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Supergiant fast X–ray transients: a review

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Abstract. We review the status of our knowledge on supergiant fast X–ray transients (SFXTs), a new hot topic in multi wavelength studies of binaries. We discuss the mechanisms believed to power these transients and then highlight the unique contribution *Swift* is giving to this field, and how new technology complements and sometimes changes the view of things.

Key words. X-rays: binaries – X-rays: individual: IGR J16479−4514, XTE J1739–302, IGR J17544−2619, AX J1841.0−0536

1. Introduction

The recognition of supergiant fast X-ray transients (SFXTs) as a new class of high-mass X–ray binaries is inevitably linked with the observations performed by *INTEGRAL* during its Galactic Plane survey, which started after the launch, in 2002.

As testified by the IBIS/ISGRI catalogue (Bird et al. 2007, and references therein) about a third of the catalogued objects are cataclysmic variables and low-mass X–ray binaries (CVs and LMXB are 13 % and 14 % of the total, respectively), 38 % are active galactic nuclei (AGNs), and about 35 % are high-mass X–ray binaries (HMXBs). Among the latter, several are intrinsically highly absorbed and were obviously more difficult to discover with previous missions (e.g. IGR J16318–4848, Walter et al. 2003). Others are the newly recognized class of HMXBs, the supergiant fast X–ray transients (SFXT), which constitute a new hot topic in multi-wavelength studies of binaries.

SFXTs are firmly associated with an O or B supergiant, and display outbursts which are significantly shorter than typical Be/X-ray binaries and which are characterized by bright flares with a duration of a few hours and peak luminosities of 10^{36}–10^{37} erg s^{-1} (Sguera et al. 2005; Negueruela et al. 2006). The quiescence, characterized by a soft spectrum (likely thermal) and a low luminosity at $\sim 10^{32}$ erg s^{-1} is a rarely-observed state (IGR J17544–2619, in't Zand 2005; IGR J08408–4503, Leyder et al. 2007) which, combined with the outburst luminosity, yields a very large dynamic range of 3–5 orders of magnitude. Their hard X–ray spectra resemble the typical shape of HMXBs hosting X–ray pulsars, with a flat hard power law below 10 keV, and a high energy cut-off at about 15–30 keV, sometimes strongly absorbed at soft energies (Walter et al. 2006; Sidoli et al.

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2006). As their spectral properties are similar to those of accreting pulsars, it is generally assumed that all members of the new class are HMXBs hosting a neutron star (NS), although the only SFXTs with a measured pulse period are AX J1841.0−0536 ($P_{\rm spin} \sim 4.7$ s, Bamba et al. 2001, IGR J16465–4507 ($P_{\rm spin} \sim 228$ s, Lutovinov et al. 2005), IGR J11215–5952 ($P_{\rm spin} \sim 187$ s, Swank et al. 2007), and IGR J18483–0311 ($P_{\rm spin} \sim 21$ s, Sguera et al. 2007). Currently, there are 10 confirmed members of the SFXTs class and ~20 more candidates which showed short transient flaring activity, but with no confirmed association with an OB supergiant companion. The field is rapidly evolving, so this number is bound to increase in the near future.

2. Outburst mechanisms

The mechanisms responsible for the observed short outbursts are still being debated. The proposed explanations (see Sidoli 2009, for a recent review) mainly involve the structure of the wind from the supergiant companion or the properties of the accreting NS.

1. **Spherically symmetric clumpy winds**. In the spherically symmetric clumpy wind model, the short flares in SFXTs are supposed to be produced by accretion of massive clumps (10^{22}–10^{23} g) in the supergiant winds (in't Zand 2005; Walter & Zurita Heras 2007; Negueruela et al. 2008), which are believed to be strongly inhomogeneous (Oskinova et al. 2007) with large density contrasts (10^4–10^5). In this model, the SFXTs should display wider orbits than persistent HMXBs.
2. **Equatorially enhanced wind.** Alternatively (Sidoli et al. 2007), the outbursts can be due to the presence of an equatorial wind component, denser, possibly clumpy, and slower than the symmetric polar wind from the blue supergiant, inclined with respect to the orbital plane of the system. The enhanced accretion rate occurring when the NS crosses this wind component can explain SFXTs showing periodic outbursts, such as IGR J11215–5952, as well as other SFXTs, by assuming different geometries of the equatorial wind. The recurrence in the outbursts from IGR J08408–4503 can indeed be explained within this model (Romano et al. 2009a).
3. **Gated mechanisms.** Other authors explain the high dynamic range in SFXTs with gated mechanisms (Grebenev & Sunyaev 2007; Bozzo et al. 2008) where the accretion is halted by a magnetic or a centrifugal barrier, dependent on the properties of the NS, its $P_{\rm spin}$ and its surface magnetic field B. In particular, Bozzo et al. (2008) conclude that SFXTs should host neutron stars with long $P_{\rm spin} \gtrsim 1000$ s and magnetar-like $B \gtrsim 10^{14}$ G fields.

3. Searching for the equatorial wind components in SFXTs with Swift

Thanks to *Swift*, for the very first time, we have the chance to give SFXTs non serendipitous attention throughout all phases of their life, by observing them during the bright outbursts, the intermediate intensity state, and the quiescence. In this section we report on the results of an entire year of intense monitoring campaign with *Swift* of a sub-sample of 4 SFXTs, IGR J16479–4514, XTE J1739–302, IGR J17544–2619, and AX J1841.0–0536, which were chosen as confirmed SFXTs, i.e. they display both a 'short' transient (and recurrent) X–ray activity and they have been optically identified with supergiant companions. XTE J1739–302 and IGR J17544−2619, are generally considered prototypical SFXTs AX J1841.0−0536/IGR J18410−0535, was chosen because at the time it was the only SFXT, in addition to IGR J11215–5952, where a pulsar had been detected (Bamba et al. 2001). Finally, IGR J16479−4514 had displayed in the past a more frequent X–ray outburst occurrence than other SFXTs (see, e.g. Walter & Zurita Heras 2007), and offered an *a priori* better chance to be caught during an outburst.

As part of our ongoing campaign, we obtained 2–3 observations ($\sim$ 1 ks long) per week

Table 1. Summary of the *Swift*/XRT monitoring campaign.

Name	Campaign Start –End ((yyyy-mm-dd)	Exposure[b] (N[a]) (ks)	Outburst[c] Dates (yyyy-mm-dd)	References
IGR J16479−4514	2007-10-26–2008-10-25	75.2 (70)	2008-03-19	Romano et al. (2008c)
			2008-05-21	
			2009-01-29	*Romano et al. (2009e), La Parola et al. (2009)*
XTE J1739−302	2007-10-27–2008-10-31	116.1 (95)	2008-04-08	Sidoli et al. (2009b)
			2008-08-13	Romano et al. (2008b), Sidoli et al. (2009a)
			2009-03-10	*Romano et al. (2009d)*
IGR J17544−2619	2007-10-28–2008-10-31	74.8 (77)	2007-11-08	Krimm et al. (2007)
			2008-03-31	Sidoli et al. (2009b)
			2008-09-04	Romano et al. (2008a), Sidoli et al. (2009a)
			2009-03-15	*Krimm et al. (2009)*
AX J1841.0−0536	2007-10-26–2008-11-15	96.5 (88)	none	
Total		362.6 (330)		

[a] Number of observations obtained during the monitoring campaign.
[b] *Swift*/XRT net exposure.
[c] BAT trigger dates. We report the outburst that occurred in 2009 in italics, for the sake of completeness.

per object. This observing pace naturally fits in the regular scheduling of γ-ray bursts, the main targets for *Swift*. Our goals were to fully characterize the long-term behavior of SFXTs, to determine the properties of their quiescent state (where the accumulation of large observing time is needed to allow a meaningful spectral analysis of this faintest emission), to monitor the onset of the outbursts, and to measure the outburst recurrence period(s) and duration.

During the first year (the program is still ongoing), we collected a total of 330 *Swift* observations, for a total net XRT exposure of $\sim$ 363 ks and distributed as shown in Table 1. The main results of this campaign can be found in Sidoli et al. (2008, Paper I, X-ray out-of-bright-outburst emission), Romano et al. (2008c, paper II, outburst of IGR J16479–4514), Sidoli et al. (2009b,a, Paper III and IV, outbursts of XTE J1739–302 and IGR J17544−2619), and Romano et al. (2009b, Paper V, first year results).

3.1. XRT light curves

In Fig. 1 we show the XRT 0.2–10 keV light curves collected from 2007 October 26 to 2008 November 15. Each point in the light curves refers to the average flux observed during each observation performed with XRT; the exception are the outbursts (listed in Table 1 and in Fig. 1) where the data were binned to include at least 20 source counts per time bin to best represent the count rate dynamical range.

3.2. Outbursts

We obtained multi-wavelength observations of 5 outbursts of 3 different sources (see Table 1) during this first year of monitoring. AX J1841.0−0536 is the only source which has not undergone a bright outburst, yet. The light curves are shown in Fig. 2. As reported in Romano et al. (2008c), Sidoli et al. (2009a), and Sidoli et al. (2009b), we ex-

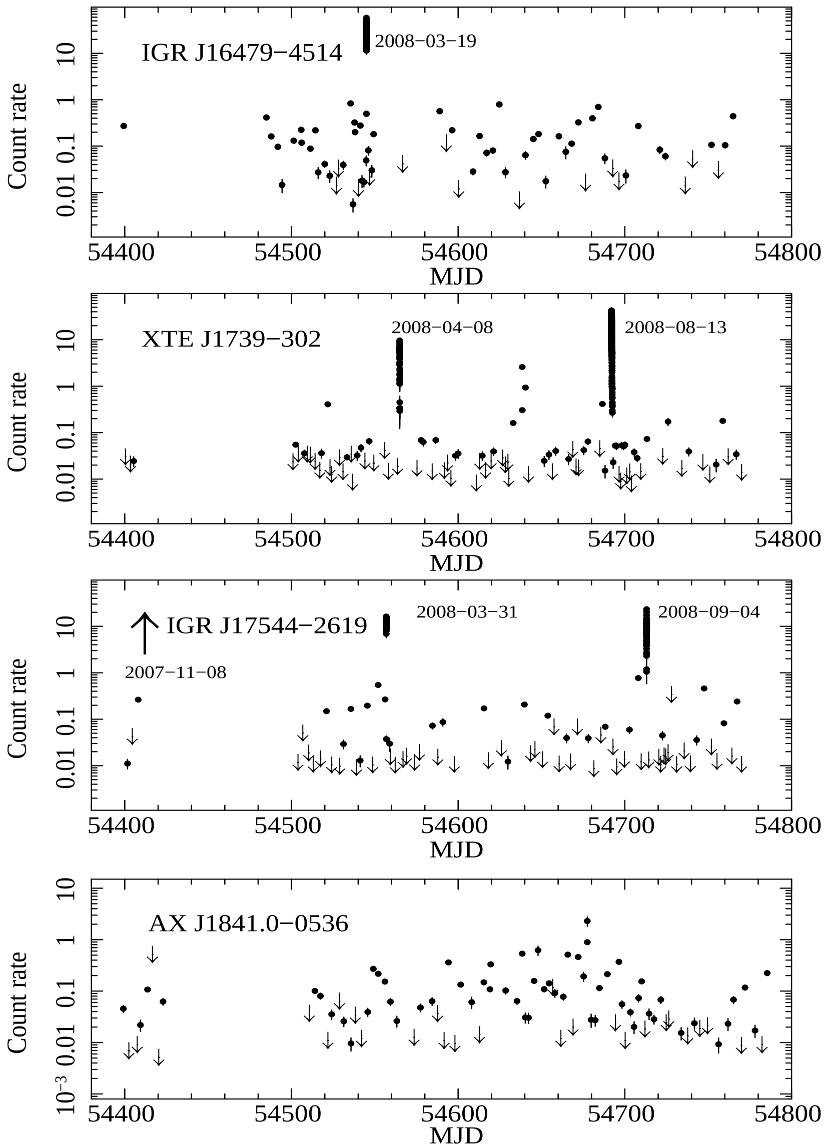

Fig. 1. *Swift*/XRT (0.2–10 keV) light curves, corrected for pile-up, PSF losses, vignetting and background-subtracted. The data were collected from 2007 October 26 to 2008 November 15. The downward-pointing arrows are 3-σ upper limits. The upward pointing arrow marks an outburst that triggered the BAT on MJD 54,414, but which could not be followed by XRT because the source was Sun-constrained for the XRT. Due to the sources being Sun-constrained between roughly 2007 December and 2008 January, depending on the target coordinates, no data were collected during those months. Adapted from Romano et al. (2009b).

Table 2. Spectroscopy of outbursts.

Parameter	IGR J16479−4514	IGR J17544−2619	XTE J1739−302
Date	2008-03-19	2008-03-31	2008-04-08
$N_{\rm H}^{\rm a}$ (10^{22} cm^{-2})	6.2 ± 0.5	1.1 ± 0.2	$12.5^{+1.5}_{-4.3}$
Γ	1.15 ± 0.14	0.75 ± 0.1	$1.4^{+0.5}_{-1.0}$
$E_{\rm cut}$ (keV)	6.6 ± 0.9	18 ± 2	6^{+6}_{-7}
$E_{\rm fold}$ (keV)	15.3 ± 2.5	4 ± 2	16^{+12}_{-8}
$L^{\rm b}_{0.5-10\,{\rm keV}}$	28	1.9	1.9
$L^{\rm b}_{0.5-100\,{\rm keV}}$	57	5.3	3
Reference	Romano et al. (2008c)	Sidoli et al. (2009b)	Sidoli et al. (2009b)

[b] In units of 10^{36} erg s^{-1}.

amined the broad-band simultaneous spectra (0.3–150 keV) of three SFXTs. They can be fit with absorbed cutoff power laws, which are models traditionally adopted for accreting X–ray pulsars even in the objects where proof of the presence of a neutron star (as derived from a spin period) is still unavailable. Considerable differences can be found in the behaviour of the absorbing column among the examined cases. In Table 2 we summarize the spectral fits of the first three outbursts we studied (Romano et al. 2008c; Sidoli et al. 2009a).

Individual sources behave somewhat differently; nevertheless, common X–ray characteristics of this class are emerging such as outburst lengths well in excess of hours, with a multiple peaked structure. We observed a high dynamic range (including bright outbursts) of $\sim$ 4 orders of magnitude in IGR J17544−2619 and XTE J1739−302, of $\sim$3 in IGR J16479−4514, and of about 2 in AX J1841.0−0536 (in the latter, due to the lack of bright flares).

3.3. Inactivity duty cycle

The light curves can be used not only to trace the activity states of these objects, but also their inactivity, since they represent a casual sampling of the flux state at an average resolution of $\sim$ 4 days. Therefore, we can determine how long each source spends in each state using a systematic monitoring with a sensitive instrument.

We define as *duty cycle of inactivity*, the time each source spends *undetected* down to a flux limit of $(1\text{–}3)\times10^{-12}$ erg cm^{-2} s^{-1} (the flux limit achieved for an exposure of 900 s)

$$\mathrm{IDC} = \Delta T_{\Sigma}/[\Delta T_{\rm tot}\,(1-P_{\rm short})]\,,$$

where ΔT_{Σ} is sum of the exposures accumulated in all observations, each in excess of 900 s, where only a 3-σ upper limit was achieved, $\Delta T_{\rm tot}$ is the total exposure accumulated (Table 1, column 5), and $P_{\rm short}$ is the percentage of time lost to short observations (exposure $<$ 900 s). We obtain that IDC $\sim$ $17, 28, 39, 55\,\%$, for IGR J16479−4514, AX J1841.0−0536, XTE J1739−302, and IGR J17544−2619, respectively, with an estimated error of $\sim$ 5 % on these values. Therefore, compared with estimates from less sensitive instruments, true quiescence, which is below our detection ability even with the exposures we collected in one year, is a relatively rare state. This demonstrates that these transients accrete matter throughout their lifetime at different rates.

3.4. Out-of-outburst emission

Our *Swift* monitoring campaign demonstrates for the first time that X–ray emission from SFXTs is still present outside the bright outbursts, although at a much lower level (10^{33}–

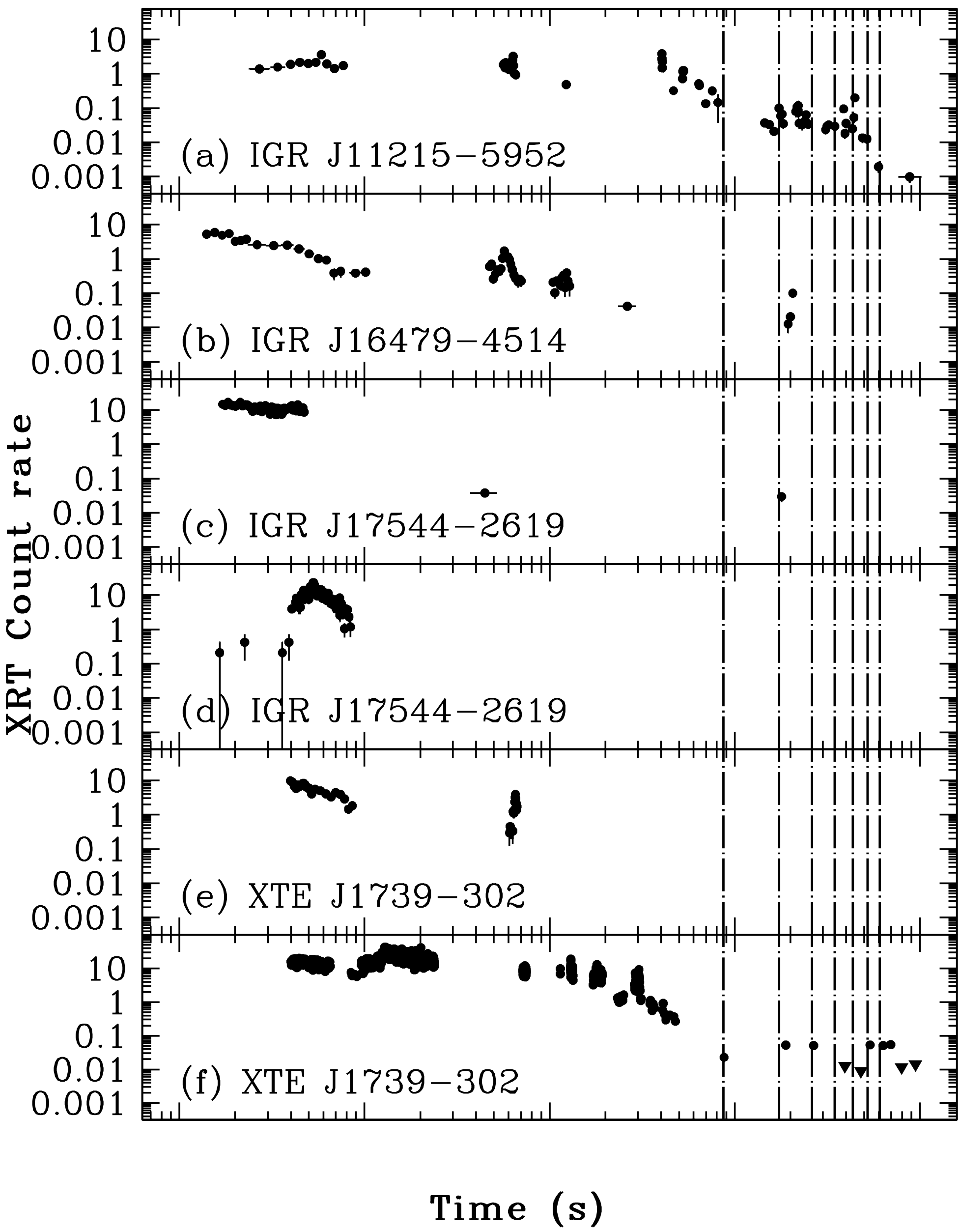

Fig. 2. *Swift*/XRT light curves of IGR J11215–5952 (a), IGR J16479−4514 (b), and of four of the outbursts observed during the observing campaign (see Table 1).

10^{34} erg s^{-1}). This was already emerging from the first four months of this campaign (Sidoli et al. 2008), but now we have accumulated enough statistics to allow intensity-selected spectroscopy of the out-of-outburst emission. When the spectra are fit with simple models (Fig. 3), such as an absorbed power law or a blackbody (more complex models were not required by the data), we obtain hard power law photon indices (always in the range $\Gamma \sim 0.8$–2) or hot black bodies ($kT_{BB} \sim 1$–2 keV). In particular, when a blackbody model is adopted, the resulting radii of the emitter for all 4 SFXTs (and all the intensity states) are always only a few hundred meters. This clearly indicates an emitting region which is only a fraction of the neutron star surface, and can be naturally associated with the polar caps of the neutron star, (Hickox et al. 2004). This evidence, coupled with the high level of flux variability and hard X–ray spectra, strongly supports the fact that the intermediate and low intensity level of SFXTs is produced by the accretion of matter onto the neutron star, demonstrating that SFXTs are sources which do not spend most of their lifetime in quiescence.

4. Conclusions

Let us review, as a conclusion, how each of the examined models for the outburst mechanisms fares when compared with the newly acquired *Swift* data.

1. **Clumping in spherically symmetric winds:** This model cannot explain the outburst periodicity and the light curve shape (width) of IGR J11215–5952. However, it could explain the low level of accretion at 10^{33} – 10^{34} erg s^{-1} outside the bright outburst assuming a distribution in the clump sizes or masses.
2. **Gated mechanism: SFXTs as magnetars:**
   These models can reproduce the *Chandra* observation of IGR J17544–2619 (in't Zand 2005) and need a variable wind mass loss rate. However, they also require both long spin periods (much shorter than the spin periods have been measured until now in 4 SFXTs) and magnetar magnetic fields (10^{14} – 10^{15} G, but cut-off power laws observed in our sample of SFXTs are compatible with low and more standard surface NS magnetic fields). Furthermore, they cannot explain on their own the periodic IGR J11215–5952.
3. **Equatorially enhanced wind:** This model explains the outburst periodicity and light curve shape observed in IGR J11215–5952 (Romano et al. 2007; Sidoli et al. 2007; Romano et al. 2009c). It also naturally explains the low level of accretion outside the bright outbursts as accretion from the polar wind component. Its key prediction is that the outburst recurrence should be periodic or almost periodic (or with a double/triple periodicity); alternatively, outbursts should be at least phase-locked, or concentrate preferentially in a particular orbital phase. Periodicities are starting to be found: we have indications of outbursts occurring every 11 and 24 days in IGR J08408–4503 (Romano et al. 2009a); a quasi-periodicity at $\sim$ 150 days was found in IGR J17544–2619 (Sidoli et al. 2009b); finally, IGR J18483–0311 shows a periodicity of 18.5 days (based on INTEGRAL data Sguera et al. 2007).
   For all other sources a longer monitoring is required since the expected orbital periods are in the order of months, and the picture could be much more complicated than in IGR J11215–5952.

5. DISCUSSION

JOERN WILMS: I would like to throw my weight behind the clumpy wind model. The reason is that we have seen behavior similar to that in SFXTs in HMXB. A key object is Vela X-1, where Staubert et al. and Kreykenbohm et al. have seen flares that look similar to SFXT flares. A clumpy wind model with an equatorial enhancement similar to that you suggest would be a good explanation for Vela X-1 as well, i.e., we'd get a sequence HMXB–Vela X-1-like sources–SFXTs.

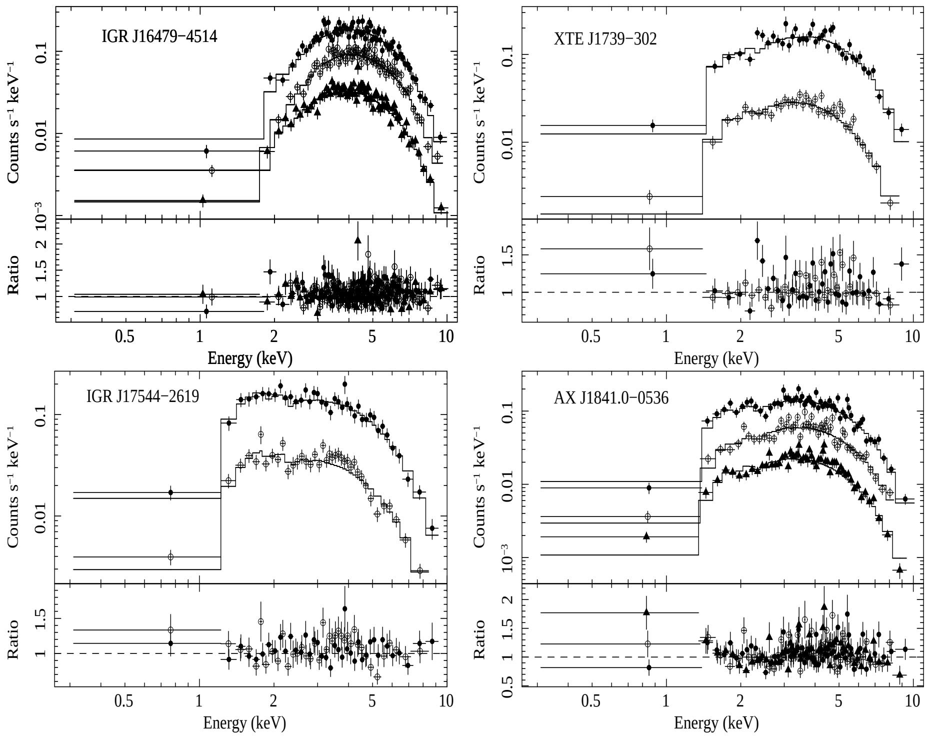

Fig. 3. Spectroscopy of the 2007-2008 *Swift* observing campaign. Upper panels: XRT/PC data fit with an absorbed power law. Lower panels: the data/model ratios. Filled circles, empty circles, and filled triangles mark high, medium, and low states, respectively.

P. ROMANO: I'm glad you mentioned this. Indeed, there is a nice paper by Lorenzo Ducci (Ducci et al. 2009), who developed a stellar wind model for OB supergiants with a distribution for the masses and initial dimensions of the clumps. This model, together with the Bondi–Hoyle theory of wind accretion modified to take into account the presence of clumps, allows us to compare with the observed properties of both the light curves and luminosity distributions of the flares in SGXBs and SFXTs. This model was successfully applied to three representative HMXBs: two persistent supergiant systems (Vela X–1 and 4U 1700–377) and the Supergiant Fast X-ray Transient IGR J11215–5952. For the latter source, we had to introduce a denser equatorial component (still with a clumpy structure) in order to reproduce the flare duration. So, I guess, we are moving in the same direction.

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