**INTEGRAL results on Supergiant Fast X–ray Transients and accretion mechanism interpretation: ionization effect and formation of transient accretion disks**

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**ABSTRACT**

We performed a systematic analysis of all INTEGRAL observations from 2003 to 2009 of 14 Supergiant Fast X–ray Transients (SFXTs), implying a net exposure time of about 30 Ms. For each source we obtained lightcurves and spectra (3–100 keV), discovering several new outbursts. We discuss the X–ray behaviour of SFXTs emerging from our analysis in the framework of the clumpy wind accretion mechanism we proposed (Ducci et al. 2009). We discuss the effect of X–ray photoionization on accretion in close binary systems like IGR J16479–4514 and IGR J17544–2619. We show that, because of X–ray photoionization, there is a high probability of formation of an accretion disk from capture of angular momentum in IGR J16479–4514, and we suggest that the formation of transient accretion disks could be responsible of part of the flaring activity in SFXTs with narrow orbits. We also propose an alternative way to explain the origin of flares with peculiar shapes observed in our analysis applying the model of Lamb et al. (1977), which is based on the accretion via Rayleigh–Taylor instability, and was originally proposed to explain type II bursts.

**Key words:** X–rays: binaries – X-rays: individuals: IGR J16479–4514, XTE J1739–302/IGR J17391–3021, AX J1841.0–0536/IGR J18410–0535, IGR J18483–0311, SAX J1818.6–1703, IGR J16418–4532, AX J1820.5–1434, AX J1845.0–0433, IGR J16195–4945, IGR J16207–5109, IGR J16465–4507, IGR J17407–2808, XTE J1743–363.

1 INTRODUCTION

Supergiant Fast X–ray Transients (SFXTs) are a sub-class of High Mass X–ray Binaries (HMXBs) discovered by the INTEGRAL satellite in the last seven years, during the Galactic plane monitoring (Sguera et al. 2005). SFXTs host an OB supergiant and an accreting compact object, and show a sporadically X–ray transient emission composed by many flares reaching a luminosity of $10^{36}–10^{37}$ erg s$^{-1}$, with flare durations of $\sim 10^3–10^4$ s. For most of their lifetime, SFXTs accrete at an intermediate level, showing an X–ray luminosity of $10^{33}–10^{34}$ erg s$^{-1}$, as discovered by the Swift/XRT monitoring (see e.g. Sidoli et al. 2008, Romano et al. 2009). The quiescent level (about $10^{32}$ erg s$^{-1}$) has been observed only in a few sources (see in't Zand 2005, Levdner et al. 2007, Bozzo et al. 2010). Thus SFXTs show a large dynamic range of about $10^{3}–10^{6}$. Many accretion mechanisms have been proposed to explain the transient behaviour. in’t Zand (2005) suggested that the large dynamic range could be produced by the accretion of dense clumps from the donor wind. Sidoli et al. (2007) invoked the presence of an equatorial wind component, denser than the polar wind component and inclined with respect to the orbital plane of the compact object to explain the transient periodic emission of IGR J11215–5952. Bozzo, Falanga & Stella (2008a) proposed that SFXTs host a magnetar with large spin period ($\sim 10^3$ s): the changes in X–ray luminosity are ascribed to the gated accretion mechanisms, where changes in the reciprocal positions of accretion, magnetospheric and corotation radii lead to different accretion regimes.

In this paper we report the results from the analysis of INTEGRAL data of 14 SFXTs, for a total exposure time of $\sim 30$ Ms. The results obtained here are discussed considering the structure of the clumpy supergiant winds (Ducci et al. 2009), the effect of X–ray photoionization of the outflowing wind by the compact object (in the framework of the Ho & Arons 1987 accretion model), and the possible formation of transient accretion disks, as those proposed by Taam, Brown & Fryxell (1988) to reproduce the flares from EXO 2030+375.

2 OBSERVATIONS AND DATA ANALYSIS

The INTEGRAL observatory, launched in October 2002, carries 3 co-aligned coded mask telescopes: the imager IBIS (Imager on
Figure 1. IBIS/ISGRI lightcurves of IGR J16479−4514, XTE J1739−302, IGR J17544−2619, AX J1841.0−0536 (20−40 keV). A binned time corresponding to the ScW duration (∼2000 s) has been used.

Table 1. Total exposure time $T_{\text{exp}}$, duration and number of ScWs where the source is detected with a significance greater than 5.

| Source               | $T_{\text{exp}}$ (d) | Duration (d) | # ScWs $S/N > 5$ | # Outbursts $S/N > 5$ |
|----------------------|-----------------------|--------------|------------------|-----------------------|
| IGR J16479-4514      | 115.74                | 3.19         | 107              | 38                    |
| XTE J1739-302        | 260.42                | 2.16         | 65               | 18                    |
| IGR J17544-2619      | 259.92                | 1.33         | 43               | 14                    |
| AX J1841.0-0536      | 83.23                 | 0.41         | 16               | 4                     |
| IGR J18483-0311      | 84.61                 | 2.68         | 90               | 13                    |
| SAX J1818.6-1703     | 179.45                | 1.08         | 34               | 11                    |
| IGR J16418-4532      | 112.87                | 1.45         | 40               | 23                    |
| AX J1820.5-1434      | 120.95                | 0.09         | 4                | 2                     |
| AX J1845.0-0433      | 77.85                 | 0.21         | 7                | 7                     |
| IGR J16195-4945      | 105.22                | 0.14         | 4                | 3                     |
| IGR J16207-5129      | 101.67                | 0.48         | 15               | 9                     |
| IGR J16465-4507      | 110.25                | 0.27         | 10               | 2                     |
| IGR J17407-2088      | 234.75                | 0.12         | 4                | 3                     |
| XTE J1743-363        | 232.04                | 0.48         | 20               | 7                     |

Board the INTEGRAL satellite; Ubertini et al. 2003, sensitive in the energy range 15 keV to 10 MeV, the spectrometer SPI (SPectrometer on INTEGRAL, 20 keV−8 MeV; Vedrenne et al. 2003), and the two X-ray monitors JEM-X1 and JEM-X2 (Joint European X−ray Monitor; Lund et al. 2003), sensitive in the energy range 3−35 keV. IBIS is composed of the low-energy detector ISGRI (INTEGRAL Soft Gamma Ray Instrument; 15−600 keV; Lebrun et al. 2003) and the CsI layer PICsIT (Pixellated Imaging Caesium Iodide Telescope; 175 keV−10 MeV; Labanti et al. 2003). INTEGRAL observations are divided in pointings called Science Windows (ScWs), which have a typical exposure of 2 ks.

We analysed all the public and our private data, between 2003 and 2009, where the SFXTs IGR J16479−4514, XTE J1739−302, AX J1841.0−0536 and IGR J17544−2619 were within 15$^\circ$ from the center of the field of view. This resulted in 14426 Science Windows, corresponding to a total exposure time of ∼30 Ms. We considered in our analysis also the other SFXTs (and candidate SFXTs) observed in the ScWs selected (see Table 1). We analysed IBIS/ISGRI and JEM-X data using the Off-line Scientific Analysis package OSA 8.0 (Goldwurm et al. 2003). For the spectral analysis, which was performed with XSPEC (ver. 11.3), we added a 2% systematic error to both IBIS/ISGRI and JEM-X data sets.

For each source reported in Table 1 we extracted the IBIS/ISGRI lightcurve at a ScW time resolution (∼2000 s), in the energy range 20−40 keV, and we considered only the pointings where the sources are detected with at least a 5σ significance. For each source, Table 1 reports the number of out-
burst[1] we identified. For each outburst observed, we also extracted IBIS/ISGRI lightcurves (18–60 keV) with a bin time of 50 s, and an IBIS/ISGRI spectrum in the energy range 18–100 keV. We found that the outbursts are characterized by a flaring activity, typical of SFXTs. Due to its smaller field of view, we were able to extract the JEM-X spectra in only a few pointings.

3 RESULTS

With IBIS/ISGRI we discovered several previously unnoticed outbursts from XTE J1739–302, IGR J16479–4514, IGR J17544–2619, IGR J18483–0311, AX J1845.0–0433, IGR J16195–4945, IGR J16465–4507, IGR J17407–2808, IGR J16207–5129, and IGR J16418–4532. We reported these outbursts in Table 2 and 3, together with the mean flux and best fit parameters of the IBIS/ISGRI spectra.

Figure 1 displays the 20–40 keV IBIS/ISGRI lightcurves of IGR J16479–4514, XTE J1739–302, IGR J17544–2619 and AX J1841.0–0536 collected from 2003 to 2009, where each “detection” refers to the average flux observed during each ScW, when the sources are detected at a significance > 5σ. Solid boxes represent the observations where the sources are not detected (< 5σ). For most of the time each source is not significantly detected.
The results of our analysis of all available age JEM-X spectrum for AX J1841.0−0536 (see Table 2), and residuals (lowest panels) in units of standard deviations. No evidence of spectral variability has been found between different outbursts of these four SFXTs. To achieve the best statistics, we extracted an average JEM-X spectrum for each source (Figures 2 and 3). We did not extract an average JEM-X spectrum for AX J1841.0−0536 because we detected the source only in one pointing, with a low flux. The models which best fit the average spectra are reported in Table 2.

3.1 Clumpy wind in IGR J16479−4514

The results of our analysis of all available INTEGRAL observations of SFXTs can be compared with quantitative expectations from our new clumpy wind model (Ducci et al. 2009). A meaningful comparison can be performed only in SFXTs where a large number of flares has been observed. For this reason we will concentrate only on IGR J16479−4514. In order to apply the model, we have to establish the stellar parameters of the system and to confirm the eclipse duration.

In Figure 4 we show the IBIS/ISGRI ScWs where IGR J16479−4514 has been detected in outburst, folded on the orbital period of the system assuming a zero time \( t_0 = 54546.742 \text{ MJD} \) (Bozzo et al. 2008b). This histogram is consistent with the presence of an eclipse with duration \( \Delta t \approx 0.6 \) d (Jain, Paul & Dutta 2009).

The Roche Lobe radius \( R_L \) of IGR J16479−4514, adopting...
the approximated formula obtained by Egele (1983), is the following:

$$R_L = \alpha \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})} \quad 0 < q < \infty$$

where $\alpha$ is the orbital separation, $q = M_p/M_\ast$ is the mass ra-

### Table 3. Summary of the new flares discovered of 3 candidate SFXTs (IBIS/ISGRI data). We fitted the spectra with a powerlaw or a bremsstrahlung model.

| Source        | Date (UTC)          | Mean Flux (erg cm$^{-2}$ s$^{-1}$) | $kT$ (keV)$\Gamma$  | $\chi^2$ (d.o.f.) |
|---------------|---------------------|-----------------------------------|---------------------|--------------------|
| IGR J17407-2808 | 2003 Sep. 21, 04:27–04:29 | $2.6 \times 10^{-9}$ | $kT = 44^{+35}_{-16}$ $\Gamma = 1.9^{+0.3}_{-0.3}$ | 1.38 (10) |
|               | 2006 Sep. 20, 12:18–13:47 | $4.9 \times 10^{-10}$ | $\Gamma = 1.9^{+0.3}_{-0.3}$ | 0.55 (14) |
| IGR J16207-5129 | 2004 Jan. 21, 09:23–09:56 | $5.8 \times 10^{-10}$ | $kT = 38^{+81}_{-17}$ $\Gamma = 1.8^{+0.8}_{-0.8}$ | 1.37 (10) |
|               | 2005 Feb. 07, 06:48–07:45 | $2.0 \times 10^{-10}$ | $kT = 30^{+94}_{-16}$ $\Gamma = 1.8^{+0.8}_{-0.8}$ | 0.69 (11) |
|               | 2005 Feb. 11, 03:04–04:01 | $2.2 \times 10^{-10}$ | $\Gamma = 2.0^{+0.9}_{-0.9}$ | 0.78 (10) |
|               | 2005 Feb. 13, 10:59–11:56 | $2.2 \times 10^{-10}$ | $\Gamma = 1.8^{+0.8}_{-0.8}$ | 1.06 (10) |
|               | 2005 Feb. 18, 22:41–19, 01:41 | $3.2 \times 10^{-10}$ | $\Gamma = 2.2^{+0.8}_{-0.8}$ | 1.06 (11) |
| IGR J16418-4532 | 2003 Feb. 3, 12:37–13:13 | $4.6 \times 10^{-10}$ | $\Gamma = 1.8^{+1.2}_{-0.9}$ | 1.07 (5) |
|               | 2003 Mar. 4, 21:39–22:07 | $2.1 \times 10^{-10}$ | $kT = 15^{+16}_{-10}$ | 1.12 (14) |
|               | 2004 Feb. 18, 03:42–04:16 | $3.0 \times 10^{-10}$ | $\Gamma = 3.2^{+1.2}_{-0.9}$ | 1.75 (14) |
|               | 2004 Mar. 20, 21:27–21, 11:24 | $2.5 \times 10^{-10}$ | $\Gamma = 3.0^{+0.7}_{-0.6}$ | 0.96 (14) |
|               | 2004 Aug. 9, 13:57–14:56 | $1.9 \times 10^{-10}$ | $\Gamma = 2.7^{+1.0}_{-0.9}$ | 0.70 (14) |
|               | 2004 Aug. 24, 13:32–14:56 | $2.0 \times 10^{-10}$ | $kT = 20^{+4.2}_{-1.2}$ | 1.00 (14) |
|               | 2005 Feb. 13, 02:17–15:02 | $1.6 \times 10^{-10}$ | $\Gamma = 15^{+16}_{-10}$ | 1.34 (14) |
|               | 2005 Feb. 22, 04:54–06:14 | $1.5 \times 10^{-10}$ | $kT = 22^{+23}_{-10}$ | 1.13 (14) |
|               | 2005 Feb. 24, 09:20–09:10 | $1.3 \times 10^{-10}$ | $\Gamma = 2.8^{+1.1}_{-0.9}$ | 0.87 (14) |
|               | 2005 Feb. 27, 05:41–Mar. 1, 12:09 | $1.9 \times 10^{-10}$ | $kT = 21^{+17}_{-10}$ | 1.02 (14) |
|               | 2005 Mar. 8, 04:35–05:35 | $3.2 \times 10^{-10}$ | $kT = 14^{+8}_{-4}$ | 1.16 (14) |
|               | 2005 Mar. 18, 14:09–14:42 | $1.3 \times 10^{-10}$ | $\Gamma = 4.2^{+3}_{-1.4}$ | 0.62 (7) |
|               | 2005 Aug. 26, 18:08–27, 08:56 | $2.5 \times 10^{-10}$ | $kT = 28^{+13}_{-10}$ | 1.16 (14) |
|               | 2005 Oct. 2, 00:32–01:15 | $3.6 \times 10^{-10}$ | $\Gamma = 2.6^{+1.6}_{-1.4}$ | 0.76 (8) |
|               | 2006 Aug. 13, 23:48–14, 21:01 | $2.9 \times 10^{-10}$ | $kT = 20^{+16}_{-10}$ | 1.65 (14) |
|               | 2007 Feb. 19, 03:58–04:39 | $3.9 \times 10^{-10}$ | $\Gamma = 2.3^{+0.9}_{-0.8}$ | 0.74 (8) |
|               | 2007 Mar. 15, 04:43–05:27 | $5.4 \times 10^{-10}$ | $kT = 15^{+12}_{-10}$ | 1.48 (8) |
|               | 2007 Mar. 30, 02:19–03:01 | $3.0 \times 10^{-10}$ | $\Gamma = 2.0^{+1.9}_{-1.6}$ | 0.87 (5) |
|               | 2009 Apr. 7, 10:15–10:43 | $4.8 \times 10^{-10}$ | $\Gamma = 2.8^{+0.9}_{-0.9}$ | 0.92 (10) |
|               | 2009 Apr. 7, 21:13–21:41 | $4.1 \times 10^{-10}$ | $\Gamma = 2.28^{+0.99}_{-0.91}$ | 1.22 (9) |

### Table 4. Best fit parameters of the average spectra of IGR J16479–4514, XTE J1739–302, and IGR J17544–2619 observed with JEM-X and IBIS/ISGRI (see Figure 2), and best fit parameters of the average spectrum of AX J1841.0–0536 observed with IBIS/ISGRI (see Figure 3). $\Gamma$ is the powerlaw photon index, $E_c$ is the cutoff energy, $E_F$ is the e-folding energy.

| Source        | Fit model                          | $N_H$ (10$^{22}$ cm$^{-2}$) | $\Gamma$ | $E_c$, $E_F$ (keV) | $\chi^2$ (d.o.f.) |
|---------------|------------------------------------|-------------------------------|----------|-------------------|--------------------|
| JEM-X & IBIS/ISGRI | cutoff-powerlaw                   |                               |          |                   |                    |
| IGR J16479-4514 | cutoff-powerlaw                   | $25^{+17}_{-13}$              | $1.2^{+0.4}_{-0.4}$ | $E_c = 25.1^{+12}_{-10}$ | 0.90 (23) |
| XTE J1739-302  | cutoff-powerlaw                   | $8.6^{+7.4}_{-1.6}$           | $1.6^{+0.2}_{-0.2}$ | $E_c = 26.5^{+6.5}_{-4.7}$ | 1.12 (45) |
| IGR J17544-2619| powerlaw with high-energy cutoff   | $0.2^{+0.8}_{-0.15}$          | $1.1^{+0.3}_{-0.1}$ | $E_c = 19.7^{+5.5}_{-4.7}$ | 1.03 (27) |
| IBIS/ISGRI    | powerlaw                          |                               |          |                   |                    |
| AX J1841.0–0536| powerlaw                          |                               |          |                   | 1.20 (10) |

$M_p$ is the mass of the primary star (i.e. the supergiant star), and $M_\ast$ is the mass of the compact object.
mass $M_\text{f} = 31 M_\odot$ and radius $R_\text{f} = 19 R_\odot$. This set of parameters is in agreement with the expected values for a O8.5I star (e.g. Martins, Schaerer & Hillier 2005, Vacca, Garmany & Shull 1996), and excludes the Roche Lobe overflow. However, we point out that other parameters for $M_\text{cl}$, $P_\text{p}$, and $R_\text{p}$ are allowed.

We applied our clumpy wind model in its spherical configuration (Ducci et al. 2009) to the IBIS/ISGRI observations of IGR J16479−4514, for which we have a significant number of flares ($N_\text{f} = 80$). We will apply this model to the other SFXTs in a future work, when the number of their flares will be enough. Our model assumes that a fraction $f$ of the mass lost by the supergiant wind is in form of clumps ($f = M_\text{cl}/M_\text{sec}$). The clumps are assumed to follow a power-law mass distribution $p(M_\text{cl}) \propto M_\text{cl}^{-\alpha}$ in the mass range $M_\text{a} - M_\text{b}$, a power-law radius distribution $N \propto R_\text{cl}^{-\beta}$, and a $\beta$-velocity law (see Ducci et al. 2009 for details).

We compared the observed and calculated number of flares, their luminosity distribution, the X-ray luminosity outside flares and the average time duration of flares.

For each of the 80 flares found, we derived the peak luminosity in the energy range $1 - 100$ keV by means of the spectral parameters found by fitting simultaneously the IBIS/ISGRI and JEM-X data (see Table 3). The luminosity ($1 - 100$ keV) outside flares is $L_{\text{out-flares}} \lesssim 10^{36}$ erg s$^{-1}$ (Sguera et al. 2008).

Figure 5 shows the comparison between the observed and calculated distributions of flare luminosities which results in the best agreement. The wind parameters obtained are reported in Table 5 with $M = 10^{-7} M_\odot$ yr$^{-1}$, $v_\infty = 1800$ km s$^{-1}$, $\beta = 1$, $M_\text{a} = 5 \times 10^{18}$ g, $M_\text{b} = 5 \times 10^{21}$ g, $\zeta = 1.1$, $f = 0.5$, $\gamma = -4$, and, since $T_{\text{eff}} = 34000$ K, the multiplier parameters adopted from Shimada et al. (1994) are: $k = 0.375$, $\alpha = 0.522$, $\delta = 0.099$ (see Ducci et al. 2009 for details). With this set of wind parameters we are able also to reproduce the observed X-ray luminosity outside bright flares and the average flare duration.

Figure 6 shows the comparison between observed (solid line) and calculated (dashed line) distributions of the flare luminosities of IGR J16479−4514.

\[ \zeta=1.1, \gamma=-4, f=0.5 \]

\[ L_x \propto n(r_\xi) R_\xi^2 \]

\[ \xi \equiv \frac{L_x}{n(r_\xi) R_\xi^2} \]

\[ (2) \]

4 DISCUSSION

The wind parameters obtained for IGR J16479−4514 in section 3.1 are in agreement with those of the sources previously studied (see Ducci et al. 2009, Romano et al. 2010, with the exception of $f$ ($f = 0.75$ for the other persistent HMXBs and SFXTs). Moreover, the mass loss rate found for IGR J16479−4514 ($M = 10^{-7} M_\odot$ yr$^{-1}$) is lower if compared to the typical mass loss rate from a O8.5I star, which is of the order of $M \approx 4 \times 10^{-6} M_\odot$ yr$^{-1}$ (see Table 5). This difference could be due to the fact that the mass loss rates derived from homogeneous-wind model measurements with the Hα method are overestimated by a factor 2-10 if the wind is clumpy (see e.g. Lépine & Moffat 2008, Hamann, Feldmeier & Oskinova 2008). Another possibility is that the X-ray flaring behaviour in IGR J16479−4514 is not totally due to the accretion of clumps, but other mechanisms could be at work, like, e.g. the centrifugal inhibition of accretion, the formation of transient accretion disks, or the Rayleigh–Taylor instability. The role of these mechanisms in SFXTs will be treated in this section.

4.1 X-ray photoionization

4.1.1 Direct accretion

Here we discuss the effects of X-ray photoionization on the mass transfer onto a neutron star in a close binary system, modifying the analytic model by Ho & Arons (1987) and applying it to SFXTs.

In HMXBs, the wind reaching the compact object is overionized by the X-ray photons produced by the compact object (Hatchett & McCray 1977). This high ionization alters the dynamics of the line-driven stellar wind of the primary: the wind becomes highly ionized and does not interact anymore with the UV photons emitted by the primary, which drive the wind. Hence, the wind velocity and density around the neutron star is different from what expected neglecting the X-ray photoionization. The accretion onto the compact object is modified accordingly since it depends onto the wind velocity.

For a source with a X-ray luminosity $L_x$, the ionization state $\xi$ of the wind at a radius $R_\xi$ is defined by:

\[ \xi \equiv \frac{L_x}{n(r_\xi) R_\xi^2} \]
where \( n(r_\xi) \) is the particle number density at a distance \( r_\xi = D - R_\xi \) from the supergiant (see Figure 7). The parameter \( \xi \) defined in equation 3 determines the thermal and ionic state of the gas, assuming optically thin gas in thermal balance (see Tarter, Tucker & Salpeter 1969).

Several attempts have been made to include the effects of X-ray ionization in the accretion of HMXBs (e.g. Ho & Arons 1987; MacGregor & Vitello 1982; Blondin et al. 1990; Stevens & Kallman 1990; Stevens 1991). Here we adopt the analytic model developed by Ho & Arons (1987). They assumed a spherically symmetric wind, ionized by the X-rays from the compact object. They assumed that the radiation line force is turned off at \( \xi_e = 10^4 \) erg cm\(^{-1}\) s\(^{-1}\). Thus, the wind follows the standard \( \beta \)-velocity law (with \( \beta = 0.5 \)) up to a distance \( R_\xi \) from the compact object such that \( L_\xi / n(\xi_e) R^2_\xi = \xi_e \), i.e. where the wind is sufficiently ionized to become transparent to the UV photons. Inside this sphere with the neutron star in the centre, the radiation force (Kudritzki & Puls 2000) is turned off and the wind velocity is assumed constant. The wind velocity will be lower in the vicinity of the compact object (with respect to the non-ionized case), leading to an enhancement of the mass accretion rate. With these assumptions, Ho & Arons (1987) developed a model to describe the accretion of the wind, taking into account the feedback effect of the X-rays which ionize the wind, and consequently controls the mass transfer onto the compact object.

We propose the following important changes to this model:

(i) a generic \( \beta \)-velocity law, with \( \beta \) not fixed;
(ii) we consider the orbital velocity of the neutron star in the calculations, which cannot be neglected in close binary systems such as IGR J16479−4514 (\( P_{\text{orb}} = 3.32 \) d; Jain et al. 2009);
(iii) we modified the equations developed by Ho & Arons (1987) to take into account the possibility that the mass loss rate towards the neutron star is reduced because of the high ionization state of the wind, which reduces the radiative acceleration given by the absorption and re-emission of UV photons (emitted by the supergiant) in the resonance lines of ions forming the wind. Assuming for the wind particles a velocity distribution centered on \( v_w(r_\xi) \) (equation 3), a part of them may decelerate enough not to be able to reach the neutron star;

(iv) a force cutoff value \( \xi_{\text{cs}} = 3 \times 10^2 \) erg cm\(^{-1}\) s\(^{-1}\) (Stevens 1991).

We assumed the standard wind velocity law obtained from the radiation line-driven mechanism of Castor, Abbott & Klein (1975):

\[
v_w(r_\xi) = v_\infty \left( \frac{r_\xi}{r_\xi + \beta} \right)^\beta
\]

where \( r_\xi \) is the distance from the primary (see Figure 7), and \( v_\infty \) is the terminal velocity.

In wind-fed systems, the mass accretion rate is defined as the flux of matter passing through a circular area with radius \( R_a \), and is written as:

\[
M_{\text{accr}} = \frac{\dot{M}}{4\pi D^2 v_w} \pi R^2_a
\]

where \( \dot{M} \) is the wind mass loss rate from the supergiant, the factor contained in square brackets is the stellar wind flux at a distance \( D \) from the primary, \( v_w = \sqrt{v^2_\infty + v^2_{\text{orb}}} \) is the relative velocity between the wind and the neutron star, and \( R_a \) is the accretion radius, defined as:

\[
R_a = \frac{2GM_\xi}{v^2_{\text{rel}} + c^2}
\]

where \( M_\xi = 1.4 M_\odot \) is the mass of the neutron star and \( c_\xi \) is the sound velocity. Hence, the accretion luminosity, given by equations 3, 4, 5 is:

\[
L_x = \frac{GM_\xi M_{\text{accr}}}{R_a} = \frac{(GM_\xi)^3}{R_a} \frac{\dot{M}}{D^2 v_w(r_\xi)} \frac{1}{(v^2_{\text{rel}} + c^2)^{3/2}}
\]

where \( R_\xi \) is the distance from the primary to the neutron star, and \( v_\text{rel} \) is the relative velocity between the wind and the neutron star.

The radius \( r_{\text{lim}} \) where the sum of the radiation force \( g_r \) due to scattering of continuum photons by free electrons, and the gravitational forces of the primary and neutron star acting on a parcel of the wind is zero (see Figure 9) can be derived as follows:

\[
\frac{GM_\xi}{r_{\text{lim}}^2} (1 - \Gamma_e) = \frac{GM_\xi}{(D - r_{\text{lim}})^2}
\]

where \( \Gamma_e \) is defined as:

\[
\Gamma_e = \frac{\sigma T_\text{p}}{4\pi GM_\xi}
\]

is obtained from the formula of the force due to electron scattering:
where \( \sigma_c \) is the opacity for electron scattering, assumed to be equal to \( \sim 0.3 \text{ cm}^2 \text{ g}^{-1} \) and constant, as suggested by Lamers & Cassinelli (1999).

When the radiation force is turned off, a parcel of gas is only subject to the gravitational force of the two stars and to the force due to electron scattering. Assuming that this parcel of gas reaches the distance \( r_{\text{lim}} \) with null velocity, the initial velocity can be obtained from the momentum equation:

\[
\frac{dv}{dr} = -\frac{GM_e}{r^2} (1 - \Gamma_e) + \frac{GM_e}{(D - r)^2}.
\] (10)

For a particle starting at a distance \( r \), with velocity \( v \), the solution obtained from equation (10) is:

\[
\int_0^r v dv = -\int_{r_{\text{lim}}}^r \frac{GM_e}{r^2} (1 - \Gamma_e) dr' + \int_{r_{\text{lim}}}^r \frac{GM_e}{(D - r')^2} dr'.
\] (11)

Thus:

\[
v_{\text{lim}}(r) = \left[ -2GM_e(1 - \Gamma_e) \left( \frac{1}{r_{\text{lim}}} - \frac{1}{r} \right) - 2GM_e \left( \frac{1}{D} - \frac{1}{r_{\text{lim}}} - \frac{1}{D - r} \right) \right]^{1/2}.
\] (12)

The wind particles have a temperature of \( \approx 10^5 \) K (Lamers & Cassinelli 1999). Assuming for the particles velocity, at a distance \( r \) from the primary, a gaussian distribution centered on \( v_{\infty}(1 - R_p/r)^{\beta} \) with \( \sigma_c \approx 10^{7} \text{ cm s}^{-1} \), it is possible to calculate the density probability to have particles with \( v \) at \( r = r_c \):

\[
S = \frac{1}{\sqrt{2\pi}\sigma_c} \int_{r_{\text{lim}}}^{r_{\infty}} \frac{(v - v_d)^2}{2\sigma_c^2} dv.
\] (13)

where \( v_d \) is given by equation (3).

We now propose a new version of the self-consistent steady state equation developed by Ho & Arons (1987), improved with the considerations described above. The accretion luminosity \( L_a \) from equations (3), (6), and (13) is then:

\[
L_a(r_c) = \frac{(GM_e)^3}{R_x} \frac{M_S(r_c)}{D^2
\int_{r_{\text{lim}}}^{r_{\infty}} \left(1 - R_p/r_c\right)^{\beta} \left(\frac{v_{\text{rel}}}{c_{\text{esc}}} + \frac{c_{\text{esc}}}{c_{\text{esc}}}\right)^{\beta}/2}
\] (14)

which we call, following the nomenclature of Ho & Arons (1987), the accretion equation. Then we obtain the feedback equation from equations (3), (6), (13):

\[
\frac{L_b(r_c)}{\xi_c} = \frac{MS(r_c)}{4\pi c^2 m_p c_{\text{esc}}(1 - R_p/r_c)^\beta}
\] (15)

where \( \mu \) is the mean atomic weight. The steady state solution is given by: \( L_a(r_c) = L_b(r_c) \), thus, by equating equations (14) and (15), it is possible to obtain the X-ray luminosity \( L_x \) and the corresponding Strömgren radius \( r_c \).

We assume for the force cutoff value \( \xi_c = 3 \times 10^2 \text{ erg cm}^{-2} \text{ s}^{-1} \), which is two orders of magnitude smaller than the value considered by Ho & Arons (1987), but in agreement with the calculations of Stevens (1991), who found that for this value the wind material is already basically completely ionized.

We calculate the X-ray luminosity and \( r_c \) of IGR J16479−4514 from the steady state solution obtained from equations (14) and (15), assuming the parameters reported in Table 5. We obtain an expected luminosity of \( L_x \approx 10^{37} \text{ erg s}^{-1} \), reached by the neutron star when \( r_c \approx 1.33 \times 10^{12} \text{ cm} \). This luminosity level is in agreement with the peak flare luminosities observed. However, IGR J16479−4514 has an out-of-flare luminosity of the order of \( 10^{34} - 10^{35} \text{ erg s}^{-1} \) (Sidoli et al. 2008). This luminosity level can be obtained possibly invoking the presence of the centrifugal inhibition of accretion.

For IGR J17544−2619 we assumed the system parameters suggested by Clark et al. (2009), with eccentricity \( e = 0.4 \). We found that the X-ray photoionization acts to increase the difference in luminosity when the neutron star is at periastron \( (L_x \approx 10^{37} \text{ erg s}^{-1} \) and apastron \( (L_x \approx 10^{35} \text{ erg s}^{-1} \), see Table 6. In fact, at periastron the wind is highly ionized by the X-ray sources \( (r_c \approx 0.9 \times 10^{12} \text{ cm} \), leading to a low wind velocity in the vicinity of the neutron star \( (v_{\text{rel}} \approx 230 \text{ km s}^{-1} \) and accordingly to a higher X-ray luminosity (since \( L_x \propto v_{\text{rel}}^3 \)). At apastron the ionization is lower \( (r_c \approx 3.3 \times 10^{12} \text{ cm} \), therefore its effect on the wind velocity is small \( (v_{\text{rel}} \approx 1400 \text{ km s}^{-1} \).

### 4.1.2 Centrifugal inhibition of accretion

In this section we apply for the first time the centrifugal inhibition (c.i.) of accretion to the modified model of Ho & Arons (1987) described in section 4.1.1.

The magnetospheric radius \( R_m \) is defined as the radius where the magnetic field pressure \( B^2(R_m)/8\pi \) equals the ram pressure of the accreting plasma \( c_{\text{esc}}^2(R_m) \). We use the definition obtained by Davidson & Ostriker (1973):

\[
R_m(r_c) = \sqrt[3/2]{\frac{B_c^2 R_0^6}{4M_{\text{acc}} (GM_e)^{3/2}}}.
\] (16)
where $B_0$ is the surface magnetic field. When $R_m \gtrsim R_{co}$ (where $R_{co}$ is the corotation radius), the accretion flow is halted at the magnetospheric boundary, which behaves like a closed barrier (Illarionov & Sunyaev 1975). The expected X-ray luminosity in this regime is:

$$L_m = \frac{GM}{R_m} \dot{M}_{\text{accr}}.$$  

(17)

The position of the magnetospheric radius depends also on the effect of the X-ray ionization on the accreting matter. Here we obtain the formula which gives the steady position of the magnetospheric radius and the related position of the Strömgren radius for which the accretion luminosity is equal to the feedback luminosity.

The accretion equation (14) can be written as follows:

$$L_{\text{a,c.i.}}(r_{\xi}) = \frac{(GM_x)^3}{R_m^2 v_{\infty}(1 - \frac{R_{co}}{R_{\xi}})\frac{\dot{M}}{\dot{m}}} (v_{\text{rel}}^2 + c_s^2)^{3/2}.$$

(18)

We obtain $R_m$ as a function of $r_{\xi}$ by equating $L_m$ of the feedback equation (15) to the $L_{\text{a,c.i.}}$ of the accretion equation (18):

$$R_{m,c.i.}(r_{\xi}) = \frac{(GM_x)^3 4\pi \mu m_p}{(v_{\text{rel}}^2 + c_s^2)^{3/2} \frac{\dot{m}}{\dot{M}}} (D - r_{\xi})^2.$$

(19)

Hence, if the centrifugal inhibition of accretion is at work in an X-ray binary system where the X-ray ionization cannot be neglected, the steady values for $R_m$ and $r_{\xi}$ can be derived by equating equations (16) and (19):

$$R_m(r_{\xi}) = R_{m,c.i.}(r_{\xi}).$$

(20)

In Table 7 we report the steady state solutions obtained for IGR J16479−4514 (assuming the system parameters reported in Table 5 in the case of direct accretion and in the case of centrifugal inhibition of accretion. Assuming a transition from direct accretion to the centrifugal inhibition of accretion for a mass-loss rate of $M = 4 \times 10^{-6} M_\odot$ yr$^{-1}$, we obtain steady state solutions in agreement with the observations for a magnetic field of $B_0 = 10^{12}$ Gauss and a spin period of $\approx 1$ s. When the neutron star enters the state of centrifugal inhibition of accretion, the X-ray luminosity is reduced, thus also the photoionization is lower; this leads to a shift of the magnetospheric radius to a higher value. The opposite transition (from centrifugal inhibition to direct accretion) needs $M$ greater than $4 \times 10^{-6} M_\odot$ yr$^{-1}$ (e.g. the accretion of a dense clump). This behaviour allows longer durations for the low-luminosity state. When $R_m \approx R_{co}$, the oblate spheroid shape of the magnetospheric boundary (see Jetzer, Strassmeier & Straumann 1998) results in the intermediate luminosity state observed ($\sim 10^{30}$ erg s$^{-1}$) because simultaneously $R_m < R_{co}$ in the magnetic polar region and $R_m > R_{co}$ in the magnetic equatorial region (Campana et al. 2001; Perna, Bozzo & Stella 2006).

### 4.2 Formation of an accretion disk

In the previous section we discussed the effect of X-ray photoionization in a close X-ray binary system like IGR J16479−4514, where a compact object accretes matter from a wind with a low relative velocity $v_{\text{rel}} \approx 460$ km s$^{-1}$. In section 4.1.1, we have excluded for this system the possibility of the formation of an accretion disk due to Roche Lobe overflow. However, it is also possible that an accretion disk forms from the capture of angular momentum from a slow wind (see Illarionov & Sunyaev 1975, Shapiro & Lightman 1976, Wang 1991). The existence of a disk in IGR J16479−4514 requires that the relative velocity between the neutron star and the wind is lower than $\approx 500$ km s$^{-1}$ (see formula [31] in Wang 1991), therefore the presence of a disk in IGR J16479−4514 cannot be ruled out. The formation of a transient disk from the mass and angular momentum capture from an asymmetric stellar wind can lead to a flaring activity, as proposed by Taam et al. (1988) to explain the recurrent flares observed in EXO 2030+375 (Parmar et al. 1989). Recently, the formation of transient disks has been proposed by Kreykenbohm et al. (2008) to explain part of the flaring behaviour of the persistent HMXB Vela X−1. In the model of Taam et al. (1988), the density and velocity inhomogeneities in the wind lead to an instability in the accretion flow. Because of this instability, the interaction of the accretion flow with the shock fronts of the accretion wake leads to the formation and dissipation of transient accretion disks (see e.g. Edelstein 2004 and references therein for a recent review). In their model, Taam et al. (1988) gave an approximative formula for the time scale for the duration of flares:

$$\tau \sim \frac{6GM_x}{v_{\text{rel}}^2}.$$  

(21)

Assuming relative velocities reported in Table 7 (in the case of direct accretion), we found for IGR J16479−4514 a time scale for the duration of flares of $\sim 10^3 - 10^4$ s, in agreement with the observed flare durations. The flares produced by the formation of transient accretion disks can be distinguished from those produced

### Table 7. Model results for IGR J16479−4514

|                | Direct accretion ($R_m < R_{co}$): | Centrifugal inhibition of accretion ($R_m > R_{co}$): |
|----------------|-----------------------------------|-----------------------------------------------|
| $M$ (M$_\odot$ yr$^{-1}$) | $\gtrsim 4 \times 10^{-6}$ | $4 \times 10^{-6}$ |
| $r_{co}$ (cm)     | $\sim 1.33 \times 10^{12}$ | $\sim 2 \times 10^{12}$ |
| $L_{in}$ (erg s$^{-1}$) | $\gtrsim 10^{37}$ | $\gtrsim 8 \times 10^{34}$ |
| $v_{rel}$ (km s$^{-1}$) | $\sim 460$ | $\sim 760$ |
| $R_m$ (cm)        | $1.6 \times 10^8$ | $1.7 \times 10^8$ |

Figure 9. Lightcurve of the observation of XTE J1739−302, in the energy range 18 − 60 keV (IBIS/ISGRI). Arrows indicates the peaks of luminosity.
by the simple clump accretion by measuring the time derivative of the pulse period, which, in the first case, is expected to change sign for each flare (see e.g. Taam et al. 1988).

The SFXT XTE J1739–302 has shown a quasi-periodic flaring behaviour on 53612.164 MJD (see Figure 9), which could be ascribed to the mechanism of formation and dissipation of transient accretion disks described above. Adopting equation (21), we could obtain, from the measure of the flares durations ($\Delta t \sim 5000$ s), a relative velocity of $v_{rel} \approx 600$ km s$^{-1}$. This value is in agreement with the $v_{rel}$ expected from an X-ray binary system with a small orbital period ($\approx 3 - 7$ d), or with a higher orbital period and large eccentricity, where the effect of X-ray photoionization reduces significantly the wind velocity. This supports the hypothesis of Smith et al. (2006) that the fast outbursts of XTE J1739–302 could be due to an instability of an accretion disk.

4.3 Accretion via Rayleigh–Taylor instability

The shape of the flare of IGR J16479–4514 we observed with INTEGRAL and reported in Figure 10, i.e. fast rise and exponential decay, could be explained with the magnetospheric instability mechanism proposed by Lamb et al. (1977) to explain type II X-ray bursts. All equations in this section are taken from these authors. In the framework of a spherically symmetric accretion flow onto a neutron star, and under particular conditions of X-ray luminosity and of the temperature of the accreting matter, the magnetospheric surface behaves as a gate which controls the flow towards the stellar surface. When the gate is closed, a magnetospheric cavity is formed, and a reservoir of matter is accumulated on the top of the neutron star magnetosphere, leading to low X-ray luminosities. When this matter has cooled enough (because of electron–ion bremsstrahlung, which is the dominant cooling mechanism when the gate is closed), the plasma enters the magnetosphere via Rayleigh–Taylor instability, and the accretion onto the neutron star leads to a flaring behaviour. Lamb et al. (1977) found a critical luminosity

$$L_{\text{crit}} = 2 \times 10^{36} \left( 1 + \frac{T_{\text{eff}}}{T_{\text{c}}} \right)^{7/8} M_{30}^{1/4} R_{6}^{-1/8} \text{erg s}^{-1} \quad (22)$$

where $T_{\text{c}}$ is the temperature of radiation, $T_{\text{eff}} \approx 10^{9}$ K, $M_{30}$ is the mass of the neutron star in units of $10^{30}$ g cm$^{-3}$, $M$ is the mass of the neutron star and $R_{6}$ is the radius of the neutron star in units of $10^{6}$ cm. If the flare luminosity is greater than the critical luminosity (equation 22), the Compton cooling dominates the bremsstrahlung cooling at $R_{\text{m}}$, thus the magnetosphere gate is open for longer time and the flare is prolonged (Lamb et al. 1977).

The flare reported in Figure 10 has a peak luminosity of $\approx 3 \times 10^{33}$ erg s$^{-1}$, which is greater than the critical luminosity $L_{\text{crit}} \approx 2.4 \times 10^{32}$ erg s$^{-1}$ (if $T_{\text{c}} < 10^{9}$ K).

Assuming $T_{\text{c}} \approx 10^{8}$ K, we found that, because of Compton processes, beyond the radius $r_{\text{c}} \approx 2.2 \times 10^{10}$ cm at which the free-fall temperature equals the temperature of radiation, the X-ray emission of the neutron star heat the plasma (see formula [31] in Lamb et al. 1977).

If the heating time scale is less than the flow time scale the flow is choked at $R_{\text{m}}$, and we expect for the flare a time duration given by:

$$\Delta t_{\text{max}} \approx 125 \left( \frac{T_{\text{c}}}{10^{8} \text{K}} \right)^{-3/2} \left( \frac{M}{M_{\odot}} \right) \text{ s} \quad (24)$$

which results into $\Delta t_{\text{max}} \approx 175$ s assuming $T_{\text{c}} = 10^{8}$ K and $M = 1.4M_{\odot}$. This duration is not in agreement with that observed in Figure 10. However, if we assume $T_{\text{c}} \approx 2 \times 10^{7}$ K, the heating time scale is less than the flow timescale at distances $\gg r_{\text{c}}$. The condition (23) is no longer valid ($L_{\text{x}} \lesssim L_{\text{choke}} = 4 \times 10^{32}$ erg s$^{-1}$), thus the flow is choked at a radius $r_{\text{c}}' > r_{\text{c}}$. In this case the expected burst duration is given by:

$$\Delta t_{\text{max}} \approx 210 L_{37}^{-3} \left( \frac{T_{\text{c}}}{10^{8} \text{K}} \right)^{-3} \left( \frac{M}{M_{\odot}} \right)^{4} \text{ s} \approx 4900 \text{ s} \quad (25)$$

(assuming $T_{\text{c}} = 2 \times 10^{7}$ K, $M = 1.4M_{\odot}$ and $L_{\text{x}} = 3 \times 10^{37}$ erg s$^{-1}$). The assumption $T_{\text{c}} = 2 \times 10^{7}$ K is in agreement with the temperature of radiation observed in some SFXTs (see e.g. Sidoli et al. 2007). In the framework described by Lamb et al. (1977), the exponential decay in this kind of flares is described by the law $L(t) \approx L_{\text{c}} e^{-t/\tau_{\text{ff}}} \approx L_{\text{c}} e^{-t/\tau_{\text{ff}}}$, with $\tau_{\text{ff}} \approx 3/2$. From the fit of the exponential decay of the flare observed by INTEGRAL (Figure 10) we found $\tau_{\text{ff}} \approx 1.55$, thus in agreement with the value predicted by Lamb et al. 1977.

We point out that if $L_{\text{x}} > L_{\text{crit}}$, $T_{\text{c}} < T_{\text{c}}$ at $R_{\text{m}}$, and if the accretion radius is lower than $r_{\text{c}}$, the X-ray source is persistent with high luminosity (see Eisner & Lamb 1977). In our case $R_{\text{a}} \approx 1.8 \times 10^{11}$ cm and $r_{\text{c}} \approx 2.2 \times 10^{10}$ cm (if $T_{\text{c}} = 10^{8}$ K) or $r_{\text{c}} \approx 1.1 \times 10^{11}$ cm (if $T_{\text{c}} = 2 \times 10^{7}$ K). Thus, what makes IGR J16479–4514 and probably other SFXTs intermittent with

3 The material accreting onto a neutron star is decelerated by the magnetic field, hence it is shock-heated to a temperature $T_{\text{ff}} \approx 1.6 T_{\text{c}}(M_{30})^{1/4} R_{6}^{-1/8}$ cm. If the temperature of radiation is roughly constant for every $r$, below a radius $r_{\text{c}}$, the gas is cooled by Compton interaction ($T_{\text{c}} < T_{\text{ff}}$); outside $r_{\text{c}}$ we have $T_{\text{c}} > T_{\text{ff}}$, thus the gas is heated by Compton processes.

4 The condition for which the heating time scale is less than the flow time scale is expressed by:

$$L_{\text{x}} \geq L_{\text{choke}} = 1.2 \times 10^{37} \left( \frac{T_{\text{c}}}{10^{8} \text{K}} \right)^{-1/2} \left( \frac{M}{M_{\odot}} \right) \text{ erg s}^{-1} \quad (23)$$

This condition is respected if $T_{\text{c}} = 10^{8}$ K, $M = 1.4M_{\odot}$, $L_{\text{x}} \approx 3 \times 10^{37}$ erg s$^{-1}$.
respect to the other persistent HMXBs could be the X-ray photoionization which reduces the wind velocity, increasing the accretion radius with respect to $r_c$.

5 CONCLUSIONS

Up to now three accretion mechanisms have been proposed to explain the X-ray flares of SFXTs.

Here we propose other mechanisms to explain the observed X-ray behaviour of IGR J16479−4514, IGR J17544−2619 and XTE J1739−302: the effect of X-ray photoionization onto accretion (both in direct accretion and centrifugal inhibition of accretion) in the framework of the Ho & Arons (1987) model; the accretion disk instability of Lamb et al. (1977), and the Rayleigh-Taylor instability of Lamb et al. (1977).

We have shown that the X-ray photoionization reduces the mass loss rate and the wind velocity along the trajectory compact object−OB supergiant with respect to the undisturbed case (section 3.1). Their simultaneous reduction leads to X-ray luminosities in agreement with those observed during the flaring activity; moreover, a lower $v_w$ allows the formation of transient accretion disks from the capture of angular momentum, able to reproduce some kind of quasi−periodic recurrent flares observed in SFXTs.

We found in our analysis of INTEGRAL data that some flares show a peculiar shape, characterized by a sharp rise and an exponential decay (Figure 10). We found that this shape is well explained assuming the model of Lamb et al. (1977), based on the Rayleigh-Taylor instability, although this model was proposed to try to explain type II bursts.

Therefore, we conclude that in SFXTs with large orbital periods ($P_{orb} \gtrsim 15$ d; e.g.: IGR J18483−0311, SAX J1818.6−1703, IGR J11215−5952) the effects of X-ray photoionization onto accretion mechanism can be neglected. In SFXTs with smaller orbital periods ($P_{orb} \lesssim 15$ d; e.g.: IGR J16479−4514, IGR J17544−2619) we expect that part of the X-ray variability observed is due to the X-ray photoionization and consequently to the accretion disk instability. We are still not able to establish which mechanism dominates in SFXTs with smaller orbital periods. Moreover, we point out that different accretion mechanisms could be at work in a single SFXT, in the case of orbits with high eccentricities.

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