COMPLETING THE GALACTIC BULGE SURVEY: CATEGORIZING THE PLETHORA OF FAINT X–RAY SOURCES IN THE GALACTIC BULGE

Studies of X–ray sources in the Galaxy have been dominated by bright systems. Investigations of the more numerous but faint X–ray sources have been hampered by lack of optical/near–infrared identifications. This can be explained by the often large uncertainty in the source position and by the fact that the sources have been observed in a region of the Galaxy (the Galactic Center) that suffers from high extinction and crowding. Multiwavelength observations are vital for classifying the faint X–ray sources since X–ray spectral information alone is often not sufficient. Here, we propose to complete the X–ray portion of our multi–wavelength survey of the Galactic bulge. We call this the Galactic Bulge Survey (GBS). The survey combines a sensitivity for faint sources, a large area on the sky, the excellent positional accuracy of *Chandra*, with an already obtained complementary optical survey.

We have three main science goals: *i)* By comparing the observed number of sources in each source class (CVs, LMXBs) with those that have been predicted (see below) we will primarily constrain the nature of the common envelope in binary evolution. *ii)* The sample of sources will allow us to identify rare X-ray binaries such as quiescent eclipsing black hole (BH) and neutron star (NS) LMXBs and ultra–compact X–ray binaries (UCXBs which have orbital periods <1 hour). *iii)* Using our GBS survey we can determine the projected distribution of LMXBs. Using that we can determine whether LMXB formation scenarios that do not require a kick are viable.

Many stellar objects responsible for high energy phenomena, from CVs, AM CVns, to UCXBs went through one or two phases of common–envelope evolution. However, that phase is not yet understood. Compact binaries have much lower orbital energy and angular momentum than the progenitor binary that contained giants (Paczynski, 1976). The binary semi–major axis is thought to shrink mainly during a phase of unstable mass transfer and ejection, the spiral-in. If the outcome of this process is derived by assuming that the change in orbital energy is enough to eject the giant's mantle, the predicted properties do not match the observations of double white dwarf binaries. These properties can be matched with the assumption that the giant's mantle is ejected, carrying the specific orbital angular momentum (Nelemans et al. 2000), but this begs the question how the required energy is provided. It is clear that a more complete theoretical description is required that takes into account both energy and angular momentum.

To make progress on this issue we envisage a two-pronged approach by detailed studies of individual systems on one hand, and of the population on the other hand. Any viable evolutionary scheme must be able to reproduce the specific properties (such as component masses, orbital period, age, system velocity) of each observed individual system. Any viable evolution scheme must also reproduce the distributions of and correlations between these properties in the population of X-ray binaries. Observationally this implies the production of large homogeneous samples of (ultra-compact) X-ray binaries, and the detailed follow-up of a number of individual systems.

For dynamical mass measurements in LMXBs one needs to measure three parameters: the radial velocity amplitude of the companion star (K), the ratio between the mass of the companion star and the NS or BH (q) and the inclination. A measurement of the rotational broadening of the stellar absorption lines ($v \sin i$) combined with K gives this determination of q. The system inclination can be determined through modelling of the multi–colour optical lightcurves or, in systems with favorable viewing angles the X–ray eclipse duration can be used to accurately determine the inclination (Horne 1985). Since the inclination is constrained by the geometry, mass measurements in eclipsing systems are independent of the modelling that lies behind inclinations derived from ellipsoidal variations. Quiescent eclipsing systems are prime targets for optical mass measurements. Such mass measurements provide constraints on the NS equation of state (EoS). Constraining the NS EoS remains one of the final goals for NS studies. The few known quiescent eclipsing NS

LMXBs are too faint and/or in dense parts of a Globular Cluster that phase resolved optical and IR observations are not feasible.

Gilfanov (2004) showed that compact stellar objects trace the stellar mass in the Galaxy. In principle this would allow one to use stellar X–ray sources to map the triaxial Galactic bar (e.g. Bahcall & Soneira 1980; Dwek et al. 1995; Merrifield 2004). Even though CVs do not get a kick velocity at formation we cannot trace CVs down to the Galactic Center since their flux would be below our detection threshold, hence we cannot use them to map the bar. Revnivtsev et al. (2005) recently mapped the Galactic ridge X–ray emission using low angular–resolution RXTE observations and they found an asymmetric distribution in the Galactic ridge emission. Interestingly, Jonker & Nelemans (2004) found that there is a significant excess of LMXBs at $-10^\circ < l < 0^\circ$ with respect to $0^\circ < l < 10^\circ$. Jonker & Nelemans (2004) suggested that this was the result of the presence of the Galactic bar, however, strangely enough there are more LMXB in the direction of the far end of the bar. Recently, Weidenspointer et al. (2008) confirmed the asymmetric LMXB distribution using INTEGRAL data. According to the LMXB formation scenario of van den Heuvel (1983) and Kalogera (1998), LMXBs are thought to get a velocity kick at formation that would wash–out any spatial non–uniformity. Evidence for velocity kicks is found in the z–distribution of LMXBs (e.g. Jonker & Nelemans 2004) and in the velocity distribution of radio pulsars (Bailes 1989). On the other hand, the LMXB evolutionary models discussed by Pfahl et al. (2002) and Dewi et al. (2005) provide channels for the formation of LMXBs without a large kick velocity. Hence, the full GBS would also allow us to investigate the distribution of the LMXBs on much smaller scales. If the results pertain on the smaller scales the formation channels that produce LMXBs without kick velocities are important. It would also provide new impetus to explain the puzzling asymmetry.

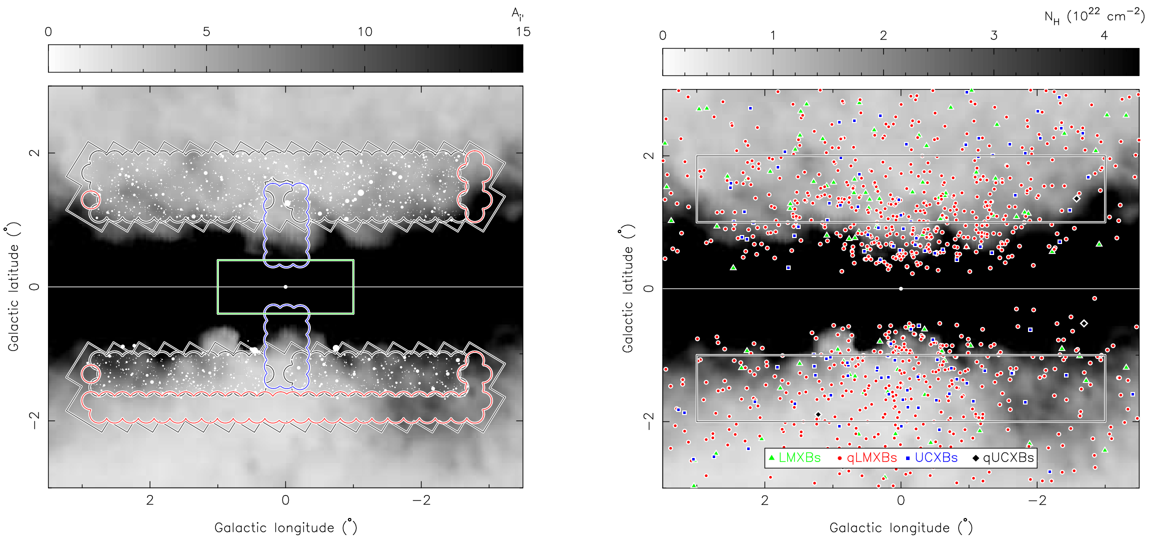


Figure 1: *Left panel*: The bulge survey area as observed in the optical by the Blanco MOSAIC II instrument is plotted over the extinction maps from Schlegel et al. (1998) in Galactic coordinates. The top scale gives the extinction in magnitudes in the i' band. It is clearly visible that the extinction is much lower outside the $|b| < 1^\circ$ area. The average $A_{i'}$ at the Galactic Center distance in the GBS fields is 4.7 for the $-b$ area and 4.1 for the $+b$ area). The regions imaged by Wang et al. (2002; see also Muno et al. 2006) and the Bulge latitude survey (Grindlay et al. 2005) are shown with a box and blue outlines area, respectively. The over-plotted white dots show the sources that we have detected in our existing GBS observations. The larger the dot the more X-ray counts in the source. The red–coloured outline shows the area that we propose to observe in AO11. *Right panel*: The large boxes indicate the two $6^\circ \times 1^\circ$ GBS fields. The over-plotted dots indicate the densities of the LMXBs and UCXBs that we expect to find *and that are detectable in our optical survey!* The colors of the dots and the different symbols indicate the nature of the source. The top scale gives the hydrogen column density. Please also visit our web site on the GBS at www.sron.nl/∼peterj/GBS

We have used a simple model to estimate the number of X–ray sources in each class (Nelemans et al. 2004) and to devise the best observing strategy to meet our goals. For each source class we have used estimates of space densities and/or total number of objects to populate the Galaxy with these sources according to the radial distribution of stars. Combining this with models for optical and X–ray emission and interstellar absorption, we predict the number of observable X–ray sources in the optical and X–rays over different survey areas. We find that our survey needs to cover an area of 12 square degrees; we have selected two strips of $6^\circ \times 1^\circ$, one centered at 1.5° above and one below the Galactic Center. To ensure that the number of detected CVs is comparable to the number of detected quiescent LMXBs, our Chandra observations are rather shallow. Deeper observations would mostly increase the number of CVs (Fig. 2), making it more difficult to classify the LMXBs among the sample of X–ray sources. The size and location of the observed area is chosen such that we will detect enough sources per source type for our science goals. The relatively low optical extinction will allow us to obtain optical spectroscopic follow–up to a large fraction of the X–ray sources, which is crucial for achieving our science goals.

Below, the number between curly brackets indicates the number of sources that we estimated would be detectable in the X-rays *and in optical* in our GBS survey. Many of the discovered sources should be CVs {445}. In our X-ray selected sample nearly all are magnetic systems in the form of IPs {425}. This is based on the observed IP/CV space density of $\sim 6 \times 10^{-6}/2 \times 10^{-5}\,\mathrm{pc}^{-3}$ (Patterson et al. 1984; Hertz et al. 1990). We expect to discover Roche lobe overflow NS and BH X-ray binaries ({400} LMXBs, including {55} persistent faint UCXBs). Nearly all of the LMXBs will be in quiescence. These numbers are based on a very simple estimate of 1000 persistent systems with $L_{\mathrm{X}} > 10^{35}\,\mathrm{erg\,s^{-1}}$ in the Galaxy (Grimm, Gilfanov & Sunyaev 2002a;Grimm, Gilfanov & Sunyaev 2002b), a number ratio of quiescent to active LMXBs of ~ 10, and we followed the prediction that about half of the total population of LMXBs may be in UCXBs (Belczynski & Taam 2004). Even though this estimate is simple, it is consistent with theoretical models for the number of LMXBs. Our survey will significantly increase the number of qLMXBs and UCXBs with an optical counterpart that allows for spectroscopic follow–up. In addition, active binary stars (such as RS CVn stars {540}) and background AGN ({25}, see Ebisawa et al. 2005) will be found. Finally, we might also find a few {5} ultra-compact double white dwarf systems (AM CVns). These numbers are uncertain and calibrating the number densities of sources using the GBS is one of the principal objectives. We will compare our identifications with the predicted numbers of binaries in each category and thus place strong constraints on important uncertainties in the theory of binary evolution, most notably the common–envelope phase and the existence and magnitude of kicks imparted on NSs and BHs.

Of the number of predicted LMXBs about 10% will have BH accretors (Romani 1992) leading to ~ 40 BH LMXBs in the GBS which more than triples the population of known Galactic BHs for which a dynamical mass measurement is possible (currently $\sim$20, Remillard & McClintock, 2006). Eclipsing BH LMXB systems should exist, but have not yet been found. It has been proposed that they are too weak to be detected by current X-ray all sky monitors because they are obscured behind the accretion disc rim (Narayan & McClintock 2005). If so, they should turn up in our GBS. Out of the 400 new qLMXBs we expect to discover $\approx$15 to be eclipsing of which 1 or 2 BHs.

To optically identify the sources we have obtained optical (r', $i' < 23.5$ at 5σ and Hα) images covering the GBS area. These data have been analyzed and used to select optical counterpart candidates (Fig. 1 and Fig. 2). We have actually found 1355 X-ray sources in the existing part of the *Chandra* survey. Out of the 1355 X-ray sources $\sim$950 have an optical star brighter than $r' < 23$ in a $1''$ region centered on the X-ray position. Randomly placing 950 circles of 1 arcsec radius in our optical images we find that on average 240 contain a source. This implies that about 240 of the 950 potential counterparts will be due to chance alignments. A good way to find out if this is the case is to take an optical spectrum of the possible optical counterpart. Additional information can be gained by searching for orbital variability. For nearly all sources *Chandra* did not detect enough counts to provide a good handle on the X-ray spectra (see Figure 3 *right panel*). Hence, classification of the sources will have to come from the optical observations of optical counterparts. Using optical spectra (the relative intensity of emission lines) and the ratio of optical to X-ray flux, we can distinguish between the different source classes that we expect to find (Patterson & Raymond, 1985; van Paradijs & McClintock 1995). In 2008 we acquired three nights of spectroscopy of bright ($r' < 17.5$) optical counterparts using the Hydra instrument mounted on the Blanco telescope. Several CVs and LMXB candidates have been identified in this high optical luminosity sample already (see Fig. 2)! Three more nights with Hydra have been awarded for semester 2009A via Chandra in AO10. Proposals for Magellan and AAT 2dF spectroscopic follow-up are pending. We have also been awarded 24 hours on a new spectrograph that is mounted on the VLT (called X-shooter) and more VLT spectroscopic observations will and have been requested (deadlines April 1, 2009 and Oct 1, 2009). Hence, many spectroscopic follow–up studies are underway.

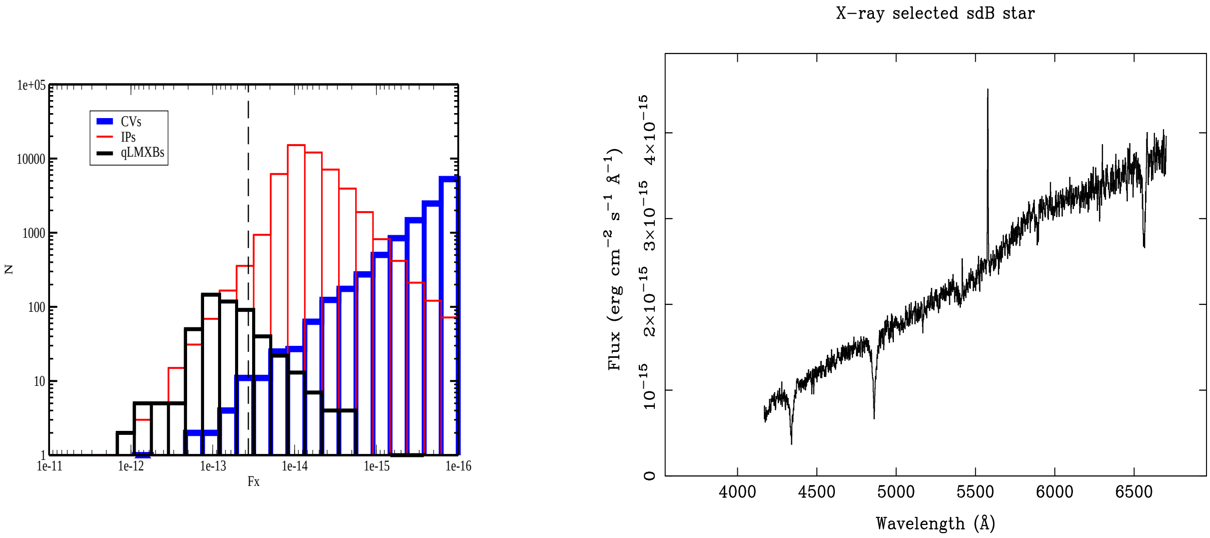
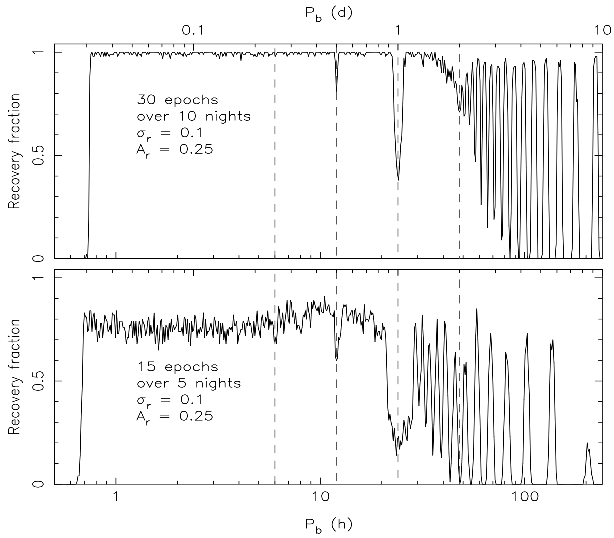


Figure 2: *Left panel:* Histograms of the number of quiescent LMXBs, CVs, and IPs as a function of observed source X–ray flux. Our flux limit of 3.5×10^{-14} erg cm^{-2} s^{-1} (dashed line) ensures that we detect the peak in the distribution of the quiescent LMXBs. Deeper observations would strongly enlarge the number of detected CVs and IPs. *Right panel:* An optical Hydra spectrum of the sdB star counterpart to one of the X–ray sources in the GBS area that has been imaged in AO9+10. The X–ray flux associated with this sdB star is consistent with wind accretion onto a NS or BH (depending on the Bondi-accretion efficiency and on the orbital parameters). The Blanco+Hydra time had been allocated as part of our previous GBS *Chandra* observations. From the optical spectrum $\log g$ and thus a mass–radius relation can be determined, making it possible to determine the mass of the accreting object (Geier et al. 2008). The emission peak at 5577Å is due to atmospheric sky emission.

Chandra Feasibility

Chandra has the best instruments for the proposed survey because of its unrivalled positional accuracy, that besides pin–pointing the position of an X–ray source also yields a low photon background. It is not foreseen that there will be another X–ray mission any time soon that will rival the *Chandra* resolution. For the faintest sources (those with only 5-6 source counts) that will be detected at the largest off–axis angle in our GBS (7 arcminutes) the positional error will be ∼3–4″(Hong et al. 2005). From our existing GBS observations we found that in such an error circle there can be more than one optical star in the densest optical fields. However, the optical color and variability information (see below) and/or multi–object spectroscopic observations will allow us to identify the counterpart in the majority of such cases. Furthermore, most sources will have positions accurate to 0.6–1″. We have obtained the observations with a small overlap using an effective circular FOV of 14 arcminutes to mitigate the loss in sensitivity towards the edges of each pointing due to vignetting. The circular FOV allows us to avoid roll angle restrictions. Pile–up might be important for some of the ROSAT detected sources in our survey area, however, pile–up will not prevent us from obtaining an accurate source position.

The proposed survey area has no overlap with any of the Galactic Center monitoring programs with *Chandra* or XMM–*Newton* (Muno et al. 2003, Wijnands et al. 2006, Warwick 2002, Sakano et al. 2004) nor with the ChaMPlane survey (Grindlay et al. 2005). We will use the pointings of the Bulge Latitute Survey for our work (see Figure 1). We propose to make use of the raster scan mode observations. We need 63 pointings of 2 ksec to complete our survey. This boils down to 126 ksec excluding overhead and to 165.5 ksec including slew time.



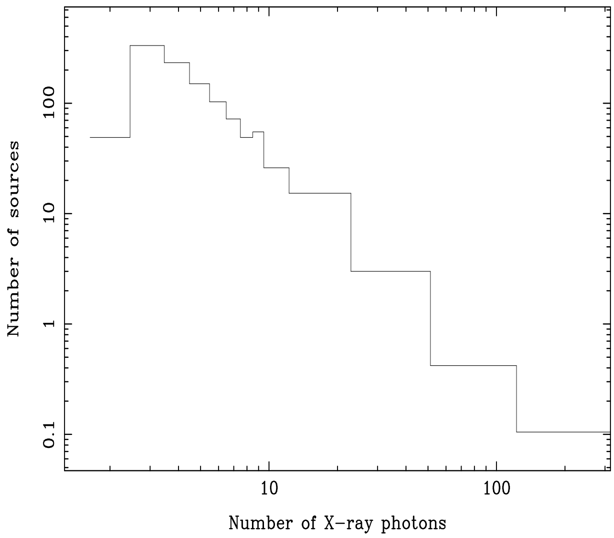


Figure 3: *Left panel:* Simulations of the recovery fraction of sinusoidial variations in magnitude for a large range of periodicities through the Lomb-Scargle method. The period is recovered when the most significant period falls within 3% of the input period. The sampling in time is pseudo random, where the field containing the variable is observed at random in three consecutive 3.2 hour periods (time needed to image all 64 fields covering the full 12 square degrees) per night. The top graph shows the recovery fraction when obtaining 30 measurements spread over 10 nights, while the bottom shows the fraction for 15 measurements in 5 nights. The figure is for 0.25 mag variations with 0.1 mag uncertainties on the individual measurements, typical for sources with $r' \approx 22$. The recovery fraction is much higher for 10 nights and more sensitive to longer periodicities and will be even better for brighter systems or larger amplitudes. *Right panel:* The distribution of the number of detected sources as a function of the number of X–ray counts (normalized to bins of 1 count wide) detected in the AO9+10 GBS *Chandra* observations. As can be seen for the vast majority of sources we have not enough counts for X–ray spectral analysis. As planned, identification has to come from the optical observations. The background count rate is so low in VFAINT mode that even 2–3 counts sources can be significant detections (most notably when detected close to on–axis; cf. Murray et al. 2005).

The reasons why we would like to complete the survey with the remaining 28% of observations that we propose here are the following. First, several of the science goals require the detection of rare X–ray binaries. In 12 square degrees we expect to find 15 eclipsing LMXBs and 5 AM CVns. However, the predicted number of sources is subject to substantial uncertainty (factor of a few). In the worst case we would only detect a few eclipsing LMXBs and the chance of detecting an eclipsing BH LMXB will be small. Reducing the area by 28% would obviously reduce that chance further. Second, the number of sources per source group will be about a third smaller in the case that we do not finish the survey, which would make the results more prone to small number statistical effects, reducing its impact. Third, much of the science of this survey will benefit from a homogeneous area when regarded in Galactic coordinates, for instance tracing the Galactic structure with (q)LMXBs. Fourth, we sample a different region in terms of the interstellar extinction with the remaining observations that we propose here. Since the interstellar extinction is lower in the remaining part it will allow us to probe the CVs deeper into the Galaxy hence closer to the Galactic bulge, allowing us to reduce effects of local populations.

Serendipitous science; one example

In a large survey as the GBS there is a significant chance for serendipitous discoveries. We have estimated that in our survey area there could be a handful of isolated NSs and magnetars in quiescence. In fact, in the existing part of our survey we have discovered a source of which only 5 counts below 2.5 keV have been detected. This source was observed within $2'$ of the pointing center. Sources that are discovered exclusively in the 0.3–2.5 keV band are foreground sources as the interstellar extinction weeds out the soft part of the spectrum for background sources. Interestingly, there is no optical counterpart in our GBS optical images for this source. Moreover, there is no counterpart in the K–band UKIDDS images (down to $K = 18$). These properties resemble that of isolated NSs or magnetars.

Technical Justification for Joint Facilities

Besides the ongoing spectroscopic follow–up, photometric follow–up is of the utmost importance as well. We will use the variability to separate the various flare stars from more periodic variable sources such as binaries. In addition, the optical variability can help determine which of the optical sources is the likely counterpart for X–ray sources with positional accuracy $> 1''$. Finally, the orbital periods of the CVs and quiescent LMXBs are important for our science goals as outlined above. We have simulated that we can detect the orbital periods of *all* periodically, sinusoidally variable sources (not just the X–ray sources but the thousands of binaries!) brighter than $r' \approx 22$ in the whole GBS area with 10 nights of Blanco MOSAIC II observations (see Figure 3 *left panel*; the assumed amplitude of variability is 0.25 magnitude whereas we took 0.1 magnitude for the variance on each individual photometric point (which corresponds to sources with $r' \approx 22$). The observed X–ray source density of ∼150 per square degree (∼40 per MOSAIC II pointing) makes photometric times series of the whole field much more efficient than follow-up of several individual sources in terms of the optical telescope time necessary. Note that we expect that the Cataclysmic Variables and the low-mass X–ray binaries will have a periodically variable component but also a flaring component.

We have allocated resources and man–power. One post–doc is currently working at SRON and one at the CfA (the application for a 3–year post–doc in the Netherlands is pending). Furthermore, 2 PhD students have started working on the GBS and one more will start in 2009.

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Previous Chandra Programs P.G. Jonker

- We obtained 5 *Chandra* DDT observations in March/April 2002 (PI Jonker). **Paper:** Jonker, P.G., Méndez, M., Nelemans, G., Wijnands, R., van der Klis, M., 2003, MNRAS,341, 823. *Chandra observations of the neutron star soft X-ray transient RX J170930.2-263927 returning to quiescence*
- As part of AO3 (PI van der Klis) four faint low–mass X-ray binaries have been observed MS 1603.6+2600 and three others. **Paper**: Wilson et al. 2003, ApJ, 596, 1220 **Paper:** Jonker et al. 2003 MNRAS, 346,684 *MS 1603.6+2600: an accretion disc corona source?*
- As part of AO4 (PI Jonker) a 35 ksec observation of the NS SXT SAX J1810.8–2609 in quiescence has been obtained.**Paper:** Jonker, Wijnands, van der Klis, 2004, MNRAS, 349, 94 *The faint neutron star soft X-ray transient SAX J1810.8-2609 in quiescence*
- As part of AO4 a 25 ksec observation of the NS SXT XTE J1709-269 in quiescence has been obtained.**Paper:** Jonker, et al. 2004, MNRAS, 354, 666 *Optical and X-ray observations of the neutron star soft X-ray transient XTE J1709-267*
- *Chandra* + VLA DDT observations of the BHXB XTE J1908+094 returning to quiescence have been obtained in March and April/May 2003.**Paper:** Jonker et al. 2004, MNRAS, 351, 1359 *Radio and X-ray observations during the outburst decay of the Black Hole Candidate XTE J1908+094*
- *Chandra* DDT observations of the millisecond pulsar NS SXT IGR J00291+5934 (returning to) quiescence have been obtained in Jan and Feb 2005.**Paper:** Jonker et al. 2005, MNRAS, 361, 511 *Chandra X-ray observations of the millisecond X-ray pulsar IGR J00291+5934 in quiescence*
- *Chandra* + VLA AO5 observations of the BHXB V4641 Sgr returning to quiescence have been obtained in July 2004.**Paper:** Gallo E. et al. 2009 to be submitted *Radio and X-ray observations during the outburst decay of the fast black hole transient V4641 Sgr*
- *Chandra* + VLA AO6 (PI: Jonker) observation of the BHXB XTE J1118+480 returning to quiescence has been obtained in Feb 2005. The source was already too faint to be detected in a short *Chandra* observation. The sequence was stopped, the remaining four observations have not been triggered. Paper in prep. Brocksopp et al.
- *Chandra* AO6 (PI: Jonker) 2 NS SXTs in quiescence.**Paper:** Jonker et al. 2006, MNRAS, 368, 1803 *The neutron star soft X–ray transient 1H 1905+000 in quiescence.* **Paper:** Jonker, Bassa, Wachter 2007, MNRAS, 377, 1295, astro-ph 0703020
- *Chandra* AO7 (PI: Jonker) A 300 ksec observation of 1H 1905+000 has been awarded. Data has been obtained and analysed. Talk given at the 2006 HEAD meeting, **Paper** Jonker, Steeghs, Chakrabarty, Juett, 2007, 665, L147, astro-ph 0706.3421
- *Chandra* AO7 (PI: Jonker) 171 ksec of ToO observations to follow a black hole towards quiescence. ToO observations have not been triggered. No data was obtained.
- *Chandra* AO8 (PI: Jonker) 171 ksec of ToO observations to follow a black hole towards quiescence. The ToO has not been triggered. No data was obtained.
- *Chandra* 5 ks DDT observation of an optical transient in M81. Paper in prep. Kasliwal, Jonker et al.
- *Chandra* AO9 (PI: Jonker) 171 ksec of ToO observations to follow a black hole towards quiescence. The ToO has been triggered last year, Paper in prep. Jonker et al.
- *Chandra* AO9 (PI: Jonker) 132 ksec of observations of an area in the Galactic Bulge. The data is obtained and analysis done (needs the completion of GBS for full interp.).
- *Chandra* AO10 (PI: Jonker) 96 ksec of observations of an area in the Galactic Bulge. The data is obtained and analysis done (needs the completion of GBS for full interp.).
- *Chandra* AO10 (PI: Jonker) 2 ksec of observations of a possible high–L ULX,paper to be submitted Jonker et al. 2009.
- *Chandra* AO10 (PI: Jonker) 157 ksec of ToO observations to follow a black hole towards quiescence. The ToO has not been triggered until now.