

The *Swift* Supergiant Fast X-ray Transients Project: A review, new results and future perspectives [☆]

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Abstract

We present a review of the Supergiant Fast X-ray Transients (SFXT) Project, a systematic investigation of the properties of SFXTs with a strategy that combines *Swift* monitoring programs with outburst follow-up observations. This strategy has quickly tripled the available sets of broad-band data of SFXT outbursts, and gathered a wealth of out-of-outburst data, which have led us to a broad-band spectral characterization, an assessment of the fraction of the time these sources spend in each phase, and their duty cycle of inactivity. We present some new observational results obtained through our outburst follow-ups, as fitting examples of the exceptional capabilities of *Swift* in catching bright flares and monitor them panchromatically.

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1. The *Swift* SFXT Project: a review

In the last decade and a half, observations by X-ray satellites led to the discovery of a new class of high mass X-ray binaries (HMXBs) with supergiant companions, called Supergiant Fast X-ray Transients (SFXTs; Smith et al., 2004; Sguera et al., 2005; Negueruela et al., 2006). The members of this class exhibit periods of enhanced X-ray activity with durations ranging from a few hours to a few days and peak luminosities of $10^{36} - 10^{37}$ erg s⁻¹. A

distinctive property of SFXTs is the high dynamic range, spanning three to five orders of magnitude, with sudden increases in luminosity from $\sim 10^{32}$ erg s⁻¹ up to the flare peak luminosity (e.g. in't Zand, 2005). The X-ray spectra can be described with models typically used to fit the X-ray emission from pulsars in HMXBs (see e.g. Walter and Zurita Heras, 2007). We generally distinguish between confirmed and candidate SFXTs based on the availability of an optical classification of the companion. We currently have 10 confirmed and about as many candidate SFXTs.

The accretion mechanisms responsible for the fast and high variability of SFXTs are still poorly known and understood. They can be divided in two categories: those models for which the X-ray variability exclusively depends

[☆] Project web page: <http://www.ifc.inaf.it/sfxt/>

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on the properties of the geometry and inhomogeneity of the stellar wind from the donor star (see e.g. in't Zand, 2005; Sidoli et al., 2007; Nequeroela et al., 2008), and the accretion mechanisms linking the observed high dynamic ranges to the properties of the compact object and assuming only modest variation in the density and/or velocity of the supergiant wind (see e.g. Grebenev and Sunyaev, 2007; Bozzo et al., 2008).

Our *Swift* SFXT project has been performing a systematic investigation of the properties of SFXTs with a strategy that combines *Swift*¹ monitoring programs with outburst follow-up observations.

1.1. Long term monitoring campaigns

The initial monitoring sample consisted of 4 confirmed SFXTs, chosen among the 10 or so SFXTs known in late 2007 and it includes the two prototypes of the class XTE J1739–302 and IGR J17544–2619. The first campaigns ran from 2007 October 26 to 2009 November 3 (MJD 54399 to 55138, shown as part of the grey data in Fig. 1) with a regularly sampled pace of 2–3 observations week⁻¹ object⁻¹, each 1 ks long, for a total on-source exposure of 606 ks divided in 558 observations. The *Swift*/X-ray Telescope (XRT, Burrows et al., 2005) was set in AUTO mode, to best exploit the XRT automatic mode switching in response to changes in the observed source intensity. This has allowed, for the very first time, to study the long term properties of SFXTs with a pointed, high sensitivity X-ray telescope.

The detailed results of these campaigns can be found in Sidoli et al. (2008) and Romano et al. (2009c); Romano et al. (2011a, and references therein) and they include the discovery, outside their outbursts, of X-ray activity in all four SFXTs, demonstrating that these transients accrete matter even outside their outbursts. This emission is highly variable, with timescales ranging from months down to the shortest timescales we can probe (a few hundred seconds) with a dynamic range in excess of 1 order of magnitude in all four SFXTs.

We also assessed how long each source spends in each state (Romano et al., 2011a) by studying the XRT count rate distributions. The overall dynamic range reaches then ~ 4 orders of magnitude when outbursts, that only account for 3–5 % of the total SFXT phase, are considered. The most common X-ray flux is $F_{2-10\text{keV}} \sim (1-2) \times 10^{-11}$ erg cm⁻² s⁻¹ (unabsorbed), corresponding to luminosities in the order of a few 10^{33} – 10^{34} erg s⁻¹, ~ 100 times lower than the bright outbursts (Romano et al., 2011a). Finally, we calculated that the duty-cycle of inactivity is in the range ~ 19 – 55 % (Romano et al., 2009c; Romano et al., 2011a). Therefore, differently from what was previously estimated using less sensitive instruments, true quiescence

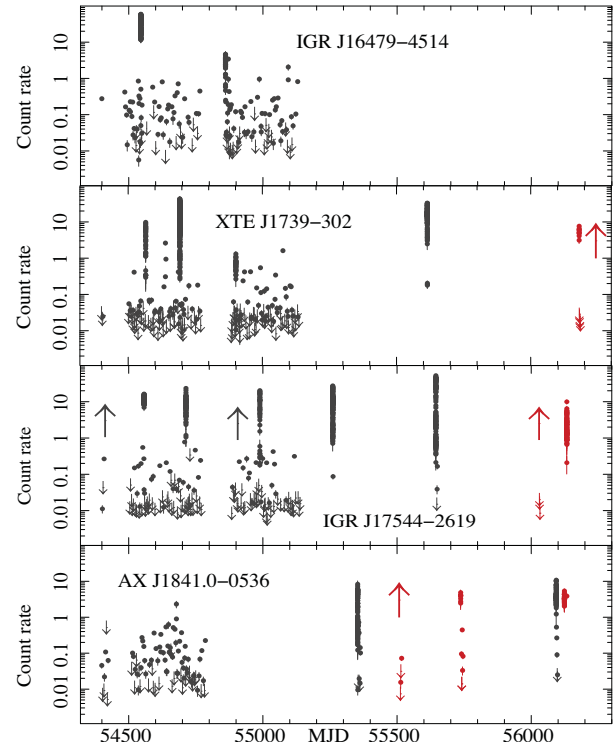


Fig. 1. *Swift*/XRT (0.2–10 keV) light curves of our 2007–2009 long-term monitoring program (MJD 54399 to 55138) and subsequent outbursts and follow-ups. Each point refers to the average count rate observed during each observation performed with XRT, except for outbursts where the data were binned to include at least 20 counts bin⁻¹ to best represent the dynamical range. Downward-pointing arrows are 3- σ upper limits. Upward pointing arrows mark bright outbursts detected by BAT (and not simultaneously followed by XRT), or by MAXI (AX J1841.0–0536, MJD 55507). Data in grey were previously published in Romano et al. (2009c); Romano et al. (2011a); Romano et al. (2011b); Romano et al. (2013) and Farinelli et al. (2012b). Data in red are presented here for the first time. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

(at $\sim 10^{32}$ erg s⁻¹) is a relatively rare state for these transients.

1.2. Outbursts and follow-ups

Many observations were collected during the SFXT outbursts, as these are certainly the most prominent manifestation of their activity (Romano et al., 2008; Romano et al., 2009b; Sidoli et al., 2009c; Sidoli et al., 2009a). Indeed, *Swift* can catch and study them in broad band (0.3–150 keV) in their early stages, thanks to the combination of its on-board triggering, autonomous fast slewing and panchromatic capabilities, thus allowing us to assess the spectroscopic and timing properties of SFXTs when they are in their brightest phases. Given the shape of the SFXT spectrum (power law with an exponential cut-off), the large *Swift* energy range allows us to both constrain the hard-X-ray spectral properties to compare with popular accreting neutron star models and to obtain a measure of the absorption.

¹ See Gehrels et al., 2004 for a description of the *Swift* satellite.

For this project, the Burst Alert Telescope (BAT, Barthelmy et al., 2005) Team devised and applied to the whole sample of SFXTs and candidates, the so called “BAT special functions”, starting from 2008 September 25. They are modifications of the on-board triggering figure of merit that allow SFXTs to trigger the BAT, perform a slew and then observe the source as if it were a γ -ray burst, *Swift*'s natural target. This ensures that the source obtains not only coverage with the BAT, but also with the narrow-field instruments, XRT and the UV/Optical Telescope (UVOT, Roming et al., 2005). Further ‘triggers’ also came from the BAT Transient Monitor (Krimm et al., 2006; Krimm et al., 2013)². After the initial automated target exposure we generally follow the decay of the outburst for at least a week with XRT through target of opportunity (ToO) observations.

Our strategy has several advantages.

1. It quickly tripled the available sets of broad-band data of SFXT outbursts (e.g. Sidoli et al., 2009b; Romano et al., 2011a; Romano et al., 2011b; Romano et al., 2013; Farinelli et al., 2012b; Mangano et al., 2012). From launch to the end of 2012, *Swift* has detected 42 outbursts, for a total of 45 on-board triggers (5 from candidates), 24 (2) with broad band coverage, 22 of which have been detected thanks to the BAT special functions being applied. Fig. 1 (red points) shows some of the most recent outbursts of the 4 monitored SFXTs after the long term monitoring described in Section 1.1 ended in 2009 November.
2. The unique *Swift* characteristic of an automated, fast repointing to potentially any target that triggers the BAT, has allowed the arcsecond localization for several SFXTs and candidates whose coordinates were only known to the arcminute level, or to improve upon previously known coordinates, and consequently help in associating with an optical counterpart. Such is the case for IGR J16328–4726, that we localized when it first went into outburst (Grupe et al., 2009), and AX J1845.0–0433, whose position we now refine with respect to a previously known *XMM-Newton* one. Both cases are presented in detail below.
3. We have now observed outbursts from most confirmed SFXTs and followed them with XRT for days after the outburst (by reaching a few tenths of a μ Crab in 10 ks), well after it had become undetectable with monitoring instruments with lower sensitivity (especially in crowded fields) such as the All-Sky Monitor on board RXTE (Levine et al., 1996, 10 mCrab in the 1.5–12 keV band at 2σ level for 1 day average) or MAXI (Matsuoka et al., 2009, 15 mCrab in the 0.5–20 keV band at 5σ level for 1 day average). The simplest piece of information we can derive from the X-ray light curves is the dynamic range, which is a discriminant (Negueruela et al., 2006;

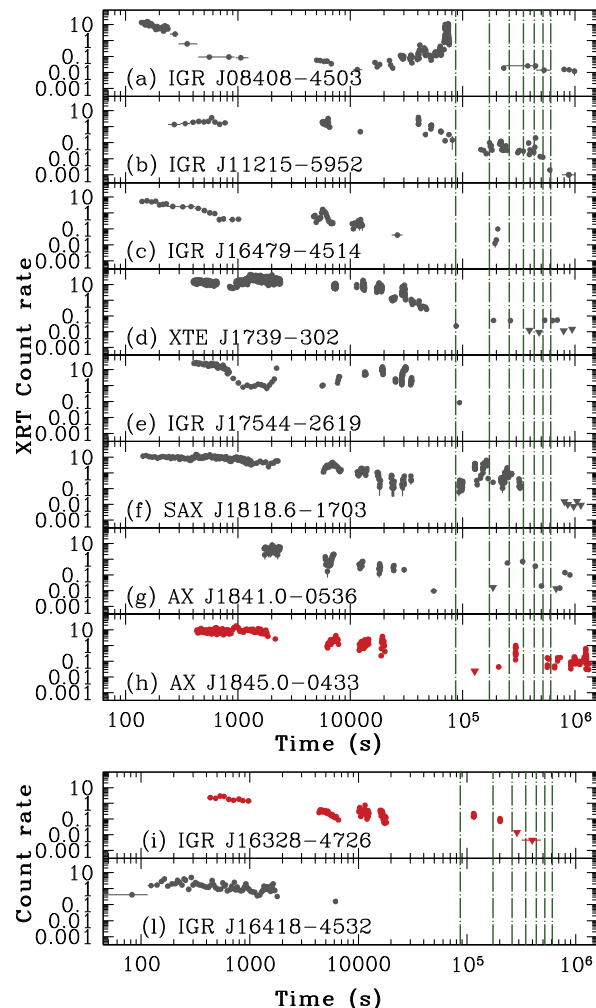


Fig. 2. Light curves of the better followed-up outbursts of SFXTs followed by *Swift*/XRT with starting times referred to their respective BAT triggers (IGR J11215–5952 did not trigger the BAT, so it is referred to MJD 54139.94; similarly, IGR J16418–4532 is referred to the start of the observation). Points denote detections, triangles 3σ upper limits. Red data points (panels h and i) refer to observations presented here for the first time, while grey points to data presented elsewhere. Vertical dashed lines mark time intervals equal to 1 day, up to a week. References: IGR J08408–4503 (2008-07-05, Romano et al., 2009b, panel a); IGR J11215–5952 (2007-02-09, Romano et al., 2007, panel b); IGR J16479–4514 (2005-08-30, Sidoli et al., 2008, panel c); XTE J1739–302 (2008-08-13, Sidoli et al., 2009a, panel d); IGR J17544–2619 (2010-03-04, Romano et al., 2011b, panel e); SAX J1818.6–1703 (2009-05-06, Sidoli et al., 2009b, panel f); AX J1841.0–0536 (2010-06-05, Romano et al., 2011b, panel g); AX J1845.0–0433 (2012-05-05, this work, panel h); candidate SFXT IGR J16328–4726 (2009-06-10, this work, panel i); candidate SFXT IGR J16418–4532 (2011-02-18, Romano et al., 2012b, panel l). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

Walter et al., 2006) between outbursts of classical supergiant HMXB (sgHMXB, $\lesssim 20$) and SFXT ($\gtrsim 100$). Fig. 2 shows the best examples of XRT outburst light curves, and highlights what we have discovered as the common X-ray characteristics of this class: outburst lengths well in excess of hours (sometimes lasting several

² <http://swift.gsfc.nasa.gov/docs/swift/results/transients/>

days), with a multiple-peaked structure, and a dynamic range (only including bright outbursts) up to ~ 3 orders of magnitude.

1.3. A physical model for SFXT broad-band spectra.

As part of our ongoing effort to understand the physical mechanisms responsible for the bright outbursts, we have recently developed a physical model, `compmag` in XSPEC (Farinelli et al., 2012a), which includes thermal and bulk Comptonization for cylindrical accretion onto a magnetized neutron star. A full description of the algorithm can be found in Farinelli et al. (2012a); here we summarize the main characteristics and the results of the first applications.

The `compmag` model considers a blackbody spectrum of photons as seed for Comptonization of the plasma. The free parameters are temperature kT_{bb} of the blackbody seed photons, the electron temperature kT_e , and vertical optical depth τ of the Comptonization plasma, the radius of the accretion column r_0 and the albedo A at the surface of the neutron star. The velocity field of the accreting matter can either be increasing towards the NS surface, in which case further free parameters are the terminal velocity β_0 at the NS surface, and the index of the law $\beta(z) \propto z^{-\eta}$, or it may be described by an approximately decelerating profile, so that the velocity law is given by $\beta(\tau) \propto -\tau$.

The `compmag` model was first applied to the SFXT class prototypes XTE J1739–302 and IGR J17544–2619 (Farinelli et al., 2012b). We note that, in general, it is not advisable to keep all the above mentioned parameters free, when trying to constrain them. We therefore assumed an increasing velocity of the infalling material towards the NS surface and set $\eta = 0.5$ and $\beta_0 = 0.2$ or 0.05. We also set $r_0 = 0.25$ (in units of the NS Schwarzschild radius) and $A = 1$. Under these assumptions, we found that the XRT+BAT spectra of the 2011 February 22 and 2011 March 24 outbursts of XTE J1739–302 and IGR J17544–2619, respectively, can be fit well with a single unsaturated Comptonization model such as `compmag`. In particular, we showed that the electron density in the region of the X-ray spectral formation, inferred from the best-fitting parameters of the `compmag` model, is about 3 orders of magnitude higher than expected from the continuity equation at the magnetospheric radius, and we proposed that this might be explained in terms of a bow shock at the NS magnetosphere. This effect is currently under investigation via 3D magnetohydrodynamical simulations.

1.4. Further monitoring campaigns.

Further monitoring campaigns featured observations along one or more orbital periods of an SFXT, to study the effects of orbital parameters on the flare distributions. Such is the case of IGR J18483–0311, observed between 2009 June 11 and July 9 (23 daily observations, ~ 2 ks each,

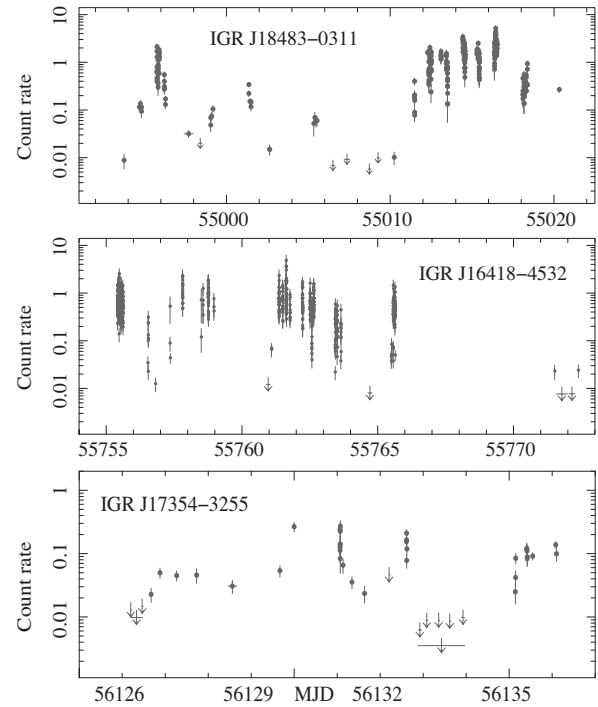


Fig. 3. *Swift*/XRT light curves of monitoring programs along one or more orbital periods. **Top:** IGR J18483–0311, with orbital period $P_{\text{orb}} = 12.545$ d (Levine et al., 2011), observed on 2009 June 11–July 9, shown at a binning of at least 20 counts bin^{-1} (adapted from Romano et al., 2010). **Middle:** IGR J16418–4532, with $P_{\text{orb}} = 3.73886$ d (Levine et al., 2011), observed on 2011 July 13–30, shown at a binning with a S/N = 3 (adapted from Romano et al., 2012b). **Bottom:** IGR J17354–3255, with $P_{\text{orb}} = 8.4474$ d (Sguera et al., 2011), observed on 2012 July 18–28, shown at a binning of at least 20 counts bin^{-1} (adapted from Ducci et al., 2013).

spread over 28 d for a total of 44 ks; Romano et al., 2010, see Fig. 3 top) with orbital period $P_{\text{orb}} = 18.545$ d (Levine et al., 2011), the candidate SFXT IGR J16418–4532, observed on 2011 July 13–30 (12 observations, ~ 2 –5 ks each, spread over 18 d for a total of 39 ks; Romano et al., 2012b, see Fig. 3 middle) with $P_{\text{orb}} = 3.73886$ d (Levine et al., 2011), and the candidate SFXT IGR J17354–3255, observed on 2012 July 18–28 (22 observations, ~ 1 ks each, spread over 11 d for a total of 24 ks; Ducci et al., 2013, see Fig. 3 bottom), with $P_{\text{orb}} = 8.4474$ d (Sguera et al., 2011). These unique datasets allowed us to constrain in these objects the different mechanisms proposed to explain their nature. In particular, we applied the clumpy wind model for blue supergiants by Ducci et al. (2009) to the observed X-ray light curve. By assuming for IGR J18483–0311 an eccentricity of $e = 0.4$ and for IGR J16418–4532 a circular orbit, we could explain their X-ray emission in terms of the accretion from a spherically symmetric clumpy wind, composed of clumps with different masses, ranging from 10^{18} to 5×10^{21} g for IGR J18483–0311, and from $\sim 5 \times 10^{16}$ g to 10^{21} g for IGR J16418–4532. The soft X-ray light curve of IGR J17354–3255 shows a moderate orbital modulation and a dip whose nature we investigated by comparing the X-ray light curve with the prediction of the Bondi-Hoyle-Littleton accretion

theory, assuming both spherical and non spherical symmetry of the outflow from the donor star. We found that dip cannot be explained with the X-ray orbital modulation. We propose that an eclipse or the onset of a gated mechanism are the most likely explanations for the observed light curve.

In the following we present some recent observational results obtained through our outburst follow-ups. As fitting examples of the exceptional capabilities of *Swift* in catching bright flares and monitor them panchromatically, we report on the datasets of the candidate SFXT IGR J16328–4726 and the confirmed SFXT AX J1845.0–0433, that went into outburst on 2009 June 10 (Grupe et al., 2009) and 2012 May 05 (Romano et al., 2012a), respectively.

2. Data reduction

The new XRT data were processed with standard procedures (`xrtpipeline` v0.12.6), filtering and screening criteria, within `FTOOLS` in the `HEASOFT` package (v.6.12). For the monitoring campaigns we generally considered photon-counting (PC) data only, and selected event grades 0–12 (Burrows et al., 2005); the outburst light curves generally start off with windowed timing (WT) data, instead, from which we selected event grades 0–2. Source events were accumulated within an annular/circular region (depending on whether pile-up correction was required or not, respectively) with an outer radius of 20–30 pixels, depending on source brightness; background events were accumulated from source-free regions. For our spectral analysis, we extracted events in the same regions as those adopted for the light curve creation; ancillary response files were generated with `xrtmkarf`, to account for different extraction regions, vignetting, and PSF corrections.

The BAT data of the outbursts were analysed using the standard BAT analysis software within `FTOOLS`. Mask-tagged BAT light curves were created in the standard energy bands and rebinned to either achieve a signal-to-noise ratio (S/N) of at least 5 or a 50-s integration time. Survey data products, in the form of Detector Plane Histograms (DPH), were analysed with the standard `batsurvey` software. BAT mask-weighted spectra were extracted during several time intervals; an energy-dependent systematic error vector was applied and response matrices were generated with `battrmgen`.

We derive astrometrically corrected X-ray positions by using the XRT–UVOT alignment and matching to the USNO–B1 catalog (Monet et al., 2003) as described in Goad et al., 2007 and Evans et al., 2009³.

Fig. 1 shows all available data on the 4 SFXT monitored in 2007–2009 in the 0.2–10 keV band. While some were previously published in Romano et al., 2009c; Romano et al., 2011a; Romano et al., 2011b; Romano et al., 2013 and Far-

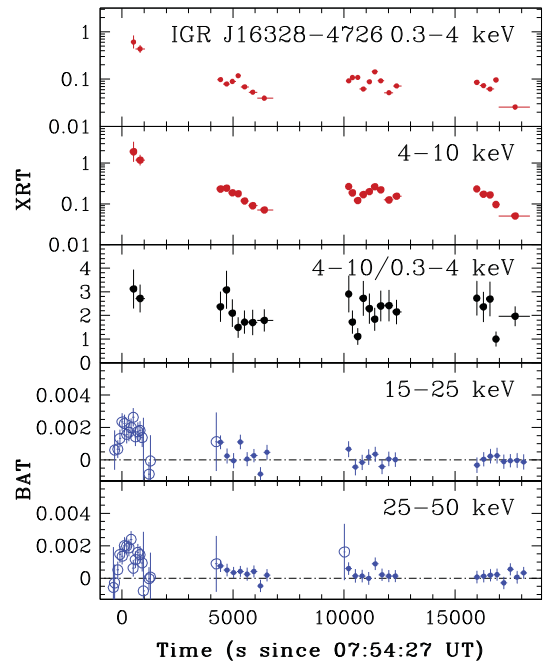


Fig. 4. 2009 June 10 outburst of IGR J16328–4726: XRT and BAT light curves of the first day of data, in units of count s^{-1} and count s^{-1} detector⁻¹, respectively. The empty (blue) circles correspond to BAT in event mode data, filled (blue) circles to BAT in survey mode data. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

inelli et al., 2012b, the data in red are presented here for the first time, and are updated to the end of 2012.

Fig. 2 shows the light curves of the most representative outbursts of confirmed SFXTs (panels a–h) and candidate SFXTs (panels i–l), that we followed with *Swift*/XRT for a few days after the BAT trigger through ToO observations. Red data points, the XRT light curves of outbursts the confirmed SFXT AX J1845.0–0433 and candidate SFXT IGR J16328–4726 (panels h and i), refer to observations presented here for the first time, while grey points indicate data presented elsewhere.

3. IGR J16328–4726

IGR J16328–4726 (Bird et al., 2010; Baumgartner et al., 2010; Cusumano et al., 2010) is considered a candidate SFXT, based on its history of hard X-ray activity characterized by short flares lasting up to a few hours (Fiocchi et al., 2010), and a lack of confirmed counterpart, with an orbital period of 10.076 ± 0.003 d (Corbet et al., 2010).

Following the BAT trigger of IGR J16328–4726 on 2009 June 10 at 07:54:27 UT (image trigger = 354542, Grupe et al., 2009), *Swift* executed an immediate slew, so XRT data are available which are simultaneous with the BAT data.

Using 7818 s of XRT Photon Counting mode data and 18 UVOT images, we find an astrometrically corrected

³ http://www.swift.ac.uk//user_objects/

X-ray position: RA(J2000) = $16^{\text{h}}32^{\text{m}}37^{\text{s}}.87$, Dec(J2000) = $-47^{\circ}23'41''.2$ with an uncertainty of $1''.4$ (90% c.l.). The XRT position is $0''.51$ from 2MASS J16323791–4723409, the most likely optical counterpart. This is the best currently available X-ray position for this source.

Fig. 4 shows the 0.3–4 keV and 4–10 keV light curves and the 4–10/0.3–4 hardness ratio of the 2009 June 10 outburst during the initial bright phase. The remainder of the XRT data (see Fig. 2 panel i) show that the count rate decreases from about 3 counts s^{-1} (first orbit) by a factor of 10 during the first 20 ks of observations. During the following two days, the source was observed at about 0.1 count s^{-1} , thus providing us with a dynamic range of ≈ 40 . The last two observations only yield 3σ upper limits at 1.4×10^{-2} counts s^{-1} and 4.5×10^{-3} counts s^{-1} , so that the overall dynamic range reaches at least 650. While this dynamic range is lower than the 4–5 orders of magnitude observed in “classical” (Chaty et al., 2010) SFXTs (such as IGR J17544–2619 and XTE J1739–302), it nonetheless places IGR J16328–4726 in the typical range for intermediate SFXTs (e.g., IGR J18483–0311 and IGR J16418–4532, Romano et al., 2010; Romano et al., 2012b). Fig. 2 (panel i) shows several flares, as also typical of the SFXT behaviour after the initial bright flare. We note that Bozzo et al., 2012 reported on a 22 ks XMM–Newton observation performed on 2011 February 20, in which they observed the source in a flux state fainter than the one observed during the outbursts (unabsorbed $F_{2-10\text{keV}} = 1.7 \times 10^{-11}$ erg cm^{-2} s^{-1}) also characterized by luminosity variations by a factor of 10.

Fig. 4 also shows the BAT light curves during the brightest part of the 2009 June 10 outburst in the 15–25 keV and 25–50 keV energy bands. The source is not detected above ~ 70 keV.

We extracted the mean BAT mask-weighted spectrum during the first orbit of data of the 2009 June 10 outburst and fit it in the 15–70 keV energy band with a simple power law. We obtained $\Gamma_{\text{BAT}} = 2.6 \pm 0.4$ ($\chi^2_{\nu} = 1.235$, 37 degrees of freedom, dof), and a 20–50 keV flux of 7.1×10^{-10} erg cm^{-2} s^{-1} . We extracted the mean XRT spectrum of the brightest X-ray emission (obs. 00354542000, first orbit $T+404$ –1036 s, 632 s net exposure, hereafter ‘000orb1’), and fit it in the 0.5–10 keV energy band with an absorbed power-law model by adopting Cash, 1979 statistics. We modelled the absorption (tbabs in xspec) with the abundance set to the values given by Wilms et al. (2000). We obtained a column of $N_{\text{H}} = 9^{+4}_{-3} \times 10^{22}$ cm^{-2} (in excess of the Galactic one, $N_{\text{H}}^{\text{Gal}} = 1.54 \times 10^{22}$ cm^{-2} ; Kalberla et al., 2005), a photon index $\Gamma = 0.65^{+0.69}_{-0.64}$ (Cash statistics 618.3, 76 % of 10^4 realizations with statistics in excess of Cstat), and 2–10 keV observed and unabsorbed fluxes of $F_{2-10\text{keV}}^{\text{obs}} = 2.9 \times 10^{-10}$ erg cm^{-2} s^{-1} and $F_{2-10\text{keV}} = 4.2 \times 10^{-10}$ erg cm^{-2} s^{-1} , respectively. Assuming a distance of 10 kpc for the luminosity calculation, we obtained $L_{2-10\text{keV}} = 5 \times 10^{36}$ erg s^{-1} .

Table 1

Spectral fits of simultaneous XRT and BAT data of IGR J16328–4726. POW: absorbed powerlaw. CPL: cutoff powerlaw, energy cutoff E_c (keV). HCT: absorbed powerlaw, high energy cutoff E_c (keV), e-folding energy E_f (keV). Absorbing column density is in units of 10^{22} cm^{-2} .

Model	N_{H}	Γ	E_c	E_f	χ^2_{ν}/dof
POW	$12.3^{+2.3}_{-1.9}$	$1.66^{+0.32}_{-0.32}$			1.38/51
CPL	$8.4^{+2.2}_{-1.9}$	$0.60^{+0.50}_{-0.48}$	19^{+15}_{-7}		1.09/50
HCT	$8.8^{+2.1}_{-1.8}$	$0.93^{+2.12}_{-1.79}$	< 28	20^{+16}_{-8}	1.09/49

Similarly, the mean XRT spectrum, extracted from the whole first observation (obs. 00354542000, $T+404$ –18375 s, 8181 s net exposure, hereon ‘000’) and rebinned with a minimum of 20 counts bin^{-1} to allow χ^2 fitting, yielded $N_{\text{H}} = 9.0^{+2.2}_{-1.8} \times 10^{22}$ cm^{-2} , and $\Gamma = 0.96^{+0.41}_{-0.37}$ ($\chi^2_{\nu} = 1.07$, 41 dof). The 2–10 keV observed and unabsorbed fluxes are $F_{2-10\text{keV}}^{\text{obs}} = (5.6^{+0.3}_{-2.7}) \times 10^{-11}$ erg cm^{-2} s^{-1} and $F_{2-10\text{keV}} = (8.3^{+0.4}_{-1.6}) \times 10^{-11}$ erg cm^{-2} s^{-1} , respectively; this corresponds to a luminosity $L_{2-10\text{keV}} = 1 \times 10^{36}$ erg s^{-1} .

In order to perform broad-band spectroscopy of the 2009 June 10 outburst, we matched the BAT spectrum with the ‘000’ XRT one. We note that the chosen spectra are not strictly simultaneous, as they span the first and the first 4 orbits of data, respectively. The XRT ‘000’ spectrum, however, offers the advantage of higher S/N than the strictly simultaneous ‘000orb1’, and a consistent photon index, despite a decrease in average flux by a factor of ~ 5 . Therefore, constant factors were included in the fitting to allow for both normalization uncertainties between the two instruments (generally constrained within 10%) and normalization differences due to the non strict simultaneity of the XRT and the BAT data. We considered models that are generally used to describe the X-ray emission from accreting pulsars in HMXBs. i.e., a simple absorbed power-law, an absorbed power-law with an exponential cut-off (cutoffpl in xspec), and an absorbed power-law with a high energy cut-off (highecut). We performed joint fits in the 0.5–10 keV, 15–70 keV energy bands for XRT and BAT, respectively. Our results are reported in Table 1. The simple power-law model yields a clearly unsatisfactory fit. The absorbed power-law with a high energy cut-off yields a poorly constrained value of the cut-off energy. The absorbed power-law with an exponential cut-off, on the other hand, yields a very good fit ($\chi^2_{\nu}/\text{dof} = 1.09/50$; see Fig. 5), with $N_{\text{H}} = (8 \pm 2) \times 10^{22}$ cm^{-2} , $\Gamma = 0.60^{+0.50}_{-0.48}$, and a high-energy cut-off at $E_c = 19^{+15}_{-7}$ keV.

4. AX J1845.0–0436

AX J1845.0–0433/IGR J18450–0435 (Bird et al., 2010; Baumgartner et al., 2010; Cusumano et al., 2010) was discovered in ASCA data (Yamauchi et al., 1995) as a source variable on timescales of tens of minutes and classified as a

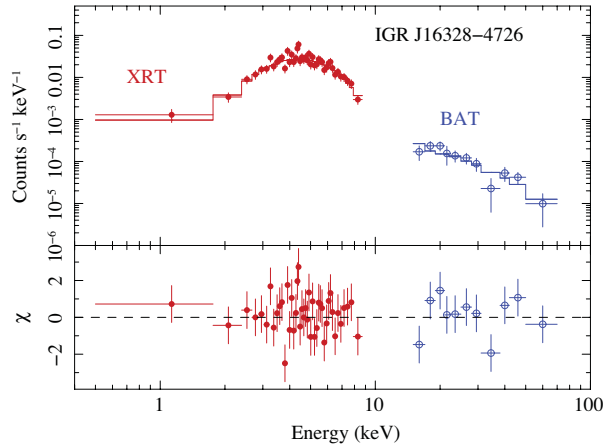


Fig. 5. Broad-band spectroscopy of the 2009 June 10 outburst of IGR J16328–4726. Top: simultaneous XRT/PC (filled red circles) and BAT (empty blue circles) data fit with the `cutoffpl` model. Bottom: the residuals of the fit (in units of standard deviations). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

SFXT (Sguera et al., 2007a) with an O9.5I companion (Coe et al., 1996; Zurita Heras and Walter, 2009).

AX J1845.0–0433 triggered the BAT on 2012 May 05 at 01:44:39 UT⁴ (image trigger=521567, Romano et al., 2012a). *Swift* slewed to the target immediately, so that the XRT began observing the field about 423 s after the trigger.

To obtain an arcsecond level position of this source, we used the first 2775 s PC mode data and, by correcting for the astrometric errors by utilizing *Swift*/UVOT data, we found RA(J2000) = 18^h45^m01^s.58, Dec(J2000) = –04°33′57.″4, with an estimated error of 1.″4 radius (90% c.l.). The XRT position is 2.″2 from the most likely optical counterpart proposed by Coe et al. (1996) ~ 1″ error, and it is the best currently available X-ray position for this source since (Zurita Heras and Walter, 2009, based on *XMM-Newton*) reports a localization with an error of 2″.

We extracted the mean BAT mask-weighted spectrum (T–239 to T+963 s; 1202 s net exposure) during the first orbit of data and fit it in the 15–70 keV energy band with a simple power law. We obtained $\Gamma_{\text{BAT}} = 2.4 \pm 0.4$ ($\chi^2_{\nu} = 0.9$, 24 dof), and a 15–70 keV flux of 1.7×10^{-9} erg cm⁻² s⁻¹.

Fig. 2 (panel h) shows the XRT light curve that we followed for a total of 18 days. In the XRT AX J1845.0–0433 reached an initial peak at about 20 count s⁻¹ at T+1000 s, immediately followed by several more flares. The following day, the source was not detected (3σ upper limit at about 2.4×10^{-2} count s⁻¹), and in the following days, it showed several more flares. The overall dynamic range therefore

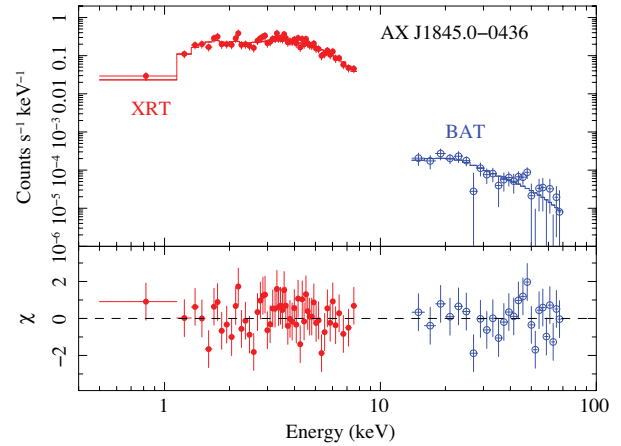


Fig. 6. Broad-band spectroscopy of the 2012 May 05 outburst of AX J1845.0–0433. Top: XRT/PC (filled red circles) and BAT (empty blue circles) data fit with the `cutoffpl` model. Bottom: the residuals of the fit (in units of standard deviations). (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)

reaches at least 750 which places AX J1845.0–0433 neatly in the typical SFXT range. The initial XRT/WT spectrum (T+429 to T+846 s; 417 s net exposure) can be fit with an absorbed power law, with a photon index of $\Gamma = 1.3 \pm 0.1$, and an absorbing column density of $N_{\text{H}} = 1.8^{+0.3}_{-0.2} \times 10^{22}$ cm⁻², in slight excess of the Galactic value of 1.30×10^{22} cm⁻², (Kalberla et al., 2005). The mean flux is $F_{2-10 \text{ keV}} = 7 \times 10^{-10}$ erg cm⁻² s⁻¹ (unabsorbed). The XRT/PC spectrum (T+848 to T+1891 s; 1043 s net exposure) shows a power law shape with $N_{\text{H}} = (1.4^{+0.4}_{-0.3}) \times 10^{22}$ cm⁻², $\Gamma = 0.8 \pm 0.2$ and an average flux of $F_{2-10 \text{ keV}} = 8 \times 10^{-10}$ erg cm⁻² s⁻¹ (unabsorbed). These fluxes translate into a luminosity of $L_{2-10 \text{ keV}} = 1 \times 10^{36}$ erg s⁻¹ (assuming the optical counterpart distance of 3.6 kpc, Coe et al., 1996), comparable with the one observed in previous outbursts of this source (Sguera et al., 2007a; Zurita Heras and Walter, 2009).

We fit the nearly simultaneous BAT and XRT/PC spectra in the 0.5–10 keV and 15–70 keV energy bands for XRT and BAT, respectively, with the same models as those used for IGR J16328–4726. Our results are reported in Table 2. The simple power-law model yields a clearly unsatisfactory fit, showing systematic residuals that indicate the need for a curved spectrum. The absorbed power-law with a high energy cut-off yields a poorly constrained value of the

Table 2

Spectral fits of simultaneous XRT and BAT data of AX J1845.0–0433. POW: absorbed powerlaw. CPL: cutoff powerlaw, energy cutoff E_c (keV). HCT: absorbed powerlaw, high energy cutoff E_c (keV), e-folding energy E_f (keV). Absorbing column density is in units of 10^{22} cm⁻².

Model	N_{H}	Γ	E_c	E_f	χ^2_{ν}/dof
POW	$2.0^{+0.5}_{-0.4}$	$1.20^{+0.26}_{-0.25}$			1.24/78
CPL	$1.3^{+0.4}_{-0.3}$	$0.56^{+0.26}_{-0.25}$	17^{+8}_{-5}		0.79/77
HCT	$1.2^{+0.4}_{-0.3}$	$0.60^{+0.31}_{-0.21}$	< 19	18^{+8}_{-5}	0.78/76

⁴ Previously, *Swift* caught a flare from this source on 2005 November 4 and 2009 June 28 (Romano et al., 2009a). The historical light curve from the BAT hard X-ray transient monitor can be found at <http://swift.gsfc.nasa.gov/docs/swift/results/transients/weak/>.

cut-off energy. The absorbed power-law with an exponential cut-off, on the other hand, yields a better fit (see Fig. 6), with $N_{\text{H}} = (1.3_{-0.3}^{+0.4}) \times 10^{22} \text{ cm}^{-2}$, $\Gamma = 0.56_{-0.25}^{+0.26}$, and a high-energy cut-off at $E_{\text{c}} = 17_{-5}^{+8} \text{ keV}$. These results are consistent with those of Sguera et al. (2007a) and Zurita Heras and Walter (2009) both in terms of overall luminosity of the outbursts and detailed spectral parameters.

5. Conclusions and Future Perspectives

In this paper we have given a review of our *Swift* SFXT Project, its underlying observing strategy and its advantages. Given the shape of the SFXT spectrum, broad band spectroscopy with *Swift* (0.3–150 keV) generally allows us to both model the hard-X spectral properties and to measure the absorption. Furthermore, we can use our detailed light curves to determine the overall dynamic range, a discriminant between outbursts of classical sgHMXBs and SFXTs.

We used two recent outbursts to highlight the typical results of our activity. IGR J16328–4726 is considered a candidate SFXT, based on its recorded history of flaring activity and lack of a confirmed counterpart. Our evidence, based on *Swift* data, points towards an intermediate SFXT classification. The temporal and spectroscopic properties of this source, including the high peak luminosities, the large dynamic range, and the length (days) and flaring nature of the X-ray outburst are strongly reminiscent of those of the prototypes of the SFXT class. AX J1845.0–0436, on the other hand, is a confirmed SFXT with a well-known optical companion. Our *Swift* simultaneous broad band spectroscopy allows us to obtain a good fit with an absorbed flat power-law with an exponential cut-off at $\sim 18 \text{ keV}$, as is typical for wind-fed HMXBs. In Fig. 2 we draw a comparison among the best light curves of outbursts of confirmed SFXTs and candidate SFXTs, as caught during our monitoring campaigns with *Swift*. Similarly to the observations for all confirmed SFXTs, the outburst of IGR J16328–4726 (hence, in the SFXT framework, the length of the accretion phase) lasts a few days. In particular, we show for the first time, a long monitoring of AX J1845.0–0436 after an outburst, also showing remarkable activity for several days, at least. Furthermore, in both cases we also observed the multiple-peak structure of the light curve that can now be considered a defining characteristic of the SFXT class, which is likely due to inhomogeneities in the accretion flow (e.g. in't Zand, 2005) and/or unstable accretion due to the spin and magnetic field of the compact object (Grebenev and Sunyaev, 2007; Bozzo et al., 2008).

Currently the Project is catching bright flares at the rate of several per year, that we follow with XRT for at least one week (often longer if previously not observed in the soft X-rays) through ToO observations through the *Swift* GI program (PI: P. Romano) and regular ToOs. We aim at observing bright flares of the remaining candidate SFXTs in order to localize them to the arcsecond level

and identify their optical/infrared companion, as well as the remaining SFXTs for which no soft X-ray observations are available, yet. At the time of writing long term monitoring campaigns are still ongoing to systematically study the out-of-outburst behaviour of the whole SFXT class.

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References

- Barthelmy, S.D., Barbier, L.M., Cummings, J.R., et al. The Burst Alert Telescope (BAT) on the SWIFT midex mission. *Space Sci. Rev.* 120, 143–164, 2005.
- Baumgartner, W.H., Tueller, J., Markwardt, C. The Swift-BAT 58 month survey. In: AAS/HEAD #11. *BAAS* 42, 675, 2010.
- Bird, A.J., Bazzano, A., Bassani, L., et al. The fourth IBIS/ISGRI soft gamma-ray survey catalog. *ApJS* 186, 1–9, 2010.
- Bozzo, E., Falanga, M., Stella, L. Are there magnetars in high mass X-ray binaries? The case of supergiant fast X-ray transients. *ApJ* 683, 1031–1044, 2008.
- Bozzo, E., Pavan, L., Ferrigno, C., et al. XMM-Newton observations of four high mass X-ray binaries and IGR J17348–2045. *A&A* 544, A118, 2012.
- Burrows, D.N., Hill, J.E., Nousek, J.A., et al. The Swift X-ray Telescope. *Space Sci. Rev.* 120, 165–195, 2005.
- Cash, W. Parameter estimation in astronomy through application of the likelihood ratio. *ApJ* 228, 939–947, 1979.
- Chaty, S., Zurita Heras, J.A., Bodaghee, A. The INTEGRAL legacy on high mass X-ray binaries. *ArXiv e-prints*, 1012.2318, 2010.
- Coe, M.J., Fabregat, J., Negueruela, I., et al. Discovery of the optical counterpart to the ASCA transient AX 1845.0–0433. *MNRAS* 281, 333–338, 1996.
- Corbet, R.H.D., Barthelmy, S.D., Baumgartner, et al. A 10 day period in IGR J16328–4726 from Swift/BAT observations. *The Astronomer's Telegram* 2588, 2010.
- Cusumano, G., La Parola, V., Segreto, et al. The Palermo Swift-BAT hard X-ray catalogue. III. Results after 54 months of sky survey. *A&A* 524, A64, 2010.
- Ducci, L., Romano, P., Esposito, P., et al. Swift/XRT orbital monitoring of the candidate supergiant fast X-ray transient IGR J17354–3255. *A&A* 556, A72, 2013.
- Ducci, L., Sidoli, L., Mereghetti, S., et al. The structure of blue supergiant winds and the accretion in supergiant high mass X-ray binaries. *MNRAS* 398, 2152–2165, 2009.
- Evans, P.A., Beardmore, A.P., Page, K.L., et al. Methods and results of an automatic analysis of a complete sample of Swift-XRT observations of GRBs. *MNRAS* 397, 1177–1201, 2009.
- Farinelli, R., Ceccobello, C., Romano, P., et al. Numerical solution of the radiative transfer equation: X-ray spectral formation from cylindrical accretion onto a magnetized neutron star. *A&A* 538, A67, 2012a.

- Farinelli, R., Romano, P., Mangano, V., et al. Swift observations of two supergiant fast X-ray transient prototypes in outburst. *MNRAS* 424, 2854–2863, 2012b.
- Fiocchi, M., Sguera, V., Bazzano, A., et al. IGR J16328–4726: A new candidate supergiant fast X-ray transient. *ApJL* 724, L68–L72, 2010.
- Gehrels, N., Chincarini, G., Giommi, P. The Swift Gamma-ray Burst Mission. *ApJ* 611, 1005–1020, 2004.
- Goad, M.R., Tyler, L.G., Beardmore, A.P., et al. Accurate early positions for Swift GRBs: enhancing X-ray positions with UVOT astrometry. *A&A* 476, 1401–1409, 2007.
- Grebenev, S.A., Sunyaev, R.A. The first observation of AX J1749.1-2733 in a bright X-ray state—Another fast transient revealed by INTEGRAL. *Astronomy Letters* 33, 149–158, 2007.
- Grupe, D., Kennea, J., Evans, P., et al. Swift detection of a flare from IGR J16328–4726. *The Astronomer's Telegram* 2075, 2009.
- in't Zand, J.J.M. Chandra observation of the fast X-ray transient IGR J17544–2619: Evidence for a neutron star? *A&A* 441, L1–L4, 2005.
- Kalberla, P.M.W., Burton, W.B., Hartmann, D., et al. The Leiden/Argentine/Bonn (LAB) survey of galactic HI. Final data release of the combined LDS and IAR surveys with improved stray-radiation corrections. *A&A* 440, 775–782, 2005.
- Krimm, H., Barbier, L., Barthelmy, S.D., et al. Announcement of the Swift/BAT hard X-ray transient monitor. *The Astronomer's Telegram* 904, 2006.
- Krimm, H.A., Holland, S.T., Corbet, R.H.D., et al. The Swift/BAT hard X-ray transient monitor. *ApJS*, in press, 2013.
- Levine, A.M., Bradt, H., Cui, W., Jernigan, J.G., Morgan, E.H., Remillard, R., Shirey, R.E., Smith, D.A. First results from the all-sky monitor on the rossi X-ray timing explorer. *ApJL* 469, L33, 1996.
- Levine, A.M., Bradt, H.V., Chakrabarty, D., et al. An extended and more sensitive search for periodicities in rossi X-ray timing explorer/all-sky monitor X-ray light curves. *ApJS* 196, 6, 2011.
- Mangano, V., Romano, P., Ceccobello, et al. IGR J08408–4503 in outburst observed by Swift. *American Institute of Physics Conference Series* 1505, 442–445, 2012.
- Matsuoka, M., Kawasaki, K., Ueno, et al. The MAXI mission on the ISS: Science and instruments for monitoring all-sky X-ray images. *PASJ* 61, 999, 2009.
- Monet, D.G., Levine, S.E., Canzian, B., et al. The USNO-B catalog. *AJ* 125, 984–993, 2003.
- Neguera, I., Smith, D. M., Reig, P., et al. Supergiant fast X-ray transients: A new class of high mass X-ray binaries unveiled by INTEGRAL. *ESA Special Publication* 604, 165, 2006.
- Neguera, I., Torrejón, J.M., Reig, P., et al. Supergiant fast X-ray transients and other wind accretors, in: *American Institute of Physics Conference Series* 1010, pp. 252–256, 2008.
- Romano, P., Barthelmy, S., Margutti, R., et al. Swift observations of an outburst of the SFXT AX J1845.0-0433/IGR J18450–0435. *The Astronomer's Telegram* 2102, 2009a.
- Romano, P., Barthelmy, S.D., Chester, M.M., et al. Swift observes a new outburst from the supergiant fast X-ray transient AX J1845.0-0433. *The Astronomer's Telegram* 4095, 1, 2012a.
- Romano, P., La Parola, V., Vercellone, S., et al. Two years of monitoring supergiant fast X-ray transients with Swift. *MNRAS* 410, 1825–1836, 2011a.
- Romano, P., Mangano, V., Cusumano, G., et al. Confirmation of the supergiant fast X-ray transient nature of AX J1841.0-0536 from Swift outburst observations. *MNRAS* 412, L30–L34, 2011b.
- Romano, P., Mangano, V., Ducci, L., et al. From hours to years: Swift's revolutionary view of SFXTs. *Memorie della Societa Astronomica Italiana Supplementi*, in press, 2013.
- Romano, P., Mangano, V., Ducci, L., et al. Swift/X-ray Telescope monitoring of the candidate supergiant fast X-ray transient IGR J16418–4532. *MNRAS* 419, 2695–2702, 2012b.
- Romano, P., Sidoli, L., Cusumano, G., et al. Multiple flaring activity in the supergiant fast X-ray transient IGR J08408–4503 observed with Swift. *MNRAS* 392, 45–51, 2009b.
- Romano, P., Sidoli, L., Cusumano, G., et al. Monitoring supergiant fast X-ray transients with Swift: Results from the first year. *MNRAS* 399, 2021–2032, 2009c.
- Romano, P., Sidoli, L., Ducci, L., et al. Swift/XRT monitoring of the supergiant fast X-ray transient IGR J18483–0311 for an entire orbital period. *MNRAS* 401, 1564–1569, 2010.
- Romano, P., Sidoli, L., Mangano, V., et al. Swift/XRT observes the fifth outburst of the periodic supergiant fast X-ray transient IGR J11215–5952. *A&A* 469, L5–L8, 2007.
- Romano, P., Sidoli, L., Mangano, V., et al. Monitoring supergiant fast X-ray transients with Swift. II. Rise to the outburst in IGR J16479–4514. *ApJL* 680, L137–L140, 2008.
- Roming, P.W.A., Kennedy, T.E., Mason, K.O., et al. The Swift Ultraviolet/Optical Telescope. *Space Sci. Rev.* 120, 95–142, 2005.
- Sguera, V., Barlow, E.J., Bird, A.J., et al. INTEGRAL observations of recurrent fast X-ray transient sources. *A&A* 444, 221–231, 2005.
- Sguera, V., Bird, A.J., Dean, A.J., et al. INTEGRAL and Swift observations of the supergiant fast X-ray transient AX J1845.0-0433 = IGR J18450–0435. *A&A* 462, 695–698, 2007a.
- Sguera, V., Drave, S.P., Bird, A.J., et al. IGR J17354–3255 as a candidate intermediate supergiant fast X-ray transient possibly associated with the transient MeV AGL J1734–3310. *MNRAS* 417, 573–579, 2011.
- Sidoli, L., Romano, P., Ducci, L., et al. Supergiant fast X-ray transients in outburst: New Swift observations of XTE J1739–302, IGR J17544–2619 and IGR J08408–4503. *MNRAS* 397, 1528–1538, 2009a.
- Sidoli, L., Romano, P., Esposito, P., et al. The first broad-band X-ray study of the supergiant fast X-ray transient SAX J1818.6-1703 in outburst. *MNRAS* 400, 258–262, 2009b.
- Sidoli, L., Romano, P., Mangano, V., et al. Monitoring supergiant fast X-ray transients with Swift. III. Outbursts of the prototypical supergiant fast X-ray transients Igr J17544–2619 and XTE J1739–302. *ApJ* 690, 120–127, 2009c.
- Sidoli, L., Romano, P., Mangano, V., et al. Monitoring supergiant fast X-ray transients with Swift. I. Behavior outside outbursts. *ApJ* 687, 1230–1235, 2008.
- Sidoli, L., Romano, P., Mereghetti, S., et al. An alternative hypothesis for the outburst mechanism in supergiant fast X-ray transients: The case of IGR J11215–5952. *A&A* 476, 1307–1315, 2007.
- Smith, D.M., Negueruela, I., Heindl, W.A. High mass fast transients – a new class of X-ray binary?, in: *BAAS* 36, 954, 2004.
- Walter, R., Zurita Heras, J., Bassani, L., et al. XMM-Newton and INTEGRAL observations of new absorbed supergiant high-mass X-ray binaries. *A&A* 453, 133–143, 2006.
- Walter, R., Zurita Heras, J. Probing clumpy stellar winds with a neutron star. *A&A* 476, 335–340, 2007.
- Wilms, J., Allen, A., McCray, R. On the absorption of X-rays in the interstellar medium. *ApJ* 542, 914–924, 2000.
- Yamauchi, S., Aoki, T., Hayashida, K., et al. New transient X-ray source in the scutum region discovered with ASCA. *PASJ* 47, 189–194, 1995.
- Zurita Heras, J.A., Walter, R. INTEGRAL and XMM-Newton observations of AX J1845.0-0433. *A&A* 494, 1013–1019, 2009.