Two years of monitoring supergiant fast X-ray transients with Swift

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ABSTRACT

We present results based on 2 yr of intense Swift monitoring of three supergiant fast X-ray transients (SFXTs), IGR J16479−4514, XTE J1739−302 and IGR J17544−2619, which we started in 2007 October. Our out-of-outburst intensity-based X-ray (0.3–10 keV) spectroscopy yields absorbed power laws characterized by hard photon indices (Γ1 ∼ 1–2). The broad-band (0.3–150 keV) spectra of these sources, obtained while they were undergoing new outbursts observed during the second year of monitoring, can be fitted well with models typically used to describe the X-ray emission from accreting neutron stars in high-mass X-ray binaries. We obtain an assessment of how long each source spends in each state using a systematic monitoring with a sensitive instrument. By considering our monitoring as a casual sampling of the X-ray light curves, we can infer that the time these sources spend in bright outbursts is between 3 and 5 per cent of the total. The most probable X-ray flux for these sources is ∼(1–2) × 10−11 erg cm−2 s−1 (2–10 keV, unabsorbed), corresponding to luminosities of the order of a few 1033 to a few 1034 erg s−1 (two orders of magnitude lower than the bright outbursts). In particular, the duty-cycle of inactivity is ∼19, 39 and 55 per cent (∼5 per cent uncertainty) for IGR J16479−4514, XTE J1739−302 and IGR J17544−2619, respectively. We present a complete list of BAT onboard detections, which further confirm the continued activity of these sources. This demonstrates that true quiescence is a rare state and that these transients accrete matter throughout their life at different rates. Variability in the X-ray flux is observed at all time-scales and intensity ranges we can probe. Superimposed on the day-to-day variability is intraday flaring, which involves flux variations up to one order of magnitude that can occur down to time-scales as short as ∼1 ks, and which can be naturally explained by the accretion of single clumps composing the donor wind with masses Mcl ∼ (0.3–2) × 1019 g. Thanks to the Swift observations, the general picture we obtain is that, despite individual differences, common X-ray characteristics of this class are now well defined, such as outburst lengths well in excess of hours, with a multiple peaked structure, and a high dynamic range (including bright outbursts), up to approximately four orders of magnitude.

Key words: X-rays: binaries – X-rays: individual: IGR J16479−4514 – X-rays: individual: XTE J1739−302 – X-rays: individual: IGR J17544−2619.

1 INTRODUCTION

Supergiant fast X-ray transients (SFXTs) constitute a new class of high-mass X-ray binaries (HMXBs). Discovered by INTEGRAL...
EASOFT INTEGRAL ∼ (Sguera et al. 2006; Walter & Zurita Heras 2007; Blay 2010) reported the discovery of a 51 mCrab (20–40 keV) and some were found in archival BeppoSAX observations (in’t Zand et al. 2004). Subsequent flares were observed by Swift (Krimm et al. 2007; Paper III; Paper IV) and Suzaku (Rampy, Smith & Negueruela 2009). Recently, Clark et al. (2009) reported the discovery of a 4.926 ± 0.0001 d orbital period based on the ∼4.5 yr of INTEGRAL data. The optical counterpart is an O9Ib star (Pelizza, Chaty & Negueruela 2006).

IGR J16479−4514 was discovered by INTEGRAL in 2003 (Molkov et al. 2003), during an outburst that reached the flux level of ∼12 mCrab (18–25 keV). Since then the source has shown frequent flaring activity, recorded by both INTEGRAL (Sguera et al. 2005, 2006; Walter & Zurita Heras 2007) and Swift (Kennea et al. 2005, 2006; Krimwardt & Krimm 2006; Paper II; Bozzo et al. 2009; Paper V), which led to its inclusion in the SFXT class. The optical counterpart is an O8.5I star (Rahoui et al. 2008). Recently, Bozzo et al. (2008b) reported an episode of sudden obscuration in a long XMM–Newton observation obtained after the 2009 March 19 outburst, possibly an X-ray eclipse by the supergiant companion. This was later confirmed by Jain, Paul & Dutta (2009), who discovered a 3.32 d orbital period in the first 4 yr of BAT data and RXTE/ASM data, and by Paper V by using XRT observations spanning 1 yr.

We monitored the first two targets as they are generally considered prototypical SFXTs and the latter because of its frequent triggering of the BAT since the beginning of the mission. We planned two observations per week per object (IGR J16479−4514 and IGR J17544−2619) and three observations per week per object (XTE J1739−302), each 1 ks long. The observation logs are reported in Tables 1–3. This strategy was chosen to fit within the regular observing schedule of the main observing targets for Swift, gamma-ray bursts (GRBs).

Furthermore, in order to ensure simultaneous narrow field instrument (NFI) data, the Swift Team enabled automatic rapid slews to these objects following detection of flares by the BAT, in the same fashion as is currently done for GRBs. During the campaign, we often requested target of opportunity (ToO) observations whenever one of the sources showed interesting activity or following outbursts to better monitor the decay of the XRT light curve, thus obtaining a finer sampling of the light curves and allowing us to study all phases of the evolution of an outburst.

During the second year (2009), we collected a total of 228 Swift observations as part of our programme, for a total net XRT exposure of ∼243 ks accumulated on all sources and distributed as shown in Table 4.

### 3 DATA REDUCTION

The XRT data were uniformly processed with standard procedures (XRTPipeline v0.12.3), and filtering and screening criteria by using FTOOLS in the HEASOFT package (v6.7). We considered both windowed-timing (WT) and photon-counting (PC) mode data, and selected event grades 0–2 and 0–12, respectively (Burrows et al. 2005). When appropriate, we corrected for pile-up by determining the size of the affected core of the point spread function (PSF) by comparing the observed and nominal PSF (Vaughan et al. 2006),
Table 1. Observation log for IGR J16479−4514. The full table is available online (see Supporting Information).

| Sequence   | Instrument/mode | Start time (UT)        | End time (UT)         | Net exposure (s) |
|------------|-----------------|------------------------|-----------------------|------------------|
| 00030296096  | XRT/PC          | 2009-02-19 21:23:39    | 2009-02-19 23:11:56   | 1178             |
| 00030296097  | XRT/PC          | 2009-02-23 15:15:37    | 2009-02-23 17:08:58   | 1925             |
| 00030296098  | XRT/PC          | 2009-02-26 20:38:22    | 2009-02-26 22:21:58   | 902              |
| 00030296099  | XRT/PC          | 2009-03-01 01:36:58    | 2009-03-01 03:20:57   | 1014             |
| 00030296101  | XRT/PC          | 2009-03-08 01:58:11    | 2009-03-08 02:11:58   | 813              |

Table 2. Observation log for IGR J17391−3021. The full table is available online (see Supporting Information).

| Sequence   | Instrument/mode | Start time (UT)        | End time (UT)         | Net exposure (s) |
|------------|-----------------|------------------------|-----------------------|------------------|
| 00030987098  | XRT/PC          | 2009-02-21 13:32:13    | 2009-02-21 15:19:57   | 1382             |
| 00030987099  | XRT/PC          | 2009-02-23 07:26:20    | 2009-02-23 09:11:58   | 1354             |
| 00030987100  | XRT/PC          | 2009-02-25 14:13:53    | 2009-02-25 15:56:58   | 1123             |
| 00030987101  | XRT/PC          | 2009-02-27 23:51:23    | 2009-02-27 23:59:44   | 487              |
| 00030987102  | XRT/PC          | 2009-03-02 01:42:07    | 2009-03-02 01:57:57   | 939              |

Table 3. Observation log for IGR J17544−2619. The full table is available online (see Supporting Information).

| Sequence   | Instrument/mode | Start time (UT)        | End time (UT)         | Net exposure (s) |
|------------|-----------------|------------------------|-----------------------|------------------|
| 00035056083  | XRT/PC          | 2009-02-21 16:45:15    | 2009-02-21 18:32:57   | 1387             |
| 00035056084  | XRT/PC          | 2009-02-24 07:31:27    | 2009-02-24 07:50:58   | 1160             |
| 00035056085  | XRT/PC          | 2009-02-28 01:28:32    | 2009-02-28 01:45:57   | 1034             |
| 00035056086  | XRT/PC          | 2009-03-03 19:35:54    | 2009-03-03 21:18:57   | 784              |
| 00035056087  | XRT/PC          | 2009-03-07 20:30:32    | 2009-03-07 21:41:56   | 268              |

Table 4. Summary of the Swift/XRT monitoring campaign.

| Name         | Campaign Start (yyyy-mm-dd) | Campaign End (yyyy-mm-dd) | N<sup>a</sup> | Exposure<sup>b</sup> (ks) | Outburst dates<sup>c</sup> | BAT trigger | Reference |
|--------------|------------------------------|----------------------------|-------------|---------------------------|---------------------------|-------------|-----------|
| IGR J16479−4514 | 2007-10-26                   | 2008-10-25                 | 70          | 75.2                      | 2007-08-19                | 306829      | Romano et al. (2008d) |
| XTE J1739−302  | 2007-10-27                   | 2008-10-31                 | 95          | 116.1                     | 2007-08-04                | 308797      | Romano et al. (2008b), Sidoli et al. (2009a) |
| IGR J17544−2619 | 2007-10-28                   | 2008-10-31                 | 77          | 74.8                      | 2007-11-08                | BTM         | Krimm et al. (2007)  |
|               |                              |                            | 89          | 89.6                      | 2009-03-10                | 346069      | Romano et al. (2009d), this work |
|               |                              |                            | 65          | 68.0                      | 2009-03-15                | BTM         | Krimm, Romano & Sidoli (2009), this work |

<sup>a</sup>Number of observations (individual ObsIDs) obtained during the monitoring campaign.
<sup>b</sup>Swift/XRT net exposure.
<sup>c</sup>BAT trigger dates. BTM = triggered the BAT Transient Monitor; XM = discovered in XRT monitoring data.

Note. We report the data from the first year in italics.

and excluding from the analysis all the events that fell within that region. We used the latest spectral redistribution matrices in CALDB (20091130).

The BAT data of the outbursts (see Section 5) were analysed using the standard BAT software within FTOOLS. Mask-tagged BAT light curves were created in the standard energy bands, and rebinned to fulfil at least one of the following conditions, achieving a signal-to-noise ratio (S/N) of 5 or bin length of 100 s. Response matrices were generated with BATDRMGEN using the latest spectral redistribution matrices. For this paper, we also considered the BAT
Transient Monitor data (Krimm et al. 2006, 2008), covering the same time-interval as the NFI pointed observations. The data were rebinned to a 4-d resolution to ensure a larger number of detections and to closely match the NFI sampling.

The UVOT observed the three targets simultaneously with the XRT. The data of XTE J1739–302 and IGR J16479–4514 were taken in general with the ‘Filter of the Day’ (FoD), that is, the filter chosen for all observations to be carried out during a specific day in order to minimize the filter wheel rotation (u, uvw1, uvw2 and uvm2), while IGR J17544–2619 was only observed with UVOT from 2009-06-06 to 2009-09-30, in the uvw1 and v filters, and in FoD for the remainder of the campaign. However, during the outbursts on 2009-03-10 of XTE J1739–302 and on 2009-06-06 of IGR J17544–2619, all filters were used in the typical GRB sequence (Roming et al. 2005). The data analysis was performed using the uvotsum and uvsotsource tasks included in the FTOOLS software. The latter task calculates the magnitude through aperture photometry within a circular region and applies specific corrections due to the detector characteristics. The reported magnitudes are on the UVOT photometric system described in Poole et al. (2008) and are not corrected for Galactic extinction. At the position of IGR J16479–4514, no detection was achieved down to a 3σ limit of \( u = 21.27 \) mag.

All quoted uncertainties are given at 90 per cent confidence level for one interesting parameter, unless otherwise stated. The spectral indices are parametrized as \( F_{\nu} \propto \nu^{-\alpha} \), where \( F_{\nu} \) (erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\)) is the flux density as a function of frequency \( \nu \); we adopt \( \Gamma = \alpha + 1 \) as the photon index, \( N(E) \propto E^{-\Gamma} \) (photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\)).

## 4 TIMING

### 4.1 XRT light curves and inactivity duty-cycle

The 0.2–10 keV XRT light curves collected from 2007 October 26 to 2009 November 3 are shown in Fig. 1. They are corrected for pile-up, PSF losses and vignetting, and background-subtracted. Each point in the light curves refers to the average flux observed during each observation performed with XRT; the exceptions are the outbursts (listed in Table 4), where the data were binned to include at least 20 source counts per time-bin to best represent the count rate dynamical range.

One of our goals is to calculate the percentage of time each source spent in each flux state. We consider our monitoring as a casual sampling of the light curve at a resolution of \( \sim 3–4 \) d over a >2 yr baseline. We considered the following three states: (i) BAT-detected outburst; (ii) intermediate state (all observations yielding a firm detection, excluding outburst ones); and (iii) ‘non-detections’ (detections with a significance below 3σ). From the latter state, we excluded all observations that had a net exposure below 900 s [corresponding to 2–10 keV flux limits that vary between 1 and 3 \( \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\) (3σ), depending on the source, see Paper V]. This was done because Swift is a GRB-chasing mission and several observations were interrupted by GRB events; therefore, the consequent non-detection may be due to the short exposure and not, exclusively, due to the source being faint.

The duty-cycle of inactivity is defined (Paper V) as the time each source spends undetected down to a flux limit of \((1–3) \times 10^{-12}\) erg cm\(^{-2}\) s\(^{-1}\); and \(\Delta T_{\Sigma}\) is detailed in the text (Section 6).

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1 http://swift.gsfc.nasa.gov/docs/swift/results/transients/
4.2 BAT transient monitor data and onboard detections

The 15–50 keV BAT Transient Monitor light curves collected from 2007 October 26 to 2009 November 3 are shown in Fig. 2, rebinned at a 4-d resolution. The two gaps in each of the BAT light curves preceded and followed by points with large error bars are an artefact of Swift’s Sun-avoidance pointing strategy. When the sources are near the Sun, they will be found only at the edges of the BAT FOV, where the sensitivity is reduced and for a few weeks each year, the sources cannot be observed at all.

In Table 6, we report the BAT onboard detections in the 15–50 keV band. If an alert was generated, a BAT trigger was assigned (Column 4) and notices were disseminated. For some of these triggers, a burst response (slew and repointing of the NFI) was also initiated, depending on GRB observing load, observing constraints and interest in the sources. More details on several of these triggers can be found in the papers of our series (see Table 4 for references). The combination of all these data shows how active the sources are outside the bright outbursts when observed by the BAT.

4.3 UVOT light curves

The UVOT performed observations simultaneously with the XRT, throughout most of the Swift/XRT monitoring of the SFXTs. Figs 3(a) and (b) show the UVOT $u$ and $uvw1$ light curves of XTE J1739–302 of the whole campaign. The dashed vertical lines mark the X-ray outbursts. The $u$ and $uvw1$ magnitudes show variability of marginal statistical significance; a fit against a constant yields $\chi^2(u) = 2.13$ for 45 degrees of freedom (d.o.f.), null hypothesis probability (nhp) = $1.5 \times 10^{-5}$ ($\sim 4\sigma$) and $\chi^2(uvw1) = 2.18$ for 20 d.o.f., nhp = $1.6 \times 10^{-3}$ ($\sim 3\sigma$). The $uvw2$ magnitudes are mostly upper limits, and the five detections yield a mean of $uvw2 = 20.42 \pm 0.14$ mag. In Paper V, we reported a marginally significant ($2\text{--}3\sigma$) increase in the $u$ magnitude during the first recorded outburst of this source (2008-04-08, MJD 54565), while during the second outburst (2008-08-13, MJD 54692), the $u$ magnitude is consistent with the mean for the whole campaign. The third reported outburst (2009-03-10, MJD 54901), like the second, shows no variation of the $u$ magnitude, with respect to the mean of the campaign. Observations were also taken once in the $v$ and $b$ filters during 2009 as a follow-up ToO (ObsID 00030987132), where we measure $v = 15.25 \pm 0.03$ and $b = 18.21 \pm 0.07$ mag. Both values are consistent with the ones obtained during and away from outbursts.

Table 6. BAT onboard detections in the 15–50 keV band during 2009.

| MJD  | Date        | Time$^a$ | BAT trigger number$^b$ | S/N$^c$ |
|------|-------------|----------|------------------------|---------|
| 54860 | 2009-01-29  | 06:32:06–06:48:1 | 341452 (NFI) | 10.68   |
| 54895 | 2009-03-04  | 17:43:07–18:13:47 | 341452 (NFI) | 10.68   |
| 54915 | 2009-03-25  | 00:13:07 | 341452 (NFI) | 10.68   |
| 54958 | 2009-05-06  | 19:06:51 | 341452 (NFI) | 10.68   |
| 54986 | 2009-06-03  | 23:45:07 | 341452 (NFI) | 10.68   |
| 55079 | 2009-09-05  | 00:09:35 | 341452 (NFI) | 10.68   |
| 55116 | 2009-10-12  | 03:25:31–03:47:39 | 341452 (NFI) | 10.68   |

*Time of the start of the BAT trigger or the time-range when onboard detections were obtained.

$^b$BAT regular trigger, as was disseminated through GCNs. NFI indicates that there are data from the narrow-field instrument.

$^c$Onboard image significance in units of $\sigma$.

$^d$This work, Section 5.1.

$^e$This work, Section 5.2.
In Fig. 4, we show the UVOT $uvw1$ light curve of IGR J17544$-$2619. It is remarkably stable, as a fit against a constant yields $\chi^2_{uvw1} = 1.08$ for 26 d.o.f., nhp=0.35. There are also a few observations performed in the other filters. We obtain $uvw2 = 20.3 \pm 0.3, 20.0 \pm 0.3, 19.9 \pm 0.2$ and $19.9 \pm 0.3$ mag (ObsID 00035056089, 00035056141, 00035056142 and 00035056148, respectively), $uvw2 = 18.93 \pm 0.06$ and $18.05 \pm 0.06$ mag (ObsID 00035056143 and 00035056144, respectively), and $u = 15.25 \pm 0.09$ mag (ObsID 00035056145). During the June 6 outburst (ObsID 354221000, MJD 549 88), all filters were used. The observed magnitudes are $u = 15.16 \pm 0.01$ mag, $b = 14.55 \pm 0.04$ mag and $uvw1 = 16.7 \pm 0.2$ mag. The $uvw1$ value is consistent with those obtained during the remainder of the campaign. The $b$ magnitude is very close to the coincidence limit, thus heavily corrected for coincidence loss.

5 OUTBURSTS IN 2009

The year 2009 opened with the outburst of IGR J16479$-$4514 on January 29, which we reported in Paper V. Here, we analyse the data from three more outbursts caught from the sources in our sample.

5.1 IGR J17391$-$3021

XTE J1739$-$302 triggered the BAT on 2009 March 10 at 18:39:55 UT (image trigger = 346069). We report the BAT light curve in the 15–25 keV band in Fig. 5. The time-averaged spectrum ($T+0.0$ to $T+320.0$ s) is best fitted by a simple power-law model with a photon index of $2.9 \pm 0.8$, and the 15–50 keV flux is $7.6 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$. Swift did not slew immediately in response to this trigger, so no NFI data were collected simultaneously with the BAT data. Observation 00030987107 (1.9 ks net exposure, see Table 2) was obtained as a high-priority ToO observation, instead. The light curve obtained between $T+5257$ and $T+10538$ s, since the trigger shows a mean count rate of $0.4 \pm 1$ counts s$^{-1}$. The mean XRT/PC spectrum can be fitted with an absorbed power law with a photon index of $\Gamma = 1.1 \pm 0.4$ and an absorbing column density of $N_H = (3 \pm 1) \times 10^{21}$ cm$^{-2}$ ($\chi^2 = 1.1$ for 25 d.o.f.). The mean unabsorbed 2–10 keV flux is $9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$, which translates into a luminosity of $7 \times 10^{34}$ erg s$^{-1}$ (assuming a distance of 2.7 kpc, Rahoui et al. 2008). Further ToO observations were performed on 2009 March 11 (ObsID 00030987108 and 00030987109 in Table 2), when the XRT count rate was down to a few $10^{-2}$ counts s$^{-1}$. These spectral results are in general agreement with those obtained during previous outbursts, both in terms of hard photon index and in terms of a relatively lower column density (comparable with the out-of-outburst values).

5.2 IGR J17544$-$2619

Two outbursts of IGR J17544$-$2619 were caught during 2009. The first was observed by the BAT Transient Monitor as a sequence of bright flares. In the Swift pointings starting at 2009-03-15 23:52:40 UT (1024 s exposure) and at 2009-03-16 01:27:36 UT (1152 s), the source reached $0.26 \pm 0.005$ counts s$^{-1}$ cm$^{-2}$ (115 mCrab, 15–50 keV band) and $0.32 \pm 0.005$ counts s$^{-1}$ cm$^{-2}$ (140 mCrab), respectively. It then faded below detectability before re-brightening twice more on 2009 March 16: 95 mCrab in a 1152-s exposure beginning at 06:16:40 UT and then to 85 mCrab in a 384-s exposure beginning at 09:25:52 UT. XRT observations were performed as part of our regular monitoring on 2009 March 14 (see Table 3), ~46 h before the BAT outburst. A $3\sigma$ upper limit was obtained at $1.6 \times 10^{-2}$ counts s$^{-1}$. A later observation, obtained as a ToO on 2009 March 16 (~16 h after the outburst), yielded a $3\sigma$ upper limit at $1.3 \times 10^{-2}$ counts s$^{-1}$.

IGR J17544$-$2619 triggered the BAT on 2009 June 6 at 07:48:59 UT (image trigger = 354221). Swift immediately slewed to the target, so that the NFIIs started observing about 164 s after the trigger. Fig. 6 shows the XRT and BAT light curves, where it must be noted...
that the first two XRT points, preceding the outburst, were collected as a pointed observation, part of our monitoring programme. The initial XRT burst data (WT mode in ObsID 00354221000, see Table 3, 170–446 s since the trigger) show a decaying light curve with a count rate that started at about 300 counts s\(^{-1}\). The following PC data (448–538 s) seamlessly continue the decaying trend down to about 2 counts s\(^{-1}\). The WT spectrum, extracted during the peak of the outburst (with a grade 0 selection to mitigate residual calibration uncertainties at low energies), results in a hard X-ray emission. When fitted with an absorbed power law, we obtain a photon index of 1.05\(^{+0.15}_{-0.14}\) and a column density of \(N_H = (1.3 \pm 0.2) \times 10^{22} \text{cm}^{-2}\) \((\chi^2 = 1.04 \text{ for } 104 \text{ d.o.f.})\). The unabsorbed 2–10 keV flux is \(9.5 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}\). The PC spectrum (unabsorbed 2–10 keV flux \(\sim 2 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1}\)) fitted with a power-law model yields a photon index of 1.1 \(\pm 0.7\) and \(N_H = (1.2^{+0.5}_{-0.2}) \times 10^{22} \text{cm}^{-2}\) (Cash 1979) statistics and spectra binned to 1 count bin\(^{-1}\); C-stat = 69.08 for 47 per cent of 10\(^4\) Monte Carlo realizations with fitted statistic less than C-stat, consistent with the WT data fit.

**Table 7.** Spectral fits of simultaneous XRT and BAT data of IGR J17544–2619 during the 2009 June 6 outburst.

| Model  | \(N_H\) \(^{a}\) | \(\Gamma\) | \(E_c\) | \(E_i\) | Flux \(^{e}\) | \(\chi^2/\text{d.o.f.}\) |
|--------|-----------------|---------|--------|--------|--------------|----------------|
| POW\(^b\) | 2.2\(^{+0.3}_{-0.2}\) | 1.7\(^{+0.1}_{-0.1}\) | 2.6 | 1.53/117 |
| HCT\(^b\) | 1.0\(^{+0.2}_{-0.3}\) | 0.6\(^{+0.2}_{-0.4}\) | 3\(^{+1}_{-1}\) | 8\(^{+4}_{-3}\) | 1.9 | 0.92/115 |
| CPL\(^b\) | 1.0\(^{+0.3}_{-0.2}\) | 0.4\(^{+0.1}_{-0.3}\) | 7\(^{+2}_{-4}\) | 1.9 | 0.94/116 |

\(^{a}\) Absorbing column density in units of \(10^{22} \text{cm}^{-2}\).

\(^{b}\) POW = simple absorbed power law; HCT = absorbed power law with high energy cut-off \(E_c\) (keV) and e-folding energy \(E_i\) (keV); and CPL = cut-off power law with energy cut-off \(E_c\) (keV).

\(^{c}\) Unabsorbed 0.5–100 keV flux in units of \(10^{-9} \text{erg cm}^{-2} \text{s}^{-1}\).

**Figure 7.** Spectroscopy of the 2009 June 6 outburst of IGR J17544–2619. Top panel: data from the XRT/WT spectrum and simultaneous BAT spectrum fitted with a CUTOFFPL model. Bottom panel: residuals in units of standard deviations.

**Table 8.** XRT spectroscopy of the three SFXTs (2007–2009 data set).

| Name         | Spectral parameter | Spectrum | Rate (counts s\(^{-1}\)) | \(N_H\) \(^{a}\) \(10^{22} \text{cm}^{-2}\) | Parameter | Flux \(^{a}\) \(2–10\text{ keV}\) | Luminosity \(^{b}\) \(2–10\text{ keV}\) | \(\chi^2/\text{d.o.f.}\) | C-stat (per cent) |
|--------------|--------------------|----------|--------------------------|------------------------------------------|------------|-----------------|-----------------|-----------------|-----------------|
| IGR J16479–4514 | High               | \(>0.55\) | 8.2\(^{+0.8}_{-0.7}\) | 1.1\(^{+0.2}_{-0.2}\) | 120 | 5 | 1.2/193 |
|               | Medium             | [0.22–0.55] | 8.6\(^{+0.8}_{-0.8}\) | 1.3\(^{+0.2}_{-0.2}\) | 53 | 2 | 0.9/197 |
|               | Low                | [0.06–0.22] | 7.1\(^{+0.6}_{-0.6}\) | 1.4\(^{+0.2}_{-0.1}\) | 17 | 0.7 | 1/205 |
|               | Very low\(^d\)    | <0.06    | 3.3\(^{+0.4}_{-0.0}\) | 1.8\(^{+0.3}_{-0.2}\) | 1.3 | 0.04 | 302.5(99.5) |
| XTE J1739–302  | High               | \(>0.405\) | 3.7\(^{+0.4}_{-0.4}\) | 0.8\(^{+0.2}_{-0.1}\) | 120 | 1 | 1/160 |
|               | Medium             | [0.07–0.405] | 3.8\(^{+0.4}_{-0.4}\) | 1.4\(^{+0.1}_{-0.1}\) | 18 | 0.2 | 0.9/164 |
|               | Very low\(^d\)    | <0.07    | 1.7\(^{+0.3}_{-0.0}\) | 1.4\(^{+0.2}_{-0.1}\) | 0.5 | 0.004 | 321.9(98.6) |
| IGR J17544–2619 | High               | \(>0.25\) | 1.9\(^{+0.3}_{-0.2}\) | 1.3\(^{+0.1}_{-0.1}\) | 46 | 0.8 | 1/118 |
|               | Medium             | [0.07–0.25] | 2.3\(^{+0.3}_{-0.3}\) | 1.7\(^{+0.2}_{-0.2}\) | 14 | 0.3 | 1/108 |
|               | Very low\(^d\)    | <0.07    | 1.1\(^{+0.1}_{-0.0}\) | 2.1\(^{+0.2}_{-0.2}\) | 0.2 | 0.003 | 183.1(85.1) |

\(^{a}\) Average observed 2–10 keV fluxes in units of \(10^{-12} \text{erg cm}^{-2} \text{s}^{-1}\).

\(^{b}\) Average 2–10 keV X-ray luminosities in units of \(10^{35} \text{erg s}^{-1}\) calculated adopting distances determined by Rahoui et al. (2008).

\(^{c}\) Reduced \(\chi^2\) and d.o.f., or C-stat and percentage of realizations (10\(^4\) trials) with statistic > C-stat.

\(^{d}\) Fit performed with the constrained column density (see Section 6).

**6 OUT-OF-OUTBURST X-RAY SPECTROSCOPY**

We characterize the spectral properties of the sources in several states, by accumulating the events in each observation when the source was not in outburst and a detection was achieved. We selected three count rate levels, CR\(_1\), CR\(_2\) and CR\(_3\) (reported in Table 8), that
would yield comparable statistics in the ranges \( CR_1 < CR < CR_2 \) (low), \( CR_2 < CR < CR_3 \) (medium) and \( CR > CR_3 \) (high). When the statistics did not allow this, we considered only two intensity levels (high and medium). Exposure maps and ARF files were created following the procedure described in Paper V. The spectra were rebinned with a minimum of 20 counts per energy bin to allow \( \chi^2 \) fitting. Each spectrum was fitted in the energy range 0.3–10 keV with a single absorbed power law.

We accumulated all data for which no detections were obtained as single exposures (whose combined exposure is \( \Delta T \), reported in Table 5, column 2) and performed a detection. The resulting cumulative mean count rate for each object is reported in Table 5 (column 5). Spectra were also extracted from these event lists. They consisted of \(~200–300\) counts each, so Cash statistics and spectra binned to 1 count bin\(^{-1}\) were used, instead. When fitting with free parameters, the best-fitting value for \( N_H \) turned out to be consistent with 0, that is, well below the column derived from optical spectroscopy. We therefore performed fits by adopting as a lower limit on the absorbing column the value derived from the Galactic extinction estimate along the line of sight to each source from Rahoui et al. (2008), with a conversion into hydrogen column, \( N_H = 1.79 \times 10^{21} \text{A}_V \text{cm}^{-2} \) (Predehl & Schmitt 1995). Fig. 8 shows

![Figure 8](https://academic.oup.com/mnras/article/410/3/1825/963410)

\[ \Delta \chi^2 = 2.3, 4.61 \text{ and } 9.21 \] contour levels for the column density in units of \( 10^{22} \text{ cm}^{-2} \) versus the photon index, with best fits indicated by crosses. The labels L, M and H mark low, medium and high states, respectively.

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the spectra and contour plots of photon index versus column density; the spectral parameters are reported in Table 8, where we also report the average 2–10 keV luminosities calculated by adopting distances of 4.9 kpc for IGR J16479—4514, 2.7 kpc for XTE J1739—302 and 3.6 kpc for IGR J17544—2619 determined by Rahoui et al. (2008) from optical spectroscopy of the supergiant companions. We also performed fits with an absorbed blackbody, obtaining consistent results with Paper V.

7 DISCUSSION

In this paper, we report the results of a monitoring campaign with *Swift* that spans more than a 2-yr baseline. Thanks to the unique characteristics of *Swift*, we can investigate the properties of SFXTs on several time-scales (from minutes to days to years) and in several intensity states (bright flares, intermediate intensity states and down to almost quiescence).

During the second year of monitoring, two different sources flared three times, and in two cases, we obtained multiwavelength observations (see Table 4). XTE J1739—302 triggered the BAT on 2009 March 10. Our results are in general agreement with those obtained during previous outbursts, both in terms of hard photon index and in terms of a relatively lower column density (comparable with the out-of-outburst values). When IGR J17544—2619 triggered the BAT on 2009 June 6, simultaneous BAT and XRT data were collected, thus allowing broad-band spectroscopy. The soft X-ray spectral properties observed during this flare are generally consistent with those observed with *Chandra* [$\Gamma = 0.73 \pm 0.13$, $N_H = (1.36 \pm 0.22) \times 10^{22}$ cm$^{-2}$, peak flux of $\sim 3 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$; in’t Zand 2005]. However, when XRT and BAT data are jointly fitted, an absorbed power-law model is inadequate in fitting the broad-band spectrum, and more curvy models are required. We considered an absorbed power-law model with a high energy cut-off and an absorbed power-law model with an exponential cut-off, models typically used to describe the X-ray emission from accreting neutron stars in HMXBs. We obtained a good deconvolution of the 0.3–150 keV spectrum, characterized by a hard power law below 10 keV and a well-constrained cut-off at higher energies.

In Fig. 9, we compare the light curves of the most recent outbursts of XTE J1739—302 and IGR J17544—2619 (red points) observed by *Swift* during the second year of monitoring, together with the previous outbursts of these sources followed by *Swift*/XRT (grey points). The light curves are referred to their respective BAT triggers (unless the flare did not trigger the BAT, Fig. 9e). The most complete and deep set of X-ray observations of an outburst of an SFXT is the one of the periodic SFXT IGR J11215—5952 (Romano et al. 2007; Sidoli et al. 2007; Romano et al. 2009c), which was instrumental in discovering that the accretion phase during the bright outbursts lasts much longer than a few hours, as seen by lower sensitivity instruments, and contrary to what initially thought at the time of the discovery of this new class of sources (e.g. Sguera et al. 2005). This behaviour is now found to be a common characteristic of the whole sample of SFXTs followed by *Swift*, as our observations on IGR J16479—4514, IGR J08408—4503 and SAX J1818.6—1703 demonstrate (Paper V, Romano et al. 2009a and Sidoli et al. 2009b, respectively; the vertical dashed lines in Fig. 9 mark time-intervals equal to 1 d, up to a week). In the same manner, our observations show that both the large dynamical range (up to 4 orders of magnitude) in flux and a multiple-peaked structure of the light curves of the bright outbursts are equally common characteristics of the sample.

In the optical/ultraviolet (UV), we see only marginal variability in the $u$ and $uvw1$ magnitudes of XTE J1739—302, and we could exclude a variation of flux corresponding to the X-ray outburst. The $uvw1$ light curve of IGR J17544—2619 is observed to be remarkably stable. This is consistent with the optical/UV emission being dominated by the constant contribution of the companion stars.

Variability in the X-ray flux is observed at all time-scales and intensity ranges we can probe. Fig. 10 shows, for each of the monitored sources, a montage of time-sequences of the *Swift*/XRT data, where detection was achieved (binned at 100- and 20-s resolutions for PC and WT data, respectively) and with observing and orbital gaps removed from the time-axis. Superimposed on the day-to-day variability (best shown in Fig. 1, which is binned to 1-d resolution) is intraday flaring. As Fig. 10 shows, the latter involves flux variations up to one order of magnitude that can occur down to time-scales as short as an XRT snapshot ($\lesssim 1$ ks). This remarkable short time-scale variability cannot be accounted for by accretion from a homogeneous wind. On the contrary, it can be naturally explained by the accretion of single clumps composing the donor wind, independently on the detailed geometrical and kinematical properties of the wind and the properties of the accreting compact object. If, for example, we assume that each of these short flares is caused by the accretion of a single clump on to the NS (e.g. in’t Zand 2005), then its mass can be estimated (Walter & Zurita Heras 2007) as $M_f = 7.5 \times 10^{21}$ $(L_{X,36}/f_{x,36})^3$ g, where $L_{X,36}$ is the average X-ray luminosity in units of $10^{36}$ erg s$^{-1}$ and $f_{x,36}$ is the duration of the flares in units of 3 ks. We can confidently identify flares down to a
count rate of the order of $0.1 \text{ counts s}^{-1}$ (within a snapshot of about 1 ks; see Fig. 10); these correspond to luminosities of the order of $(2-6) \times 10^{33} \text{ erg s}^{-1}$, which yield $M_\text{cl} \sim (0.3-2) \times 10^{19} \text{ g}$. These masses are about those expected (Walter & Zurita Heras 2007) to be responsible of short flares, below the INTEGRAL detection threshold and which, if frequent enough, may significantly contribute to the mass-loss rate.

Our Swift monitoring campaign has demonstrated for the first time that X-ray emission from SFXTs is present outside the bright outbursts (Paper I; Paper V), although at a much lower level, thus showing how frequent and typical in SFXTs is accretion at a low level rate. In this paper, we refined the intensity-selected spectroscopy of the out-of-outburst emission by adopting absorbed power laws, which yield hard power-law photon indices ($\Gamma_1 \sim 1-2$). All these results are consistent with our findings in Paper V and show that accretion occurs over several orders of magnitude in luminosity (three for XTE J1739–302 and two for the others; Table 8), even when excluding the bright outbursts. In particular, the lowest luminosities we could study with Swift are $4 \times 10^{32}$ and $3 \times 10^{32} \text{ erg s}^{-1}$ (2–10 keV; ‘very low’ intensity level in Table 8) for XTE J1739–302 and IGR J17544–2619, respectively. These low luminosities are not consistent with Bondi–Hoyle accretion from a spherically...
symmetric steady wind (Bondi & Hoyle 1944), as previously reported by Drave et al. (2010) and Clark et al. (2009) for these two SFXTs, thus arguing for a clumpy nature of the accreting wind. This is consistent with our findings on short time-scale variability, which also requires inhomogeneities in the wind.

In the following, we assess the percentage of time each source spends at a given flux state. Fig. 11 shows the distributions of the observed count rates after removal of the observations where a detection was not achieved (same sample as in Fig. 10, with PC and WT data binned at 100 s). In all cases, a roughly Gaussian shape is observed, with a broad peak at \( \approx 0.1 \) counts s\(^{-1}\) and a clear cut at the detection limit for 100 s at the low end. In particular, when the distributions are fitted with a Gaussian function, we find that their means and \( \sigma \) are 0.12 and 3.4 counts s\(^{-1}\) for IGR J16479-4514; 0.06 and 4.9 counts s\(^{-1}\) for XTE J1739-302; and 0.13 and 3.1 counts s\(^{-1}\) for IGR J17544-2619. This indicates that the most probable flux level at which a random observation will find these sources, when detected, is \( 3 \times 10^{-11}, 9 \times 10^{-12} \) and \( 1 \times 10^{-11} \) erg cm\(^{-2}\) s\(^{-1}\) (unabsorbed 2–10 keV, obtained using the medium spectra in Table 8), corresponding to luminosities of \( \sim 8 \times 10^{34}, 8 \times 10^{33} \) and \( 2 \times 10^{34} \) erg s\(^{-1}\), respectively. Fig. 11 also shows the hint of an excess at \( \gtrsim 10 \) counts s\(^{-1}\). Since this count rate is where the WT data of the outbursts are concentrated, we also show them in the insets (dashed histograms) binned at 20-s resolution, which is more appropriate for such count rates. In this case, a clear peak emerges to represent the flaring state of the sources.

We have also calculated the time each source spends undetected down to a flux limit of \((1–3) \times 10^{-12} \) erg cm\(^{-2}\) s\(^{-1}\), and we obtain IDC = 19, 39 and 55 per cent for IGR J16479-4514, XTE J1739-302 and IGR J17544-2619, respectively, with an estimated error of \( \sim 5 \) per cent. We note that these values are based on the whole 2-yr campaign, and that the IDC calculated with the observations of 2009 only is 21, 39 and 55 per cent, respectively. These results can be compared with the ones reported in Paper V, where we obtained IDC = 17, 39 and 55 per cent for IGR J16479-4514, XTE J1739-302 and IGR J17544-2619, respectively. We now have a baseline twice as long and almost a factor of 2 higher exposure; the sampling of the light curves has slightly changed during 2009. Nevertheless, the calculated IDC values are remarkably stable, which is indicative of the robustness of this method with respect to the sampling pace.

Considering our monitoring as a casual sampling of the light curve for 2 yr, we can also infer that the time these sources spend in bright outbursts is between 3 and 5 per cent of the total.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this paper:

Table 1. Observation log for IGR J16479−4514.
Table 2. Observation log for IGR J17391−3021.
Table 3. Observation log for IGR J17544−2619.

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