Unveiling the hard X-ray spectrum from the “burst-only” source SAX J1753.5–2349 in outburst

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ABSTRACT
Discovered in 1996 by BeppoSAX during a single type-I burst event, SAX J1753.5–2349 was classified as “burst-only” source. Its persistent emission, either in outburst or in quiescence, had never been observed before October 2008, when SAX J1753.5–2349 was observed for the first time in outburst. Based on INTEGRAL observations, we present here the first high-energy emission study (above 10 keV) of a so-called “burst-only”. During the outburst the SAX J1753.5–2349 flux decreased from 10 to 4 mCrab in 18–40 keV, while it was found being in a constant low/hard spectral state. The broad-band (0.3–100 keV) averaged spectrum obtained by combining INTEGRAL/IBIS and Swift/XRT data has been fitted with a thermal Comptonisation model and an electron temperature \( T_e \gtrsim 24 \) keV inferred. However, the observed high column density does not allow the detection of the emission from the neutron star surface. Based on the whole set of observations of SAX J1753.5–2349, we are able to provide a rough estimate of the duty cycle of the system and the time-averaged mass-accretion rate. We conclude that the low to very low luminosity of SAX J1753.5–2349 during outburst may make it a good candidate to harbor a very compact binary system.

Key words: X-ray: binaries – X-ray: bursts – Stars: neutron – Accretion, accretion discs – Galaxy: bulge – Stars: Individual: SAX J1753.5–2349

1 INTRODUCTION
SAX J1753.5–2349 is a neutron star Low Mass X-ray Binary (LMXB) discovered in 1996 by BeppoSAX/Wide Field Camera (WFC) during a single type-I X-ray burst (in’t Zand et al. 1999). However, no steady emission was detected from the source leading to an upper limit of about 5 mCrab (2–8 keV) for a total exposure of 300 ks (in’t Zand et al. 1999). Cornelisse et al. (2004) proposed SAX J1753.5–2349 being member of a possible non-homogeneous class of LMXBs, the so-called “burst-only” sources (see also Cocchi et al. 2001). These are a group of nine bursters discovered by BeppoSAX/WFC when exhibiting a type-I burst without any detectable persistent X-ray emission.

\* Based on observations with INTEGRAL, an ESA project with instruments and science data centre funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), Czech Republic and Poland, and with participation of Russia and the USA.
Table 1. Log of the INTEGRAL observations of the SAX J1753.5−2349 region: orbit number (Rev.), start and end time of the observations, exposures time for each orbit taking into account the whole data-set, and number of pointings (SCW) are reported. Observations within a single orbit are not continuous. The first INTEGRAL detection of SAX J1753.5−2349 occurred in rev. 732. A data sub-set from rev. 732 to 736 has been used to compute the averaged spectra. The last column reports the exposures of spectra in each orbit.

| Rev. | Start (MJD) | End (MJD) | Total Exp. (ks) | SCW | Spec. Exp. (ks) |
|------|-------------|-----------|----------------|-----|----------------|
| 724  | 54727.50    | 54728.23  | 58             | 17  | -              |
| 725  | 54729.11    | 54731.52  | 198            | 56  | -              |
| 726  | 54732.52    | 54734.46  | 160            | 45  | -              |
| 729  | 54741.37    | 54741.86  | 42             | 12  | -              |
| 731  | 54749.22    | 54749.55  | 20             | 8   | -              |
| 732  | 54749.90    | 54750.85  | 83             | 32  | 26.2           |
| 733  | 54754.96    | 54755.46  | 38             | 11  | 10.8           |
| 734  | 54756.87    | 54758.54  | 128            | 48  | 36.5           |
| 735  | 54760.91    | 54761.53  | 43             | 13  | 23.2           |
| 736  | 54762.03    | 54763.63  | 38             | 49  | 30.0           |

In 2002 observations with Chandra and XMM-Newton allowed to reveal the nature of four BeppoSAX “burst-only” sources: one persistent very-faint source, two faint transient systems (with 2–10 keV peak luminosity in the range $10^{35}$–$10^{37}$ erg s$^{-1}$), and one VFXT (see Wijnands et al. 2006 and reference therein). For the other five bursters, including SAX J1753.5−2349, only the quiescent emission could be derived ($\sim10^{32}$ erg s$^{-1}$; Cornelisse et al. 2004). Wijnands et al. (2006) proposed these systems, as good candidates to be classified as VFXTs (see also Campa 2009).

In 2008 October 11, RXTE/PCA, Swift/BAT (Markwardt et al. 2008) and INTEGRAL/IBIS (Cadolle Bel 2008) detected an outburst from SAX J1753.5−2349 at 10 mCrab flux level. Then, Swift/XRT pointed SAX J1753.5−2349 on October 23 (Degenaar & Wijnands 2008), during the decline phase of the outburst (Fig. 1). An improvement in the source position, R.A.(J2000)=17°53′31.90″, Dec.(J2000)=−23°48′16.7′′, has been provided (Starling & Evans 2008). On 2009 March 13, it was re-pointed by Swift and a 3σ upper-limit derived. This translates in a luminosity level $\lesssim5 \times 10^{32}$ erg s$^{-1}$ (Del Santo et al. 2009).

In this paper we present the hard X-ray outburst of SAX J1753.5−2349 observed by INTEGRAL/IBIS, as well as the first broad-band spectral analysis of the steady emission of a “burst-only”. We estimate the long-term mass-accretion rate and discuss the nature of the transient system.

2 OBSERVATION AND DATA ANALYSIS

2.1 INTEGRAL

This paper is based on INTEGRAL observations of the Galactic Centre region carried out in the framework of the AO6 Key-Programme. Moreover, we used data from a public ToO on the source H 1743-322, at 8.6″ from SAX J1753.5−2349, performed on 2008 October, for a total exposure time of 800 ks (see Tab. 1). We reduced the data of the IBIS (Ubertini et al. 2003) low energy detector ISGRI using the INTEGRAL Off-Line Scientific Analysis, release 8.0. Due to the source weakness, no signal was found in the JEM-X data. On October 10, the first IBIS detection of SAX J1753.5−2349 was found (rev. 732). We extracted the IBIS/ISGRI light curves from each revolution as reported in Tab. 1 (binning size as the Total Exposure column) in the energy range 18–40 keV, 40–80 keV, 80–150 keV. For the spectral extraction, we used a sub-set of the data reported in Tab. 1 selecting only pointings including SAX J1753.5−2349 in the IBIS FOV up to 50% coding (15″×15″). We obtained four averaged spectra from revolutions 732, 733, 734 and 735-736 (the latests have been added together because of the poor statistics). Spectral fits were performed using the spectral X-ray analysis package XSPEC v. 11.3.1.

2.2 Swift

A Swift ToO was performed on October 23 (Degenaar & Wijnands 2008). The Swift/XRT data of observation 00035713002 were collected in photon counting (PC) mode between 2008-10-23 17:48:53 and 21:08:57 UT, for a total on-source net exposure of 1 ks.

They were processed with standard procedures (xrtpipeline v0.12.1), filtering and screening criteria by using the Heasoft package (v.6.6.1). Moderate pile-up was present, so source events were extracted from an annular region (radii of 20 and 3 pixels; 1 pixel $\sim 2''36$), while background events were extracted from an annular region (radii 120 and 80 pixels) away from background sources. An XRT spectrum was extracted and ancillary response files were generated with xrtmkarf, to account for different extraction regions, vignetting and PSF corrections. We used the spectral redistribution matrices v011 in the Calibration Database maintained by HEASARC. All spectra were rebinned with a minimum of 20 counts per energy bin.

We retrieved the BAT daily light curves (15–50 keV) available starting from MJD=54754, from the

(Lebrun et al. 2003), and JEM-X (Lund et al. 2003) data using the INTEGRAL Off-Line Scientific Analysis, release 8.0. Due to the source weakness, no signal was found in the JEM-X data. On October 10, the first IBIS detection of SAX J1753.5−2349 was found (rev. 732). We extracted the IBIS/ISGRI light curves from each revolution as reported in Tab. 1 (binning size as the Total Exposure column) in the energy range 18–40 keV, 40–80 keV, 80–150 keV. For the spectral extraction, we used a sub-set of the data reported in Tab. 1 selecting only pointings including SAX J1753.5−2349 in the IBIS FOV up to 50% coding (15″×15″). We obtained four averaged spectra from revolutions 732, 733, 734 and 735-736 (the latests have been added together because of the poor statistics). Spectral fits were performed using the spectral X-ray analysis package XSPEC v. 11.3.1.
Swift/BAT transient monitor (Krimm et al. 2006, 2008; http://heasarc.gsfc.nasa.gov/docs/swift/results/transients/) page.

3 RESULTS

The IBIS/ISGRI and BAT count rate of SAX J1753.5−2349 are shown in Fig. 1. Based on the IBIS data, the hard X-ray outburst started on October 10 at a flux level of 10 mCrab (18–40 keV) and lasted at least 14 days (last pointing at 4 mCrab). This outburst is hence characterised by a fast increase of the flux and a linear decay with a slope of −0.13±0.01.

An INTEGRAL pointing with no SAX J1753.5−2349 detection was performed eight hours before the outburst started. We also averaged all our data (from rev 724 to 731) collected before the first source detection for a total of 500 ks, resulting in a 3σ upper limit of 1 mCrab (Fig. 1).

In order to look for any possible spectral variability, we fitted the four averaged IBIS spectra with a simple power law. We obtained a constant value (within the errors) of the photon index (Γ≈ 2) which indicates, in spite of the flux variation, a steady spectral state.

The lack of spectral parameter variation led us to average the IBIS spectra of different revolutions. The 18–100 keV averaged spectrum is well described by a simple power law model such as the power law (Fig. 2, left). The best fit parameters and mean fluxes are reported in Tab. 2.

Thus, using a physical thermal Comptonisation model, COMPTT (Titarchuk 1994) in XSPEC, the electron temperature is not constrained, while a lower limit of ∼24 keV (at 90%) can be inferred (see Tab. 2 and contour levels in Fig. 3). This is consistent with the electrons temperature observed in burster systems, even brighter than SAX J1753.5−2349 (Barret et al. 2000).

With the addition of the BB component to the thermal Comptonisation, a typical value of the black-body temperature (kTBB ∼0.3 keV) is obtained (Fig. 2, right), even though this component is not requested by the Ftest probability (7×10−2). We may argue that the high absorption observed in SAX J1753.5−2349 could be a strong obstacle to the firm detection of this component.

As a first approximation, the accretion luminosity Lacc is coincident with the bolometric luminosity of the source (0.1−100 keV). Using the mean 0.1–100 keV flux obtained with the COMPTT model fit and assuming a distance of 8 kpc (Galactic Centre), a value of Lacc = 4.3 ×1036 erg s−1 (∼0.02 L_Edd) is derived. The averaged mass-accretion rate (Ṁacc = RLacc/GM, where G is the gravitational constant, M = 1.4 M⊙ and R = 10 km for a neutron star accretor) during the outburst is 6.7 ×10−10 M⊙ yr−1.

\(^1\) http://heasarc.gsfc.nasa.gov/docs/tools.html

\textbf{Figure 2.} XRT and IBIS/ISGRI count rate spectra fitted with a simple power-law (left); the total \texttt{bb+comppt} model (continuous line) and the two single components (dashed lines) (right).
4 DISCUSSION

We report here for the first time the broad-band spectrum, from soft to hard X-rays, of the persistent emission from a so-called “burst-only” source. In particular, none of these sources have ever been studied above 10 keV during their persistent emission.

The outburst from SAX J1753.5–2349 observed with INTEGRAL/IBIS has a duration of at least 14 days, without any evidence for type-I X-ray bursts, all along the performed INTEGRAL observations of the Galactic Centre region started in 2003.

From the RXTE/PCA flux detection at 8 mCrab (Markwardt et al. 2008) we can derive an absorbed 2–10 keV peak flux of about 1.7 × 10^{-10} erg cm^{-2} s^{-1} which translates in an unabsorbed luminosity higher than 1.3 × 10^{36} erg s^{-1}. This value seems to indicate SAX J1753.5–2349 being a hybrid system (such as AX J1745.6–2001 and GRS 1741.9–2853, see Degenaar & Wijnands 2009) which displays very-faint outbursts with 2–10 keV peak luminosity \( L_X < 10^{36} \) erg s^{-1} (as resulted from WFC observations in 1996), as well as outbursts with luminosities in the range \( 10^{36–37} \) erg s^{-1}, which are classified as X-ray (FXT; Wijnands et al. 2006). However, it is worth to know that the low X-ray luminosity \( L_X \) boundary as \( 10^{36} \) erg s^{-1} is somewhat arbitrary (such as the VFXT/FXT classification). Nevertheless, our result reinforces the hypothesis that the so-called “burst-only” sources belong to the class of the subluminous neutron star X-ray binaries.

A rough estimate of the duty cycle (as the ratio of \( t_{ob}/t_{rec} \)) can be obtained. The time interval between the two 2008 measurements of the quiescence (February 2008–March 2009) is about 13 months while the outburst recurrence \( t_{rec} \) is about 12 years (from the burst event in 1996). However, it is possible that we missed other outbursts of SAX J1753.5–2349 that occurred between 1996 and 2008 within periods not covered by Galactic Centre monitoring. The outburst duration \( t_{ob} \) ranges from a minimum of 14 days (as observed) and a maximum of 13 months, since there are not any other X-ray observations but the ones in October. In fact, we cannot exclude that the hard X-ray outburst may be part of a longer outburst occurred at a lower luminosity level, only detectable by high-sensitivity X-ray telescopes.

This translates into a duty cycle ranging from a minimum of 0.3% to a maximum of 9% and into a long-term time-averaged accretion rate \( (\langle \dot{M}_{\text{obs}} \rangle = (\dot{M}_{\text{obs}}) \times t_{ob}/t_{rec} \) ranging from \( 2.2 \times 10^{-12} \) to \( 6.0 \times 10^{-11} \) M_{\odot} yr^{-1}.

Table 2. The parameters the XRT/IBIS spectra fitted four different models.

| Model     | \( N_H \) (10^{22} cm^{-2}) | \( kT_{BB} \) (keV) | \( \Gamma \) | \( E_{e} \) (keV) | \( kT_e \) (keV) | \( \tau \) | \( \chi^2/\nu \) (dof) | \( F^a_{bol} \) (erg cm^{-2} s^{-1}) |
|-----------|-----------------|-----------------|-------------|-----------------|-----------------|--------|----------------|----------------|----------------|
| POW       | 2.5^{+0.5}_{-0.4} | -               | 2.3 ± 0.3   | -               | -               | -      | 0.91(19)       | 1.3 \times 10^{-9} |
| BB+POW    | 2.8^{+2.0}_{-1.0} | 0.4^{+0.3}_{-0.1} | 2.1 ± 0.3   | -               | -               | > 24   | 0.2^{+1.3}_{-0.1} | 1.07(18)       | 5.6 \times 10^{-10} |
| Comptt    | 1.9^{+0.4}_{-0.4} | -               | -           | -               | > 24            | 0.8^{+2.2}_{-0.6} | 0.86(16)       | 6.3 \times 10^{-9} |
| BB+Comptt | 2.5^{+2.0}_{-1.0} | 0.4^{+0.3}_{-0.2} | -           | -               | > 17            | 0.9^{+2.0}_{-0.1} | 0.86(16)       | 6.3 \times 10^{-10} |

* The bolometric flux of the unabsorbed best-fit model spectrum.

Figure 3. Confidence contour levels of electron temperature and plasma optical depth for the \texttt{comptt} model fitting the broad-band spectrum.

King & Wijnands (2006) suggested that neutron star in transient LMXBs with low time-averaged mass accretion rate might pose difficulties explaining their existence without invoking exotic scenarios such as accretion from a planetary donor. However, the regime of \( \langle \dot{M}_{\text{obs}} \rangle \) estimated for SAX J1753.5–2349 can be well explained within current LMXB evolution models.

In spite of the flux variability along the outburst, the spectral state of SAX J1753.5–2349 remains steady, in low/hard state. This is in agreement with the fact that a very low X-ray luminosity, \( L_X = 0.01 \)L_{\text{Edd}} or so, produces a hard state in most sources (van der Klis 2000).

Following in’t Zand et al. (2007), we have estimated the hardness ratio 40–100/20–40 keV within which INTEGRAL revolutions. We find a value consistent with 1 which confirms the hard nature of the system. This is also consistent with the low mass accretion rate inferred (see also Paizis et al. 2006), i.e. SAX J1753.5–2349 is not a fake faint system and there would be no reason to assume that the system is obscured to explain the low \( M \).

Moreover, King (2000) argued that the faint low-mass X-ray transients are mainly neutron star X-ray binaries in very compact binaries with orbital periods lower than 80 min. We suggest that the SAX J1753.5–2349 system is a good candidate to harbor an accreting neutron star in a very compact system.

In conclusion, SAX J1753.5–2349 joins a sample of low-luminosity transient LMXBs (Degenaar & Wijnands 2009).
which display different behaviour in terms of peak luminosity, outburst duration and recurrence time from year to year. Up to now, it is not understood whether these variations should be interpreted as being due to changes in the mass-transfer rate or as results of instabilities in the accretion disc (Degenaar & Wijnands 2009 and reference therein).

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