BeppoSAX WFC monitoring of the Galactic Center region

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We review the results obtained with the Galactic center campaigns of the BeppoSAX Wide Field X-ray Cameras (WFCs). This pertains to the study of luminous low-mass X-ray binaries (LMXBs). When pointed at the Galactic center, the WFC field of view contains more than half of the Galactic LMXB population. The results exemplify the excellent WFC capability to detect brief X-ray transients. Firstly, the WFCs expanded the known population of Galactic thermonuclear X-ray bursters by 50%. At least half of all LMXBs are now established to burst and, thus, to contain a neutron star as compact accretor rather than a black hole candidate. We provide a complete list of all 76 currently known bursters, including the new case 1RXS J170854.4-321857. Secondly, the WFCs have uncovered a population of weak transients with peak luminosities up to $\sim 10^{37}$ erg s$^{-1}$ and durations from days to weeks. One is the first accretion-powered millisecond pulsar SAX J1808.4-3658. Thirdly, the WFCs contributed considerably towards establishing that nearly all (12 out of 13) luminous low-mass X-ray binaries in Galactic globular clusters contain neutron stars rather than black holes. Thus, the neutron star to black hole ratio in clusters differs from that in the Galactic disk at a marginal confidence level of 97%.

1. INTRODUCTION

Bleeker \cite{Bleeker} reviewed in general terms the prospects and results of the BeppoSAX Wide Field Camera instrument package (“WFCs”). The unique capability of matching a wide field of view of $40^\circ \times 40^\circ$ per each of two identical cameras with a good angular resolution of 5’ \cite{Cusson} not only led to a revolution of gamma-ray burst research (e.g., \cite{Romani}) but also to a serious advance of our knowledge on X-ray bursts and other transient emission processes in low-mass X-ray binaries (LMXBs). Much of the relevant data was acquired during the only dedicated BeppoSAX observation program involving the WFCs as prime instrument. This encompasses observations pointed at the Galactic center during semi-yearly visibility windows that lasted from mid February to mid April and from mid August to mid October. Table \ref{tab:campaigns} summarizes the twelve campaigns during the six-year BeppoSAX lifetime. The combined exposure time represents 8% of the total BeppoSAX exposure budget. The success of this program may be anticipated by the mere fact that the field of view of one WFC encompasses more than half the Galactic LMXB population according to pre-WFC catalogs \cite{Zand}. Another important ingredient for the success is that nearly all observations were analyzed in a near to real-time fashion. This was possible thanks to the 24 hr per day, 7 days a week, manning of the BeppoSAX Science Operations center (which was also crucial to the success of the GRB program of BeppoSAX \cite{Ubertini}) and the dedicated support by the ‘duty scientists’.

Tied to this program a dedicated target-of-opportunity program was in place for the BeppoSAX Narrow Field Instruments (NFIs) to follow up new transients or bursters. This program was triggered 14 times, with exposure times...
Table 1
WFC observation campaigns on the Galactic center. The effective exposure times are for the position of the Galactic center. Adapted from [6,7].

| Campaign          | # obs. | $t_{\text{exp}}$ (ks) |
|-------------------|--------|-----------------------|
| 1996 Aug.15–Oct.29 | 67     | 1017                  |
| 1997 Mar.02–Apr.26 | 21     | 654                   |
| 1997 Sep.06–Oct.12 | 13     | 302                   |
| 1998 Feb.11–Apr.11 | 17     | 551                   |
| 1998 Aug.22–Oct.23 | 10     | 410                   |
| 1999 Feb.14–Apr.11 | 14     | 470                   |
| 1999 Aug.24–Oct.17 | 24     | 801                   |
| 2000 Feb.18–Apr.07 | 21     | 633                   |
| 2000 Aug.22–Oct.16 | 29     | 767                   |
| 2001 Feb.14–Apr.23 | 5      | 215                   |
| 2001 Sep.04–Sep.30 | 7      | 284                   |
| 2002 Mar.05–Apr.15 | 5      | 91                    |

between 20 and 40 ksec. Whenever new transients or bursters were discovered, these were announced in IAU circulars. This happened on 20 occasions and triggered independent TOO programs on BeppoSAX, the Rossi X-ray Timing Explorer (RXTE), XMM-Newton, and ground-based radio and optical telescopes, illustrating a community service of the WFC program.

In the present paper, we provide a general overview of the accomplishments obtained through the WFC Galactic center program. We categorize the achievements in three areas: thermonuclear X-ray bursts, transients, and luminous globular cluster sources.

2. THERMONUCLEAR X-RAY BURSTS

Arguably, the most interesting results obtained are those on type-I X-ray bursts. These are events that last between a few seconds and a few minutes, exhibit a much faster rise than (usually exponential) decay, and radiate X-ray spectra having simple black body shapes with temperatures up to roughly 3 keV that cool during decay. The origin of these bursts lies in thermonuclear flashes in the top layers of a neutron star that consist of freshly accreted material from a usually non-degenerate companion star in a close orbit [8,9]. The duration of an X-ray burst is mainly determined by the hydrogen abundance in the layer that is unstably burned during the flash; longer X-ray bursts indicate larger hydrogen abundances. For reviews we refer to [10,11,12].

The WFC observations resulted in roughly 2200 type-I X-ray burst detections (1800 from the Galactic center field; see also [13] and [14]) from 54 sources, and have increased the X-ray burster population by roughly 50% from the pre-WFC era [5]. In Table 2 we provide a complete list of the 76 currently known Galactic X-ray bursters. This represents half the total known LMXB population [16]. The 23 bursters not seen bursting with the WFCs are either known to be transients not active during the WFC era or very sporadic bursters (e.g., Cir X-1 [17,18,19]).

Figure 1 presents the light curve of the single burst-like event detected from this source with the WFC in 1999. It exhibits a fast rise, a spectrum which is best fit with a black body of temperature $kT = 1$ to 2 keV (although other models are formally acceptable as well), a 300 s duration, and its 1.9'-radius error circle (99% confidence) is within 1.1' consistent with the ROSAT source.

Since the search for bursts is not complete yet, these totals could change by 5%.
Table 2
List of all 76 Galactic type-I X-ray bursters currently known. Updated up to November 2003. References are to WFC publications.

| Source            | Ref. | Source            | Ref. | Source            | Ref. |
|-------------------|------|-------------------|------|-------------------|------|
| MX 0513-40 (NGC 1851) | 20   | 1E 1724-3045 (Terzan 2) | 20, 30 | 2S 1803-245^w     | 16   |
| 4U 0614+09        |      | GX 354-0          | 25   | SAX J1806.5-2215^w | 15   |
| EXO 0748-676      |      | KS 1731-260^a     | 25, 31 | SAX J1808.4-3658^w | 17   |
| GS 0836-429       |      | XB 1733-30 (Terzan 1) |      | SAX J1810.6-2609^w | 48   |
| 2S 0918-549       | 21   | Rapid burster (Liller 1) |      | XTE J1814-337    |      |
| 4U 1246-588^w     | 22   | SLX 1735-269^w    | 32   | GX 13+1          |      |
| 4U 1254-69^a      | 23   | 4U 1735-44^a      | 33   | 4U 1812-12        | 19   |
| 4U 1323-62        |      | SLX 1737-282^w    | 34   | GX 17+2          |      |
| SAX J1324.5-6313^w| 21   | GRS 1741.9-2853^w | 35   | SAX J1818.7+1424^w,a | 21 |
| Cen X-4^x         |      | KS 1742-293       | 36, 37 | 4U 1820-303^a (NGC 6624) | 21, 25 |
| Cir X-1           |      | A 1742-294        | 25   | AX J1824-2451 (M28) |      |
| 4U 1608-522       | 24   | A 1742-289        |      | GS 1826-24^w     | 25, 50, 51 |
| 4U 1636-536^a     | 25   | A1744-361         |      | SAX J1828.5-1037^w | 21   |
| MXB 1658-298      | 26   | SLX 1744-299      |      | 1H 1832-33^w (NGC 6652) | 52   |
| 4U 1702-429       | 27   | SLX 1744-300      | 28   | Ser X-1^*        | 63   |
| 4U 1705-440       | 29   | XB 1745-248 (Terzan 5) |      | 4U 1850-08 (NGC 6712) |      |
| 4U 1708-40        |      | 4U 1746-37 (NGC 6441) |      | MXB 1906+000    |      |
| 1RXS J170854.4-321857^w | 27 | GRS 1747-312^w (Terzan 6) | 38, 39 | Aql X-1         |      |
| XTE J1709-267^w   | 28   | EXO 1747-212      |      | 4U 1915-05       |      |
| XTE J1710-281     |      | GX 3+1^a          | 30   | XB 1940-04       |      |
| 2S 1711-339^w     | 29   | SAX J1747.0-2853^w | 40, 41 | XTE J2123-058    |      |
| SAX J1712.6-3739^w| 30   | SAX J1748.9-2021^w,n |      | 4U 2129 + 11 (M15) | 20   |
| MX 1716-31        |      | SAX J1750.8-2900^w | 31   | 4U 2129+47      |      |
| RX J1718.4-4029^w | 32   | SAX J1752.4-3138^w | 33   | Cyg X-2         |      |
| XTE J1723-376     | 33   | SAX J1753.5-2349^w | 34   | SAX J2224.9+5421^w,a | 21 |
|                  |      | XTE J1759-220     |      |                  |      |

^w discovered through WFC observations; ^a uncertain type-I classification; ^b underluminous burst from an underluminous source in a globular cluster [54]; ^in NGC 6440; ^superburster; ^xCen X-4 exhibited the brightest type-I X-ray bursts of all bursters (25 Crab peak flux; [55]).

1RXS J170854.4-321857 which in the mid 1990s exhibited an intensity of 5 to 20 mCrab in the ROSAT HRI band and 0.3 mCrab in the PSPC band while its persistent emission was never detected with the WFCs above an upper limit of 5 mCrab. The double-peaked burst nature with a peak-to-peak delay of 3 minutes is somewhat unusual for a type-I X-ray burst.

Because of the sheer volume of X-ray bursts, the WFCs picked up a considerable number of bursts of rare kinds. Primarily these concern the so-called 'superbursts', a phenomenon discovered with the WFCs [33]. These are X-ray bursts which last \(10^3\) times longer than ordinary bursts and emit \(10^3\) times more energy. After the discovery, theoretical work quickly established that unstable carbon burning [56] in a heavy-element ocean [57], possibly combined with photo-disintegration-triggered nuclear energy release [58], is responsible for most superbursts. The carbon is located in a deeper layer than the hydrogen and helium that is burned in ordinary X-ray bursts, which accounts for the long duration of the phenomenon. Currently, eight superbursts have been detected, 4 with the WFCs and 4 with instruments on RXTE. The theory (e.g.,
predicts that superbursts should occur on any neutron star that is accreting matter at least as fast as one tenth of the Eddington limit. Thus far, they have only been seen in systems that accrete near the lower boundary, but efforts are under way to search for superbursts in more luminous neutron stars. The reason they were not found thus far may be because more luminous systems tend to be more variable in their persistent emission and provide less dynamic range between the persistent flux level and the Eddington limit. For a more detailed review of (WFC results on) superbursts we refer to [13].

Despite millions of seconds of coverage of many known LMXBs, 12 out of the 54 bursters seen bursting by the WFCs exhibited just a single burst. Many of those are low accretion rate LMXBs. Six had persistent emission levels below the detection limit [21] and present an interesting subset that is further discussed elsewhere in these proceedings [14].

Cornelisse et al. [25] investigated the burst properties of the 9 most prolific bursters in the Galactic center region as a function of mass accretion rate, using the complete WFC database. The number of bursts per burster ranges from 49 (for 4U 1820-30) to 423 (GX 354-0/4U 1728-33). The properties investigated are the wait time from burst to burst, the burst duration and the presence of quasi periodicities in burst occurrences. With regards to the latter, an intriguing discovery was made earlier by Ubertini et al. [50] with the WFCs: all bursts from GS 1826-24 between 1996 and 1998 recur after a quasi-fixed interval time of \(76 \pm 0.26\) hr. Later the coherence was found to be even higher because the period was seen to have a decreasing trend that matched a gradual increase of the persistent flux and, ergo,
Figure 4. A schematic diagram of the burst frequency as a function of luminosity for the 9 most prolific bursters in the Galactic center region. Between solid lines the rate mostly drops. No bursts were detected to the right of the dashed line. The dash-dotted line indicates the theoretical transition from hydrogen-rich to pure helium bursts. From [25].

Particularly new findings uncovered by Cornelisse [25] concern KS 1731-260, because this is the only prolific burster which is transient and, therefore, traces the largest dynamic range in mass accretion rate [51] (see also [15]).

This interpretation of the burst rate versus luminosity relation uncovers an inconsistency. Bildsten [61] presented GS 1826-24 as a textbook case of an X-ray burster in the upper burst regime, based on an accurate measurement of the mass accretion rate based on broadband BeppoSAX work [62] while the above work suggests that it is in the low burst regime. It seems this inconsistency can only be resolved by observations of this object at higher mass accretion rates. This will test whether the object will start to show shorter (helium-fueled) and less frequent bursts like KS 1731-260 did in reverse (i.e., from higher to lower mass accretion rates) which would prove it to be in the low burst regime. If so, we would lose one of the only few textbook cases we have adhering to the burst theory so nicely. Unfortunately, there are indications that the brightening trend that GS 1826-24 exhibited since the launch of RXTE and BeppoSAX (by about 40%) is lev-
3. LMXB TRANSIENTS

The WFC observations revealed 14 previously unknown transients in the Galactic center field that remained active for at least a few hours (most for at least a few days; see Table 3). Except perhaps for two less obvious cases (SAX J1818.6-1703 [88] and IGR J17544-2619), they are all LMXBs. One contains a dynamically confirmed black hole candidate (V4641 Sgr = SAX J1819.3-2525; [84]), one is suspected to be a black hole candidate (SAX J1711.6-3808; [69]), seven contain neutron stars (as established through X-ray burst detections), and one is undetermined (SAX J1805.5-2031; [87]). Furthermore, the WFCs detected recurrences of six already known transients. Three new transients were detected only during type-I X-ray bursts; they are so-called 'bursting-only sources' [21]. In total, the WFCs detected 34 LMXB transients in the field, while the total number of transients known to have been active during 1996-2002 is just two larger: 36.

When browsing through the list (Table 3) it is striking that there are only 8 out of the 36 transients that reached peak fluxes in excess of 0.2 Crab units; a substantial fraction of 13 out of 36 is even fainter than 0.05 Crab. Sometimes this is accompanied by a short duration, but this is not the rule (e.g., [84]). An example of this is given in Fig. 5 which presents the light curve of the 1998 outburst of SAX J1748.9-2021 in the globular cluster NGC 6440 which had an e-folding decay time as short as 5 d. A further noteworthy detail is that most (22) transients burst and, thus, contain a neutron star. The low outburst peak fluxes indicate sub-Eddington luminosities for a canonical 8 kpc distance.

The fact that the observations have detected recurrence in half of all transients suggests that a fair fraction of the LMXB transients with recurrence times below a few years and on-times longer than a few days have now been discovered in this field. Assuming that the sample is complete and that this field represents half the total Galactic population, there must be roughly 40 such transients in total. Quicker transients, such as SAX J1748.9-2021 [78] or SAX J1810.8-2609 [48], are more elusive unless they recur often enough (such as V4641 Sgr, see Table 3).

4. X-RAY LUMINOUS OBJECTS IN GLOBULAR CLUSTERS

There are 150 globular clusters in the Galaxy and 12 contain 13 luminous LMXBs (M15 has two). In a number of clusters, considerable quantities of quiescent LMXBs have been found. Pooley et al. [72] estimate a total of 100 mostly quiescent LMXBs in Galactic globular clusters. Thus, it is obvious that LMXBs are abundant in clusters; for instance, luminous LMXBs are 100 times more abundant than in the Galactic disk, in terms...
Table 3

36 LMXB transients that were seen to be active in 1996-2002 within 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](http://xte.mit.edu)). Other characteristics were obtained from the references listed, that are incomplete and emphasized on WFC results. This is an update from [91]. Similar lists for transients before 1996 are given in Chen et al. (1997).

| Name | Peak flux mCrab | Duration days | Bursts? | Outburst Yrs | Comments | Refs |
|------|-----------------|---------------|---------|--------------|----------|------|
| GRO J1655-40 | 4500 | 200 | Y | 94,95,96-97 | bhc | 65 |
| X1658-398 | 30 | 1000 | Y | 78, 99-01 | eclipses | 65 |
| IGR J17091-3624 | 10 | > 10 | Y | 94,96,01,03 | | |
| XTE J1709-267 | 200 | 100 | Y | 97,02 | | 67 |
| XTE J1710-281 | 10 | > 1700 | Y | 99- | eclipses | 67 |
| SAX J1711.6-3808 | 60 | 170 | Y | 01 | bhc | 69 |
| 2S 1711-339 | 50 | 700−1700 | Y | 76, 98- | | 21 |
| SAX J1712.6-3739 | 50 | > 1100? | Y | 98,01- | | 21,69 |
| RX J1718-4029 | burst only | y | [97] | | | 21 |
| XTE J1723-376 | 80 | 70-100 | Y | 99 | | 70,71 |
| Rapid burster | 300 | 70 | Y | every year | | 72 |
| GRS 1737-31 | 25 | 30 | Y | 97 | bhc | 72 |
| GRS 1739-278 | 800 | 250 | Y | 96 | jet, bhc | 72 |
| XTE J1739-285 | 200 | 40 | Y | 99,01,03 | | 75 |
| KS 1741-293 | 30 | few | Y | 89, 98 | | 76 |
| GRS 1741.9-2853 | 70 | 10? | Y | 90,96 | | 76 |
| XTE J1743-363 | 15 | > 600 | Y | 99- | | 68 |
| GRO J1744-28 | 2600 | 60 | Y | 95-97 | type-II only? | 76 |
| EXO 1745-248 | 600 | > 200 | Y | 80,84,00,02 | any type-II? | 76 |
| SXT J1747.0-2853 | 140 | 70 | Y | 767,98,99,00,01 | | 76 |
| GRS 1747-312 | 40 | 18 | Y | every year | eclipses | 76 |
| SXT J1748.9-2021 | 40 | 8 | Y | 717,98,01 | | 76 |
| XTE J1748-288 | 500 | 15 | Y | 98 | jet, bhc | 76 |
| SAX J1750.8-2900 | 120 | 230 | Y | 97,01 | | 76 |
| XTE J1751-305 | 55 | 12 | Y | 02 | ms pulsar | 76 |
| SAX J1752.3-3138 | burst only | y | [98] | | | 44 |
| SAX J1753.5-2349 | burst only | y | [96] | | | 44 |
| IGR J17544-2619 | 200 | 0.1 | Y | 96,97,99,00,03 | uncertain LMXB | 83,84 |
| XTE J1755-324 | 150 | 40 | Y | 97 | bhc | 85 |
| 2S 1803-245 | 700 | 25 | Y | 76, 98 | jet | 86 |
| SAX J1805.5-2031 | 50 | 250 | Y | 02 | | 87 |
| SAX J1806.5-2215 | 13 | > 800 | Y | 96 | | 88 |
| SAX J1808.4-3658 | 100 | 18 | Y | 96,98,00,02 | ms pulsar | 47 |
| SAX J1810.8-2609 | 15 | 3 | Y | 98 | | 48 |
| SAX J1818.6-1703 | 200 | 0.1 | Y | 98 | uncertain LMXB | 85 |
| SAX J1819.3-2525 | 12000 | 210 | Y | 99,02,03 | jet, bhc | 89,90 |
of number per unit mass \[ \frac{dN}{dm} \].

The nature of the compact accretor has been determined in 12 of the 13 cases as neutron stars through the detection of type-I X-ray bursts. The WFCs have established three of these bursters (see Table 2). The one unresolved case, AC211 in M15, has recently been argued to contain a neutron star as well on the basis of an optical study \[ \text{[95]} \]. Furthermore, AC211 is a persistent source while all black hole LMXBs are transient. Thus, another disk versus cluster difference concerns the number ratio of black holes to neutron stars in LMXBs. None of the luminous cluster LMXBs has a confirmed or even a suspected black hole (0/13), while there are 37 cases in the Galactic disk (of which 15 dynamically confirmed and 22 suspected; \[ \text{[96]} \]). The difference is not very significant though. If the same disk ratio of 37/150 applies to globular clusters as well, there would be a 3% probability that no black hole systems would be found in a random sample of 13.

The WFCs made interesting observations of two particular luminous globular cluster LMXBs. The first concerns NGC 6440. No X-ray outburst was detected from this cluster since January 1972 \[ \text{[97]} \], but in August 1998 the WFCs detected an outburst which included first-time observations of X-ray bursts. Follow-up observations were carried out with the BeppoSAX-NFI and ROSAT, and Fig. 5 shows the combined light curve. The transient lasted only a little over a week, and the peak flux was about 50 mCrab. Follow-up observations were also carried out at high spatial resolution in the optical. Comparison with later observations when the transient was off revealed the first-time detection of an optical counterpart...
to an X-ray transient in a globular cluster, see Fig. 6. This identification was later confirmed by Chandra high-resolution X-ray observations during another outburst. The fact that some outbursts last very short makes clear that a swift response of follow-up observations is sometimes imperative.

The other interesting WFC observation of a luminous cluster LMXB concerns Terzan 6. First detected by Granat and ROSAT in 1990, WFC and RXTE observations showed that this is a transient with a very regular outburst pattern like in the Rapid Burster and Aql X-1 with a (quasi) period of 4.5 months. By combining WFC data from the first half of the mission it was found that this transient is one of now six known completely eclipsing LMXBs in the Galaxy. The orbital period of 12.4 hr is typical for an LMXB.

5. CONCLUSION

The results of the Galactic center campaigns of the BeppoSAX WFCs are plentiful. This is mainly due to its large field of view which enabled to monitor a large fraction of the Galactic LMXB population and resulted in a large exposure of roughly 7 million seconds over six years on tens of sources. Such an exposure has not been accomplished by any other device yet. Thus, it has been possible to detect rare phenomena such as superbursts, burst-only sources and swift transients (e.g., V4641 Sgr). The analysis of WFC data will continue and new results are expected to come out. This particularly concerns time scales of a few hours and the longest time scales, and weak signals (e.g., X-ray bursts fainter than 0.5 Crab).

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