Supergiant Fast X-ray Transients in outburst: new Swift observations of XTE J1739–302, IGR J17544–2619 and IGR J08408–4503

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ABSTRACT

We report on new X-ray outbursts observed with Swift from three Supergiant Fast X-ray Transients (SFXTs): XTE J1739–302, IGR J17544–2619 and IGR J08408–4503. XTE J1739–302 underwent a new outburst on 2008 August 13, IGR J17544–2619 on 2008 September 4 and IGR J08408–4503 on 2008 September 21. While the XTE J1739–302 and IGR J08408–4503 bright emission triggered the Swift/Burst Alert Telescope, IGR J17544–2619 did not, thus we could perform a spectral investigation only of the spectrum below 10 keV. The broad-band spectra from XTE J1739–302 and IGR J08408–4503 were compatible with the X-ray spectral shape displayed during the previous flares. A variable absorbing column density during the flare was observed in XTE J1739–302 for the first time. The broad-band spectrum of IGR J08408–4503 requires the presence of two distinct photon populations, a cold one (~0.3 keV) most likely from a thermal halo around the neutron star and a hotter one (1.4–1.8 keV) from the accreting column. The outburst from XTE J1739–302 could be monitored with a very good sampling, thus revealing a shape which can be explained with a second wind component in this SFXT, in analogy to what we have suggested in the periodic SFXT IGR J11215–5952. The outburst recurrence time-scale in IGR J17544–2619 during our monitoring campaign with Swift suggests a long orbital period of ~150 d (in a highly eccentric orbit), compatible with what previously observed with INTEGRAL.

Key words: X-rays: binaries – X-rays: individual: XTE J1739–302 – X-rays: individual: IGR J17544–2619 – X-rays: individual: IGR J08408–4503.

1 INTRODUCTION

The discovery of a new class of Galactic bright X-ray transients, composed of a compact object and an OB supergiant companion, the so-called Supergiant Fast X-ray Transients (SFXTs), is one of the most intriguing results obtained by the INTEGRAL satellite (Sguera et al. 2005, Negueruela et al. 2006). Since its launch in 2002 October, the Galactic plane monitoring performed with INTEGRAL/IBIS led to the discovery of several new sources (Bird et al. 2007), some of which were characterized by short flares reaching 10^{36}–10^{37} erg s^{-1}, and later optically associated with blue supergiant stars (e.g. Masetti et al. 2006b). A couple of members of the class were discovered years before 2002, with other satellites, and later re-discovered with INTEGRAL and firmly classified as SFXTs: XTE J1739–302 (Smith et al. 1998), now considered the prototype of the class, and the X-ray pulsar AX J1841.0–0536 (Bamba et al. 2001). SFXTs display a broad-band spectral shape similar to that of accreting X-ray pulsars (Walter et al. 2006), and a high dynamic range in X-rays (up to four or five orders of magnitude) down to a quiescent luminosity at ~10^{32} erg s^{-1} (in’t Zand 2005). Although X-ray pulsations have not been discovered, to date, in all the members of the class, the spectral similarity with the accreting X-ray pulsars suggests that all, or at least most of them, host neutron stars. Their peculiar transient behaviour is still waiting for a convincing theoretical explanation, although all the physical mechanisms proposed to date are mainly related to the structure of the supergiant wind and/or to the properties of the accreting neutron star (see Sidoli 2009 and references therein for a recent review).

The first systematic monitoring of the X-ray activity of SFXTs has been performed with Swift, during a campaign (still in progress) which started in 2007 October, with the main aim of studying the

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of archival INTEGRAL observations of the source field showed that IGR J08408–4503 was previously active on 2003 July 1 (Mereghetti et al. 2006). A refined position with Swift/XRT (Kennea & Campana 2006) allowed to associate the source with a O8.5Ib(f) supergiant star, HD 74194, at a distance of about 3 kpc (Masetti et al. 2006a). Three additional flares observed with INTEGRAL and Swift were studied by Götz et al. (2007). A new outburst from IGR J08408–4503 was caught on 2008 July 5 by Swift/BAT and then followed up at softer energies with Swift/XRT (Romano et al. 2009a).

In that occasion, the source displayed a multiple flaring activity (the XRT light curve showed three bright flares in excess of $10^{-3}$ erg s$^{-1}$). The properties of the flares and of the times of the outbursts suggested an orbital period of $\sim$35 d (Romano et al. 2009a).

### 2 Observations and Data Reduction

As a response to a first BAT trigger from XTE J1739–302 on 2008 August 13 at 23:49:17 UT (image trigger 319963), Swift executed an immediate slew and was on target in $\sim$390 s; a second trigger (319964) occurred while XTE J1739–302 was in the XRT field of view on 2008 August 14 at 00:12:53 UT. The bright flare of IGR J17544–2619 was instead discovered as part of the yearly monitoring with Swift/XRT, starting on 2008 September 04 at about 00:19:00 UT. The Swift/BAT did not trigger on it. IGR J08408–4503 triggered the BAT on 2008 August 21 at 07:55:08 UT (image trigger 325461). Swift slewed immediately and the narrow field instruments were on target in $\sim$147 s.

Table 1 reports the log of the Swift observations of the outbursts used for this work. The XRT data were processed with standard procedures (xrtpipeline v0.12.1), filtering and screening criteria by using ftools in the heasoft package (v6.6.1). We considered both windowed timing (WT) and photon counting (PC) 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 point spread function (PSF) core affected by comparing the observed and nominal PSF (Vaughan et al. 2006), and excluding all the events that fell within that region from the analysis. Background events were extracted in source-free annular regions, centred on the source. Ancillary response files were generated with xrtmkarf, and they account for different extraction regions, vignetting and PSF corrections. We used the latest spectral redistribution matrices (v011) in caldb.

The BAT data were collected in event mode for several hundred seconds after the triggers of XTE J1739–302 and IGR J08408–4503, as detailed below, while IGR J17544–2619 was not detected. The BAT data were analysed using the standard BAT analysis software distributed within ftools. The BAT mask-weighted spectra were extracted over the time intervals simultaneous with XRT data when possible, and response matrices were generated with ratrigger. For our spectral fitting (xspec v11.3.2), we applied an energy-dependent systematic error.

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, $N(E) \propto E^{-\Gamma}$ (ph cm$^{-2}$ s$^{-1}$ keV$^{-1}$). Times in the light curves and the text are referred to their respective BAT triggers with the exception of IGR J17544–2619 which did not trigger the BAT, thus the start time was set at the beginning of the observation.
1.15 (average value) and then re-fitted the eight spectra selected for the time-resolved spectroscopy. This still resulted in a variable absorbing column density. As final tests, we fixed the absorbing column density (by a factor of three) and the spectral shape (photon index, \( \Gamma \), or the BB temperature, \( kT_{\text{bb}} \)) remains constant, within the uncertainties (see Fig. 2). In particular, spectra WT 3 and WT 5 are the hardest and the softest ones, respectively, thus demonstrating that the hardness ratio variability in Fig. 1 is due to a variable absorption into the line of sight. As final tests, we fixed the photon index \( \Gamma = 1.15 \) (average value) and then re-fitted the eight spectra. This still resulted in a variable absorbing column density. We then fixed the absorbing column density to a mean value of \( \sim 10^{22} \text{ cm}^{-2} \) and refitted the spectra. Those spectra where the absorption was previously found to be very different from this mean value resulted in unacceptable fits.

Fig. 3 shows the comparison between the time-resolved spectrum of the XRT/WT data (Table 2) of the 2008 August outburst and two more spectral analyses: the out-of-outburst emission (Paper I) and the spectroscopy of a previous flare from XTE J1739–302 (Paper III). There is no evidence for a spectral change with the source flux, or for a correlation of the absorbing column density with the source flux. The absorption is higher during the rising phase of the bright flare.

3 ANALYSIS AND RESULTS

3.1 XTE J1739–302

The complete light curve of the bright flaring of XTE J1739–302 as observed with Swift/XRT on 2008 August 13 is reported in Fig. 9(c), while the first part (~2000 s) of the observation (WT data, observation 00319963000) is expanded in Fig. 1, where a soft (below 2 keV) and a hard (above 2 keV) light curve are reported, together with their hardness ratio. Since the source hardness appears to be variable, we performed a time-resolved spectroscopy extracting eight XRT/WT spectra as shown in Fig. 1. These spectra could be adequately fitted both with an absorbed power-law model and with an absorbed single blackbody (BB; see Table 2 for the results, spectra from WT 1 to WT 8). There is a clear time variability of the absorbing column density (by a factor of ~3), whereas the spectral shape (photon index, \( \Gamma \), or the BB temperature, \( kT_{\text{bb}} \)) remains constant, within the uncertainties (see Fig. 2). In particular, spectra WT 3 and WT 5 are the hardest and the softest ones, respectively, thus demonstrating that the hardness ratio variability in Fig. 1 is due to a variable absorption into the line of sight. As final tests, we fixed the photon index \( \Gamma = 1.15 \) (average value) and then re-fitted the eight spectra. This still resulted in a variable absorbing column density. We then fixed the absorbing column density to a mean value of \( 5 \times 10^{22} \text{ cm}^{-2} \) and refitted the spectra. Those spectra where the absorption was previously found to be very different from this mean value resulted in unacceptable fits.

Fig. 3 shows the comparison between the time-resolved spectroscopy of the XRT/WT data (Table 2) of the 2008 August outburst and two more spectral analyses: the out-of-outburst emission (Paper I) and the spectroscopy of a previous flare from XTE J1739–302 (Paper III). There is no evidence for a spectral change with the source flux, or for a correlation of the absorbing column density with the source flux. The absorption is higher during the rising phase of the bright flare.

A high-energy spectrum (BAT) was also available, but only simultaneously to the XRT/WT spectrum n. 1. A joint fit of XRT/WT and BAT spectra was performed including constant factors to allow for normalization uncertainties between the two instruments.
Table 2. Time-resolved spectroscopy of XTE J1739−302 (XRT data).

| Spectrum | Time (s since trigger) | Model | $N_H$ (10^{22} cm^{-2}) | $\Gamma$ | $kT_{bb}$ (keV) | Flux\textsuperscript{a} (10^{-9} erg cm^{-2} s^{-1}) | $R_{bb}$ (km)\textsuperscript{b} | $\chi^2$/d.o.f. |
|----------|------------------------|-------|--------------------------|--------|-----------------|-----------------------------|-----------------|-----------------|
| WT 1     | 397–656                | Pow   | 5.8±0.8                  | 1.25±0.18 | 1.88±0.12     | 2.69                        | 1.191/139       |
|          |                        |       | 3.1±0.5                  | 1.32±0.21 | 1.93±0.16     | 3.31                        | 1.038/112       |
| WT 2     | 961–1170               | Pow   | 8.2±0.9                  | 1.12±0.13 | 1.18±0.30     | 1.044/139                   |
|          |                        |       | 5.4±0.4                  | 1.80±0.23 | 1.98±0.32     | 0.873/66                    |
| WT 3     | 1170–1255              | Pow   | 7.3±0.5                  | 1.24±0.16 | 1.13±0.17     | 4.16                        | 1.080/112       |
|          |                        |       | 4.4±0.1                  | 1.03±0.08 | 1.05±0.2      | 5.14                        | 0.809/66        |
| WT 4     | 1255–1407              | Pow   | 5.3±0.5                  | 1.24±0.16 | 1.82±0.11     | 0.961/159                   |
|          |                        |       | 5.3±0.5                  | 1.24±0.16 | 3.12±0.17     | 0.910/159                   |
| WT 5     | 1410–1520              | Pow   | 3.3±0.5                  | 1.11±0.16 | 1.80±0.12     | 3.95                        | 1.074/114       |
|          |                        |       | 1.4±0.2                  | 1.08±0.11 | 1.43±0.05     | 4.00                        | 1.241/243       |
| WT 6     | 1522–1876              | Pow   | 6.3±0.5                  | 1.33±0.13 | 1.83±0.08     | 1.241/243                   |
|          |                        |       | 3.4±0.3                  | 1.41±0.08 | 1.83±0.08     | 1.047/243                   |
| WT 7     | 1877–2005              | Pow   | 3.8±0.6                  | 1.05±0.21 | 1.90±0.16     | 3.02                        | 1.345/98        |
|          |                        |       | 1.5±0.3                  | 1.26±0.13 | 1.21±0.14     | 5.07                        | 1.083/229       |
| WT 8     | 2006–2390              | Pow   | 5.1±0.5                  | 1.26±0.13 | 1.22±0.13     | 3.07                        | 1.227/98        |
|          |                        |       | 2.6±0.3                  | 1.58±0.13 | 1.82±0.09     | 1.3±0.1                    | 0.969/229       |
| WT 9\textsuperscript{c} | 5631–47671          | Pow   | 3.6±0.4                  | 1.17±0.1 | 1.89±0.08     | 1.02                        | 1.396/259       |
|          |                        |       | 1.5±0.2                  | 1.26±0.17 | 1.17±0.11     | 0.72±0.02                  | 1.128/259       |
| PC 1\textsuperscript{c} | 17212–48475          | Pow   | 3.0±0.4                  | 1.26±0.17 | 1.64±0.10     | 0.23                        | 1.095/113       |
|          |                        |       | 1.3±0.2                  | 1.26±0.16 | 0.43±0.04     | 1.082/113                  |

\textsuperscript{a} Unabsorbed 1–10 keV flux in units of 10^{-9} erg cm^{-2} s^{-1}.
\textsuperscript{b} Assuming a distance of 2.7 kpc.
\textsuperscript{c} Observation 0030987070.

Figure 2. Swift/XRT (WT data) time-resolved spectroscopy of XTE J1739−302: spectral results of the absorbed power-law fit (reported in Table 2). Numbers mark the eight WT spectra, as shown in Table 2.

(Always constrained to be within their usual ranges). A single power law is unable to describe the broad-band spectrum. We then tried models usually adopted to describe the X-ray emission from accreting pulsars, resulting in the spectral parameters listed in Table 3: a cut-off power law $[E^{-\Gamma}b^{E/E_{\text{cut}}}]$ and two kinds of Comptonization models. The best deconvolution of the broad-band spectrum has been obtained with these latter models: a Comptonization of seed photons (with a temperature $kT_{bb}$) in a hot plasma (with electron temperature $kT_e$) as described by COMP\textsuperscript{TT} in XSPEC (Titarchuk 1994) or by BMC (Titarchuk, Mastichiadis & Kylafis 1996).

The BMC model is the sum of a BB plus its Comptonization, the latter obtained as a consistent convolution of the BB itself with Green’s function of the Compton corona. The BMC model is not...
limited to the thermal Comptonization case (as e.g. \texttt{COMP\_TT}) and accounts also for dynamical (bulk) Comptonization due to the converging flow. Similar to the ordinary \texttt{BBODY XSPEC} model, the normalization of \texttt{BMC} is the ratio of the source luminosity to the square of the distance (in units of 10 kpc). The free parameters of the \texttt{BMC} model (apart from the normalization) are the blackbody (BB) colour temperature, $kT_{\text{BB}}$, the spectral index, $\alpha$, and the logarithm of the illuminating factor $A$, $\log A$. The parameter $\alpha$ indicates the overall Comptonization efficiency related to an observable quantity in the photon spectrum of the data. The lower $\alpha$, the higher the efficiency that is the higher the energy transfer from the hot electrons to the soft seed photons. The $\log A$ parameter is an indication of the fraction of the up-scattered BB photons with respect to the BB seed photons directly visible. In the extreme cases, the seed photons can be completely embedded in the Comptonizing cloud (none directly visible, $A \gg 1$, e.g. $\log A = 8$) or there is no coverage by the Compton cloud ($A < 1$, e.g. $\log A = -8$), and we directly observe the seed photon spectrum (equivalent to a simple BB, with no Comptonization).

The XTE J1739–302 broad-band spectrum fitted with the \texttt{COMP\_TT} model is shown in Fig. 4. The estimated X-ray luminosity during the flare is $3.8 \times 10^{38}$ erg s$^{-1}$ (0.1–100 keV) at a source distance of 2.7 kpc.

As can be seen in Table 3, the parameters describing the properties of the Comptonizing corona (be they the temperature and optical depth in \texttt{COMP\_TT} or the illumination parameter $\log A$ in \texttt{BMC}) are not constrained. This is expected, given the poor statistics of the high-energy part of the spectrum. Nevertheless, the applied models do give a first-order description of the physical processes involved in this system (see Section 4).

### 3.2 IGR J17544–2619

A new bright flare from IGR J17544–2619 was caught on 2008 September 4 with \textit{Swift}, and it was preceded by intense activity in the previous few days observed during the \textit{INTEGRAL} Galactic bulge monitoring program (Romano et al. 2008a), reaching about 50 mCrab (18–40 keV) on 2008 August 30. The flare was caught by \textit{Swift}/XRT, only thanks to the on-going monitoring campaign just targeted on the source, while \textit{Swift}/BAT did not trigger on it. The XRT light curve (Fig. 5) shows a peak exceeding 20 s$^{-1}$, brighter than the previous one observed with \textit{Swift} on March 31, at 20:53:27 UT (Paper III).

The total PC spectrum resulted in an exposure time of 632 s and a source net count rate of $0.67 \pm 0.03$ s$^{-1}$, while the WT data, extracted with a net exposure of 217 s, resulted in an average count rate of $8.2 \pm 0.2$ s$^{-1}$. Fitting the two spectra separately with simple models (an absorbed power law or a BB) resulted in the parameters listed in Table 4. A BB is a better fit to the WT data than a single power law, which produces systematic positive residuals around 1 keV. The resulting BB radius at an assumed source distance of 3.6 kpc is $R_{\text{bb}} = 1.35^{+0.15}_{-0.11}$ km. More complex models are not required by the data. We also fit together PC and WT spectra, adopting free normalization constant factors between the two spectra. The best fit

### Table 3. Spectral fits of simultaneous XRT and BAT data of XTE J1739–302.

| Model       | Parameters |
|-------------|------------|
| CUT-OFFPL   | $N_H^a$ $10^{22}$ cm$^{-2}$, $\Gamma$ 2 $E_{\text{cut}}^b$ keV, $\text{Flux}^c$ photons cm$^{-2}$ s$^{-1}$, $\chi^2$/d.o.f. |
| 5.5$^{+0.8}_{-0.8}$ $0.87^{+0.27}_{-0.28}$ $15^{+6}_{-4}$ $6.6$ 1.166/161 |
| BMC         | $N_H^a$ $kT_{\text{BB}}^d$ keV, $\alpha^d$ $\log A^d$ $\text{Flux}^e$ $\chi^2$/d.o.f. |
| 3.4$^{+0.6}_{-0.5}$ $1.6^{+0.2}_{-0.3}$ $1.3^{+0.4}_{-0.4}$ $0.5^{+0.7}_{-0.6}$ $4.9$ 1.080/160 |
| COMP\_TT$^a$ | $N_H^a$ $kT_{\text{bb}}^b$ keV, $kT_{\text{e}}^b$ keV, $\tau$ $\text{Flux}^f$ $\chi^2$/d.o.f. |
| 2.8$^{+0.6}_{-0.5}$ $1.35^{+0.12}_{-0.17}$ $0$ $4.3^{+3.6}_{-4.0}$ $4.6$ 1.061/160 |

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

\(b\)High-energy cut-off ($E_{\text{cut}}$), electron temperature ($kT_{\text{e}}$), seed photons temperature ($kT_{\text{bb}}$) and the BB colour temperature $kT_{\text{BB}}$ are all in units of keV.

\(c\)Unabsorbed 0.1–100 keV flux is in units of $10^{-12}$ erg cm$^{-2}$ s$^{-1}$.

\(d\)The parameter $kT_{\text{BB}}$ is the BB colour temperature of the seed photons, $\alpha$ is the spectral index and $\log A$ is the illumination parameter (see Section 3.1 for details).

\(e\)Assuming a spherical geometry.
obtained with a BB model of the joint PC plus WT data is reported in Fig. 6.

### 3.3 IGR J08408–4503

The IGR J08408–4503 Swift/XRT light curve during the new outburst detected on 2008 September 21 is reported in Fig. 7 in two energy ranges, together with their hardness ratio. Since the hardness ratio was quite constant along the XRT/WT observation, we extracted a total spectrum. It resulted in a net exposure time of 1159 s with an average count rate of 28.3 ± 0.2 s⁻¹. The fit to the 0.7–10 keV WT spectrum with an absorbed power-law model is unacceptable (χ² = 1.309 for 630 d.o.f.). A significantly better fit can be obtained either with a cut-off power law (χ² = 1.187 for 629 d.o.f.) or with a power-law model together with a BB (χ² = 1.116 for 628 d.o.f.). We note that an absorbed BB model is the worst fit to the WT data, resulting in a reduced χ² > 3.6. The peak flux of ∼2.5 × 10⁻⁹ erg cm⁻² s⁻¹ translates into an X-ray luminosity of 2.5 × 10³⁶ erg s⁻¹ (at 3 kpc).

The spectral parameters resulting from these fits are reported in Table 5. A second total spectrum from the fainter emission observed in PC mode has been also investigated, yielding a spectrum with a net exposure of 4100 s, and a fainter rate of 0.26 ± 0.08 s⁻¹. A fit with a single absorbed power law results into a softer spectrum than the brighter emission observed in WT mode (see Table 5 for the PC spectral results).

### Table 4. IGR J17544–2619 spectral fits of XRT data.

| Spectrum | Model | NH (10²² cm⁻²) | Γ | kT₉₅ (keV) | Flux × 10⁻⁹ | R₉₅ (km) | χ²/d.o.f. |
|----------|-------|---------------|---|-------------|-------------|---------|-----------|
| Total WT | Pow   | 1.8±0.4       | 1.28±0.18 | 0.97       | 1.170/82     |
|          | BB    | 0.52±0.17     | 1.51±0.10 | 1.35±0.15 | 0.808/82     |
| Total PC | Pow   | 1.3±0.8       | 0.76±0.40 | 0.27       | 1.290/18     |
|          | BB    | 0.42±0.38     | 1.87±0.40 | 0.53±0.17 | 1.080/18     |
| Joint fit WT + PC | Pow | 1.8±0.10 | 1.20±0.17 | 1.227/102   |
|          | BB    | 0.52±0.15     | 1.55±0.09 | 0.979/102   |

aUnabsorbed 1–10 keV flux in units of 10⁻⁹ erg cm⁻² s⁻¹.

bAssuming a distance of 3.6 kpc.
L. Sidoli et al.

Table 5. IGR J08408−4503 spectral fits of XRT data.

| Spectrum   | Time (s since trigger) | Model | \(N_H\) (10^{22} \text{ cm}^{-2}) | \(\Gamma\) | \(kT_{bb}/E_{cut}\) (keV) | Flux\(^a\) | \(R_{bb}\) (km)\(^b\) | \(\chi^2/\text{d.o.f.}\) |
|------------|------------------------|-------|-----------------------------------|-----------|--------------------------|----------|-----------------------|------------------------|
| Total WT   | 523–1653               | Pow   | 0.25^{+0.02}_{-0.02}             | 0.82^{+0.03}_{-0.03} | 2.7                      | 1.309/630 |                      |
|            |                        | Pow+BB| 0.43^{+0.09}_{-0.09}             | 2.20^{+0.04}_{-0.04} | 1.95^{+0.08}_{-0.08}    | 2.5       | 1.22^{+0.12}_{-0.12} | 1.116/628             |
|            |                        | CUT-OFFPL | 0.11^{+0.03}_{-0.03} | 0.22^{+0.12}_{-0.12} | 6.6^{+1.5}_{-1.1}       | 2.5       | 1.187/629             |
| Total PC   | 4880–23388             | Pow   | 0.70^{+0.24}_{-0.19}             | 1.10^{+0.18}_{-0.16} | 0.056                    | 1.126/50  |                      |
|            |                        | BB    | <0.1                               | 1.44^{+0.09}_{-0.09} | 0.044                    | 0.31^{+0.04}_{-0.03} | 1.170/50             |

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

\(^b\)Assuming a distance of 3 kpc.

Table 6. Spectral fits of simultaneous XRT and BAT data of IGR J08408−4503. See Section 3.3 for the description of the adopted models.

| Model                        | Parameters |
|------------------------------|------------|
| CUT-OFFPL                   |            |
| \(N_H\)                     | 0.10^{+0.04}_{-0.04} |
| \(\Gamma\)                  | 0.50^{+0.08}_{-0.08} |
| \(E_{cut}\)                 | 13^{+2}_{-2} |
| BMC*HIGHCUT+BB              |            |
| \(N_H\)                     | 0.10^{+0.70}_{-0.05} |
| \(kT_{bb}\)                 | 0.32^{+0.05}_{-0.06} |
| \(d\)                       | 6^{+13}_{-5} \times 10^{-4} |
| \(\alpha\)                  | 3.3^{+0.5}_{-0.2} |
| \(E_{cut}\)                 | 21^{+4}_{-4} |
| \(R_{bb}\)                  | 1.85^{+0.16}_{-0.13} |
| \(R_{bb}\)                  | 1.20^{+0.2}_{-0.8} |
| \(\chi^2/\text{d.o.f.}\)   | 10.102/292  |
| BMC*HIGHCUT+BB              |            |
| \(N_H\)                     | 0.10^{+0.06}_{-0.03} |
| \(kT_{bb}\)                 | 1.4^{+0.1}_{-0.1} |
| \(d\)                       | 0.35^{+0.08}_{-0.06} |
| \(\alpha\)                  | 0.82^{+0.15}_{-0.14} |
| \(E_{cut}\)                 | 21^{+5}_{-5} |
| \(R_{bb}\)                  | 22^{+8}_{-8} |
| \(R_{bb}\)                  | 0.33^{+0.82}_{-0.04} |
| \(\chi^2/\text{d.o.f.}\)   | 12^{+4}_{-1}  |

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

\(^b\)High-energy cut-off (\(E_{cut}\)), e-folding energy (\(E_{fold}\)) and BB temperatures are in units of keV.

\(^c\)Unabsorbed 0.1–100 keV flux is in units of 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}.

\(^d\)\(kT_{bb}\) is the BB colour temperature of the seed photons in the BMC model, \(\alpha\) is the spectral index and \(\log A\) is the illumination parameter.

\(^e\)The radius of the \(\text{BMC}\) model is in units of km at an assumed source distance of 3 kpc.

A fit can be obtained with a cut-off power law (CUT-OFFPL in XSPEC; \(\chi^2 = 1.029\), for 292 d.o.f.), obtaining a hard spectrum with a photon index of 0.5, a cut-off at 13 keV, and a luminosity of 10^{37} \text{ erg s}^{-1} at 3 kpc. We also tried other deconvolutions of the broad-band spectrum, i.e. Comptonization-emission models (thermal and with bulk motion) or a power-law plus a BB model, but they always yielded unacceptable fits with structured residuals at high energies. We next adopted more complex models for the continuum, as a BMC model modified with a high-energy cut-off. This resulted in a better fit than the single absorbed BMC model, but structured residuals still appear below 10 keV. The best fit is obtained adding a BB model to a BMC modified with a high-energy cut-off (HIGHCUT in XSPEC). A summary of all the spectral parameters reported in Table 6, while the best deconvolution of the broad-band IGR J08408−4503 emission is shown in Fig. 8.

Unlike XTE J1739−302, a cut-off is clearly needed in the spectrum of IGR J08408−4503. Indeed, BMC alone (that is a non-attenuated power law at high energies) does not fit the data well and the multiplicative factor HIGHCUT is needed. We note that the fit clearly points to two distinct photon populations (\(\sim 0.3\) and 1.5–2 keV), but the current statistics does not allow us to constrain which of the two is seen directly as a BB and which provides part of the seed photons for Comptonization (hence, we include twice the same model in Table 6, one per configuration. See the Section 4 for possible interpretations).

### 3.4 Timing analysis

We performed a timing analysis on the three sources to investigate for the presence of X-ray pulsations. A Z2 test (Buccheri et al. 1983) on the fundamental harmonics was applied on the events collected in each WT mode sequence (see Table 1) searching in the frequency range between 0.005 and 100 Hz with a frequency resolution of 1/\(\Delta T\) Hz, where \(\Delta T\) is the duration of the WT segment. The resulting power spectrum does not reveal any significant deviations from a statistically flat distribution. Data collected in PC mode were not analysed because of their much lower statistics content.

### 4 DISCUSSION AND CONCLUSIONS

We report on three new outbursts from three different Supergiant Fast X-ray Transients, XTE J1739−302, IGR J17544−2619 and IGR J08408−4503, observed with Swift.

#### 4.1 Spectroscopy

All these three sources were observed in outburst with Swift in the past, thus allowing a proper comparison between the spectral properties of the different flares.

For IGR J17544−2619, only the spectrum below 10 keV is available. Compared with the emission previously observed (Paper III), it displays a more absorbed and softer emission (single power-law model). A similar behaviour from IGR J17544−2619 has been recently reported by Rampy, Smith & Negueruela (2009) during a Suzaku observation catching the source during a long outburst (at least three days of accreting phase) in 2008 March (the same reported in Paper III). The XRT/WT spectrum is compatible with spectral parameters reported for the segment n. 6 of the XIS observation (Rampy et al. 2009). A good fit to the IGR J17544−2619 XRT spectrum can also be obtained with a BB model, resulting in a temperature of 1–2 keV, and in a BB radius (at 3.6 kpc) of about 1–1.5 km, compatible with an origin in the neutron star polar cap.

XTE J1739−302 displays for the first time a variable absorption column density within a flare. This behaviour was also observed.
the BB component of the BMC model is about 1.6 km (at 2.7 kpc), thus consistent with a polar cap origin. The model COMPTT allows us to quantify the physical conditions of the Comptonizing plasma, since it returns the plasma temperature $kT_e$ and optical depth $\tau$, instead of the Comptonization efficiency $\alpha$. As shown in Table 3, the $kT_e$ temperature could not be constrained and this is consistent with the fact that the data could be fitted well by the BMC model that indeed has no cut-off in its spectral shape. These two results point to the fact that the current statistics and data coverage do not require a cut-off, although they cannot exclude it. The reason why the CUT-OFFPL model fits the data much better than a simple power law resides in the fact that the residuals using a simple power law show an excess around 1–2 keV, whereas the curved shape of the CUT-OFFPL linked to the interplay with the absorbing column density can describe the data in a satisfactory way. We note that this excess is naturally taken into account in the physical models, COMPTT and BMC, where a 1–2 keV BB seed photon population is obtained. Unfortunately, the current data set does not allow us to investigate the evolution of the high-energy part of the spectrum, so little can be currently said about the possible evolution of the Comptonizing medium. For the remaining part of the outburst, only the softer part below 10 keV is available. Nevertheless, it can be seen from Table 2 that a BB is more suitable to fit the Swift/XRT data rather than a power law, consistent with what is obtained in the overall XRT+BAT spectrum.

A comparison of the IGR J08408–4503 broad-band spectrum extracted from the bright flare observed in 2008 September with the ones observed with Swift in 2008 July and in 2006 October (Romano et al. 2009a) reveals that the new spectrum is more similar to that observed in 2006 (very low absorption, a hard photon index, and a similar high-energy cut-off at around 10–15 keV). Unlike XTE J1739–302, the spectrum of IGR J08408–4503 could not be fit with a single Comptonization model, two additive components were needed: a BB plus a BMC model (the latter with high-energy cut-off). This could be due to the very low absorption at low energy with respect to the other SFXTs studied here that required an additional component to take into account the softer part of the spectrum. The presence of the cut-off implies that the overall spectrum is the result of thermal Comptonization (the BMC model alone has a non-attenuated power-law shape). The low value of the $\alpha$ parameter obtained ($\alpha < 0.4, \Gamma < 1.4$) is typical for saturated Comptonization.

The seed photon temperature for the thermal Comptonization BMC component and the BB temperature could not be linked to the same value in the fitting process and indeed resulted in two clearly different photon populations, a cold one at about 0.3 keV and a hotter one at 1.4–1.8 keV. The current data did not allow us to establish in a solid way, which one of these two populations is seen directly as a BB and which one ends up being seed photons for the thermal Comptonization. As can be seen in Table 6, both scenarios are statistically acceptable. In one case, we obtain a cold (0.3 keV) BB of about $R = 12$ km directly visible (few percent of the total flux), together with a hotter photon population (1.4 keV) thermally Comptonized (the dominant component), part of which is directly visible ($\log A = 0.8$). This could depict a thermal halo around the neutron star [0.3 keV, as in Ferrigno et al. (2009)] together with BB seed photons from the accreting material, part of which is directly visible (e.g. at the column boundaries) and part is thermally Comptonized (from the accreting matter). This scenario is consistent with what was observed for XTE J1739–302 (Table 3) with the thermal cold halo buried in the high column absorption (an order of magnitude higher than for IGR J08408–4503).

**Figure 8.** Swift/XRT broad-band spectrum (BAT plus simultaneous WT data) of IGR J08408–4503, fitted with a BMC model in XSPEC modified with a high-energy cut-off (HIGHCUT in XSPEC), together with a simple BB at low energies (last model in Table 6 tab:sec:spec). The upper panel shows the counts spectrum together with the residuals in units of standard deviations. The lower panel shows the photon spectrum.
In the second case, we obtain a hotter BB (1.9 keV, possibly from the base of the accreting column, $R \sim 1$ km) directly visible, accounting for about 30 per cent of the total flux, together with a colder plasma (0.3 keV) embedded in a thermally Comptonizing medium ($\log A \sim 3$) such as an atmosphere confined by multipolar or crustal components of the magnetic field [e.g. Ferrigno et al. (2009) and references therein].

With the information at hand, we cannot exclude either of these scenarios. The spectra of High Mass X-Ray Binaries (HMXBs) have been generally described by phenomenological models, and this work is one of the few cases where two distinct spectral components linked to two different physical conditions have been observed (see also Ferrigno et al. 2009).

### 4.2 Search for periodicities

IGR J17544$-2619$ was previously observed in outburst with *Swift* in two occasions: on 2007 November 8 and 2008 March 31 (Paper III). This implies that the three bright flares are spaced by $\sim 144$ and $\sim 157$ d, respectively. We note, however, that in IGR J17544$-2619$ the flare that occurred on 2008 September 4 was preceded by intense activity in the previous few days during the observations part of the *INTEGRAL* Galactic bulge monitoring program performed on 2008 August 30, reaching a flux of about 50 mCrab (18–40 keV, Romano et al. 2008a). This seems to indicate an outburst phase which began a few days before the BAT trigger, suggesting an outburst duration of several days (an outburst lasting at least 3 d has also been caught with Suzaku; Rampy et al. 2009): this could imply a periodic occurrence of the bright flaring activity, every $\sim 150$ d. If the X-ray bright flares are triggered periodically during the periastron passage in an eccentric binary, the orbital period is probably about 150 d in IGR J17544$-2619$. This is consistent with previous findings with *INTEGRAL*, where a possible outburst recurrence time-scale of 165 $\pm$ 3 d has been suggested (Walter et al. 2006).

From the times of previous IGR J08408$-4503$ flares, we suggested (Romano et al. 2009a) that a double-periodicity outburst recurrence of $\sim 11$ and 24 d was present, thus consistent with the picture where the outbursts are triggered when the compact object, along its orbit, crosses twice an inclined second component of an outflowing dense wind, confined along a preferential plane (e.g. the supergiant equator), inclined with respect to the orbital plane. On the other hand, the last flare from IGR J08408$-4503$ did not occur at the right times predicted by these double periodicities (the nearest outburst was predicted to occur on 2008 September 13, instead of 2008 September 21). This could indicate that either these derived periodicities are actually wrong (and the flaring activity is not periodic but sporadic) or another mechanism is at work when producing this latter kind of outburst: a possible explanation is that, while the previous outbursts were produced when the neutron star crossed twice the denser wind component, this latter outburst was triggered when the neutron star approached the periastron passage, accreting matter from the polar wind, in an eccentric orbit.

The three sources analysed here do not show any evidence for X-ray pulsations (see Section 3.4).

### 4.3 SFXTs as a class

During the last outburst, a very good sampling of the XTE J1739$-302$ light curve was possible [the best light curve during an outburst from this source, to date; see Fig. 9(c)]. We can compare the *Swift*/XRT light curve of XTE J1739$-302$ with the X-ray luminosity predicted by a Bondi–Hoyle accretion on to the neutron star from a spherically symmetric homogeneous wind for different values of the orbital period and eccentricity. We assume for the supergiant a stellar mass of $33 M_\odot$, a radius of $23 R_\odot$ (Vacca, Garmany & Shull 1996), a beta-law for the supergiant wind with $\beta = 1$, a wind terminal velocity of 1900 km s$^{-1}$, a wind mass loss rate of $10^{-6} M_\odot$ yr$^{-1}$ and a temperature of the stellar wind of $10^5$ K.

We find that for any choice of the orbital period and eccentricity the decline of the light curve observed with *Swift* is too rapid compared with the calculated light curve, even adopting high values for the orbital period and eccentricity. Since a spherical distribution of wind matter is not able to explain the observed shape of the X-ray light curve, a possible explanation is the presence of a second outflowing wind component, denser than the supergiant polar wind, which is crossed by the neutron star along its orbit, in analogy to what we proposed for IGR J11215$-5952$ (Sidoli et al. 2007). Alternatively, if we consider the clumpy wind scenario, from the duration of the

Figure 9. Light curves of the outbursts of SFXTs followed by *Swift*/XRT referred to their respective BAT triggers. Points denote detections and triangles 3σ upper limits. Red data points (panels c, e and g) refer to observations presented here for the first time, while grey data points refer to data presented elsewhere. Note that where no data are plotted, no data were collected. Vertical dashed lines mark time intervals equal to 1 d, up to a week. We show the IGR J11215$-5952$ light curve (panel a) with an arbitrary start time, since the source did not trigger the BAT (Romano et al. 2007). Panels (b) and (c) report the two flares from XTE J1739$-302$ observed on 2008 April 8 (Paper III) and on 2008 August 13 (reported here), respectively. Panels (d) and (e) show the outbursts of IGR J17544$-2619$ which occurred on 2008 March 31 (Paper III) and the latest one reported here (this outburst, as in IGR J11215$-5952$, did not trigger the BAT, thus the start time is arbitrary and was set at the beginning of the observation). Panels (f) and (g) show the last two outbursts from another SFXT, not part of the XRT campaign, IGR J08408$-4503$, which occurred on 2008 July 5 (Romano et al. 2009a) and on 2008 September 21 (reported in this paper).
Swift observes outbursts from three SFXTs

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Swift observes outbursts from three SFXTs

S. Ducci, L. Dotti, L. Paizis, S. Mereghetti and A. Romano

1537

bright part of the flare in XTE J1739—302 (0.6 d) and its luminosity (~10^36 erg s^-1), we can derive an accreted mass of ~4 x 10^32 g and a size of ~10^13 cm (Walter & Zurita Heras 2007), which corresponds to more than six supergiant radii, thus making very unlikely that it is a very large single clump ejected by the supergiant (Walter & Zurita Heras 2007). Instead, it can be alternatively explained with a huge gas stream composed by several smaller clumps.

In Fig. 9, we compare some of the outbursts from SFXTs as observed during our monitoring campaign. In particular, the three outbursts discussed here are shown in panels c, e and g from XTE J1739—302, IGR J17544—2619 and IGR J08408—4503, respectively. One could be tempted to conclude, from this comparison, that different types of outburst are present, even in the same source. It is actually not possible to compare, for example, the two outbursts from IGR J08408—4503 (last panels in Fig. 9): the several upper limits to the flux in the declining part of the outbursts are compatible with the source detections during the previous IGR J08408—4503 outburst [Fig. 9(f)], thus it is not possible to conclude that the new outburst from IGR J08408—4503 [Fig. 9(g)] is shorter than the previous one [Fig. 9(f)]. On the other hand, the light curve from XTE J1739—302 [Fig. 9(c)] allows us to perform a proper comparison with the outburst from the periodic SFXTs IGR J111215—5952 [Fig. 9(a); Sidoli, Paizis & Mereghetti 2006; Romano et al. 2007]: these two sources appear to undergo similar outbursts with a similar duration. Interestingly, Rampy et al. (2009) report on a long outburst activity from IGR J17544—2619 during the 2008 March outburst, with a rise time much longer than what observed with Chandra during an X-ray flare in 2004 (in’t Zand 2005) in the same source. These authors suggest that different kinds of outbursts can occur in the same SFXT.

From the duration of single well-sampled short flares in IGR J08408—4503, we derived an orbital period of about 35 d (Romano et al. 2009a) adopting an expansion law for the clump sizes as the clump is accelerated far away from the supergiant donor, in the framework of an inhomogeneous wind (Romano et al. 2009a). Adopting this same expansion law, and from the observed durations of the short flares which compose the outburst light curves in XTE J1739—302 and IGR J17544—2619, we can derive the distance of the accreted clump from the supergiant star, as we did in IGR J08408—4503 (Romano et al. 2009a). More details will be reported in Ducci et al. (2009). Fitting with a Gaussian a few well-sampled flares in XTE J1739—302, we obtain a full width at half-maximum (FWHM) of 260 ± 60 and 390 ± 60 s, while in IGR J17544—2619 the observed flare has a duration of 220 ± 10 s (FWHM). From the clump expansion law reported in Romano et al. (2009a), we derive a distance of the compact object from the supergiant donor in these two sources as follows: in the range from 6.8 x 10^12 to 1.25 x 10^13 cm for XTE J1739—302, while near to 6.8 x 10^12 cm for IGR J17544—2619 (assuming a supergiant mass of 33 M⊙ and a stellar radius of 23 R⊙). Assuming a circular orbit, these distances translate into orbital periods ranging from 20 to 50 d in XTE J1739—302 and around 20 d for IGR J17544—2619. This latter orbital period is not consistent with that of ~150 d, suggested by the outburst recurrence in IGR J17544—2619. This discrepancy can be easily reconciled if the orbit in this SFXT is highly eccentric.

Jain, Paul & Dutta (2009) recently reported on the discovery of an orbital period of 3.3 d from the SFXT IGR J16479—4514. This orbital periodicity is even shorter than that displayed by several persistent HMXBs with supergiant companions. This poses serious problems to the different physical mechanisms proposed for SFXTs, implying an orbital separation of about 2 x 10^12 cm (assuming a supergiant mass of ~30 M⊙), which is about 1.2 stellar radii, thus well inside the region where the highest wind clump number density is expected, and a persistent X-ray emission is predicted (Negueruela et al. 2008). The very different orbital periods discovered in SFXTs to date (ranging from 3.3 to 165 d) possibly point to different kinds of SFXTs (different mechanisms at work in different sources, and possibly in the same source, as discussed above).
