PROCEEDINGS OF SCIENCE

Supergiant Fast X-ray Transients observed by INTEGRAL

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We review X-ray properties of the Supergiant Fast X-ray Transients following from their observations with INTEGRAL and show that a compact object in these systems is a neutron star with strong magnetic field accreting from the stellar wind of a donor star. We show that presence of a centrifugal barrier at the magnetospheric boundary of the neutron star may be a key to understanding of abrupt short X-ray outbursts of these transients and long intervals of their quiescence.

The Extreme sky: Sampling the Universe above 10 keV
October 13-17, 2009
Otranto (Lecce), Italy

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1. Introduction

Only a few of ~ 50 high mass X-ray binaries (HMXBs) known before the launch of INTEGRAL had supergiants of early (O-B) spectral types as optical counterparts (most of HMXBs contained Be-stars). In spite of different origin of compact objects (e.g., a black hole in Cyg X-1 or neutron stars in Vela X-1 and 4U 1700-37) all these HMXBs were bright quasi-persistent X-ray sources powered completely or in part by accretion from the stellar wind of the supergiant. The observed amount of such sources, small in comparison with theoretical expectations, was explained by inhibition of steady accretion in a numerous 'dark' population of the sources due to a centrifugal barrier at the magnetospheric boundary of the neutron star – the so-called "propeller effect" [6].

The situation became more complex with INTEGRAL that (thanks to its high sensitivity in hard X-rays, large fields of view of main telescopes and long uninterrupted observations of the Galactic disk and Galactic center regions [14]) discovered two completely new groups of supergiant X-ray binaries (SXBs): 1). "strongly absorbed sources", enshrouded in the very dense opaque wind and thus invisible in the standard X-ray band, and 2). "supergiant fast X-ray transients" (SFXTs), flaring up in X-rays for rather a short (one day or less) time (see for review [8, 11, 1]). The latter sources and actual mechanisms of their outbursts are the subject of our report.

2. Observations

Since the discovery of first SFXTs [13, 12, 7, 4] the amount of known sources of this type increased significantly. Table 1 lists several broadly discussed SFXTs and their key parameters: a companion type, spin P_s and orbital P_b periods, a distance d. Note that already the detection of coherent pulsations in some of the sources implies that their compact object is a neutron star with strong magnetic field, while the orbital periods $P_b \sim 3.5-30$ days imply that SFXTs could be bright

Table 1: Known SFXTs and their most important parameters

Source name	Companion type	P_s s	P_b d	d kpc
IGR J08408-4503	O8.5 Ib(f)			3
IGR J11215-5952	B0.7 Ia	186.8	165.	6.2
IGR J16465-4507	B0.5 I/O9.5 Ia	228.		9.4
IGR J16479-4514	O8.5 I/O9.5 Iab		3.32	4.9
XTE J1739-302	O8 Iab(f)		12.87	2.7
AX J1749.1-2733		131.9	185.5	>8
IGR J17544-2619	O9 Ib		4.93	3.6
SAX J1818.6-1703	B0.5-1 Iab		30.0	2.1
AX J1841.0-0536	B0 I/B1 Ib	4.74		6.9
AX J1845.0-0433	O9.5 I			3.6
IGR J18462-0223				~ 6
IGR J18483-0311	B0-1 Iab	21.05	18.55	2.8

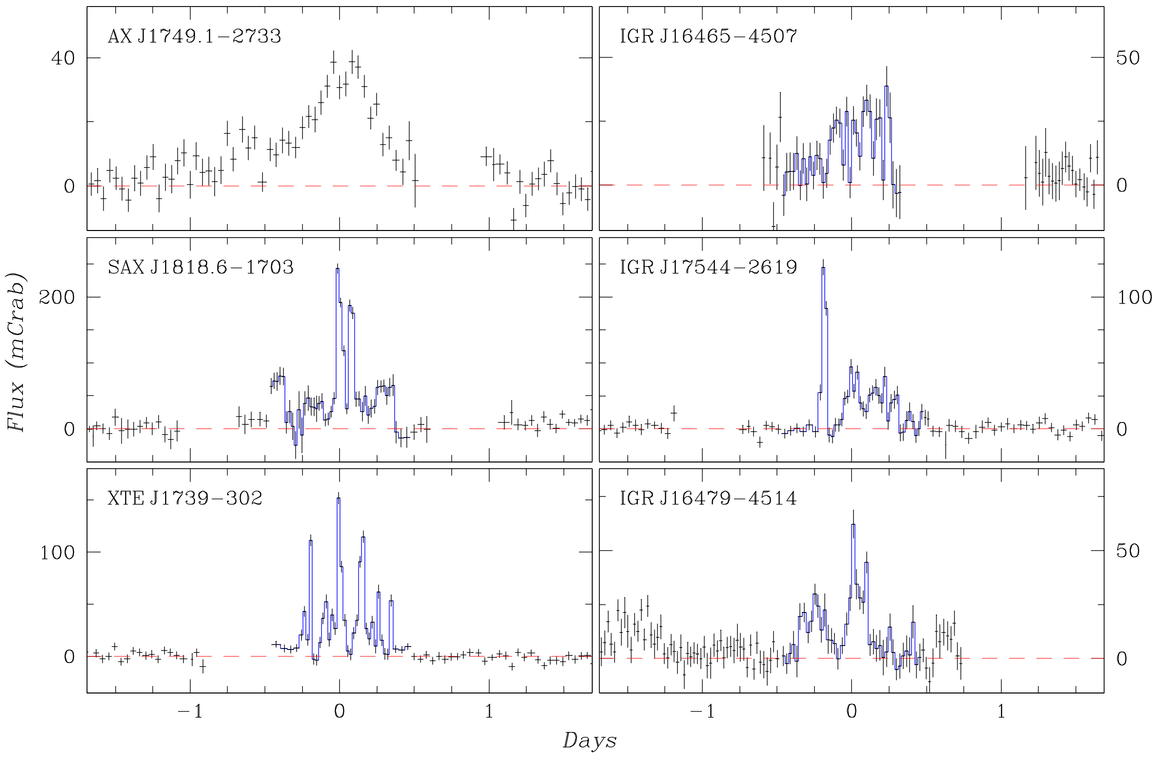


Figure 1: IBIS/ISGRI 20-60 keV light curves measured in 2003-2004 during first detected outbursts of 6 most reliable SFXTs (epoch "0" corresponds to UT 2003, August 10.4505 and 27.0495 for IGR J16479-4514 and XTE J1739-302, September 9.4695, 9.5895 and 17.2695 for SAX J1818.6-1703, AX J1749.1-2733 and IGR J17544-2619, and 2004, September 7.4103 for IGR J16465-4507). Points in the central (± 0.5 day) part of the curves are given with better temporal resolution ($\sim 10^3$ s) and connected with a solid line (for clarity).

sources of persistent X-ray emission $L_X \sim 2.3 \times 10^{36}\, P_*^{-4/3}\, \dot{m}_*\, v_*^{-4}$ erg s^{-1} due to accretion from the dense stellar wind (in the case of circular orbits and without centrifugal inhibition of accretion). Here $\dot{m}_* = \dot{M}_w/10^{-5}\, M_\odot$ yr^{-1} and $v_* = v_w/10^3$ km s^{-1} are the wind ejection rate and velocity, $P_* = P_b/10$ days. We assume that mass and radius of the neutron star $M_1 = 1.4\, M_\odot$, $R_1 = 10$ km.

Fig. 1 shows the light curves from 6 SFXTs of the list measured with the IBIS/ISGRI instrument on board INTEGRAL during their first X-ray outbursts. Most of the curves demonstrate strong flaring activity of the sources and have rather short details in profile, although the curve of AX J1749.1-2733 is sufficiently smooth. The intensity of sources rises by 4–5 orders of magnitude during a very short time. Each outburst lasts for about 1 day in total. Such a duration is the main distinctive feature of SFXTs. The only exception is IGR J11215-5952 with the outbursts lasted for ~ 5 days, but this source may be non-typical and flare up when its compact object approaches the perigee [10]. Other SFXTs have rather long intervals of recurrence (months or years) significantly exceeding their orbital periods. Many SFXTs do not show any regularity in the outbursts at all.

The short life-time does not allow SFXTs to form an accretion disk with a size comparable with the binary separation. It is obvious that the outbursts are connected with some type of instable accretion from the wind of an optical star. However, accretion from the wind occurs on a free-fall timescale which is usually much shorter ($< 10^3$ s) than the characteristic life-time of SFXTs.

The X-ray emission of SFXTs is characterized by a hard spectrum extending to 15–200 keV. Being approximated by an optically thin thermal bremsstrahlung it leads to the temperatures $kT \sim 10-30$ keV. The spectra of 6 SFXTs measured with IBIS/ISGRI during their outbursts in 2003-2004 are shown in Fig. 2 together with their best-fit approximation. Such spectra are typical for accreting neutron stars. To illustrate this point we show in Fig. 3 the hard X-ray spectra of 2 bright SXBs, Cyg X-1 (which harbours a black hole) and 4U 1700-37 (harbours a neutron star). We compare them with that of SAX J1818.6-1703. The spectrum of Cyg X-1 is obviously the hardest one ($kT \sim 75$ keV). The spectra of two other sources are much softer and similar to each other if not identical.

3. Models

There were four models proposed to explain peculiar properties of SFXTs and their outbursts:

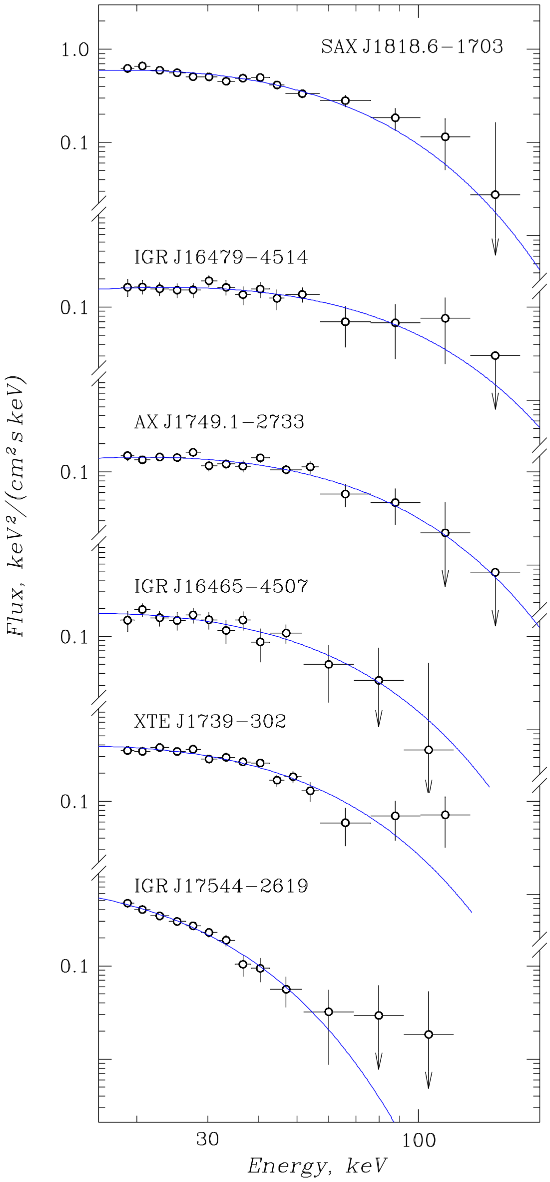
- the Be-type model assuming a very elliptical orbit for the binary, the outbursts are triggered at the moments when a compact object travels through its periastron [1, 10],
- the highly structured (clumpy) stellar wind from the supergiant, the outburst begins due to swallowing of one of the clumps of dense matter from the wind [7, 9],
- overcoming of a centrifugal barrier at the magnetospheric boundary of the neutron star which stops steady accretion onto its surface (the "propeller effect" [6]), the overcoming may occur due to even small increase in the wind local density or decrease in the wind velocity [5],
- overcoming of a magnetic barrier of the neutron star which could stop steady accretion onto its surface if the magnetic field of the neutron star $> 10^{14}$ G and its spin period $> 10^4$ s [3].

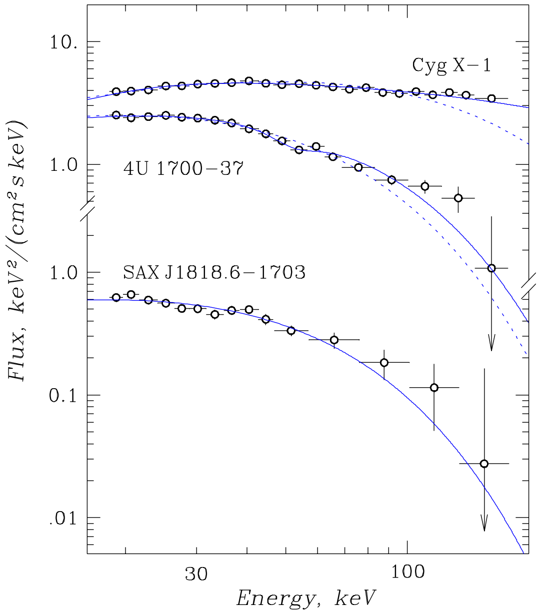
The first effect is responsible for observed activity of IGR J11215-5952 [10]. Taking into account that the P_s and P_b periods of AX J1749.1-2733 are close to those of IGR J11215-5952 and that its light-curve differs from the curves of other SFXTs in Fig. 1, we can suggest that this source also is a representative of Be-type SFXTs. For other SFXTs the eccentricity e seems to be too close to 1 to explain the high ~ 100 ratio between the recurrence interval of outbursts and their duration.

In the clumpy wind model the contrast ξ of the gas density in clumps relatively to the average density should be of $\sim 10^4$ to explain the X-ray luminosity ratio between outburst and quiescent states of SFXTs. It is difficult to believe that such dense clumps can exist in the hot wind of OB supergiants. But even if they exist the compact object should intersect and swallow them on a time scale of $a\,\xi^{-1/3} v_{\rm w}^{-1} \sim 10^3$ s that is much shorter than the life-time of SFXTs. Here a is the binary separation, $a = [G(M_1+M_2)]^{1/3}(P_b/2\pi)^{2/3} \simeq 62\ P_*\ R_\odot$, and $M_2 \simeq 30\ M_\odot$ is the companion mass.

Two latter models of the list can explain the outburst/quiescence luminosity ratio with ease. They assume that a compact object in SFXTs is a neutron star with sufficiently strong magnetic field $H = 10^{12} h_*$ G. We have already shown that this is really the case. The magnetic inhibition regime takes place when the accretion radius of the neutron star $R_a = 2GM_1/v_{\rm w}^2 \simeq 0.54\ v_*^{-2}\ R_\odot$ is smaller than its magnetospheric radius $R_m = [0.5H^2R_1^6/\dot{M}/(2GM_1)^{1/2}]^{2/7} \simeq 0.0066\, h_*^{4/7} v_*^{8/7} P_*^{8/21} \dot{m}_*^{-2/7}\ R_\odot$ where $\dot{M} = 0.25(R_a/a)^2\dot{M}_w \simeq 1.9\times10^{-10} v_*^{-4} P_*^{-4/3} \dot{m}_*\ M_\odot{\rm yr}^{-1}$ is the accretion rate. This regime works when H is in the magnetar range $> 10^{14}$ G that is unlikely for SFXTs [3].

The propeller regime takes place when R_m exceeds the corotation radius of the neutron star $R_c = (GM_1/\Omega^2)^{1/3} \simeq 0.0024\ P_s^{2/3}\ R_\odot$ remaining smaller than R_a ($R_c < R_m < R_a$). The magnetospheric radius depends on accretion rate (or the stellar wind local density and velocity), so if R_c





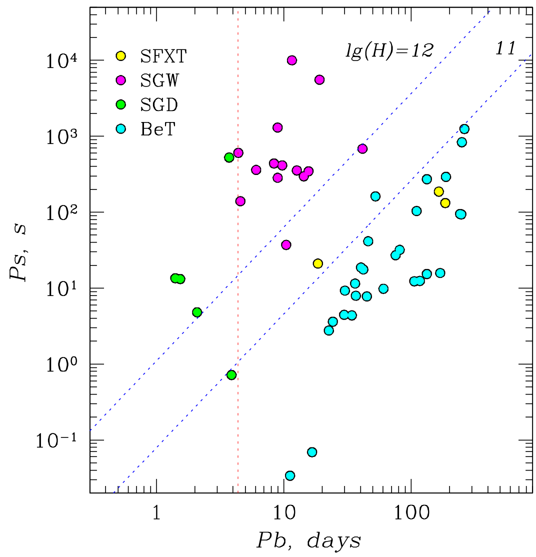


Figure 2: Hard X-ray spectra of 6 SFXTs (the same as in Fig. 1) and their approximation with thermal bremsstrahlung. The spectra were obtained with IBIS/ISGRI in 2003-2004 during the first detected outbursts of the sources. The best-fit temperature $kT = 37.5 \pm 6.3$ keV (IGR J16479-4514), 32.5 ± 3.1 keV (AX J1749.1-2733), 28.8 ± 1.7 keV (SAX J1818.6-1703), 24.0 ± 4.3 keV (IGR J16465-4507), 22.4 ± 1.4 keV (XTE J1739-302), 10.9 ± 0.8 keV (IGR J17544-2619).

Figure 3: IBIS/ISGRI spectra of two persistent SXBs, Cyg X-1 (measured on June 8, 2003, during the intermediate state) and 4U 1700-37 (measured on September 12, 2003), in comparison with that of SAX J1818.6-1703. Dotted lines show the approximation of these spectra with thermal bremsstrahlung, $kT = 75.4 \pm 0.9$ keV for Cyg X-1, 30.6 ± 0.5 keV for 4U 1700-37 and $28.8 \pm .7$ keV for SAX J1818.6-1703.

Figure 4: $P_s - P_b$ diagram for HMXBs. Different colours show SFXTs, disk-fed (SGD) and wind-fed (SGW) supergiant binaries, and Be-transients (BeT). The red line indicates P_b at which the supergiant with $R = 20R_\odot$ and $M = 22M_\odot$ fills its Roche lobe, blue lines – P_s below which the centrifugal barrier inhibits quasi-spherical accretion from the stellar wind (for $H = 10^{11}$ and 10^{12} G, $v_w = 800$ km s^{-1}).

differs only slightly from R_m transitions between propeller and direct accretion regimes may occur even due to rather a small increase in the wind density (or decrease in its velocity). The equilibrium $R_c = R_m$ takes place when the neutron star's spin period $P_s{}^* \simeq 4.5\, h_*^{6/7} \dot{m}_*^{-3/7} v_*^{12/7} P_*^{4/7}$ s. According to [5] SFXTs should have P_s slightly smaller than $P_s{}^*$. They become bright in X-rays when the wind density increases in $(P_s{}^*/P_s)^{7/3}$ times and R_m drops below R_c. The outburst duration is determined by the time that the neutron star spent in the region of enhanced density. If its orbit is circular the enhancement may be related to only rather a long change in the wind rate. It should be an intrinsic property of the supergiant amplified by the effect of its surface heating by X-rays from the outburst.

Using $R_c = (GM_1/\Omega^2)^{1/3}$ in such estimates in [5] we have compared the magnetospheric velocity with the Keplerian one $v_K = (GM_1/R_c)^{1/2}$. In reality the specific angular momentum that accreting matter carries to the neutron star $j = \pi R_a^2/P_b$ is smaller than the Keplerian value [6, 2]. The velocity at the corotation radius should be $v = \pi R_a^2/R_c/P_b$, the radius itself $R_c = (0.5 P_s/P_b)^{1/2} R_a \simeq 0.00041\, P_*^{-1/2} P_s^{1/2} v_*^{-2}\, R_\odot$, and the equilibrium period $P_s{}^* \simeq 258\, P_*^{37/21} h_*^{8/7} v_*^{44/7} \dot{m}_*^{-4/7}$ s.

In Fig. 4 we show by blue lines this dependence for two reliable values of the neutron star's magnetic field $H = 10^{11}$ and 10^{12} G. The figure shows the $P_s - P_b$ diagram for a large sample of HMXBs. Three distinct populations of sources are seen: wind-fed and disk-fed SXBs and Be-transients. We expect SFXTs to appear in the diagram somewhere between the blue lines. Unfortunately of 3 SFXTs with currently known P_s and P_b 2 already mentioned sources are located among Be-transients, and only the last one, IGR J18483-0311, approved our expectations. Further search for all types of periodicities in SFXTs is extremely important for understanding of their nature.

Acknowledgments

This research was supported by the program "The origin, structure and evolution of objects of the Universe" of the Presidium of RAS and the grant NSh-5069.2010.2 of the Russian President.

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