Two Thousand X-ray Stars in the Inner 20 pc of the Galaxy

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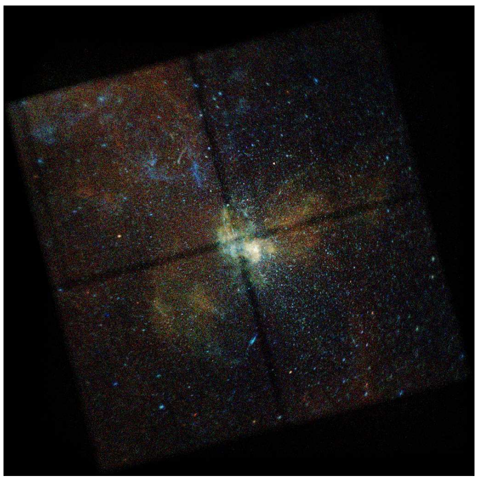
Introduction

There are several reasons to study faint Galactic X-ray sources in the 2–8 keV band:

- These systems are important laboratories for studying shock physics, the interactions between strong magnetic fields and plasma, the equation of state of degenerate matter, general relativity, and exotic pathways of binary evolution.
- As Galactic X-ray sources, they are important tracers of stellar populations in the vast regions of the Galaxy too heavily extinguished at optical wavelengths by gas and dust.
- Unresolved X-ray point sources may comprise a large fraction of the diffuse X-ray emission observed toward the Galactic plane, the origin and energetics of which is otherwise a mystery.

Large numbers of these systems are likely to be observable at the Galactic center, since both the stellar density (Mezger, Duschl, & Zylka, 1996, A&A Rev., 7, 289) and the surface brightness of diffuse X-ray emission (Koyama et al. 1996, PASJ, 48, 249) increases dramatically in the 20 pc around Sgr A*.

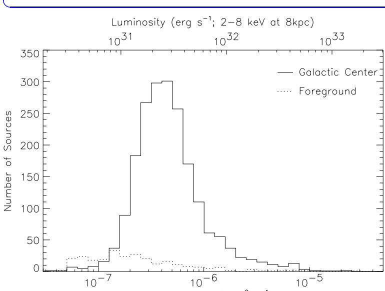
Observations of Sgr A*



Three color image of the 17' by 17' field around Sgr A*. Red: 2.0–3.3 keV. Green: 3.3–4.7 keV. Blue: 4.7–8.0 keV.

We have observed the 17' by 17' field around Sgr A* with *Chandra* for a total of 625 ks. 590 ks of observations have been combined for this image.

X-ray Point Sources



Foreground sources are those detected between 0.5–1.5 keV, for which 1 photons cm^{-2} s^{-1} = 3×10^{-9} erg cm^{-2} s^{-1} (0.5–2.0 keV). Galactic center sources are absorbed below 1.5 keV, and 1 photons cm^{-2} s^{-1} = 8×10^{-9} erg cm^{-2} s^{-1} (2.0–8 keV).

We have detected 2287 point sources in the field, where previous observations only resolved 17. We estimate that about 60 of these sources are background AGN. Sources in the foreground (detected below 1.5 keV) account for 278 objects, and the rest are likely to be at the Galactic center. The faintest sources have luminosities of 10^{30} erg s^{-1}, while we estimate that our sample is complete in the inner region of the survey down to about 10^{31} erg s^{-1}.

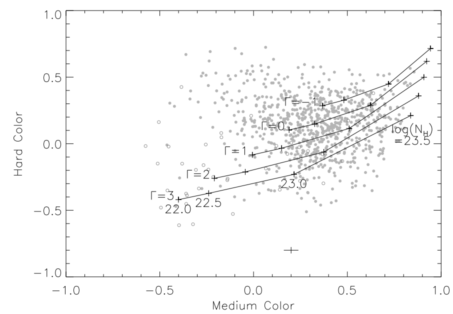
Nature of the Point Sources

Object	$\log(L_X)$ $\log(\text{erg s}^{-1})$	Spectrum
MS Stars	25 – 30.3	$kT < 1$ keV Plasma
YSOs	29 – 31.1	$kT = 1 - 10$ keV Plasma
RS CVn/Algol	29 – 31.7	$kT = 0.1 - 2$ keV Plasma
WR/O Stars	31 – 35	$kT = 0.1 - 6$ keV Plasma
CVs	29.5 – 32.6	$kT = 1 - 10$ keV Plasma
Pulsars	29.3 – 39	$\Gamma = 1 - 2.5$ PL ; $kT = 0.3$ keV BB
NS LMXBs	31.6 – 38	$kT \sim 0.3$ keV BB ; $\Gamma = 1 - 2$ PL
BH LMXBs	30 – 39	$\Gamma = 2$ PL
HMXBs	32.7 – 38	$\Gamma = 0.5 - 2.5$ PL

Notes: Luminosities represent ranges reported in the literature. Below $L_X \sim 10^{29}$ erg s^{-1}, sources are difficult to detect, and lower bounds at this level represent the sensitivity limits of the respective observations. Spectra of point sources are typically described by thermal plasma, power laws (denoted by PL), or blackbodies (denoted by BB). For the LMXBs, we include only spectral properties in quiescence ($L_X < 10^{34}$ erg s^{-1}).

While main sequence stars are not luminous enough to contribute to the number of Galactic center sources we observe, all other classes of source may be present in the field.

Spectra of the Point Sources

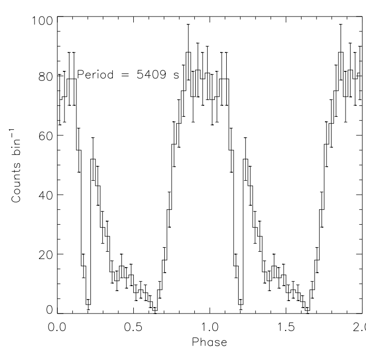


Colors for the 913 sources with more than 60 net counts ($L_X \approx 10^{31}$ erg s^{-1}). The colors are defined as the fractional difference between the count rates in two energy bands, $(H - L)/(H + L)$, where H is the higher and L the lower energy band, so that the ratio is bounded by -1 and $+1$. The soft color is defined by the fractional difference between counts with energies 2.0–3.3 keV and 0.5–2.0 keV. The hard color is defined as the fractional difference between the counts with energies 3.3–4.7 keV and 4.7–8.0 keV. Data from point sources are indicated in grey, with open circles denoting foreground sources and filled circles those sources at the Galactic center. The crosses connected with solid lines indicate the expected colors for absorbed power laws, with the values indicated on the plot. Larger hard colors are produced by flatter power laws, as indicated by the series of lines progressing toward the top of the plot. Higher absorption primarily increases the soft color between $\log(N_H) = 21.5 - 23$. For $\log(N_H) > 23$, the hard color is also increased dramatically.

Hard colors less than 0.1 are consistent with thermal spectra, and indicate that sources are likely to be YSOs, RS CVNs, or CVs. However, more than half of the sources brighter than 10^{31} have hard colors larger than 0.2, which corresponds to $\Gamma < 1$ power laws. Only two populations have been identified with such hard spectra: magnetic cataclysmic variables (polars and intermediate polars; Ezuka & Ishida 1999, ApJS, 120, 277), and wind-accreting X-ray pulsars in high mass X-ray binaries (HMXBs; Campana et al. 2002, ApJ, 575, L15).

The large number of hard sources is difficult to understand. We would only expect about 150 magnetized CVs in this field if we scale the local number density (Warner 1995, in *Cataclysmic Variable Stars*) to the Galactic center. The number of wind-accreting neutron stars expected is uncertain because it is not clear how much star formation has occurred in the last 10^8 years (Serabyn & Morris 1996 Nature, 382, 602).

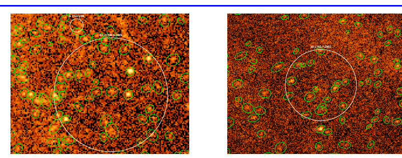
Periodic X-ray Variability



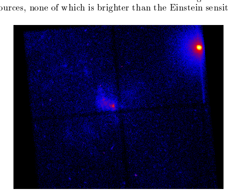
Folded light curve of one of the five sources with periodic variability.

We found that 5 of these 161 brightest sources exhibited periodicities between 90 minutes and 4.5 hours. These sources are probably also polars or intermediate polars, although it is possible that they are very slowly rotating neutron stars.

Quiescent LMXBs



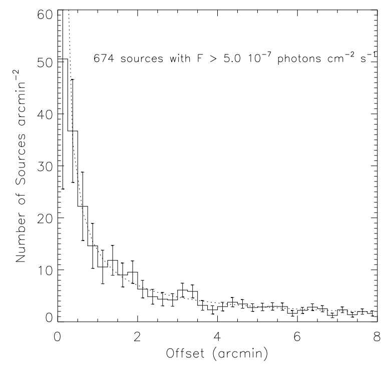
Left: Chandra sources (green) detected within the error circles of (*i*) A 1742−289, a transient X-ray binary that was localized via its radio counterpart in 1975, and (*ii*) AX J1745.6-2901, a neutron star LMXB discovered with ASCA that exhibits thermonuclear bursts and eclipses at its 8.5 hour orbital period. *Right:* One of six error circles from the Einstein survey of the Galactic center. One circle is associated with the Sgr A complex, while the rest, like this one, contain multiple X-ray sources, none of which is brighter than the Einstein sensitivity threshold ($10^{32.9}$ erg s^{-1}, 0.9–4.0 keV at 8 kpc).



A bright transient was observed during the second observation, on 2000 October 26, and is not present in the other observations. It had a flux in outburst of 8×10^{-11} erg cm^{-2} s^{-1}, but was not present with a flux greater than 4×10^{-15} erg cm^{-2} s^{-1} $(1-\sigma)$ in the previous observation. The source also exhibited one thermonuclear X-ray burst. It is most likely the known transient GRS 1741.9–2853, and we place it at 17h 45m 2.23s, -28° 54′ 51″.5 (J2000).

As many as eight bright transients have been observed in this field, which suggests that neutron star and black hole X-ray binaries form very efficiently near the Galactic center.

Radial Distribution of Point Sources



Surface density of Galactic center point sources as a function of offset, within 8' from Sgr A*. The dotted line is the best-fit power law.

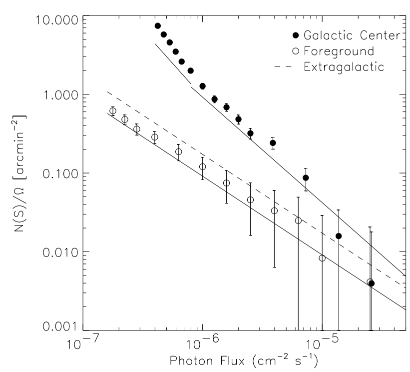
The surface density of Galactic center sources can be fit with a power law:

$$\Sigma(\rho) = (13 \pm 3)\rho^{-1.0\pm0.1}\text{sources arcmin}^{-2}, \quad (1)$$

where ρ is the offset from Sgr A* in arcminutes. This distribution is consistent with an isothermal sphere observed in projection. It is also consistent with the spatial distribution of infrared stars observed in the inner 30 pc of the Galaxy (Mezger et al. 1996). This demonstrates that the X-ray sources trace the stellar population at the Galactic center.

If the nature of these sources can be identified, they could provide important information about the star formation history in the galactic center. If they are neutron stars accreting from the winds of massive companions, it would confirm that star formation occurred in the last tens of millions of years. If they are magnetized cataclysmic variables, they would provide the first tracers of the distribution of low-mass stars in the Galactic center.

Contribution to the Diffuse Emission



Cumulative number of sources as a function of flux from the inner 9′ of the field. The counts have been normalized according to (1) the solid angle over which we conducted our survey, and (2) the reduced surface density that would be expected for sources over the entire 9′ survey, given that the density of sources falls of as $1/\rho$. We have only included those sources with fluxes for which we believe our sample is complete. About 1/3 of the sources in out survey satisfy our strict selection criteria. The model distributions (*solid lines*) appear to under-estimate the observed distribution because of the Eddington bias in the observed number counts, which is removed in the model distribution.

We have modeled the unbinned flux distribution using a maximum-likelihood technique. The cumulative number counts can be modeled approximately by:

$$N(S) = \begin{cases} (4.4 \pm 0.2)\left(\frac{S}{4\times10^{-7}}\right)^{-1.7\pm0.2} & 4.0\times10^{-7} < S < 8.0\times10^{-7} \\ (1.11 \pm 0.07)\left(\frac{S}{8\times10^{-7}}\right)^{-1.34\pm0.08} & S > 8.0\times10^{-7} \end{cases} \quad (2)$$

The total flux contributed by sources brighter than a limiting flux is then proportional to $S^{-(\alpha-1)}$. We find that point sources brighter than our completeness limit (about 10^{31} erg s^{-1}) produce 5–10% of the flux previously attributed to diffuse emission (Koyama et al. 1996; Sidoli & Mereghetti 1999 A&A, 349, L49). However, if the integral flux contribution continues to increase as $S^{-0.7}$ down to luminosities of 10^{29} erg s^{-1}, point sources could produce *all* of the observed diffuse emission.

Summary

We have identified 2287 point sources in the 17' by 17' field around the Galactic center, of which 287 are foreground sources and fewer than 60 are likely to be background AGN. We find:

- Although many classes of source are likely to be present in the field, the spectra of the majority of the Galactic center sources are consistent with a power law ($E^{-\Gamma}$) with photon index $\Gamma < 1$. This indicates that there are large numbers of magnetically accreting white dwarfs (polars and intermediate polars) and/or neutron stars (pulsars) in the field.
- As many as 8 bright X-ray transients have been observed previously in the field, but are currently in quiescence. These systems are likely to be black hole or neutron star X-ray binaries.
- The surface density of X-ray sources falls off as $1/\rho$ away from Sgr A*, which is very similar to the distribution of stars observed in the infrared.
- The observed point sources account for 5–10% of the previously reported diffuse X-ray emission, but can account for all of it if the $\log(N) - \log(S)$ distribution extends down to 10^{29} erg s^{-1} with the slope observed at low fluxes.