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Chandra multi-wavelength plane (ChaMPlane) survey: design and initial results

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Abstract. The Chandra Multiwavength Plane (ChaMPlane) Survey of the galactic plane incorporates serendipitous sources from selected Chandra pointings in or near the galactic plane ($b<12°$; $\geq$20 ksec; lack of bright diffuse or point sources) to measure or constrain the luminosity function of low-luminosity accretion sources in the Galaxy. The primary goal is to detect and identify accreting white dwarfs (cataclysmic variables, with space density still uncertain by a factor of $>$10-100), neutron stars and black holes (quiescent low mass X-ray binaries) to constrain their space densities and thus origin and evolution. Secondary objectives are to identify Be stars in high mass X-ray binaries and constrain their space densities, and to survey the H-R diagram for stellar coronal sources. A parallel optical imaging under the NOAO Long Term Survey program provides deep optical images using the Mosaic imager on the CTIO and KPNO 4-m telescopes. The $36' \times 36'$ optical images (Hα, R, V and I) cover $\sim 5\times$ the area of each enclosed Chandra ACIS FOV, providing an extended survey of emission line objects for comparison with Chandra. Spectroscopic followup of optical counterparts is then conducted, thus far with WIYN and Magellan. The X-ray preliminary results from both the Chandra and optical surveys will be presented, including logN-logS vs. galactic position (l,b) and optical identifications.

Key words: surveys – X-rays – binary: X-ray – white dwarfs – stars: neutron

1. Introduction and objectives

The remarkable angular resolution of the Chandra X-ray Observatory enables the first high sensitivity survey of low luminosity accretion sources in the Galaxy for which optical identifications, and thus source content, can be reasonably expected. The arcsec source positions allow relatively unambiguous optical (and IR) identifications even in the most crowded galactic fields (not including dense clusters), and the point source sensitivity for sources within $\sim 4'$ of the field center allows sources with power law spectra (with photon index Γ = 1.7, as expected for both low- and high-mass X-ray binaries) to be detected at galactic bulge distances ($\sim$8 kpc) with "hard" X-ray luminosities L_X(2–8keV) $\sim 2\times10^{31}$ erg/s. This, in turn, enables the detection of the bright-half of the luminosity distribution for accreting white dwarfs (CVs), nearly the full distribution (as presently known) of qLMXBs containing either neutron stars (NSs) or black holes (BHs), and the full distribution (again, as known) of accreting high mass X-ray binaries (HMXBs) such as the accreting Be binary systems. This capability allows a major advance in previous galactic surveys, which most recently have been conducted with the ROSAT all sky survey (Voges et al 1993) and the Einstein galactic plane survey (Hertz, Bailyn, Grindlay et al 1990). XMM is of course also now able to contribute in a major way to the study of faint galactic X-ray source populations, and preliminary results have been reported by Motch et al (2002) and Warwick (these proceedings).

We have initiated the Chandra Multiwavelength Plane (ChaMPlane) survey to probe the luminosity functions and space density of cataclysmic variables (CVs) and quiescent low mass X-ray binaries (qLMXBs) containing either neutron stars (NSs) or black holes (BHs). Detecting CVs on galactic scales would constrain the origin (are they all from primordial binaries?) and evolution (which ones produce SNIa's?) of these most common accretion-powered sources. The qLMXBs, in turn, are the reservoir of even more exotic binary evolution processes leading, alternatively, to the millisecond pulsars and the largest known samples of stel-

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lar mass black holes. Secondary objectives for ChaMPlane include measuring and mapping the other major reservoir of accreting binaries, the Be systems with NS (and possibly BH) companions; and the search for isolated BHs accreting from giant molecular clouds. Finally, ChaMPlane will acquire perhaps the largest sample of identified stellar coronal sources and enable measurements or limits of X-ray activity of stars across the H-R diagram.

2. Survey design and expectations

The X-ray survey is derived from serendipitous sources detected in Chandra observations of galactic fields with nominal exposure times ≥20–30ksec, galactic latitude $b<12°$, and lack of bright sources, or extended emission in the field which would reduce sensitivity. The observations are restricted to those taken with the ACIS-I or -S instruments on Chandra to allow for spectral coverage to harder energies (important for the often-absorbed galactic fields) and at least hardness ratio (X-ray colors) if not actual spectral analysis. In order to achieve significant coverage of regions of the galactic plane and to acquire significant samples, the original proposed goal was to obtain ∼100 Chandra fields. Given the rate at which "clean" galactic fields are being observed with Chandra, this is expected to take 5 years to acquire. The X-ray data processing is done with the same XPIPE scripts as developed (Kim et al 2003) for the high latitude ChaMP survey. Thus far data have been processed for some 40 fields (of which 15 are reported here) in the same 3 bands as for ChaMP (cf. Fig. 3 below) for analysis of X-ray fluxes and colors.

A parallel deep optical imaging survey is being conducted with the CTIO and KPNO 4m telescopes and large field (36′) Mosaic cameras under the NOAO Long Term Surveys Program (see Zhao et al, these proceedings). This provides the required deep optical image for initial source identification (and followup spectroscopy) but is also designed to do an initial selection for likely accretion-powered objects by imaging in Hα vs. R to look for "blue" objects in the (Hα–R) vs. R color magnitude diagram, given that Hα is a (nearly) ubiquitous feature of accretion disks or flows. To provide additional constraints on the possible counterpart's spectral type and reddening (particularly if followup spectra are not possible), additional images in V and I are acquired so that a (V-R) vs. (R-I) plane can be constructed. Unfortunately the reddening vector is relatively closely aligned with the main sequence in this color system so that photometric classifications are relatively coarse if relative or differential reddening is not known. The red filter system (V,R,I) is itself chosen to minimize extinction and to provide the comparison R band for Hα. Total exposure times in Hα, R, V and I are ∼2.5h, 0.5h, 0.3h and 0.3h, respectively, to reach ∼5% photometry at R∼24 (10% in Hα) which allows a threshold of EW(Hα) ∼15Å for the 80Å wide Hα filter in the Mosaic cameras. Photometry has now been obtained on 24 fields, or ∼1/4 the desired total.

The CV space density has been estimated recently to be $\sim 10^{-5}$ pc^{-3} (Patterson 1998) but this is still uncertain by an order of magnitude (either way) and is largely based on both optical and X-ray surveys typically within 1kpc. The galactic distribution is essentially unknown but could be probed by ChaMPlane, for the brighter CVs, out to the galactic bulge. For a likely CV scale height of ∼200pc (e.g. Schwope et al 2002), the predicted total number interior to the Sun is $\sim 4\times10^5$. The local CV space density extrapolated to the galactic center would suggest a total ChaMPlane-CV "column" of ∼20, of which perhaps ∼ 3–5 might be detected given N_H and luminosity distributions. The likely much larger population of "quiescent" CVs (with probable $L_X \leq 10^{30}$ erg/s) suggested by Howell, Rappaport and Politano (1997) and Townsley and Bildsten (2002) could be detected to ∼1-3kpc and contribute a comparable total.

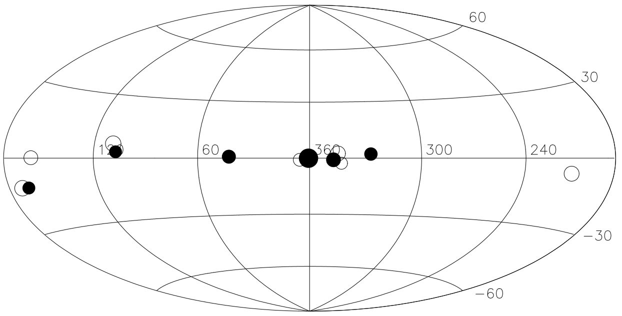

Fig. 1. Initial ChaMPlane ACIS-I (solid) and -S (open) fields in galactic coordinates.

The qLMXB estimates are based on millisecond pulsar surveys and soft X-ray transients for the NS and BH systems, respectively, with uncertainties due to both source evolution and duty cycles. The total population interior to the solar circle is probably ≥100× below the CV numbers, yielding perhaps 0.1–1 per ChaMPlane field, but again the uncertainties are large. Similar totals, or perhaps larger, obtain for estimates of the Be binary populations expected. The above estimates suggest that ChaMPlane could double (at least) the total numbers of accretion-powered X-ray binaries when identifications are completed with our followup spectroscopy. Expected numbers of previously unrecognized objects, such as isolated $\sim 10 M_\odot$ BHs accreting from GMCs, are much more difficult to predict (Agol and Kamionkowski 2002) and will likely require IR photometry and spectroscopy. An important discriminant throughout between compact objects and coronal stars is the hard X-ray spectrum (>2–3 keV) expected from accreting compact objects but not (except in flaring) stars.

3. Initial X-ray results

In Fig. 1 we show the galactic distribution of the first sample of 15 ChaMPlane fields analyzed. We first derive logN-logS, the integral number-flux counts, for comparison with other galactic and high latitude surveys. For initial analysis, sources selected from within the central 4′ of the Chandra field center (to minimize off-axis degradation of point spread function and sensitivity) and with at least 10cts in the broad band (0.3–8keV). For each field, we derive the corresponding flux for this detection limit and accumulate the effective sky areal coverage as a function of flux limit. Source counts detected are converted to flux assuming a power law spectrum ($\Gamma = 1.7$), appropriate for CVs, qLMXBs or AGN, and are corrected for absorption by the nominal N_H for that field. Results are shown in Fig. 2 for two cuts on galactic longitude for the 9 fields with $\ell \leq 44°$.

The excess sources in the galactic bulge are distributed with -1 slope appropriate to a disk distribution vs. the -3/2 slope over the same flux range exhibited by the AGN counts from ChaMP (Green et al, these proceedings), plotted as the lower curve in both figures and dashed line (top figure), which connects the Chandra Deep Field North and brighter flux ASCA counts. The galactic source population is at least a factor of 3-5 over the AGN counts and is unlikely to be due to enhanced stars in the bulge since these would be expected to be predominantly soft sources (though pre-main sequence stars may contribute). The X-ray colors and limits plotted in Fig. 3 show that most of these bulge sources are consistent with hard and absorbed spectra as expected for accretion sources. The two points at lower right may be sources with both soft and hard spectral components, such as found in magnetic CVs, and would be foreground sources.

4. Initial optical results

In Fig. 4 we show the partial R image for the Galactic Center Arc field (Mosaic; showing a chip gap) with ACIS-I chip overlay (black lines) and central pointing position (diamond) together with Chandra sources (numbers) and their 2σ error circles. The image shows both that about half of the sources have optical IDs in this image (to R$\sim$23) for which the reddening is large ($\log(N_H) \sim 22.1$). The (Hα-R) vs. R color magnitude diagram for this field (Fig. 5) shows that two Chandra sources are significant Hα objects. The R $\sim$ 20.2 object labelled X-ray CV is source #5 in Fig. 4 and enlarged in the inset in upper right corner: the 0.6$''$ radius circle shows the excellent positional astrometry, while #60 shows a typical blank field (R $\geq$ 23.5) source. Source 5 is confirmed as an emission line object and probable CV in our Magellan spectrum shown in Fig. 6. The spectrum shows Balmer line emission broadened beyond the instrumental resolution as well as weak HeI emission suggesting a reddened dwarf nova. Its X-ray/optical flux ratio is $F_X/F_R \sim 0.2$ and is plotted vs. R in Fig. 7 as the square symbol along with values for the $\sim$ 300 sources identified in these 15 fields. In Fig. 3 it is consistent with a foreground CV with $\log(N_H) \sim 21$ and photon index 1 (or a brems spectrum). The point labelled Be? is a second spectroscopically confirmed counterpart: a probable Be HMXB system. Its relatively large value of $F_X/F_R \sim 0.002$ suggests it is an accretion-powered source, probably containing a neutron star. The fact that the bulge sources have systematically lower F_X/F_R values than the anti-center sources is likely due to differential reddening: both F_R and F_X values were "de-absorbed" by the full N_H in each field. The plotted R $\gtrsim$ 10 magnitudes were actually observed as R $\gtrsim$ 14.

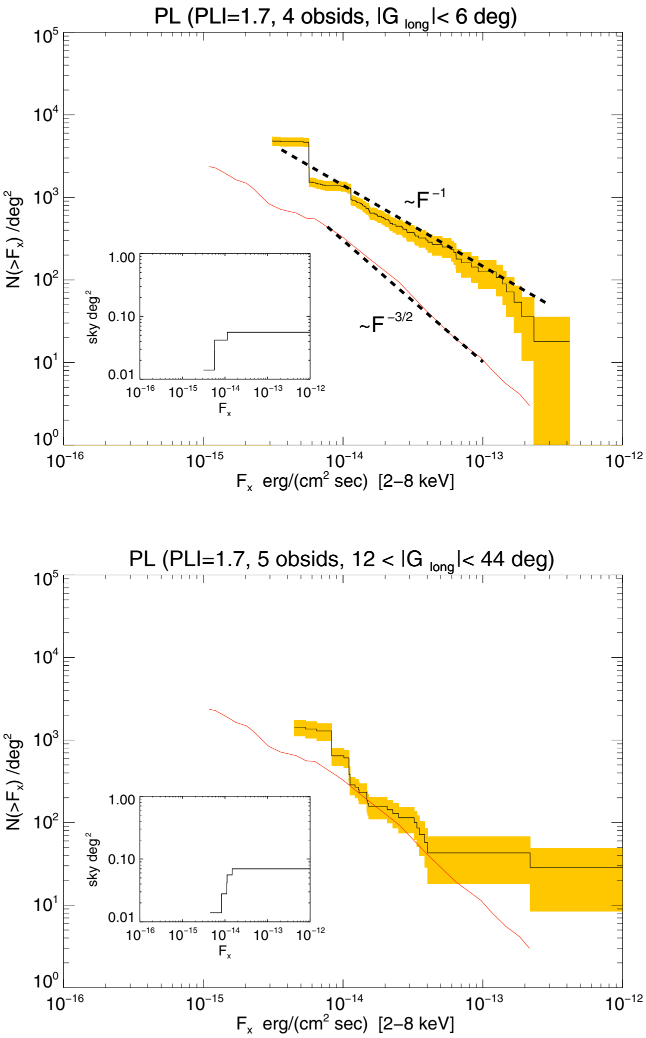

Fig. 2. (online colour at: www.interscience.wiley.com) Preliminary ChaMPlane LogN-LogS and error band for sources in central ($\lesssim 4'$) Chandra fields in galactic longitude ranges shown compared with high latitude AGN counts.

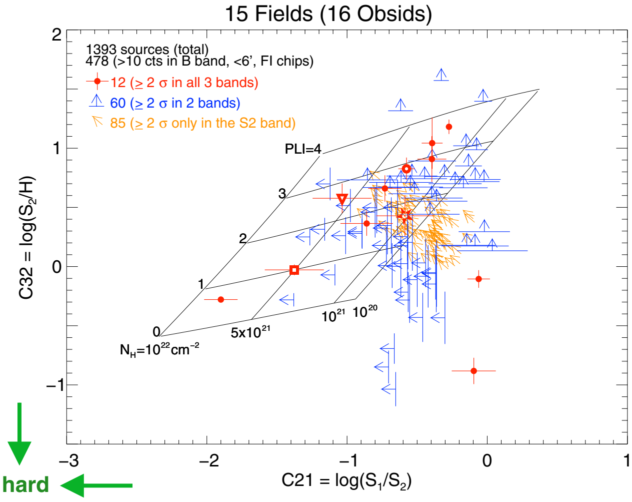

Fig. 3. (online colour at: www.interscience.wiley.com) Source X-ray colors and limits vs. PL models and N_H. Reduced source counts from 1393 total due to restriction $\leq 6'$ (from center) and separate detections in individual bands. Bands are: S1=0.3–1.2keV, S2=1.2–2.5keV, H=2.5–8keV, B=0.3–8keV.

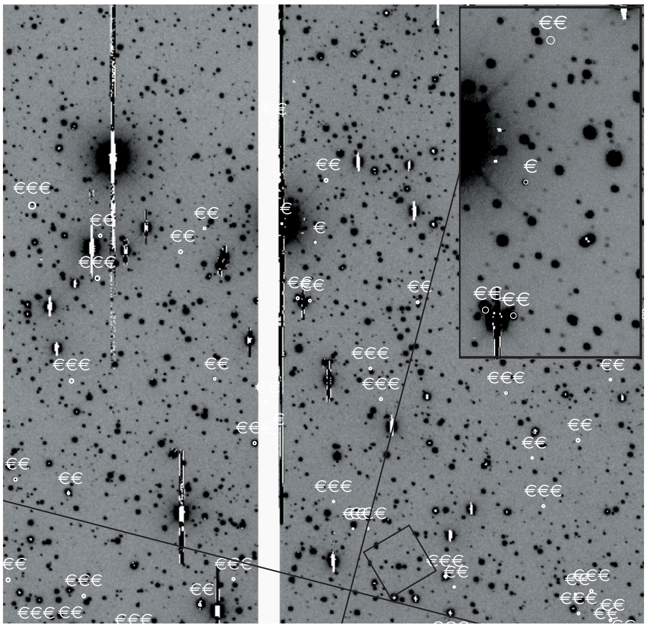

Fig. 4. R image (∼ 8′ ×8′) vs. Chandra IDs for Galactic Center Arc field and new CV (Chandra #5; cf. inset). N-right; E-up.

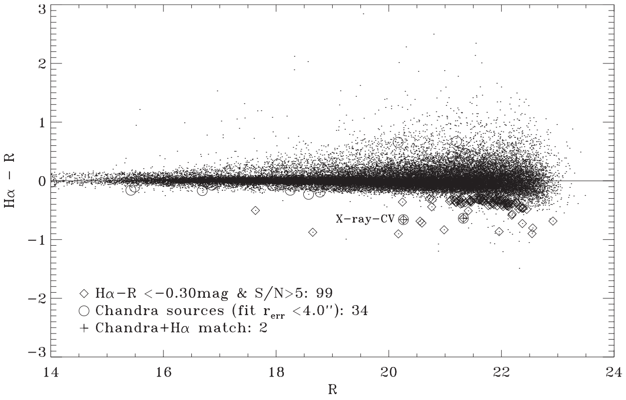

Fig. 5. CMD identifying Hα objects with 2 Chandra sources; others with similar significance are mostly outside the Chandra FoV.

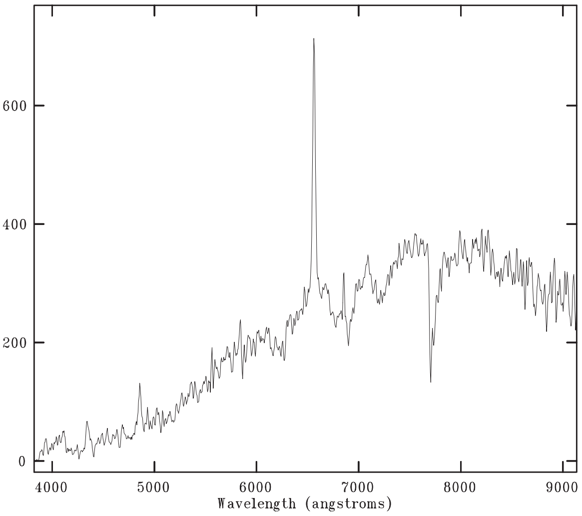

Fig. 6. Spectrum of the first ChaMPlane X-ray selected CV.

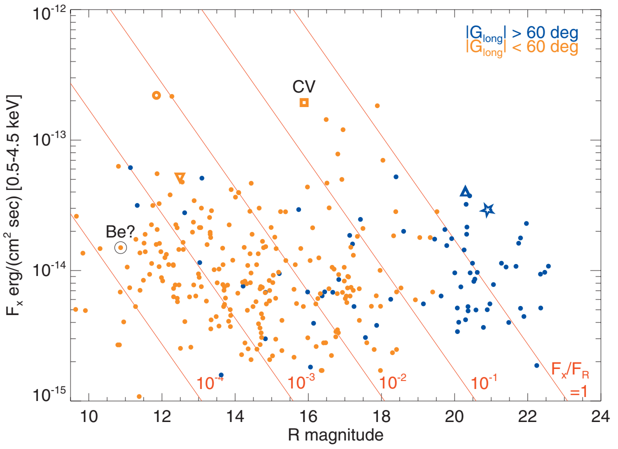

Fig. 7. (online colour at: www.interscience.wiley.com) Un-absorbed X-ray/optical flux vs. R (de-reddened) for initial sample of ChaM-Plane sources inside vs. outside $\ell = 60°$.

5. Conclusions

ChaMPlane has found dramatic evidence for a new population of low luminosity hard X-ray sources (HXs) in the central galactic bulge. Young stellar objects, found as HXs in SgrB2 by Takagi et al (2002), may not be numerous enough but models and stellar population studies (e.g. van Loon et al 2002) are needed. The source counts at $12° \leq \ell \leq 44°$ show a flattened disk component at $F_X \gtrsim 10^{-13}$ cgs that is consistent with the point source population at $\ell \sim 21°$ found by Motch et al (2002). However this "bright" galactic disk distribution is exceeded by the steeper AGN counts at fluxes $F_X \lesssim 10^{-13.5}$ cgs, only to be exceeded by the still larger normalization disk population in the central bulge. This may resolve the discrepancy between the claims for AGN dominating the faint ($\sim 3 \times 10^{-15}$ cgs) galactic source distribution at $\ell = 28.5°$ (Ebisawa et al 2001) vs. an excess in the lower-sensitivity wide-field galactic center survey (Wang et al 2002). ChaMPlane will map out this distribution, and our upcoming deep pointing on Baades Window with Chandra and HST may reveal the nature of this bulge population.

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