images are dominated by glowing clouds of partially ionized gas, as seen in the VRHa image at left, covering 0.5x0.5 degrees (the central green box on the map image). Absorption limits the distance to which we can detect even bright stars to about 3 kpc for limiting magnitude of 24.




The Color Magnitude Diagram in the near infrared can be a powerful tool for separating foreground objects from those located in the Galactic Bulge. Visual extinction (Av) averages 25 magnitudes, equivalent to approximately 1.8mag in H-K color index. Positional counterparts to Chandra X-ray sources are plotted according to the following X-ray selection criteria:

Blue = SNR>3 @ 2.5-8 keV AND SNR<3 @0.3-2.5 keV. Red=SNR>3 @ 0.3-1.5 keV

## Source Matching and Peakup Test

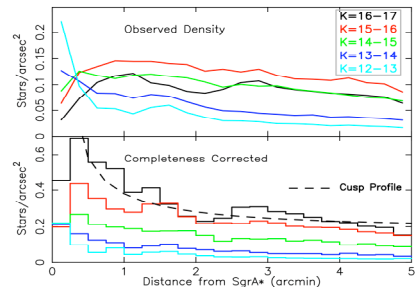



PEAKUP TEST 10'x10' FIELD.

| Kmag ($k_1$-$k_2$) | $N_m$ | $N_{ran}$ | $\sigma$ | $N_{exc}$ | Sig | C | $UL_{90\%}$ | UL (%<$k_2$) |
|---|---|---|---|---|---|---|---|---|
| Hard Sources (1453) | | | | | | | | |
| 15-16 | 84 | 83.4 | 9.0 | 0.6 | 0.1 | 0.56 | 24 | 7.1 |
| 14-15 | 83 | 67.2 | 7.8 | 15.8 | 2.0 | 0.73 | 36 | 5.4 |
| 13-14 | 37 | 36.1 | 5.9 | 0.9 | 0.2 | 0.83 | 10 | 3.0 |
| 12-13 | 30 | 23.3 | 4.3 | 6.7 | 1.6 | 0.96 | 13 | 2.3 |
| 11-12 | 11 | 8.6 | 2.4 | 2.4 | 1.0 | 1.0 | 11 | 1.4 |
| 10-11 | 6 | 5.3 | 1.9 | 0.7 | 0.4 | 1.0 | 6 | 0.7 |
| 9-10 | 2 | 2.2 | 1.3 | -0.2 | -0.1 | 1.0 | 2 | 0.2 |
| 8-9 | 1 | 0.7 | 0.8 | 0.3 | 0.4 | 1.0 | 1 | 0.1 |
| Soft Sources (105) | | | | | | | | |
| 15-16 | 8 | 5.4 | 2.3 | 2.6 | 1.1 | 0.56 | 9 | 92 |
| 14-15 | 21 | 4.9 | 2.4 | 16.1 | 6.6 | 0.73 | 26 | 84 |
| 13-14 | 10 | 3.0 | 1.2 | 7.0 | 6.1 | 0.83 | 11 | 59 |
| 12-13 | 13 | 1.2 | 1.1 | 11.8 | 10.4 | 0.96 | 14 | 48.6 |
| 11-12 | 21 | 0.4 | 0.7 | 20.6 | 30.9 | 1.0 | 21 | 35.2 |
| 10-11 | 12 | 0.2 | 0.5 | 11.8 | 25.9 | 1.0 | 12 | 15.2 |
| 9-10 | 4 | 0.0 | 0.1 | 4.0 | 29.3 | 1.0 | 4 | 3.8 |
| 8-9 | 0.0 | 0.0 | 0.0 | 0.0 | - | 1.0 | 0 | 0 |

NOTE. — In the ~ 10'x10' PANIC survey area we detect: 184467 detected K-band stars, 1453 hard X-ray sources, 105 soft X-ray sources. 2MASS point-source catalog used for K<12. $N_m$= Number of X-ray sources with one or more matches, measured at zero offset. $N_{ran}$= random matches, $\sigma$ uncertainty in number of random matches. $N_{exc}$= number of "excess" matches above random level. $Sig$ significance of excess. $C$ Completeness fraction for K-band stars. $UL$= Completeness corrected upper-limit on the number of counterparts at 90% significance. $CP$= Cumulative $UL$ brightward of $k_2$ expressed as % of number of X-ray sources.

Determining the incidence of random matches is crucial in attempting detect a counterpart population. By repeatedly matching the X-ray and IR catalogs over a large number of random offsets we build up a picture of the random match level Nran, its fluctuations and ultimately whether or not there is a significant excess. Further simulations are then performed to compute the 90% upper limit on the number of real matches among those observed.




K-band stellar density profiles in the Galactic Center Region. Completeness corrections were determined by simulation.

**References**

Hong et al 2005, ApJ, astro-ph/0509782 (see poster)

Laycock et al 2005, ApJL, astro-ph/0509783

Muno et al 2003, ApJ,589, 225

Grindlay et al 2005, ApJ, astro-ph/0509781 (see poster)

Pfahl et al 2002, ApJ, 571, 37

van den Berg et al 2005 (See poster)

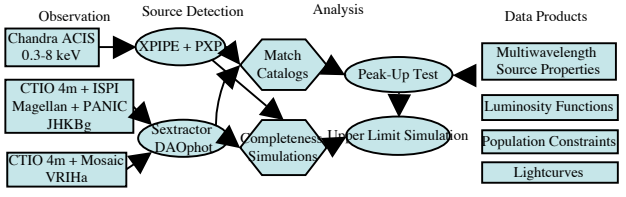
Wang et al, 2002, Nature, 415, 148

Zhao et al 2005, ApJ, astro-ph/0509785

## Progress: Population Constraints for Galactic Center Region

Our scientific goal is to measure or constrain the counterparts and hence determine the relative abundance of different species in the Bulge X-ray binary population. For the inner 10'x10' centered on SgrA* we have derived an upper limit of 10% on the fraction of hard cusp-sources that can be HMXBs, at 90% confidence. This result is based on the lack of a statistically significant excess of K<15 stars coincident with Chandra error circles. In Table 1 reproduced from our recent paper, the peak-up test results and upper limits are given for a series of magnitude ranges, for both the hard cusp sources and foreground Galactic Plane sources. Optical counterparts have been identified for ~90% of the foreground sources and a spectroscopy program is underway to identify them.

**Map of Uniform Data Reduction and Analysis**




Current efforts are focused on extending this analysis to include ALL archival Chandra observations in the bulge. The flow-chart above summarizes the many steps in our reduction/analysis pipeline. Each dataset undergoes astrometric and photometric calibration to obtain catalogs suitable for cross-correlation with an absolute minimum of positional uncertainty (significantly below 1"). Each waveband presents a unique set of challenges. Optical data reduction see Zhao et al (2005), X-ray reductions see Hong et al (2005). The IR data are calibrated via the 2MASS point source catalog. To account for crowding (loss of faint stars due to their brighter neighbors and to blending) extensive "artificial star" simulations are performed, generating as a bonus the IR luminosity function.