Swift observations of two supergiant fast X-ray transient prototypes in outburst

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ABSTRACT
We report on the results from observations of the most recent outbursts of XTE J1739−302 and IGR J17544−2619, which are considered to be the prototypes of the supergiant fast X-ray transient class. They triggered the Swift/Burst Alert Telescope on 2011 February 22 and March 24, respectively, and each time a prompt Swift slew allowed us to obtain the rich broad-band data we present. The X-ray Telescope light curves show the descending portion of very bright flares that reached luminosities of ~2 × 10^{36} and ~5 × 10^{36} erg s⁻¹. The broad-band spectra, when fitted with the usual phenomenological models adopted for accreting neutron stars, yield values of both high-energy cut-off and e-folding energy consistent with those obtained from previously reported outbursts from these sources. In the context of more physical models, the spectra of both sources can be well fitted either with a two-blackbody model or with a single unsaturated Comptonization model. In the latter case, the model can be either a classical static Comptonization model, such as COMPTT, or the recently developed COMPMAG model, which includes thermal and bulk Comptonization for cylindrical accretion on to a magnetized neutron star. We discuss the possible accretion scenarios derived by the different models, and we also emphasize the fact that the electron density derived from the Comptonization models, in the regions where the X-ray spectrum presumably forms, is lower than that estimated using the continuity equation at the magnetospheric radius and the source X-ray luminosity, and we give some possible explanations.

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

1 INTRODUCTION
Supergiant fast X-ray transients (SFXTs) are a class of high-mass X-ray binaries (HMXBs) associated with OB supergiant stars. In the X-rays they display outbursts significantly shorter than those of typical Be/X-ray binaries characterized by bright flares with peak luminosities of 10^{36}–10^{37} erg s⁻¹ which last a few hours (as observed by INTEGRAL; Sguera et al. 2005; Negueruela et al. 2006b). As their quiescence is characterized by a luminosity of ~10^{32} erg s⁻¹ (e.g. in’t Zand 2005; Bozzo et al. 2010), their dynamic range is of 3–5 orders of magnitude. While in outburst, their hard X-ray spectra resemble those of HMXBs hosting an accreting neutron star (NS), with hard power laws below 10 keV with high-energy cut-offs at ~15–30 keV. Therefore, even if pulse periods have only been measured for a few SFXTs, it is tempting to assume that all SFXTs might host a NS.

The physical context originating the outbursts has been claimed to be related either to the properties of the wind from the supergiant companion (in’t Zand 2005; Sidoli et al. 2007; Walter & Zurita Heras 2007; Negueruela et al. 2008) or to the presence of a centrifugal or magnetic barrier (Grebenev & Sunyaev 2007; Bozzo, Falanga & Stella 2008).

XTE J1739−302 was discovered by RXTE in 1997 August (Smith et al. 1998), when it reached a peak flux of 3.6 × 10^{-9} erg cm⁻² s⁻¹ (2–25 keV). It has a long history of flaring recorded by INTEGRAL (Sguera et al. 2006; Walter & Zurita Heras 2007; Blay et al. 2008) and by Swift (Sidoli et al. 2009a,b; Romano et al. 2011a,c). Recently,
Drave et al. (2010) reported the discovery of a $51.47 \pm 0.02\,d$ orbital period based on $\sim 12.4\,M_{\odot}$s of INTEGRAL data.\textsuperscript{1} The optical counterpart is an O8I ab star at $2.7\,kpc$ (Negueruela et al. 2006a; Rahoui et al. 2008).

IGR J17544$-2619$ was first detected by INTEGRAL in 2003 (Sunyaev et al. 2003), when the source reached a flux of $160\,mCrab$ ($20$–$40\,keV$). Several more flares, lasting up to $10\,h$, were detected by INTEGRAL in the following years (Grebenicche, Lutovinov & Sunyaev 2003; Grebenicche et al. 2004; Sguera et al. 2006; Kuulkers et al. 2007; Walter & Zurita Heras 2007) with fluxes up to $400\,mCrab$ ($20$–$40\,keV$); some were also found in archival BeppoSAX observations (in't Zand et al. 2004). Subsequent flares were observed by Swift (Krimm et al. 2007; Sidoli et al. 2009a,b; Romano et al. 2011b,c,d) and Sizakal (Rampy, Smith & Negueruela 2009). Clark et al. (2009) reported the discovery of a $4.926 \pm 0.001\,d$ orbital period based on $\sim 4.5\,\text{years}$ of INTEGRAL data. Recently, Drave et al. (2012) detected a transient $71.49 \pm 0.02\,s$ signal in RXTE observations from the region of IGR J17544$-2619$, which, if interpreted as the spin period of the NS in the system, places the source in the locus of the Corbet diagram (Corbet 1986) where classical wind-fed supergiant X-ray binaries can be found. The optical counterpart is an O9Ib star at $3.6\,kpc$ (Pelizziza, Chaty & Negueruela 2006; Rahoui et al. 2008).

XTE J1739$-302$ and IGR J17544$-2619$ are considered the prototypes of the SFXT class, and were extensively studied with Swift. In particular, in addition to the Burst Alert Telescope (BAT; Barthelmy et al. 2005) outburst detections and intensive X-ray Telescope (XRT; Burrows et al. 2005) follow-up, Swift has been studying their long-term properties (Romano et al. 2011c, references therein). In this paper we examine the most recent outbursts of these two sources, which triggered the BAT in 2011. In particular, we apply, for the first time to SFXTs, the new COMPMAG model by Farinelli et al. (2012, hereafter F12).

## 2 Observations and Data Reduction

XTE J1739$-302$ triggered the BAT on 2011 February 22 at 07:21:37\,UT (image trigger = 446475; Romano et al. 2011a). Swift immediately slewed to the target, so that the narrow-field instruments (NFIs) started observing about 141\,s after the trigger. After the initial automated target (AT) observation (two orbits for a total of $\sim 1.8\,ks$ net exposure spanning $\sim 6.7\,ks$), no further NFI observations were performed.

IGR J17544$-2619$ (Romano et al. 2011b) triggered the BAT on 2011 March 24 at 01:56:57\,UT (image trigger = 449907; Romano et al. 2011b). Swift immediately slewed to the target, so that the NFIs started observing about 126\,s after the trigger. The AT (sequence 00449907000) ran for two orbits, until $\sim 7.4\,ks$ after the trigger. Follow-up target of opportunity observations for a total of $2.2\,ks$ were obtained (sequences 0003506150–152) after the source emerged from Moon constraint. The data cover the first 6\,d after the beginning of the outburst. Table 1 reports the log of the Swift observations used in this paper.

The BAT data were analysed using the standard BAT analysis software within FTOOLS in the HEASOFT package (v.6.11). Mask-tagged BAT light curves were created in the standard energy bands, and rebinned to fulfil at least one of the following conditions: achieving a signal-to-noise ratio ($S/N$) of 5 or bin length of $10\,s$. Spectra were extracted from the whole event lists and within time intervals strictly simultaneous with the XRT. Response matrices were generated with BATDRMGEN using the latest spectral redistribution matrices. Survey data products, in the form of detector plane histograms, are available, and were analysed with the standard BATSURVEY software.

The XRT data were processed with standard procedures (XRTPIPELINE v0.12.6), filtering and screening criteria by using FTOOLS. We considered both windowed timing (WT) and photon counting (PC) mode data, and selected event grades 0–2 and 0–12 for WT and PC data, respectively (Burrows et al. 2005). When appropriate, we corrected for pile-up by determining the size of the affected core of the point spread function (PSF) by comparing the observed and nominal PSF (Vaughan et al. 2006), and excluding from the analysis all the events that fell within that region. Background events were accumulated from source-free regions. For our timing analysis, light curves were created for several values of $S/N$ and number of counts per bin; all were corrected for PSF losses, vignetting and background. For our spectral analysis, we extracted events in the same regions as those adopted for the light-curve creation; the data were rebinned with a minimum of 20–50 counts per energy bin, as appropriate, to allow $\chi^2$ fitting, with the exception of low-count-statistics spectra, in which Cash (Cash 1979) statistics and spectra binned to 1 count bin$^{-1}$ were used, instead. Ancillary response files were generated with XRTPMKARF to account for different extraction regions, vignetting and PSF corrections. We used the latest spectral redistribution matrices in CALDB (20110915). For the luminosity calculation, we adopted a distance of $2.7$ and $3.6\,kpc$ for XTE J1739$-302$ and IGR J17544$-2619$, respectively (Rahoui et al. 2008).

Table 1. Log of the observations of XTE J1739$-302$ and IGR J17544$-2619$ with Swift.

| Source      | Sequence | Instrument/mode | Start time (UT) (yyyy-mm-dd hh:mm:ss) | End time (UT) (yyyy-mm-dd hh:mm:ss) | Exposure (s) | Time since trigger (s) |
|-------------|----------|-----------------|--------------------------------------|-------------------------------------|--------------|------------------------|
| XTE J1739$-302$ | 00446475000 | BAT/evt | 2011-02-22 07:19:44 | 2011-02-22 07:36:46 | 1022 | −119                     |
|             | 00446745000 | XRT/WT  | 2011-02-22 07:24:10 | 2011-02-22 09:04:39 | 1271 | 147                      |
|             | 00446745000 | XRT/PC  | 2011-02-22 09:13:55 | 2011-02-22 09:36:46 | 554  | 6176                     |
| IGR J17544$-2619$ | 00449907000 | BAT/evt | 2011-03-24 01:53:04 | 2011-03-24 02:13:06 | 1202 | −239                     |
|             | 00449907000 | XRT/WT  | 2011-03-24 01:59:15 | 2011-03-24 03:18:22 | 657  | 133                      |
|             | 00449907000 | XRT/PC  | 2011-03-24 04:01:03 | 2011-03-24 06:01:06 | 3360 | 784                      |
|             | 00035056150 | XRT/PC  | 2011-03-27 19:54:23 | 2011-03-27 20:11:56 | 1046 | 323840                   |
|             | 00035056151 | XRT/PC  | 2011-03-28 20:10:36 | 2011-03-28 20:21:58 | 662  | 411213                   |
|             | 00035056152 | XRT/PC  | 2011-03-29 20:15:13 | 2011-03-29 20:23:57 | 504  | 497890                   |

\textsuperscript{1} We note, however, that Romano et al. (2009) derived marginal evidence, based on XRT data, of signal at $F_{\text{orb}} = 12.8658 \pm 0.0073\,d$, or 1/4 the period reported by Drave et al. (2010).
All quoted uncertainties are given at 90 per cent confidence level for one interesting parameter unless otherwise stated. The spectral indexes 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, $N(E) \propto E^{-\Gamma}$ (photon cm$^{-2}$ s$^{-1}$ keV$^{-1}$).

### 3 ANALYSIS AND RESULTS

Fig. 1 shows the Swift/XRT 0.2–10 keV light curve of XTE J1739–302 and IGR J17544–2619 throughout our 2007–09 monitoring programme (Romano et al. 2011c, and references therein) background subtracted and corrected for pile-up, PSF losses and vignetting. All data in one observation (1–2 ks) were generally grouped as one point, except for outbursts, which show up as vertical lines on the adopted scale. The data already presented elsewhere are in grey. The details of the 2011 outbursts of XTE J1739–302 and IGR J17544–2619, referred to their respective BAT triggers, are shown in Fig. 2. In both cases, the XRT caught the descending portion of a very bright flare in great detail. There is a similarity between the two outbursts, and also with previous outbursts of these sources [see fig. 6 of Romano et al. (2011d), for a compendium of the best light curves collected before the currently presented ones and figs 9b–(e) of Sidoli et al. (2009a)] for a comparison of different outbursts of the same source].

The details of the data selection and spectroscopic analysis on both sources are reported in the remainder of this section. Here we summarize the models we adopted for the broad-band spectra. We first considered the phenomenological models typically used to describe the X-ray emission from accreting pulsars in HMXBs, i.e. the following: (i) simple absorbed (WABS in XSPEC) power laws; (ii) absorbed power laws with exponential cut-offs (CUTOFFPL, hereafter CPL); (iii) absorbed power laws with high-energy cut-offs (HIGHECUT, hereafter HCP). The simple advantage of this approach is that these fits yield easy-to-compare estimates of fluxes and luminosities. The disadvantage, however, is that little physical insight can be obtained from such fits; therefore, we also considered the following physical models: (i) absorbed generic Comptonization models (COMPTT) in diffusion approximation for a disc geometry without a dynamical bulk component; (ii) a combination of two blackbodies (BB) with different temperatures and radii (BBODYRAD+BBODYRAD), sometimes used to fit the spectra of magnetars (Israel et al. 2008); (iii) the new COMPMAG model, recently developed by F12. We refer the reader to that paper for a detailed description of the algorithm. Here we briefly remind the reader that COMPMAG is based on the solution of the radiative transfer equation for the case of cylindrical accretion on to the polar cap of a magnetized NS. The velocity field of the accreting matter can be increasing towards the NS surface, or it may be described by an approximate decelerating profile. In the former case, the free parameters are the terminal velocity at the NS surface, $\beta_0$, and the index of the law $\beta(z) \propto z^{-\gamma}$, while in the second case the law is given by $\beta(\tau) \propto \tau$. The other free parameters of the model are the temperature of the BB seed photons, $kT_{bb}$, the electron temperature and vertical optical depth of the Comptonization plasma, $kT_e$ and $\tau$, respectively, and the radius of the accretion column, $r_{in}$, in units of the NS Schwarzschild radius. The different combinations of these parameters determine the steepness of the spectrum at high energies and the rollover energy position.

However, given that the Comptonization spectra can be determined by only three quantities (slope, cut-off position and normalization), for practical purposes it is generally not possible to keep free all the above-mentioned parameters, a procedure which otherwise leads them to be completely unconstrained during the fitting procedure. In the following sections we will report in more detail the procedure that we adopted in the spectral fitting.

#### 3.1 XTE J1739–302

The XRT light curve (Fig. 2a) shows the descending part of a flare, which started off at a peak exceeding 30 count s$^{-1}$ then decreases to about 2.5 count s$^{-1}$. A second flare is observed in the second orbit, with a count rate in the range 10–17 count s$^{-1}$. In the third orbit the count rate was ~0.2 count s$^{-1}$. In Fig. 3 are reported the first orbit data of XTE J1739–302 in several energy bands. The event-by-event mask-weighted light curves only show the initial flare, which started at $T - 70$ s with a slow rise, well defined in both soft bands. The source was still bright when the BAT event data ended, at $T + 900$ s. The BAT survey data cover the same time-span.

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Figure 1. Swift/XRT (0.2–10 keV) long-term light curves of XTE J1739–302 and IGR J17544–2619. The downward-pointing arrows are 3σ upper limits. The upward-pointing arrows mark flares that triggered the BAT transient monitor on MJD 54414 and 54906. Data up to MJD ∼55261 (grey) were published in Romano et al. (2009, 2011c,d).

Figure 2. Swift/XRT (0.2–10 keV) light curves of the 2011 outbursts of XTE J1739–302 and IGR J17544–2619, as followed by Swift/XRT, referred to their respective BAT triggers (2011 February 22 and March 24). Points denote detections and downward-pointing arrows 3σ upper limits. Where no data are plotted, no Swift data were collected. Vertical dashed lines mark time intervals equal to 1 d, up to a week.
Table 3. Best-fitting parameters of the phenomenological models for XTE J1739–302 and IGR J17544–2619 broad-band spectra. In the latter case, an absorption edge was also included. CPL = cut-off power law; HCP = power law multiplied by exponential cut-off with e-folding factor.

| Parameter | XTE J1739–302 | IGR J17544–2619 |
|-----------|---------------|-----------------|
| $N_{\text{Hi}}(10^{22} \text{ cm}^{-2})$ | $1.97_{-0.16}^{+0.17}$ | $1.76_{-0.15}^{+0.17}$ |
| $E_{\text{edge}}$ (keV) | $22.98_{-1.12}^{+1.15}$ | $-$ |
| $\Gamma$ | $0.25_{-0.10}^{+0.11}$ | $0.42_{-0.09}^{+0.09}$ |
| $E_{\text{e}}$ (keV) | $9.19_{-0.82}^{+0.95}$ | $4.60_{-0.36}^{+0.37}$ |
| $F_{2–10 \text{ keV}}$ | $2.4_{-1.3}^{+2.3}$ | $3.1_{-0.9}^{+3.2}$ |
| $\chi^2$/d.o.f. | 364/243 | 336/242 |

Average observed flux in units of $10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$; $b$ in units of $10^{36} \text{ erg s}^{-1}$.

Table 4. Best-fitting parameters of the model WABS × (BBODYRAD + BBODYRAD) for XTE J1739–302 and IGR J17544–2619 broad-band spectra.

| Parameter | XTE J1739–302 | IGR J17544–2619 |
|-----------|---------------|-----------------|
| $N_{\text{Hi}}(10^{22} \text{ cm}^{-2})$ | $1.07_{-0.09}^{+0.09}$ | $0.58_{-0.06}^{+0.07}$ |
| $kT_{\text{bb},1}$ (keV) | $1.88_{-0.06}^{+0.07}$ | $0.93_{-0.07}^{+0.07}$ |
| $R_{\text{bb},1}$ (km) | $1.15_{-0.05}^{+0.04}$ | $3.43_{-0.34}^{+0.41}$ |
| $kT_{\text{bb},2}$ (keV) | $6.62_{-0.15}^{+0.49}$ | $3.45_{-0.08}^{+0.08}$ |
| $R_{\text{bb},2}$ (km) | $0.11_{-0.01}^{+0.01}$ | $0.77_{-0.04}^{+0.04}$ |
| $F_{2–10 \text{ keV}}$ | $2.2_{-0.9}^{+3.1}$ | $3.1_{-0.9}^{+3.2}$ |
| $\chi^2$/d.o.f. | 285/241 | 335/297 |

In units of $10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1}$; $b$ in units of $10^{36} \text{ erg s}^{-1}$.

We also tested the model WABS × COMPTT, which yields statistically similar results, and we report the main values of the model in Table 5.

Finally, we tested the COMPAGM model assuming a free-fall-like velocity profile ($\eta = 0.5$), two terminal velocities at the NS surface $v_0 = 0.05$ and 0.2, and NS albedo $A = 1$. The free parameters of the model during the fitting procedure were the seed BB temperature $kT_{\text{bb}}$, the electron temperature $kT_e$, and the vertical optical depth of the accretion column $\tau$. We note that the latter quantity in this case is a factor of about 1/1000 lower than classical optical depth because of the inclusion of an energy-independent correction term which reduces the Thomson cross-section $\sigma_T$ for photons propagating in the direction of the magnetic field (Becker & Wolff 2007, hereafter BW07).

We initially set the radius of the accretion column $r_0 = 0.25$, which corresponds to $\sim 1$ km for a NS star with mass $M = 1.4 \text{ M}_\odot$; the results for the case $r_0 = 0.05$ are reported in Table 6, while in Fig. 7 we show the deconvolved best-fitting model and data.

No significant variation is observed in the $\chi^2$ value when increasing $r_0$ from 0.25 to 1. A similar statistical result is also obtained assuming $\beta_0 = 0.2 (\chi^2$/d.o.f. = 294/241). In this case, a slight

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Thus, for given (observed) spectral slope and rollover energy, the higher the values of $\beta_0$, the lower the values of $kT_\alpha$, as the bulk Comptonization progressively increases its importance at expenses of thermal Comptonization. Even in this case, with $\beta_0 = 0.2$, the $\chi^2$ remains unchanged for varying $r_0$ from 0.25 up to 1.

An important issue we want to emphasize is that for XTE J1739−302 the value of $\tau$ obtained with COMPTT is less than 1 (see Table 6), and actually the higher the assumed value of $\beta_0$, the lower the value of $\tau$.

As the COMPMAG model is based on the solution of the Fokker-Planck approximation of the radiative transfer equation, it generally holds for an optical depth $\tau \gtrsim 1$. Our fits on XTE J1739−302 data yield values of $\tau$ which are formally smaller than unity. In general terms, this would indicate that the diffusion along the direction of the column axis is not efficient; hence, either the spatial diffusion of the photons is only efficient for photons propagating perpendicularly with respect to the column axis, or the system is significantly anisotropic due to the presence of the magnetic field. In either case, the diffusion approximation would not be recommended, as it describes the system inadequately (further details can be found in Appendix A).

We note, however, that, in our case, an acceptable fit can be achieved with a value of the optical depth within a factor of 3 of unity, so that the obtained physical parameters can be discussed with reasonable accuracy. In particular, the electron temperature $kT_\alpha$ results consistent within errors with that obtained with COMPTT and with the hotter BB temperature in the two-BB model (see Tables 4 and 5).

### 3.2 IGR J17544−2619

The XRT light curve of IGR J17544−2619 is reported in Fig. 2(b), and shows the two bright flares observed in the first orbit; the first was caught (WT mode) in the descending part and reached a peak exceeding 50 count s$^{-1}$; the second (PC mode) started off at about $T + 750$ s and reached $\sim 5$ count s$^{-1}$. At about $T + 5000$ s (second orbit), the source is still at $\sim 1$ count s$^{-1}$. Fig. 5 shows the initial data of IGR J17544−2619 in several energy bands. The BAT event-by-event mask-weighted light curves show a slow rise from $T = 200$ s to the first peak at $T = 0$ s, followed by a few more flares.

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**Table 6.** Best-fitting parameters of the model WABS×COMPMAG for XTE J1739−302 and IGR J17544−2619 broad-band spectra. In both cases, the fixed parameters are $\eta = 0.5$, $\beta_0 = 0.05$, $r_0 = 0.25$ and $A = 1$. In this case also, as in Table 3, an absorption edge was included in the model for IGR J17544−2619.

| Parameter | XTE J1739−302 | IGR J17544−2619 |
|-----------|----------------|-----------------|
| $N_H (\times 10^{22}\text{cm}^{-2})$ | $0.81^{+0.11}_{-0.10}$ | $0.58^{+0.07}_{-0.06}$ |
| $E_{\text{edge}} (\text{keV})$ | $-1.03$ | $20.97^{+1.32}_{-1.23}$ |
| $\tau_{\text{edge}}$ | $0.63^{+0.35}_{-0.31}$ | $10.67^{+0.71}_{-0.54}$ |
| $kT_w (\text{keV})$ | $1.33^{+0.07}_{-0.06}$ | $0.63^{+0.07}_{-0.08}$ |
| $kT_e (\text{keV})$ | $8.83^{+1.18}_{-1.11}$ | $3.95^{+0.18}_{-0.16}$ |
| $\chi^2$/d.o.f. | $292/241$ | $324/295$ |

$^{a}$In units of $10^{-9}$ erg cm$^{-2}$ s$^{-1}$; $^{b}$in units of $10^{36}$ erg s$^{-1}$.

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Figure 4. Absorption-corrected unfolded $E(F(E)$ models and spectra, and residuals between the data and the model in units of $\sigma$ for XTE J1739−302. Upper panel: BBODYRAD+BBODYRAD. Lower panel: COMPMAG.

Table 5. Best-fitting parameters of the model WABS×COMPTT for XTE J1739−302 and IGR J17544−2619 broad-band spectra. As for the case of Table 3, an absorption edge was included in the model for IGR J17544−2619.

| Parameter | XTE J1739−302 | IGR J17544−2619 |
|-----------|----------------|-----------------|
| $N_H (\times 10^{22}\text{cm}^{-2})$ | $0.81^{+0.11}_{-0.10}$ | $0.58^{+0.07}_{-0.06}$ |
| $E_{\text{edge}} (\text{keV})$ | $-1.03$ | $20.97^{+1.32}_{-1.23}$ |
| $\tau_{\text{edge}}$ | $0.63^{+0.35}_{-0.31}$ | $10.67^{+0.71}_{-0.54}$ |
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| $\chi^2$/d.o.f. | $292/241$ | $324/295$ |

$^{a}$In units of $10^{-9}$ erg cm$^{-2}$ s$^{-1}$; $^{b}$in units of $10^{36}$ erg s$^{-1}$.
then follows the decaying shape of the XRT light curve. The BAT survey data cover a longer time-span, and show that the source was still detected in the soft band out to 15–30 keV region (see Fig. 6). The inclusion of an absorption edge which show in the former case a sinusoidal-like feature in the H variations, as previously observed by Rampy et al. (2009). We extracted strictly simultaneous spectra from the XRT and BAT survey data for IGR J17544−2619, the fit results to be insensitive to $r_a$ increasing from 0.9–1.1. As is the case of XTE J1739−302, for IGR J17544−2619 a simple absorbed power-law model is inadequate to fit the broad-band spectrum ($\chi^2$/d.o.f. = 207/299). A significant improvement is obtained when considering the CPL and HCP models (Table 3).

The main difference in the $\chi^2$ values between the CPL and HCP models is due to the residuals of the BAT spectrum above 30 keV, which show in the former case a sinusoidal-like feature in the 15–30 keV region (see Fig. 6). The inclusion of an absorption edge in the CPL model improves the statistical result from $\chi^2$/d.o.f. = 383/298 to 344/296, with best-fitting parameters reported in Table 3. The $F$-test for discriminating between two different models (namely with and without the absorption edge) provides, however, a probability of chance improvement (PCI) of about only 20 per cent. The fact that these residuals are not observed in the HCP model besides on fact that in this case the spectrum is less smooth due to the presence of the $E_0$ term. The well-constrained determination of the latter parameter is actually indicative of the presence of a change of curvature in the X-ray spectrum around 15–20 keV.

The model $WABS \times COMPTT$ yields $\chi^2$/d.o.f. = 339/297, and the inclusion of the absorption edge improves the fit to $\chi^2$/d.o.f. = 323/295, with, however, an even lower PCI (~35 per cent) with respect to the case of a CPL and best-fitting parameters reported in Table 5.

Similarly to XTE J1739−302, a satisfactory fit can be obtained by the sum of two blackbody spectra (see Table 4), and in this case the inclusion of the absorption edge only marginally improves the fit by $\Delta \chi^2 \sim 7$.

Performing the spectral analysis with the COMPMAG model, we followed the same procedure of XTE J1739−302. First, we considered the case of free-fall velocity profile fixing $\beta_0 = 0.05$, accretion column radius $r_0 = 0.25$ and NS albedo $A = 1.0$. In this case, we obtain $\chi^2$/d.o.f. = 343/297, with an improvement of $\Delta \chi^2 \sim 20$ when including the absorption edge at 20 keV. Moreover, for IGR J17544−2619, the fit results to be insensitive to $r_0$, with the $\chi^2$ value remaining substantially unchanged for $r_0$ increasing from 0.25 to 1. In the second case, namely $\beta_0 = 0.2$, the inclusion of the absorption edge reduces similarly the fit by $\Delta \chi^2 \sim 20$, but we observed a decrease of $\chi^2$/d.o.f. from 363/295 to 332/295 by setting $r_0 = 0.25$ and 1, respectively. For higher values of $r_0$, no further improvement of the $\chi^2$ was observed, so that we consider it as our actual best-fitting parameter.

Unlike the case of XTE J1739−302, the increased value of $\beta_0$ leads to a more significant decrease of the electron temperature, with $kT_e = 1.2^{+0.1}_{-0.01}$ keV, while the optical depth to first approximation remains constant within errors, with $\tau = 1.44^{+0.11}_{-0.09}$.

The reason for this is that a higher value of $\beta_0$ is compensated by the simultaneous increase of the accretion column radius $r_0$ from 0.25 to 1.
Figure 7. Absorption-corrected EF(E) spectra, best-fitting models and residuals between the data and the model in units of σ for IGR J17544–2619. Upper panel: BBODYRAD+BBODYRAD. Lower panel: EDGE×COMPMAG.

In Fig. 6 we report as a summary the residuals to the data in units of σ for the four different adopted models described above, while Fig. 7 shows the absorption-corrected best-fitting models and residuals between the data and the model in units of σ for BBODYRAD+BBODYRAD and EDGE×COMPMAG.

4 DISCUSSION

XTE J1739–302 and IGR J17544–2619 are considered the prototypes of the SFXT class and, as such, were systematically observed with Swift, which caught several outbursts from both sources. The simplest way to parametrize the shape of the broad-band spectra is to fit them with phenomenological models typically used to describe the X-ray emission from accreting pulsars in HMXBs, i.e. absorbed power laws, absorbed power-law models with high-energy cut-offs and absorbed power-law models with exponential cut-offs.

The advantage of this approach is that the fits yield easy-to-compare estimates of fluxes and luminosities for each outburst. Indeed, the data presented in this paper yield values of both high-energy cut-off $E_c$ and e-folding energy $E_\text{fe}$ (see Sections 3.1 and 3.2) consistent with the ones obtained previously for both sources (Sidoli et al. 2009a, b; Romano et al. 2010, 2011a, c). The disadvantage is, clearly, that little physical insight can be obtained from such fits. In this paper we also apply the following more physically motivated models: absorbed Comptonization models (COMPTT); a combination of two blackbodies with different temperatures and radii; and for the first time to SFXTs, the new COMPMAG model, recently developed by F12.

There is an interesting aspect to discuss, which has not been yet fully faced in the accretion physics of SFXTs. If we focus on the results using the COMPTT and COMPMAG models, it can be shown that the electron density where Comptonization takes place is of the order of $10^{19}$ cm$^{-3}$. Indeed, the Thomson optical depth is given by

$$\tau \approx 7n_{19}r_6,$$

where $n_{19} \equiv n_e/10^{19}$ cm$^{-3}$ and $r_6 \equiv R/10^6$ cm are dimensionless electron density and system length scale, respectively. If spectral formation occurs close to the NS ($r_6 \sim 1$–2), from the COMPTT best-fitting values of $\tau$ reported in Table 5 we obtain $n_{19} \sim 1$.

The possible presence of a strong magnetic field ($B \gtrsim 10^12$ G), with associated reduction of the Thomson cross-section $\sigma_T$ would actually require an even higher electron density, which somewhat compensates the lower cross-section value in order to maintain the same Comptonization parameter $Y$, and in turn the observed spectral index.

This qualitative effect can be tested from the results of the COMPMAG model (Table 6). The electron density for column accretion, which is assumed in COMPMAG, is given by

$$n_e \approx 10^{19} \frac{m}{m_\odot} \beta_e^{-1} \text{cm}^{-3}, \quad (2)$$

where $m = M/M_{\text{Edd}}$ is the accretion rate in Eddington units, $m = M_{\text{NS}}/M_{\odot}$ is the NS mass in units of solar masses, $r_0 = R_0/(R_{\text{scw}}^2 m)$ is the accretion column radius in units of the NS Schwarzschild radius and $\beta_e = V_e/c$ is the accretion column velocity. We derived $m$ from the best-fitting value of $\tau$ reported in Table 6 for IGR J17544–2619 and XTE J1739–302 (with $r_0 = 0.25$ and $\beta_e = 0.05$) and using equation (44) in F12 for both sources. Then, substituting $\beta_e$ in equation (2) with a value averaged over the vertical $z$-coordinate ($\beta_z$), we obtain $n_e \sim 10^{21}$ cm$^{-3}$ in both sources, which is actually a factor of about 100 higher than that inferred from COMPTT.

Then, we consider the mass flow rate across the magnetosphere:

$$\dot{M} = 4\pi R_m^2 \rho v_{\text{in}}, \quad (3)$$

where $R_m$ is the magnetospheric radius and $v_{\text{in}}$ is the infall velocity at $R_m$, which is expected to be less than the free-fall velocity:

$$v_{\text{ff}} = \left(\frac{2GM_{\text{NS}}}{R}\right)^{1/2}. \quad (4)$$

The accretion luminosity at the NS surface on the other hand is

$$L_{\text{acc}} \lesssim \frac{GM_{\text{NS}}\dot{M}}{R_{\text{NS}}}. \quad (5)$$

Assuming a NS with mass $M = 1.4M_{\odot}$ and radius $R_{\text{NS}} = 10$ km, and combining equations (3) and (5), we obtain

$$n_e \gtrsim 1.3 \times 10^{14} \frac{L_{37}}{r_8^3 v_9} \text{cm}^{-3}, \quad (6)$$

where $L_{37} \equiv L_e/10^{37}$ erg s$^{-1}$, $r_8 \equiv r_8/10^8$ cm and $v_9 \equiv v_9/10^9$ cm s$^{-1}$.

We consider a magnetospheric radius $r_m \approx 10^6$ cm, calculated assuming the typical values of the magnetic field of an accreting pulsar in HMXBs and the typical stellar wind parameters of OB supergiants (Davidson & Ostriker 1973). Additionally, for the infall velocity, we assume for the sake of simplicity $v_{\text{in}} \approx v_{\text{ff}}$.

With these prescriptions in mind and noting that both sources during the joint XRT/BAT observation have shown $L_e \lesssim 10^{37}$ erg s$^{-1}$,
from equation (6) we find that at the magnetospheric radius \( n_e \geq 10^{41} \text{ cm}^{-3} \).

This value of the electron density at the magnetospheric radius is about seven orders of magnitude lower than that inferred from the best-fitting parameters of COMPMAG as shown above, and thus cannot be simply a result of a simplified treatment of the problems such as pure spherical accretion assumed in equation (6).

However, there are at least two issues which are worth mentioning. First, the electron density estimated from the best-fitting parameters of COMPMAG is related to the region where the X-ray spectral formation is assumed to take place, which, in the case of COMPMAG, corresponds to cylindrical accretion column close to the NS surface with characteristic height-scale \( H \approx 1–2R_{\text{NS}} \).

This value is about 1/100 of the assumed magnetospheric radius (\( \approx 100R_{\text{NS}} \)), and for a density scaling as \( R^{-2} \) it would imply to first approximation a density increase from \( R_m \) to \( R_{\text{NS}} \) of about \( n_e^{\text{NS}}/n_e^m \sim 10^5 \). Of course, matter channelling towards the magnetic poles may also play an important role in increasing the matter density in the region close to the NS surface.

The second point to be considered is that if the NS orbital motion is supersonic, strong shock waves are expected to form approximately at the NS magnetosphere (bow shock region). The net result would be thus an increase of the electron density with respect to the value reported in equation (6).

The Mach number of the NS is given by

\[
M \approx 10^3 v_e/n_e^{1/2},
\]

where \( v_e \) is the NS orbital velocity in units of \( 10^8 \text{ cm s}^{-1} \), \( \gamma \) is the adiabatic index of the wind, \( \mu = m_{\text{H}}/m_e \) its molecular weight, \( Z \) its the charge state and \( T_e \) its temperature in eV. For wind temperatures in the range \( 10^3–10^4 \text{ K} \) (Ducci et al. 2009), and velocities of the NS derived from the orbital parameters for both XTE J1739–302 and IGR J17544–2619, \( M \) varies from a few to about 30, and if the shock is isothermal, \( t_1/t_2 \approx M^2 \). Actually, a density increase of a factor of \( \sim 10^3 \) at the magnetospheric shock front, with respect to the value computed in equation (6), would be sufficient to take into account the electron density derived from COMPMAG at the magnetic poles (see above).

The physics of shocks in these systems is, however, rather complicated for the intrinsic 3D nature of the problem. Indeed, if on the one hand the supersonic motion of the NS ensures the formation of a bow shock, then on the other hand this discontinuity occurs in a region where the presence of a strong magnetic field plays an important role in determining the gas configuration.

A pure dipolar magnetic field may lead to the formation of a bow shock which follows approximately the shape of the magnetic lines in the direction of motion of the NS, together with a channelling of matter towards the magnetic poles. This accretion geometry close to the NS could be approximated with a cylindrical accretion, suitable to be described with some accuracy by the COMPMAG model. However, if non-negligible multipole magnetic field components are present, then matter can also (or mainly) be accreted at the equator of the NS.

As shown in the data analysis, the spectra of both XTE J1739–302 and IGR J17544–2619 can be alternatively described by a two-component model consisting of a soft and hard BB (see Table 4). The temperature of the softer BB is consistent with that of the seed photons in both COMPTT and COMPMAG, while the temperature of the harder BB is comparable with the electron temperature of the above-mentioned Comptonization models. This means that the harder BB is actually playing the role of a Comptonization feature, but the quality of the high-energy data (see Figs 4 and 7) does not allow us to distinguish between an unsaturated (COMPTT and COMPMAG) or a saturated (BB) Compton regime.

The apparent radii of both BB components are consistent with emission regions of the order of a polar cap radius, thus pointing in favour of a very compact emission region. The implications for the accretion geometry in this context are that both the regions of the soft seed photons and of the Comptonized ones are visible.

Summarizing, the current data presently do not allow us to verify whether the 0.1–60 keV X-ray spectra of XTE J1739–302 and IGR J17544–2619 form as a result of a single unsaturated Comptonization process, or arise from two different and directly visible zones of seed and Comptonized photons.

Using the calibration of stellar parameters for Galactic O stars of Martins, Schaerer & Hillier (2005), we find \( M_{\text{SG}} \sim 31M_\odot, R_{\text{SG}} \sim 21R_\odot \) for XTE J1739–302 and \( M_{\text{SG}} \sim 30M_\odot, R_{\text{SG}} \sim 22R_\odot \) for IGR J17544–2619. If the orbital period of XTE J1739–302 is 51.47 d, the minimum and maximum distances of the NS from the giant companion are, respectively, in the range \( d_{\text{min}} \sim 8.45R_{\text{SG}} \) and \( d_{\text{max}} \sim 9.8–13.4R_{\text{SG}} \) for orbital eccentricity \( e \approx 0.1–0.5 \). These values change to \( d_{\text{min}} \sim 3.2–1.8R_{\text{SG}} \) and \( d_{\text{max}} \sim 3.9–5.3R_{\text{SG}} \) if the orbital period is 12.89 d (see Section 1).

In the case of IGR J17544–2619, on the other hand, the maximum allowed eccentricity for its orbital period of 4.93 d is \( e = 0.4 \), and the ranges of minimum and maximum distances to the supergiant companion are \( d_{\text{min}} \sim 1.6–1.1R_{\text{SG}} \) and \( d_{\text{max}} \sim 1.9–2.4R_{\text{SG}} \).

The mass-loss rates of the supergiant companions of XTE J1739–302 and IGR J17544–2619 have, within the uncertainties with which we know the masses, radii, effective temperatures and bolometric luminosities of the two stars, the same value of about \( 2 \times 10^{-6} M_\odot \text{ yr}^{-1} \) (Vink, de Koter & Lamers 2000).

Whatever the actual orbital period of XTE J1739–302 and the eccentricity of the two systems, the distance to the supergiant companion is lower for IGR J17544–2619. It is thus intriguing to observe that the optical depth derived from the Comptonization models is higher in the latter source than in XTE J1739–302 (see Tables 5 and 6), as one would expect for a closer orbiting system.

5 CONCLUSIONS

We have analysed data from the outbursts of two sources, XTE J1739–302 and IGR J17544–2619, which are considered to be the prototypes of the SFXTs class. During the bright flare they reached peak luminosities of \( \sim 2 \times 10^{36} \) and \( \sim 5 \times 10^{38} \text{ erg s}^{-1} \), respectively.

The presented Swift data do not allow us to discriminate whether the X-ray spectra are the result of a single unsaturated Comptonization process, or whether we observe both regions where seed photons are produced and Comptonization mostly takes place (two-BB model).

The electron density in the region of the X-ray spectral formation, computed to first approximation using the best-fitting parameters of the COMPMAG model, is a factor about 1000 higher than expected from the continuity equation at the magnetospheric radius. We propose that the formation of a bow shock at the NS magnetosphere, due to its supersonic orbital motion around the supergiant companion, may increase the density enough to explain the difference. This effect needs to be investigated in a future work by means of 3D magnetohydrodynamical simulations using the specifically devoted FLASH code.

The possible feature around 20 keV which is observed using a one-component Comptonization model (see Fig. 7, bottom panel) is intriguing, as it cannot be attributed to any particular shape of the
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APPENDIX A: THE OPTICAL DEPTH RANGES OF APPLICABILITY OF THE COMPMAG MODEL

The theoretical spectra of the COMPMAG model were reported by F12 for the case of optical depth $\tau < 1$. In this section we better explain how this impacts the spectral fitting analysis of real data. In particular, the fits of the broad-band spectrum of XTE J1739–302 with the COMPMAG model (see Table 6) yield an optical depth formally less than 1, albeit within a factor of 3 from unity. It is worth noting that in COMPMAG, this is the vertical optical depth of the accretion column and it is computed including an energy-independent correction to the Thomson cross-section, due to the presence of a magnetic field $B \gtrsim 10^2$ G. More specifically, it is the opacity related to photons which diffuse across the field lines. The relation between the optical depths presented in Table 6 can be written in terms of Thomson optical depth $\tau \approx 10^{-3}$ for $\tau > 300$. After rearranging some terms, equation (35) in F12 can be written as

$$\frac{\sigma_{\parallel}}{\sigma_{\perp}} \delta(x, \tau) = -\frac{\sigma_{\parallel}}{\sigma_{\perp}} \frac{\partial n}{\partial \tau} + \frac{\sigma_{\parallel}}{\sigma_{\perp}} \frac{\partial n}{\partial x} + \frac{1}{3} \frac{\partial^2 n}{\partial \tau^2} - \left( \frac{\xi_e}{c} \right)^2 \frac{\sigma_{\parallel}}{\sigma_{\perp}} + \frac{kT_e}{m_e c^2} \frac{\partial n}{\partial x} \left( \mathbf{X}^T \right) \left( \mathbf{X} + \frac{1}{3} \frac{m_e c^2}{kT_e} \frac{\partial n}{\partial x} \right) .$$  

(A1)

In the escape time prescription provided by BW07, the spatial diffusion of photons is described by

$$\frac{1}{3} \frac{\partial n}{\partial \tau} = -\left( \frac{\xi_e}{c} \right)^2 \frac{\sigma_{\parallel}}{\sigma_{\perp}} n = \lambda^2 n ,$$  

(A2)

or, more clearly, by

$$\frac{1}{3} \frac{\partial n}{\partial \tau} = \frac{n}{r_0 n \sigma_{\parallel}} \frac{1}{\tau_{\parallel}} = \lambda^2 n ,$$  

(A3)

where $\tau_{\parallel} = \tau = n_0 \sigma_{\parallel} dZ$ is the optical depth along the $Z$-axis and $\tau_{\parallel} = n_0 \sigma_{\parallel} d\tau$ is the optical depth along the $\tau$-axis, perpendicular
to the magnetic field, and $\lambda$ is the eigenvalue. The right-hand side of equation (A2) can be approximated as

$$\left(\frac{10^2}{\tau_T}\right)^2 \left[ \frac{1}{3} - \frac{Z_0^2}{10^2 r_0^2} \right] n \approx \lambda^2 n,$$

(A4)

where $d\tau_T = n_e \sigma_T dZ$ and since the eigenvalue $\lambda^2 < 1$, the coefficient of $n$ on the right-hand side of equation (A3) should be less than 1, in order for diffusion approximation to hold. In particular, the coefficient $D_\parallel = \sigma_\parallel / (3\sigma_T^2)$ takes account the spatial diffusion of photons propagating along the magnetic field lines, while the coefficient $D_\perp = 1/(r_0 n_e \sigma_T^\perp)$ accounts for the diffusion of photon travelling perpendicular to the field.

Following the approach of BW07, from equation (A3) it follows that the diffusion approximation for photons propagating in the direction of the magnetic field is valid if the corresponding Thomson optical depth $\tau_T \gtrsim 10^2$. This can actually be the condition for a meaningful applicability of the COMPMAG model, together with the requirement that both the optical depths $\tau_\parallel$ and $\tau_\perp$ need to be larger than unity. From equation (A3), it is also evident that the ratio between the spatial diffusion in the $Z$-direction ($D_\parallel$) and that in the $r$-direction ($D_\perp$) depends upon the choice of the column size ($Z_0/r_0$).

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