PROCEEDINGS OF SCIENCE

The 100-month *Swift* Catalogue of Supergiant Fast X-ray Transients

P. Romano[*],[a] [†]**H.A. Krimm,**[b,c] **D.M. Palmer,**[d] **L. Ducci,**[e,f] **P. Esposito,**[g,h] **S. Vercellone,**[a] **P.A. Evans,**[i] **C. Guidorzi,**[j] **V. Mangano,**[k] **J.A. Kennea,**[k] **S.D. Barthelmy,**[b] **D.N. Burrows,**[k] **N. Gehrels,**[b]

[a]*INAF-IASF Palermo, Via U. La Malfa 153, I-90146, Palermo, Italy*
[b]*NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[c]*Universities Space Research Association, Columbia, MD, USA*
[d]*Los Alamos National Laboratory, B244, Los Alamos, NM 87545, USA*
[e]*IfAA, Eberhard Karls Universität, Sand 1, 72076 Tübingen, Germany*
[f]*ISDC DCfA, Université de Genève, 16 chemin d'Écogia, 1290 Versoix, Switzerland*
[g]*INAF-IASF Milano, Via E. Bassini 15, I-20133, Milano, Italy*
[h]*Harvard–Smithsonian CfA, 60 Garden Street, Cambridge, MA 02138, USA*
[i]*Department of Physics and Astronomy, Uni. Leicester, University Road, Leicester, LE1 7RH, UK*
[j]*Department of Physics and Earth Sciences, Uni. Ferrara Via Saragat 1, I-44122, Ferrara, Italy*
[k]*Department of Astronomy and Astrophysics, PSU, University Park, PA 16802, USA*
E-mail: `romano@ifc.inaf.it`

The 100-month *Swift* Catalogue of Supergiant Fast X–ray Transients collects over a thousand *Swift*/BAT flares from 11 Supergiant Fast X–ray Transients (SFXTs), and reaches down to 15–150 keV fluxes of about 6×10^{-10} erg cm^{-2} s^{-1} (daily timescale) and about 1.5×10^{-9} erg cm^{-2} s^{-1} (*Swift* orbital timescale, about 800 s). These hard X-ray flares typically last at least a few hundred seconds, reach fluxes in excess of 100 mCrab (15–50 keV), and last much less than a day. Their clustering in the binary orbital phase-space, however, demonstrates that these short flares are part of much longer outbursts, lasting up to a few days, as previously observed in deeper *Swift* soft X-ray observations. We used this large dataset to probe the high and intermediate emission states in SFXTs, to infer the properties of these binaries, to estimate the number of flares per year each source is likely to produce as a function of the detection threshold and limiting flux. The catalogue was also recently used to estimate the expected number of SFXTs in the Milky Way.

Swift: 10 Years of Discovery
2-5 December 2014
La Sapienza University, Rome, Italy

[*]Speaker.
[†]*Swift* SFXT Project web page: http://www.ifc.inaf.it/sfxt/ .

PoS(SWIFT 10)158

1. Introduction

Supergiant Fast X-ray Transients (SFXTs) are HMXBs with OB supergiant companions and are known for X-ray outbursts characterized by 10^3–10^5 luminosity increases (up to 10^{36}–10^{37} erg s^{-1}) lasting for a few hours. The compact object is quite probably a neutron star, as the X-ray spectrum and the pulsations observed in a few SFXTs testify, accreting from the wind of the companion. Currently, no prevailing model proposed to explain the bright outbursts has been agreed upon; competing models include accretion onto the NS from a "clumpy wind" [1], and, more recently, those invoking either the presence of magnetic/centrifugal barriers [2, 3] or a subsonic settling accretion regime [4]. In this framework, the *Swift* SFXT Project was born with the purpose of exploiting the unique characteristics of *Swift* [5] in an investigation of the SFXT properties. In the following, we will distinguish between a flare, which is a state of enhanced emission generally lasting less than a few hours, and an outburst, which is composed of several flares and lasts for about a day or more.

2. The catalogue

The 100-month *Swift* Catalogue of Supergiant Fast X-ray Transients [6] is a *Swift* legacy, recording a thousand flares uniformly observed in the time range 2005-02-12 to 2013-05-31. The sources in our sample of SFXTs were selected from the literature based on evidence of bright flares (peak in excess of $L \sim 10^{36}$ erg s^{-1}), as recorded by ASCA, *RXTE*, *INTEGRAL*, and *Swift*: IGR J08408−4503, IGR J11215−5952, IGR J16328−4726, IGR J16418−4532, IGR J16465 −4507, IGR J16479−4514, XTE J1739−302, IGR J17544−2619, SAX J1818.6−1703, AX J1841.0 −0536, AX J1845.0−0433, and IGR J18483−0311 (details and properties of these binaries in [6]).

2.1 The BAT data subsamples

The bright flares from SFXTs have been triggering the Burst Alert Telescope (BAT, [7]) on board *Swift*, since early after launch. However, while the most spectacular evidence of SFXT activity comes from their outbursts, SFXTs are characterized by flares in all intensity states. Therefore, in the creation of our catalogue, several sets of BAT data were used:

i) **BAT on-board detections (d)**: all on-board detections $> 5\,\sigma$ within 4 arcmin of each source.

ii) **BAT Triggers (T)**: they are on-board detections exceeding a threshold (currently set to $5.8\,\sigma$), that are also transmitted to the ground. SFXTs can trigger the BAT like γ-ray bursts do [8], although those produced by SFXTs are generally only image triggers (> 64 s, 15–50 keV).

iii) **BAT Transient Monitor data**: since BAT observes an average of 88% of the sky daily, it is ideally suited to detect flaring in hard X-ray astrophysical sources. Since 2005-02-12 the BAT Transient Monitor (BATTM [9]) has been providing near real-time light curves in the 15–50 keV band of more than 900 sources with a mean variance for one-day mosaics of 5.3 mCrab at **daily (D)** and ***Swift*-orbit (o) resolution** (~ 800 s). We applied a $5\,\sigma$ cut for the significance of the detections.

2.2 Flare properties

Our sample consists of 1117 flares from 11 sources, divided into 46 BAT triggers (T, in 43 outbursts), 126 daily-averaged BATTM light curves (D), 267 BATTM light curves averaged over

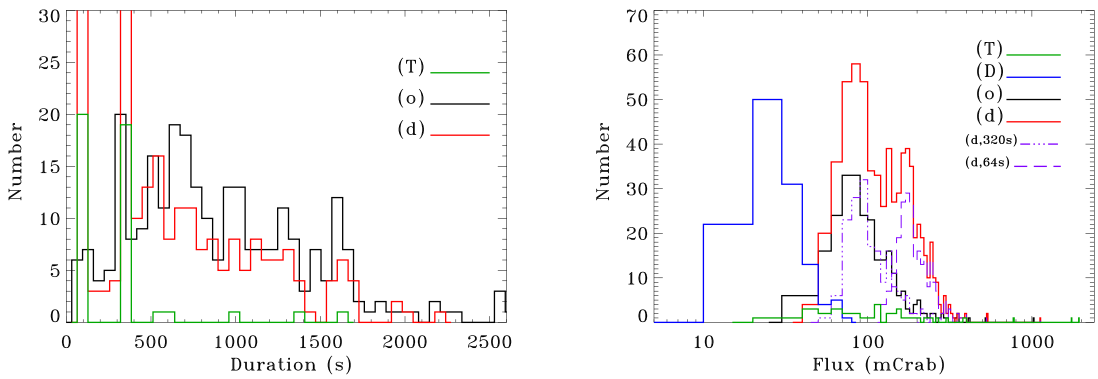

Figure 1: BAT flare properties. **Left**: Distributions of durations for BAT triggers (T), (*Swift*) orbital-averaged BATTM light curves (o), and on-board detections (d). The peaks of the (d) subsample reach ~ 270 and 250 at 64 and 320 s, respectively. **Right**: Distributions of fluxes (15–50 keV) for BAT triggers (T), daily-averaged BATTM light curves (D), orbital-averaged BATTM light curves (o), and on-board detections (d). The hashed histograms represent the on-board detections lasting 320 and 64 s and are responsible for the two peaks in the (d) overall distribution at ~ 95 and 175 mCrab, respectively. Adapted from [6].

the *Swift* orbit (see point *iii)* in § 2.1; hereon, "orbital-averaged"), and 678 on-board detections (d). Figure 1 (left) shows the distributions of the observed durations. The means are 285 s (T), 897 s (o), 351 s (d); and their medians are 320 s (T) and 792 s (o). Most on-board detections result from the (nominally) 64 s, 320 s, and full-pointing images that BAT generates. The image duration is used as a proxy for the flare duration, leading to the two peaks in Fig 1 (left). Figure 1 (right) shows the distributions of the observed 15–50 keV fluxes for the whole catalogue, depending on the detection method. The fluxes range from ~ 15 mCrab (for the daily-averages) to 1.9 Crab with a median of ~ 105 mCrab. The medians for the four subsamples are 134 mCrab (T), 27 mCrab (D), 94 mCrab (o), and 133 mCrab (d). The two peaks of the on-board (d) subsample are at~ 95 and 175 mCrab and are due to the detections in the 320 and 64 s on-board images, respectively.

The flux distributions imply that *the population of about a thousand SFXTs flares we observed is characterized by short (a few hundred seconds) and relatively bright (in excess of 100 mCrab, 15–50 keV) events. These flares generally last less than a day in the hard X–ray*, as demonstrated by the lower fluxes measured in the BATTM daily averages. As we have shown (e.g. [10, 11], and references therein), in the soft X–ray the picture is radically different, since the higher sensitivity of the focussing instrumentation allows us not only to detect the bright flares but also to follow the whole outburst, lasting up to several days, depending on the source.

Clustering of X–ray flares, however, can be used to indirectly measure the length of an outburst, even though the low-level emission is not detected. In Figure 2 we show the BATTM orbital-averaged light curves folded at the binary orbital periods [6] (top panels), and the distributions of flares along the binary orbital period (bottom panels). Therefore, outbursts are a much longer phenomenon than the flaring timescales, lasting up to a few days, as previously discovered from deeper soft X–ray observations [10, 11]. In particular, we observe (Fig. 3 left) a trend of clustering of flares at some phases as $P_{\rm orb}$ increases, as demonstrated by the trend of the mean absolute

PoS(SWIFT 10)158

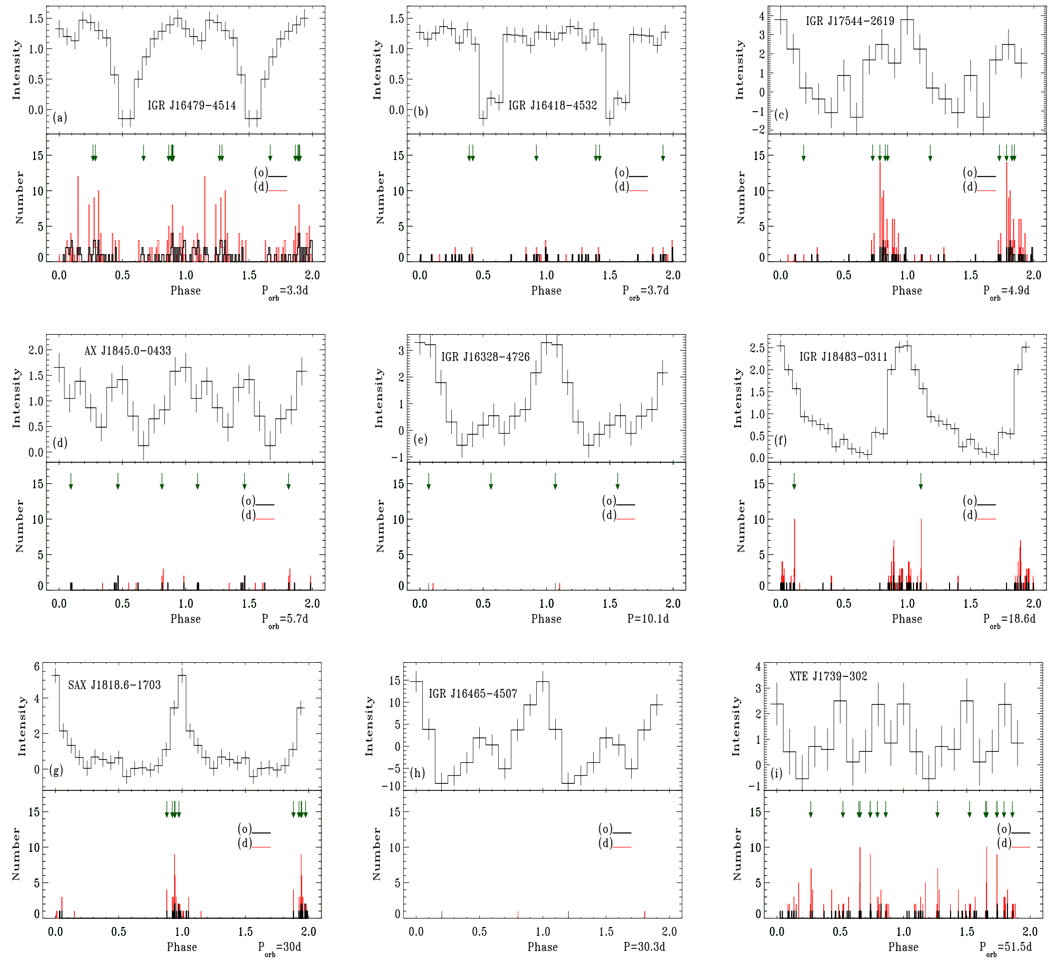

Figure 2: *Top Panels*: BAT TM light curves (15–50 keV) of the SFXT sample folded at the binary orbital periods (when known, reported in the right lower corner of each panel). *Bottom panels*: BAT on-board (d, red histograms) and BATTM orbital-averaged detections (o, black histograms) folded at the same periods. The green downward pointing arrows are the BAT triggers (T). From [6].

deviation (MAD[1]) of the flare phases, which is consistent with a progression from tight circular or mildly eccentric orbits at short periods, to wider and more eccentric orbits at longer binary orbital periods. Fig. 3 (right) reports the MAD multiplied by the binary orbital period (quantity that can be considered a good proxy for the half-length of the duty-cycle), and it shows that the duty-cycle is in the order of a few days.

2.3 Catalogue exploitation

This large dataset (the largest in a single publication) can be used to further probe the properties of the high and intermediate emission states in SFXTs, and to infer the properties of these binary systems, especially in conjunction with flares detected by other current or future missions. For the latter, we provide a simple recipe to estimate the number of flares per year each source is likely

[1]Mean Absolute Deviation = $\frac{1}{N-1}\sum_{j=1}^{N}|x_j-\overline{x}|$, where $\overline{x}$ is the mean of $x=(x_1,...,x_N)$ of the flare phases.

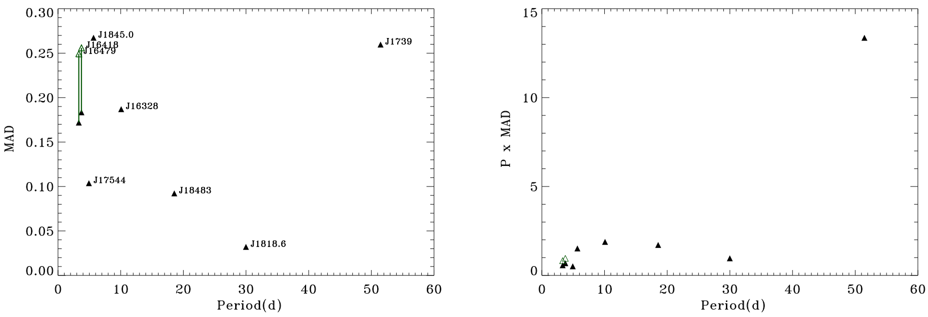

Figure 3: *Left Panel*: Mean absolute deviation (MAD) of the flare phases as a function of $P_{\rm orb}$. *Right Panel*: Mean absolute deviation of the flare phases multiplied by $P_{\rm orb}$. The dataset is the orbital-averaged detections (o, filled black points). The empty green points are obtained by simulating a population of flares for IGR J16479−4514 and IGR J16418−4532 unaffected by the presence of the eclipse. From [6].

to produce as a function of detection threshold/limiting flux. Figure 4 (left) shows the cumulative distributions of σ for the BATTM orbital-averaged detections. By considering that 5σ detections for an average *Swift* orbit correspond to 1.46×10^{-9} erg cm^{-2} s^{-1} in the 15–150 keV band (8.24×10^{-10} erg cm^{-2} s^{-1} in the 15–50 keV band), the individual plots can be used to predict the number of flares for a given limiting flux (see [6] for further details and examples).

Finally, the catalogue has recently been exploited by [12] to estimate the expected number of SFXTs in the Milky Way as $\approx 37^{+53}_{-22}$ (Fig. 4, right) from the probability that there are N SFXTs, given that s are found in a fraction f of stellar mass in the spiral arms of the Galaxy surveyed by BAT for SFXTs each day. This shows that SFXTs constitute a large portion of X-ray binaries with supergiant companions in the Galaxy.

Acknowledgments

PR acknowledges contract ASI-INAF I/004/11/0. We acknowledge financial contribution from NASA contract NAS5-00136 at PSU. HAK acknowledges NASA *Swift* GO grants NNX09AU85G, NNX12AD32G, NNX12AE57G, and NNX13AC75G. PE acknowledges a Fulbright Research Scholar grant administered by the U.S.–Italy Fulbright Commission and is grateful to the Harvard–Smithsonian Center for Astrophysics for hosting him during his Fulbright exchange. This work used the results of the *Swift*/BAT hard X-ray transient monitor: http://swift.gsfc.nasa.gov/docs/swift/results/transients/.

References

[1] J. J. M. in't Zand, *Chandra observation of the fast X-ray transient IGR J17544-2619: evidence for a neutron star?*, *A&A* **441** (2005) L1.

[2] S. A. Grebenev, and R. A. Sunyaev, *The first observation of AX J1749.1-2733 in a bright X-ray state–Another fast transient revealed by INTEGRAL*, *Astronomy Letters* **33** (2007) 149.

[3] E. Bozzo, M. Falanga, and L. Stella, *Are There Magnetars in High-Mass X-Ray Binaries? The Case of Supergiant Fast X-Ray Transients*, *ApJ* **683** (2008) 1031.

[4] N. Shakura, K. Postnov, L. Sidoli, and A. Paizis, *Bright flares in supergiant fast X-ray transients*, *MNRAS* **442** (2014) 2325.

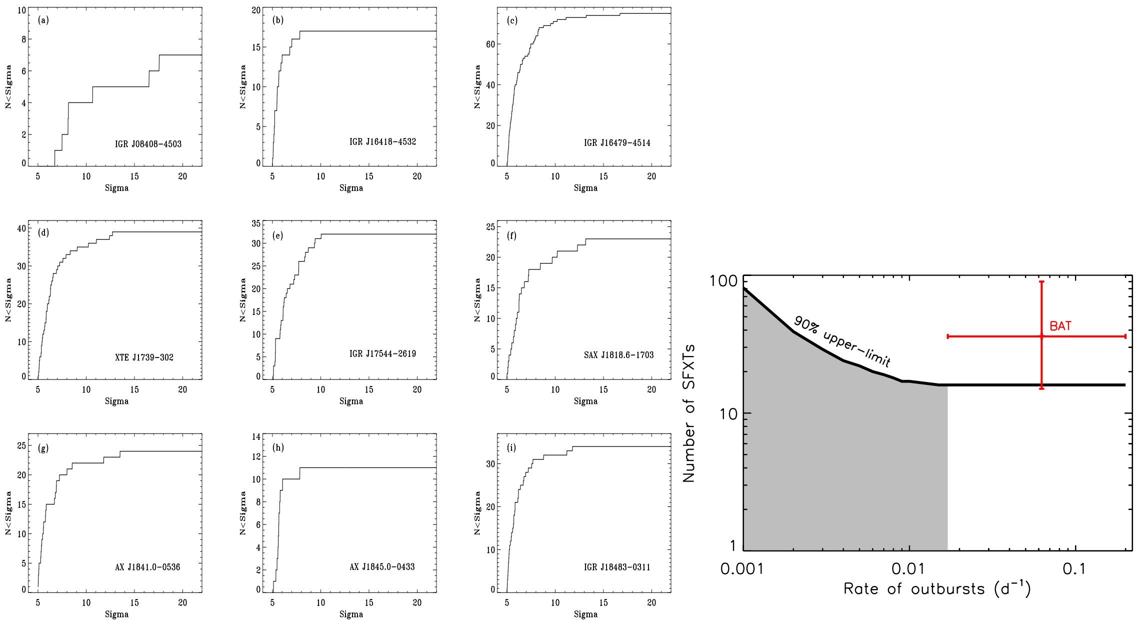

Figure 4: Exploitation of the catalogue. **Left**: Cumulative distributions of σ for BATTM orbital-averaged detections. 5σ detections for an average *Swift* orbit correspond to 1.46×10^{-9} erg cm^{-2} s^{-1} in the 15–150 keV band (8.24×10^{-10} erg cm^{-2} s^{-1}, 15–50 keV). The typical duration for an average *Swift* orbit is 800 s for our sample. From [6]. **Right**: the black line is the 90% upper limits of the total number N of SFXTs in the Galaxy as a function of the outburst rate $r = N_{\rm BAT}/T$, where T is the average monitoring timespan and $N_{\rm BAT}$ is the BAT orbital-averaged detections of outbursts per source. The grey area shows, for each assumed outburst rate, the allowed N, for $s = 0$, $T = 287.7$ d, and a fraction of the Galaxy $f = 11\%$–13%. The expected number of SFXTs obtained assuming the average outburst rate $\bar{r} = 0.06$ d^{-1}, $s = 5\pm1$ SFXTs surveyed each day by BAT, $T = 287.7$ d, and $f = 11\% - 13\%$ is also plotted. Adapted from [12].

[5] N. Gehrels, G. Chincarini, P. Giommi, et al. *The Swift Gamma-Ray Burst Mission*, *ApJ* **611** (2004) 1005.

[6] P. Romano, H. A. Krimm, D. M. Palmer, et al. *The 100-month Swift catalogue of supergiant fast X-ray transients. I. BAT on-board and transient monitor flares*, *A&A* **562** (2014) A2.

[7] S. D. Barthelmy, L. M. Barbier, J. R. Cummings, et al. *The Burst Alert Telescope (BAT) on the SWIFT Midex Mission*, *SSRv* **120** (2005) 143.

[8] E. E. Fenimore, D. Palmer, M. Galassi, et al. *The Trigger Algorithm for the Burst Alert Telescope on Swift*, *AIP Conf. Ser.* **662** (2003) 491.

[9] H. A. Krimm, S. T. Holland, R. H. D. Corbet, et al. *The Swift/BAT Hard X-Ray Transient Monitor*, *ApJS* **209** (2013) 14.

[10] P. Romano, L. Sidoli, V. Mangano, et al. *Swift/XRT observes the fifth outburst of the periodic supergiant fast X-ray transient IGR J11215-5952*, *A&A* **469** (2007) L5.

[11] P. Romano, V. Mangano, G. Cusumano, et al. *Confirmation of the supergiant fast X-ray transient nature of AX J1841.0-0536 from Swift outburst observations*, *MNRAS* **412** (2011) L30.

[12] L. Ducci, V. Doroshenko, P. Romano, A. Santangelo, and M. Sasaki, *Expected number of supergiant fast X-ray transients in the Milky Way*, *A&A* **568** (2014) A76.