X-RAY TRANSIENTS IN THE GALACTIC CENTER REGION

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ABSTRACT

In the last 15 years, 6 dedicated observation programs were carried out to monitor $\sim 20^\circ$ around the galactic center for transient activity above a few keV. Transient activity from low-mass X-ray binaries shows a strong preference for this field. Two programs are currently active, with the Wide Field Cameras on BeppoSAX and the Proportional Counter Array on RXTE. The coverage of these programs is fairly extensive, with typical sensitivities of a few mCrab and an angular resolution of a few arcminutes which is better than that of typical all-sky monitor devices. Fifteen transients with peak fluxes above 10 mCrab were discovered with these instruments so far (equivalent to 12±4 such transients per year over the whole sky), and on top of that BeppoSAX-WFC detected about 2000 X-ray bursts. We summarize some recent results.

Key words: X-ray binaries, X-ray bursts, neutron stars.

1. INTRODUCTION

The INTEGRAL mission will dedicate half of its Core Program to semi-annual deep exposures of the central radian the Galaxy, and a quarter to weekly scans of the galactic plane (Winkler 2000). Together with incidental observations from the rest of the Core Program and the General Program, the coverage of the galactic center region will be large. In this respect it is interesting to assess what prospects lie ahead for INTEGRAL in the area of detecting X-ray transients. Thanks to dedicated and sensitive observations with BeppoSAX and RXTE in recent years the observational database about these transients is growing. We summarize recent developments.

2. NATURE OF TRANSIENTS

We define a transient as a source that in the medium X-ray energy range (a few keV to a few tens of keV)

- has a quiescent level below 1 mCrab (equivalent to $\sim 10^{35}$ erg s^{-1} if at a distance equal to that of the galactic center);
- if it peaks above 10 mCrab;
- if it shows activity for at least 10 sec;
- if it is mostly in quiescence.

This definition provides fairly easy discrimination between transient and persistent sources. Usually the definition is stricter (e.g., for LMXBs see Van Paradijs & Verbunt 1984). In particular, one often demands that the difference between peak and quiescent flux is at least a factor 10^3. However, this is difficult to test without observations with narrow-field sensitive X-ray telescopes as is the case for many transients observed in the 30-year history of space-borne X-ray astronomy.

The broad range of time scales allowed in the definition is chosen to be able to include recent discoveries of bursting X-ray sources that show no simultaneously detectable persistent emission.

A variety of objects pertain to this definition. First of all, the X-ray binaries in which a neutron star or black hole orbits a non-degenerate star (for a review, see White et al. 1995). Furthermore, it includes gamma-ray bursts, nearby flare stars, pre-main sequence stars (with typical on-times of a few hours), and RS CVn stars (up to a few days). All transients have isotropic sky distributions except for the X-ray binaries (see figure 1). The high-mass X-ray binaries, with companions to the compact stars of spectral types O and B, consist of young objects that are concentrated along the galactic plane. The low-mass X-ray binaries (LMXBs), with companions of type A and later, are older and are therefore typically found in globular clusters and in a concentration towards the galactic center. In fact, more than half of all LMXBs are found within the central 20° Monitoring programs of the galactic center region, therefore, provide a unique opportunity to observe a large fraction of the LMXB population in an unbiased manner.

In the remainder, we concentrate on LMXBs.

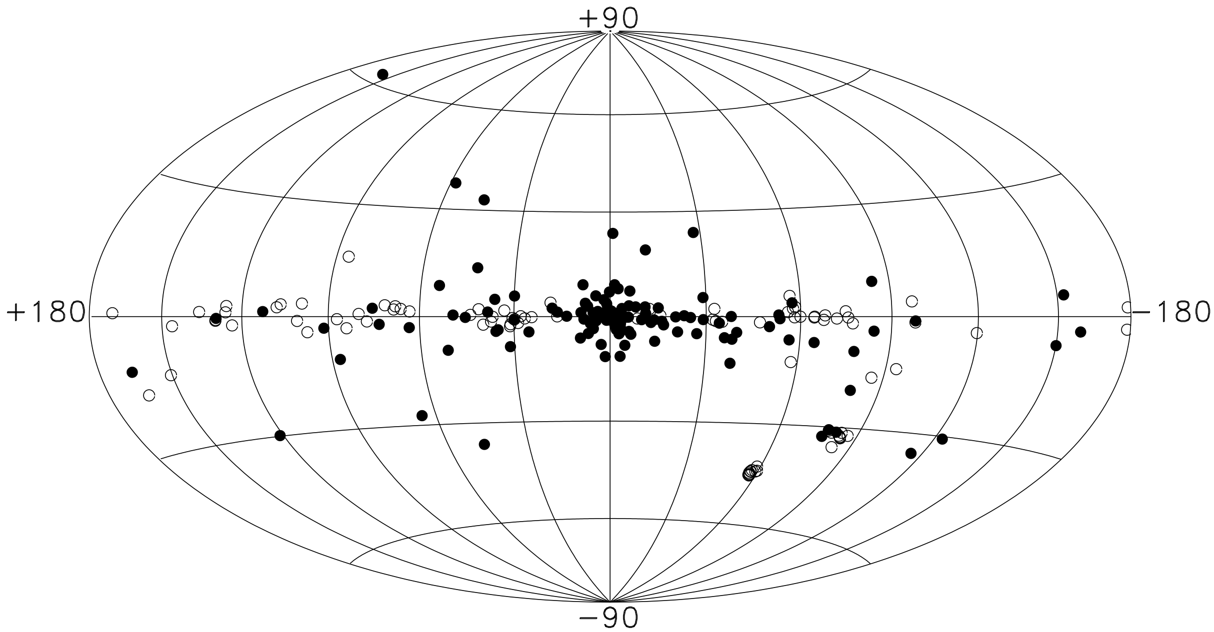

Figure 1. Galactic distribution of 225 X-ray binaries (filled circles are LMXBs and open circles HMXBs)

3. PAST AND CURRENT MONITORING PROGRAMS

Six dedicated observation programs have been carried out to monitor specifically the galactic center region for transient X-ray activity above a few keV. They are listed in table 1 together with the currently active RXTE All-Sky Monitor (ASM) program as a reference.

The X-ray telescope (XRT) was operated during the 2nd Spacelab mission in 1985 and was the first telescope to resolve an image of the galactic center region above 2 keV (Skinner et al. 1987). The COded Mask Imaging Spectrometer (COMIS) observed intermittently for 12 years but most of the exposure was gathered before 1994 (In 't Zand 1992, Emelyanov et al. 2000). ART-P on the Granat platform was operated for a more limited time (Pavlinksy et al. 1994) than SIGMA on the same platform. The SIGMA program distinguishes itself by the largest exposure time of all programs and by being the first γ-ray imaging device.

All instruments cover typical field of views of 10° combined with arcminute angular resolution and sensitivity in the 2-100 keV range (the same range as for future INTEGRAL observations). All employed instruments except PCA/RXTE are coded aperture devices.

Currently, two programs are active: the BeppoSAX-WFC galactic bulge observations program and the RXTE-PCA bulge scan program.

3.1. BeppoSAX-WFC program

The Wide Field Cameras (WFCs) on the BeppoSAX platform observe the galactic bulge since Aug. 1996 weekly during each visibility window allowed by the satellites operating constraints. These windows are mid-February to mid-April and mid-August to mid-October of each year. Up to the year 2000, nine campaigns were carried out amounting to a total net exposure time of 4 Msec (or 10^3 hrs). This WFC program takes 8% of the complete BeppoSAX observation program and is thus comparable, both in coverage and timing, to the INTEGRAL Galactic Center Deep Survey core program. Following the census by Van Paradijs (1995), the field of view of WFC encompasses more than half of all known LMXBs. Thus, this program allows a unique monitoring campaign of about 60 LMXBs with a large coverage and a moderate sensitivity. This makes the program particularly suitable to search for sub-hour flares or bursts. Figure 2 shows a typical WFC image of the field. The Principal Investigators are John Heise of SRON (Netherlands) and Pietro Ubertini of IAS/CNR (Italy).

Table 1. Overview of galactic center X-ray monitoring programs. The number of new sources is for within approximately 20° from the galactic center and includes confirmed sources weaker than 10 mCrab (note that these are not included in table 2.

Instrument	FOV deg	α[a]	S[b]	yrs	Exposure ksec	Number of new sources	Number of new bursters	Refs.[e]
XRT/SL2	6	3	0.5	85	25	6	1	1
COMIS/Kvant/Mir[c]	16	2	1	87-99	90	6	2	2,3
ART-P/Granat	5	5	1	90-92	820	4	0	4
SIGMA/Granat[d]	16	15	15	90-98	11000	6	0	5,6,7
WFC/BeppoSAX	40	5	10	96-	4000	11	17	8
PCA/RXTE	16	60	4	99-	8	8	1	9
ASM/RXTE		3	100	96-	990	2	0	10

[a] Angular resolution in arcminutes (the source location accuracy is between 3 and 5 times better).

[b] Typical sensitivity in mCrab (2-10 keV).

[c] Also known as 'TTM'.

[d] SIGMA has no coverage below 35 keV, while the others do. The sensitivity is quoted for 35-150 keV

[e] References are: 1. Skinner et al. 1987; 2. In 't Zand 1992; 3. Emelyanov et al. 2000; 4. Pavlinsky et al 1994; 5. Vargas et al. 1996; 6. Vargas et al. 1997; 7. Kuznetsov et al. 1999; 8. This publication; 9. Markwardt et al. 1999 and priv. comm.; 10. Bradt et al. 1999.

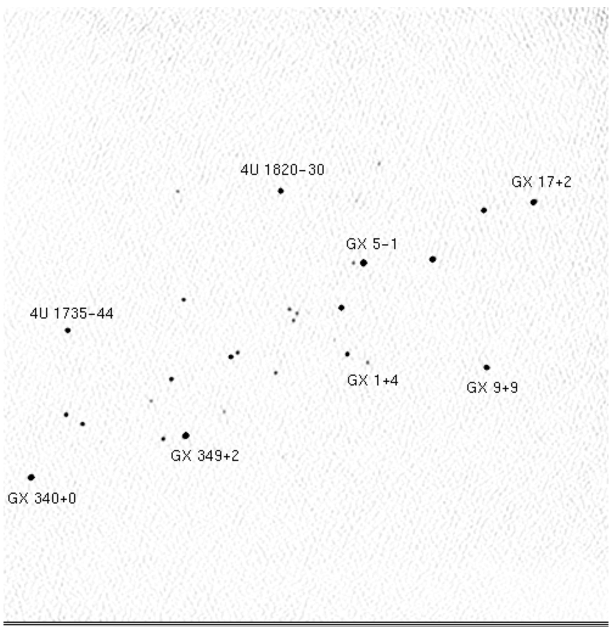

Figure 2. Typical WFC image centered on the galactic center. Usually there are about 30 active point sources above the detection limit

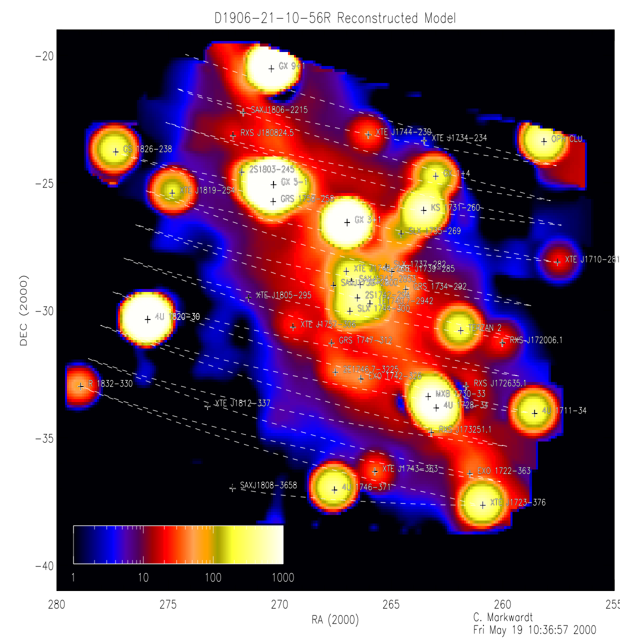

Figure 3. Reconstructed image of a typical PCA scan observation made on Mar. 22, 1999. The dashed curve shows the scan pattern for this particular observation

3.2. RXTE-PCA program

Since February 1999, scanning observations are carried out with the Proportional Counter Array (PCA) on RXTE of a rectangular region surrounding the galactic center, of approximately $16^{\circ}\times 18^{\circ}$ and on a semi-weekly basis. The orientation of the field is such that one diagonal is along the galactic plane. The scanning pattern is zig-zag, alternately along each orientation. The slew rate implies that each source in the field is in the field of view for about 1 min, except for sources that are chosen to be at the end points of the zig-zag pattern that have typical exposure times of 2 to 3 minutes. Figure 3 shows a typical reconstructed sky image of the field. The sensitivity of these scan observations is about 1 mCrab over the whole region. This is one to two orders of magnitude more sensitive than the observations with the All-Sky Monitor on RXTE. Thanks to the high frequency of the observations and the high duty cycle throughout the year ($>$ 80%), it is possible to uniformly sample outburst light curves of relatively faint transients. About 20 persistent sources are observed. Figure 4 shows a typical example of a lightcurve of a monitored source, namely the recurrent transient SAX J1747.0-2853. The PIs of this program are Craig Markwardt and Jean Swank of NASA's Goddard Space Flight Center.

Table 2. 31 LMXB transients that were seen to be active in 1996-2000 within approximately 20 degrees from the galactic center. Many of the parameter values for the bright transients were estimated from the publicly available RXTE-ASM database (at URL `http://xte.mit.edu`*). Other characteristics were obtained from the references listed, that are sometimes arbitrary. Similar lists for transients before 1996 are given in Chen et al. (1997).*

Name	Peak flux mCrab	Duration days	Bursts?	Comment	References
GRO J1655-40	4500	200	n	bhc	Kuulkers et al. 2000
X1658-298	30	>400	y		In 't Zand et al. 1999b
XTE J1709-267	200	100	y		Cocchi et al. 1998
XTE J1710-281	10	>600		eclipses	Markwardt et al. 1999
2S 1711-339	50	150	y		
SAX J1712.6-3739	50	>100?	y		In 't Zand et al. 1999c
RX J1718-4029	*burst only*		y		Kaptein et al. 2000
XTE J1723-376	80	70	y		Marshall et al. 1999
Rapid burster	300	70	y		
GRS 1737-31	25	30		bhc	Cui et al. 1997
GRS J1739-278	800	250		jet, bhc	Vargas et al. 1997
XTE J1739-285	200	40			Markwardt et al. 2000a
KS 1741-293	30	few	y		In 't Zand et al. 1998a
GRS 1741.9-2853	70	10?	y		Cocchi et al. 1999c
XTE J1743-363	15	>600			Markwardt et al. 1999
GRO J1744-28	2600	60	y	type-II only?	
EXO 1745-248	600	>200	y	type-II?	Markwardt et al. 2000c
SAX J1747.0-2853	140	70	y		Natalucci et al. 2000
GRS 1747-312	40	18		eclipses	In 't Zand et al. 2000a
SAX J1748.9-2021	40	8	y		In 't Zand et al. 1999a
XTE J1748-288	500	15		jet, bhc	Revnivtsev et al. 2000
SAX J1750.8-2900	100	6	y		Natalucci et al. 1999a
SAX J1752.3-3138	*burst only*		y		Cocchi et al. 1999a
SAX J1753.5-2349	*burst only*		y		In 't Zand et al. 1998d
XTE J1755-324	150	40		bhc	Goldoni et al. 1999
2S 1803-245	700	25	y	jet	Revnivtsev et al. 2000
SAX J1806.5-2215	*burst only*		y		In 't Zand et al. 1998d
SAX J1808.4-3658	100	18	y	ms pulsar	In 't Zand et al., 1998c, 2000c
SAX J1810.8-2609	15	3	y		Natalucci et al. 1999b
SAX J1818.6-1703	200	0.1		uncertain LMXB	In 't Zand et al. 1998a
SAX J1819.3-2525	12000	210		jet, bhc	In 't Zand et al. 2000b

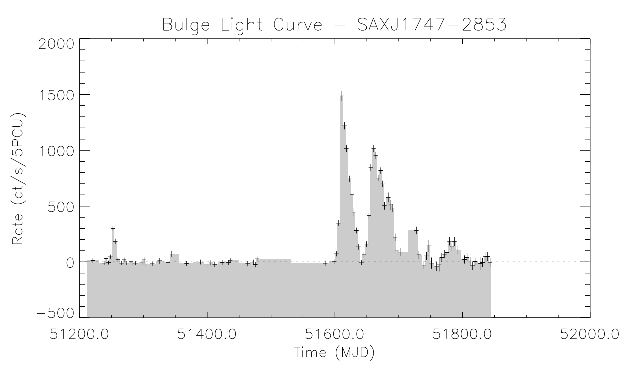

Figure 4. Light curve of SAX J1747.0-2853 as obtained with the RXTE-PCA bulge scan program since Feb. 1999 (Markwardt et al. 2000b).

4. RECENT RESULTS

If the X-ray binary catalog by Van Paradijs (1995, last updated in 1992), is taken as a reference point, and when the less clear identifications in that catalog are eliminated (i.e., the 9 Einstein sources near the galactic center, 3 unconfirmed weak KS sources, the anomalous X-ray pulsar 1E2259+587 and the white dwarf system CAL83), the total number of LMXBs known is 110. The number of new LMXB discoveries in the following years was 3 (1993), 3 (1994), 1 (1995), 4 (1996 and 1997), 6 (1998), 5 (1999) and 2 (2000, up to the summer). Obviously, all of these new cases are transients. They expand the LMXB population by 25%.

Thirty-one LMXB transients were active during WFC and PCA observations in 1996-2000 (see table 2). Interestingly, this is a large fraction of the total number of 44 known transients in the field. Eight transients were recurrent ones, with wait times between outbursts measuring between 100 days (for the Rapid Burster) and more than 20 years (e.g., MXB 1659-29). Eighteen of the 25 cases that are not black hole candidates exhibited type-I X-ray bursts. Of the remaining 7 cases, two are 'convincing' non-bursters because they are 'on' for long times (XTE J1710-281 and XTE J1743-363).

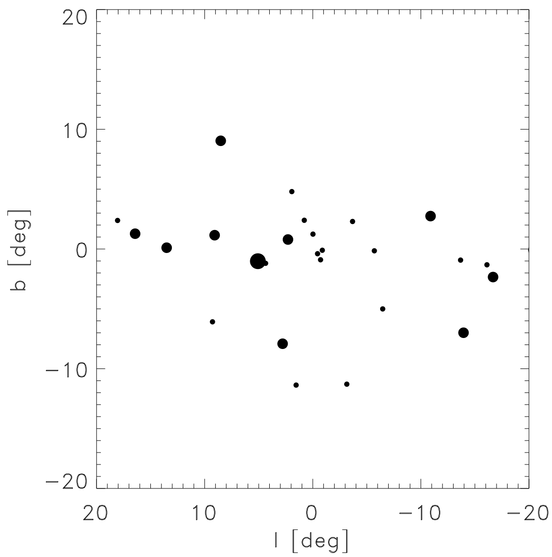

Figure 5. Map of persistent LMXBs in galactic coordinates. Four symbol sizes code the average flux f: $f < 0.1$ (smallest), $0.1 < f < 1.0$, $1.0 < f < 10$, and $f > 10$ (largest) Crab units in 2-10 keV.

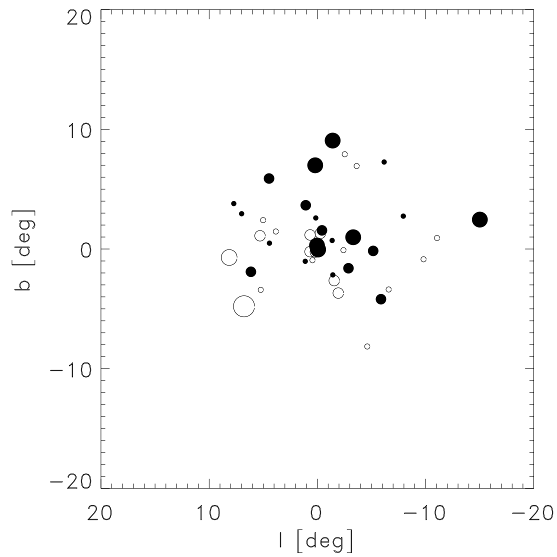

Figure 6. Map of transient LMXBs in galactic coordinates. The size coding is for peak flux and is the same as in figure 5. Open symbols denote discoveries after 1995.

4.1. Galactic distribution

In figures 5 and 6 maps are presented of all persistently bright and all transient LMXBs, respectively, within 20° from the galactic center. There is a concentration towards the galactic center that is stronger for the transients than for the persistently bright ones. This may partially be due to selection effects. However, this selection effect does not apply to WFC observations which were responsible for most new discoveries. We derive that there is a strong suggestion for a stronger concentration of transients.

4.2. X-ray bursts

There are two types of X-ray bursts: type I and II. Both have durations of order 1 minute and show fast-rise exponential-decay time profiles. The difference is that type-I bursts have few-keV black-body spectra with cooling in the tail while type-II bursts do not cool and have spectra very reminiscent to that of the emission outside bursts. Type-II bursts are assumed to be due to instabilities in the accretion disk (e.g., Lewin et al. 1993) while type-I bursts are recognized as thermonuclear flashes on surfaces of neutron stars. Currently, only two type-II bursters are known (additionally, there is a tentative type-II burster identification of the bright X-ray source in the globular cluster Terzan 5; Markwardt et al. 2000c). Type-I bursts are powerful diagnostics for the nature of the compact object: they eliminate black holes or white dwarfs as candidates.

The WFCs have detected more than 2000 X-ray bursts in LMXBs, about 1500 of these are type-I bursts. Table 3 presents a list of 35 bursters that were seen active within 20° from the galactic center. This includes 17 new identifications of bursters. Bursts were also detected from 14 sources outside this field, including 5 new ones. Bursts were not detected by WFC from 16 non-listed and known bursters. Therefore, WFC has seen 75% of the burster population in an active state.

Particularly interesting bursting behavior was seen in GS 1826-24 where the bursts follow each other without exception during years of observations quasi-periodically with a period of about 5.7 hr (Ubertini et al. 1999). This is in parellel to a very stable persistent flux which reflects a very stable mass acretion rate by the neutron star. Changes on time scales of years of the periodicity seem to go hand in hand with changes in the persistent flux (Cocchi et al. 2000b). GS 1826-24 therefore provides a unique testbed for theories on burst triggering mechanisms (e.g., Bildsten 2000).

Within the group of 49 persistent LMXBs, the fraction of bursters is 0.6 ± 0.2 (note that this fraction can only grow). For transient LMXB, this is 0.36 ± 0.09. The different fraction reflects the notion that the only black hole LMXBs found thus far are transient in nature. Within the GC field, the brightest bursting LMXB transient is A1742-289. However, the identification of A1742-289 with simultaneous bursting activity is not definite (Carpenter 1976 and Lewin et al. 1976, see also Maeda et al. 1996 and Kennea & Skinner 1996). Apart from A1742-289, the brightest bursting LMXB transient is 2S 1803-245 (Muller et al., 1998 and Revnivtsev et al. 2000) with a peak of 0.7 Crab units. All others have peak

Table 3. List of the 35 bursters seen active with WFC in the field (out of a total of 49 over the whole sky). The 17 sources in italic are bursters first identified as such by the WFCs. XTE J1723-376 was first recognized as a burster by RXTE. This list was last updated in December 2000

Source	References
MXB 1658-298	
4U 1702-429	
4U 1705-440	
XTE J1709-267	Cocchi et al. 1998
2S 1711-339[a]	Cornelisse, in preparation
SAX J1712.6-3739	Cocchi et al. 1999b
RX J1718.4-4029	Kaptein et al. 2000
XTE J1723-376	Marshall et al. 1999
1E 1724-3045	Cocchi et al. 2000c
GX 354-0	
KS 1731-260	Kuulkers, in preparation
Rapid burster[b]	
SLX 1735-269	Bazzano et al. 1997
4U 1735-44	Cornelisse et al. 2000
SLX 1737-282	in preparation
GRS 1741.9-2853	Cocchi et al. 1999c
KS 1741-293	
A 1742-294	
GRO J1744-28	
SLX 1744-300	
GX 3+1	in preparation
SAX J1747.0-2853	Natalucci et al. 2000
SAX J1748.9-2021[b]	In 't Zand et al. 1999a
SAX J1750.8-2900	Natalucci et al. 1999a
SAX J1752.4-3138	Cocchi et al. 1999a
SAX J1753.5-2349[a]	In 't Zand et al. 1998d
2S 1803-245	Muller et al. 1998
SAX J1806.5-2215	In 't Zand et al. 1998d
SAX J1808.4-3658	In 't Zand et al. 1998b, 2000c
SAX J1810.6-2609	Natalucci et al. 1999b
4U 1812-12	Cocchi et al. 2000a
GX 17+2	
4U 1820-303[b]	
GS 1826-24	Ubertini et al. 1999
1H 1832-33[b]	In 't Zand et al. 1998a

[a]uncertain type-I classification; [b]in globular cluster.

fluxes at least a factor of 2 less. The brightest bursting persistent LMXB in the field is GX 17+2 with an average flux of 0.6 Crab units.

4.3. SAX J1808.4-3658

Arguably, SAX J1808.4-3658 is the most intriguing X-ray transient found since the microquasars GRS 1915+105 and GRO J1655-40. Discovered in 1996 by the WFCs as a 0.1 Crab X-ray transient (In 't Zand et al. 1998c), it was first measured with the more sensitive PCA in a second outburst in early 1998 when a pulsar signal was found with a period of 2.5 ms (Wijnands & Van der Klis 1998). This represents the first and sofar only discovery of an accreting millisecond pulsar. Such systems were long sought after because LMXBs are thought to be the precursor of millisecond radio pulsars (e.g., Bhattacharya & Van den Heuvel 1991).

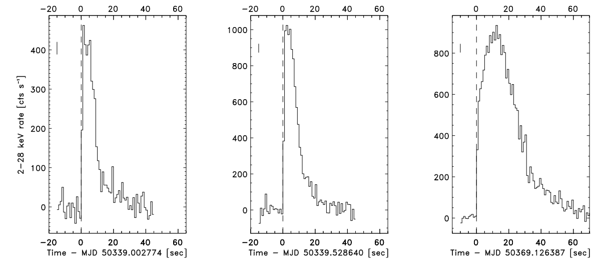

Figure 7. Time profiles of 3 bursts from SAX J1808.4-3658

There is indirect evidence for millisecond neutron star rotation periods in other LMXBs. Transient millisecond oscillations have been found in RXTE-PCA data during (parts of) X-ray bursts in 10 LMXBs (4U 1728-34, 4U 1636-53, 4U 1702-429, KS 1731-260, Aql X-1, X1658-298, 4U 1608-52, 4U 1916-05, the Rapid Burster and a source close to galactic center). Since the asymptotic frequencies of most of these oscillations are reproducable over years, the suggestion is strong to interpret these as due to the neutron star rotation (Strohmayer 1999). However, this is not a settled issue. SAX J1808.4-3658 could help resolve this issue because this is the only burster for which a rotation period has been independently determined. So far, bursts were only detected with the WFCs.

The WFC data from the first detected outburst from SAX J1808.4-3658 has recently been revisited, employing higher data coverage and a more mature calibration (In 't Zand et al. 2000c). This resulted in the detection of a third burst which was 50% brighter than the other 2 bursts already published by In 't Zand et al. (1998c), though with a similar bolometric peak flux, see figure 7. This is the brightest type-I burst detected by WFC among about 1500 cases, and is perhaps the only case for which meaningful searches for burst oscillations in the moderately sensitive WFC data are possible (note that the photon collecting area for WFC is about 40 times smaller than for RXTE's prime instrument).

A number of attempts to find a signal at 400 Hz resulted in the intriguing power density spectrum presented in figure 8. This is the average spectrum over 80 intervals of 0.25 sec starting at the onset of the burst. Therefore, the frequency resolution is rather broad at 4 Hz. At the time of this workshop, the significance of this signal is being assessed and the indications are that it is on the edge of being significant.

4.4. Is there a separate class of faint transients?

Heise et al. (1999) reports that seven LMXB transients discovered with the WFCs in this field were faint and that a large subset (six) consists of X-ray

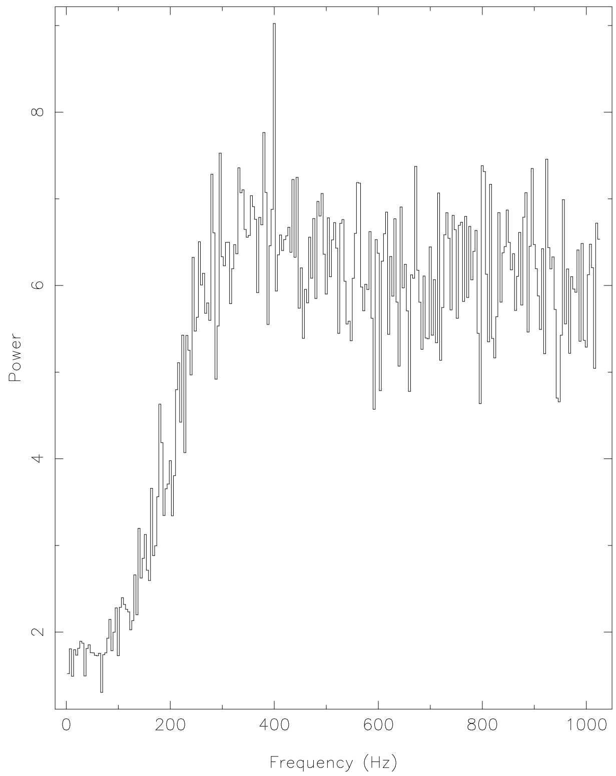

Figure 8. Power density spectrum of first 20 sec of 3rd burst from SAX J1808.4-3658

bursters. They propose that these transients make up an as yet unrecognized subclass of LMXBs. We here note eight more transients in the field:

- SAX J1712.6-3739 is a transient with a measured peak flux of 32 mCrab (In 't Zand et al. 1999c). It exhibited a burst (Cocchi et al. 1999b);
- SAX J1752.3-3138 was seen only during a burst (Cocchi et al. 1999a). The persistent emission was below 6 mCrab at the time of the burst;
- SAX J1818.6-1703 was a brief transient that was active for a few hours at a peak flux of about 0.2 Crab (In 't Zand et al. 1998a). It did not exhibit bursts. Technically speaking this is not necessarily a LMXB but we include this source because it is in this field;
- SAX J1819.3-2525 (In 't Zand et al. 2000b) was mostly faint except for a few hours when it was seen to be very bright (12 Crab units; Smith et al. 1999). It is now proven to be a black hole system at a distance between 7.4 and 12.3 kpc (Orosz et al. 2001). Despite a companion of early spectral type, this transient is more characteristic for a LMXB transient than for a HMXB transient (presumably because this is a semi-detached binary without a supergiant companion);
- XTE J1710-281 is a faint transient which is active since at least 1998 and showing a lot of variability below 10 mCrab, including eclipses (Markwardt et al. 1999);
- XTE J1723-376 was a moderately bright transient in early 1999 when it exhibited type-I bursts (Marshall et al. 1999);
- XTE J1739-285 is a fairly bright transient that stayed on for at least a few weeks (Markwardt et al. 2000a);
- XTE J1743-363 is a faint transient showing variable activity below about 15 mCrab since 1999 (Markwardt et al. 1999).

In total, fifteen faint LMXB transients have been detected, with 9 or 10 of them bursting. These are not necessarily short transients, as observations have shown of for example SAX J1747.0-2853 (figure 4) and SAX J1712.6-3739 (Cocchi et al., in preparation) which all are active for at least 200 days. This broadens the characteristics of the proposed subclass of faint LMXB transients considerably, and we conclude that such a subclass is perhaps not as strictly defined as initially thought. Nevertheless, the BeppoSAX and RXTE observations do show that there is a large fraction of likely LMXB transients that do not reach high peak luminosities. Perhaps this is related to a special nature of the companion star. For instance, the companion star in SAX J1808.4-3658 appears to be of very low mass ($\leq$ 0.1 $M_\odot$, Chakrabarty & Morgan 1998). Unfortunately, identifications of optical counterparts of these transients are scarce and difficult in this field, and measurements of orbits through pulsar timing have so far only been possible in SAX J1808.4-3658.

5. CONCLUSIONS

In the last 4 years, monitoring programs by BeppoSAX-WFC and RXTE-PCA on the Galactic center field have helped extend the LMXB population by tens of percents. Most of the new transients are fainter than the classical X-ray novae, and are type-I X-ray bursters. The frequency of LMXB transients brighter than approximately 10 mCrab in our galaxy is 12 ± 4 per year. The percentage of bursters, and therefore confirmed neutron star systems, is about 60% versus about 40% for all LMXB transients. The higher burster percentage among fainter transients may be a selection effect because low accretion rates are more favorable toward triggering thermonuclear flashes on neutron star surfaces, if present. Therefore, this measurement does not necessarily indicate a higher neutron star to black hole ratio among fainter transients.

The newly found LMXB transients comply fairly well with results from an archival study of 66 outbursts from 24 X-ray novae by Chen et al. (1997). The peak luminosity distribution for X-ray novae was shown to range from 0.003 to 5 times the Eddington luminosity, peaking at 0.2 $L_{\rm edd}$ which is equivalent to roughly a few tenths of a Crab unit if at a distance equal to that of the galactic center.

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