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A two-year monitoring campaign of Supergiant Fast X-ray Transients with *Swift*

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Swift is the only observatory which, due to its unique fast-slewing capability and broad-band energy coverage, can detect outbursts from Supergiant Fast X-ray Transients (SFXTs) from the very beginning and study their evolution panchromatically. Thanks to its flexible observing scheduling, which makes monitoring cost-effective, *Swift* has also performed a campaign that covers all phases of the lives of SFXTs with a high sensitivity in the soft X–ray regime, where most SFXTs had not been observed before. Our continued effort at monitorning SFXTs with 2–3 observations per week (1–2 ks) with the *Swift* X–Ray Telescope (XRT) over their entire visibility period has just finished its second year. We report on our findings on the long-term properties of SFXTs, their duty cycle, and the new outbursts caught by *Swift* during the second year.

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1. The *Swift* SFXT Monitoring program

Supergiant Fast X–ray Transients (SFXTs, [1]), the new class of High Mass X–ray Binaries (HMXBs) discovered by *INTEGRAL*, are characterized by outbursts which are significantly shorter than those typical of Be/X-ray binaries, peak luminosities in the order of a few 10^{36} erg s^{-1}, and a quiescent luminosity level of $\sim 10^{32}$ erg s^{-1}. It is generally agreed that SFXTs are HMXBs with an OB supergiant star companion to a neutron star (NS), because their spectral properties are similar to those of accreting pulsars, even though a pulse period was measured in only a few of them. The mechanisms responsible for the outbursts observed by *INTEGRAL* involve either the structure of the wind from the supergiant companion [2 – 5] or gated mechanisms (see [6]).

Thanks to its fast-slewing capability and its broad-band energy coverage, *Swift* is the only observatory which can catch outbursts from these transients, observe them panchromatically from as short as 100 s after their onset, and follow them as they evolve. Furthermore, *Swift*'s flexible observing scheduling makes a monitoring effort cost-effective. Thus, our campaign with *Swift* has given SFXTs the first non-serendipitous attention in all phases of their lives with a high sensitivity in the soft X-ray regime, where most SFXTs had not been observed before.

Our sample consists of 4 targets, IGR J16479−4514, XTE J1739–302/IGR J17391−3021, IGR J17544−2619, and AX J1841.0−0536/IGR J18410−0535, chosen among the 8 SFXTs known at the end of 2007, including the two prototypes of the class (XTE J1739–302, IGR J17544−2619). During the second year of *Swift* observations, we monitored three targets, XTE J1739–302, IGR J17544−2619, and IGR J16479−4514. We obtained 2 or 3 observations per week per source, each 1 ks long with the goal of systematically studying the outbursts, to monitor them during their evolution, and for the very first time, to study the long term properties of SFXTs, in particular, the out-of-outburst states, and the quiescence. This observing strategy was chosen to fit within the regular observing schedule of γ-ray bursts (GRBs). Moreover, 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, as is currently done for GRBs. We also 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 two years of monitorning we collected 558 pointed XRT observations, for a total of 606 ks of on-source exposure. Table 1 summarizes the campaign. The results on the long term X–ray properties outside the bright outbursts of our sample of SFXTs can be found in [7], [8], and [9], while the outbursts are analyzed in detail in [10], [11], [12] for IGR J16479−4514 and the prototypical IGR J17544−2619 and XTE J17391−302, respectively (also see Table 1).

2. 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. Since our monitoring is a casual sampling of the light curves at a resolution of $\sim$ 3–4 d over a $>$ 2 yr baseline (1 yr for AX J1841.0−0536), we infer that these sources spend 3–5% of the total time in bright outbursts.

Name	Campaign Dates	Obs. N.	*Swift*/XRT Exposure (ks)	Outburst Dates	Outburst References
IGR J16479–4514	2007-10-26–2009-11-01	144	161	2008-03-19	[10]
				2008-05-21	
				2009-01-29	[13, 14]
XTE J1739–302	2007-10-27–2009-11-01	184	206	2008-04-08	[15, 11]
				2008-08-13	[16, 12]
				2009-03-10	[17, 9]
IGR J17544–2619	2007-10-28–2009-11-03	142	143	2007-11-08	[18]
				2008-03-31	[19, 11]
				2008-09-04	[20, 12]
				2009-03-15	[21, 9]
				2009-06-06	[22, 9]
AX J1841.0–0536	2007-10-26–2008-11-15	88	96	none	

Table 1: The *Swift* monitoring campaign. The outburst dates refer to the outbursts that occurred during the monitoring.

Name	ΔT_Σ (ks)	$P_{\rm short}$ (%)	IDC (%)	Rate$_{\Delta T_\Sigma}$ (10^{-3}counts s^{-1})
IGR J16479−4514	29.7	3	19	3.1 ± 0.5
XTE J1739−302	71.5	10	39	4.0 ± 0.3
IGR J17544−2619	69.3	10	55	2.2 ± 0.2
AX J1841.0−0536	26.6	3	28	2.4 ± 0.4

Table 2: Duty cycle of inactivity.

We address the issue of the percentage of time each source spends in each flux state. We considered the following three states, *i)* BAT-detected outbursts, *ii)* intermediate states (firm detections excluding outbursts), *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 3×10^{-12} erg cm^{-2} s^{-1} (3σ), depending on the source, see [8]]. 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 to the source being faint.

The duty cycle of *inactivity* is defined [8] as the time each source spends *undetected* down to a flux limit of 1–3×10^{-12} erg cm^{-2} s^{-1}, IDC $= \Delta T_\Sigma / [\Delta T_{\rm tot}\,(1 - P_{\rm short})]$, where ΔT_Σ is sum of the exposures accumulated in all observations, each in excess of 900 s, where only a 3-σ upper limit was achieved, $\Delta T_{\rm tot}$ is the total exposure accumulated (Table 1), and $P_{\rm short}$ is the percentage of time lost to short observations (exposure < 900 s, Table 2, column 3). We obtain that IDC $= 19, 28, 39, 55$ %, for IGR J16479−4514, AX J1841.0−0536, XTE J1739–302, and IGR J17544−2619, respectively (Table 2, column 4), with an estimated error of ~ 5 %.

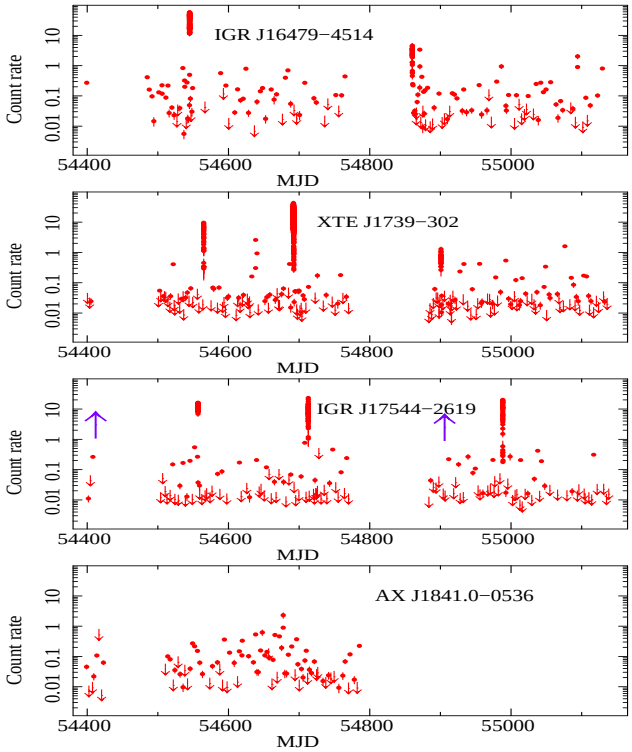

Figure 1: *Swift*/XRT light curves of our sample in the 0.2–10 keV energy range, between 2007 October 26 and 2009 November 3. The light curves are background subtracted, corrected for pile-up (when required), PSF losses, and vignetting. Each point refers to the average flux observed during each observation performed with XRT, except for outbursts (Table 1) where the data were binned to include at least 20 source counts per time bin to best represent the dynamical range. Downward-pointing arrows are 3-σ upper limits, upward pointing arrows mark either outbursts that XRT could not observe because the source was Sun-constrained, or BAT Transient Monitor bright flares. AX J1841.0−0536 was only observed during the first year.

3. Spectroscopy

Simultaneous observations with XRT and BAT allowed us to perform broad-band spectroscopy of outbursts of SFXTs from 0.3 kev to 100–150 keV. This yielded particularly valuable information, because of the shape of the spectrum, a hard power law below 10 keV with a high-energy cutoff at 15–30 keV. Therefore *Swift* is the ideal observatory to study their spectrum: BAT constrains the hard-X spectral properties (to compare with the most popular accreting NS models) while XRT gives us a measurement of the absorption, which is quite high in these objects [23], often well above the Galactic value. As an example, we report the properties of the 2009 June 6 outburst of IGR J17544−2619 (Fig. 2) for which simultaneous BAT and XRT data were collected. An absorbed power-law model is inadequate so we considered an absorbed power-law model with a high energy cut-off ($N_{\rm H} = 1.0^{+0.2}_{-0.3} \times 10^{22}$ cm^{-2}, $\Gamma = 0.6^{+0.2}_{-0.4}$, $E_c = 3^{+1}_{-1}$ keV, $E_f = 8^{+4}_{-3}$ keV, χ^2_ν/dof$= 0.92/115$) and an absorbed power-law model with an exponential cutoff ($N_{\rm H} = 1.0^{+0.3}_{-0.2} \times 10^{22}$ cm^{-2}, $\Gamma = 0.4^{+0.3}_{-0.3}$, $E_c = 7^{+4}_{-2}$ keV, χ^2_ν/dof$= 0.94/116$), models typically used to describe the X–ray emission from accreting NS in HMXBs.

On the other hand, our *Swift*/XRT monitoring campaign has demonstrated for the first time that

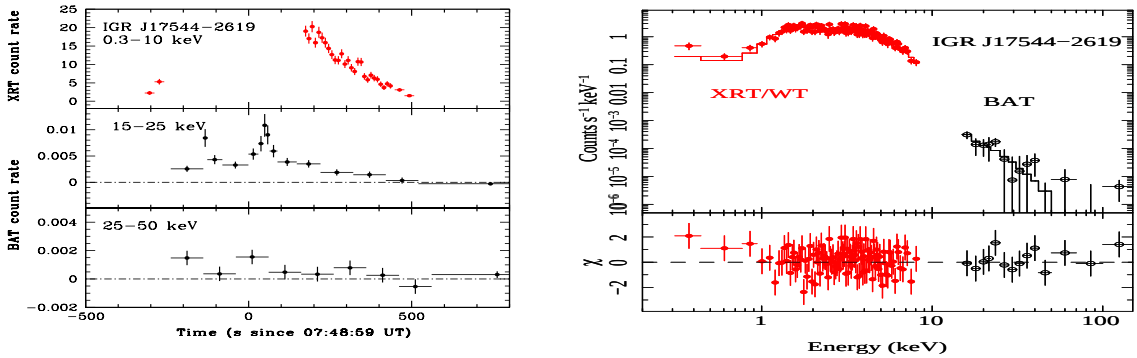

Figure 2: Left: XRT (red) and BAT (black) light curves of the 2009 June 6 outburst of IGR J17544−2619 in units of count s^{-1} and count s^{-1} detector^{-1}, respectively. The XRT data preceding the outburst were collected as a pointed observation, part of our monitoring program. **Right**: Data from the XRT/WT spectrum and simultaneous BAT spectrum fit with a CUTOFFPL model, and residuals in units of standard deviations.

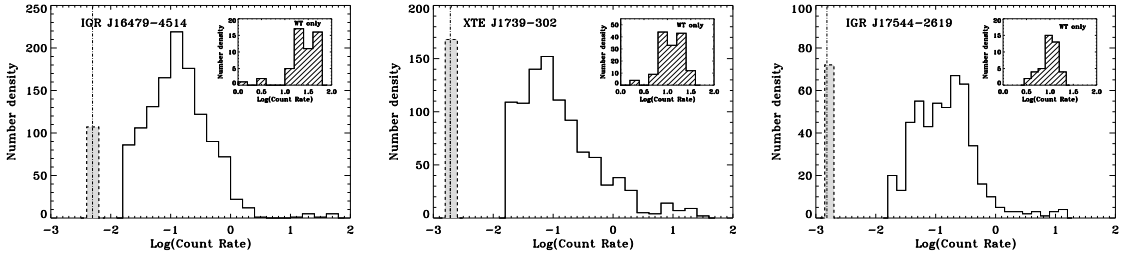

Figure 3: Distribution of the count rates when the XRT light curves are binned at 100 s, for the three sources monitored for two years. The vertical lines correspond to the background. The hashed histograms are points which are consistent with a zero count rate. The insets show the subset of WT data only, binned at 20 s.

X–ray emission from SFXTs is still present *outside* the bright outbursts, although at a much lower level [7 – 9]. Spectral fits performed in the 0.3–10 keV energy band by adopting simple models such as an absorbed power law or a blackbody (more complex models were not required by the data) result in hard power law photon indices (always in the range 0.8–2.1) or in hot blackbodies ($kT_{\rm BB} \sim$ 1–2 keV).

4. Long term properties

Figure 3 shows the distributions of the observed count rates after removal of the observations where a detection was not achieved. A roughly Gaussian shape is observed, with a broad peak at ≈ 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 fit with a Gaussian function we find that their means are 0.12 counts s^{-1} (IGR J16479−4514), 0.06 counts s^{-1} (XTE J1739–302), and 0.13 counts s^{-1} (IGR J17544−2619). Therefore, the most probable flux level at which a random observation will find these sources, when detected, is 3×10^{-11}, 9×10^{-12}, and 1×10^{-11} erg cm^{-2} s^{-1} (unabsorbed 2–10 keV, i.e. luminosities of $\sim 8 \times 10^{34}$, 8×10^{33}, and 2×10^{34} erg s^{-1}), respectively.

X-ray variability is observed at all timescales and intensities we can probe. Superimposed on the day-to-day variability is intra-day flaring which involves variations up to one order of magnitude that can occur down to timescales as short as 1 ks. These cannot be accounted for by accretion from a homogeneous wind, but can be naturally explained by the accretion of single clumps composing the donor wind. If, for example, we assume that each of these short flares is caused by the accretion of a single clump onto the NS [2], then its mass can be estimated [3] as $M_{\rm cl} = 7.5 \times 10^{21}\ (L_{\rm X,36})(t_{\rm fl,3ks})^3$ g, where $L_{\rm X,36}$ is the average X-ray luminosity in units of 10^{36} erg s^{-1}, $t_{\rm fl,3ks}$ is the duration of the flares in units of 3 ks. We can confidently identify flares down to a count rate in the order of 0.1 counts s^{-1}; these correspond to luminosities in the order of 2–6 $\times 10^{34}$ erg s^{-1}, which yield $M_{\rm cl} \sim 0.3$–2×10^{19} g. These masses are about those expected [3] to be responsible for short flares, below the *INTEGRAL* detection threshold and which, if frequent enough, may significantly contribute to the mass-loss rate.

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