Supergiant Fast X-ray Transients and other wind-fed accretors – testing with the Corbet diagram

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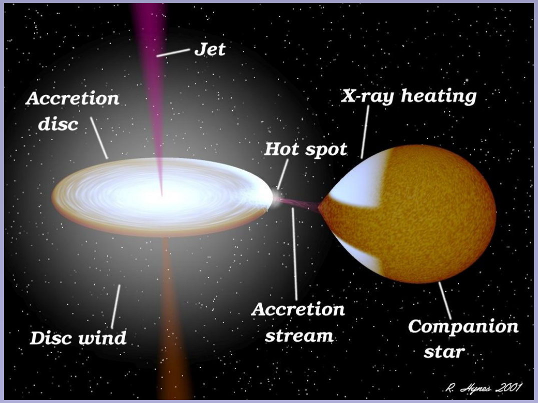
Topics

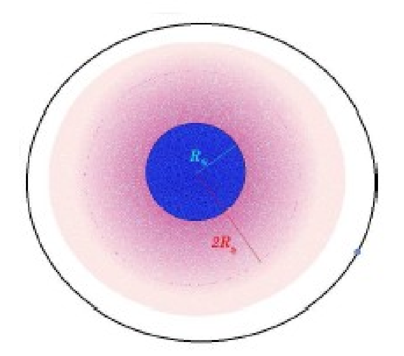
- HMXBs* and the Corbet diagram (before INTEGRAL)
- The “Propeller“ effect (PE)
- SFXTs - new population of HMXBs
- Mechanism of their outbursts based on PE
- SFXTs in the Corbet diagram

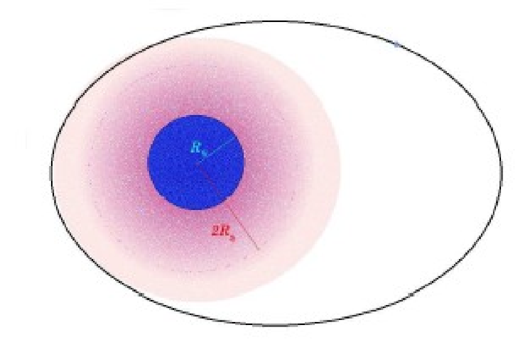
* X-ray binaries with a massive companion

HMXBs in the Galaxy (9 years ago)

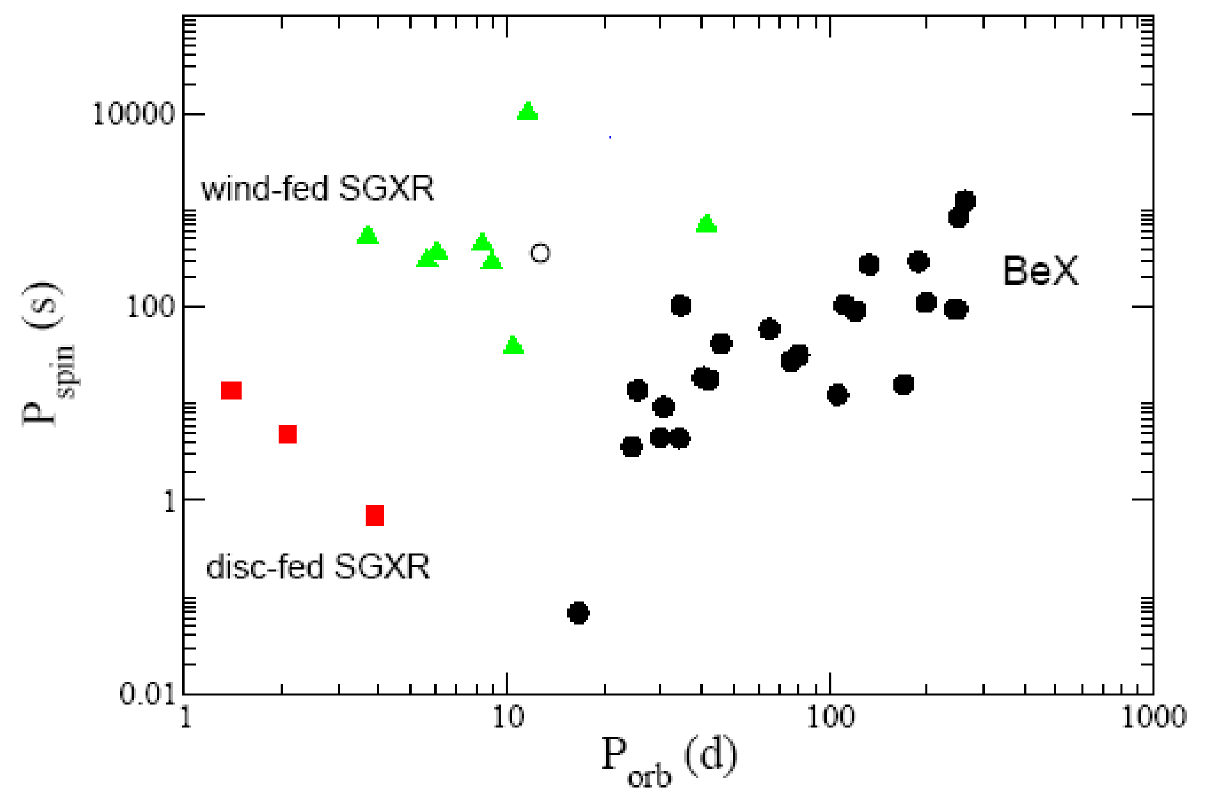
- ~1-3 – due to disk accretion from the OB supergiant by Roche lobe overflow, persistent (e.g., Cen X-3)
- ~8-10 - due to accretion from the stellar wind of the OB supergiant, variable but persistent at long time scale - with a disk (Cyg X-1) or not (Vela X-1, 4U1700-37)
- ~30 (“hard” X-ray transients) - due to accretion from the wind of Be (or OB) companions during a periastron or a decretion disc passage (V0332+53, 4U1145-61)





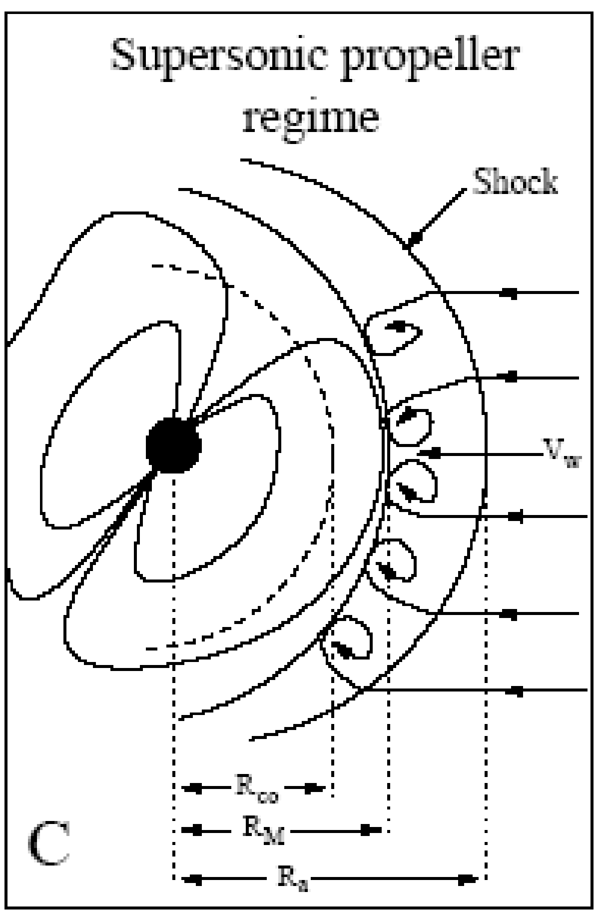


HMXBs in the Galaxy

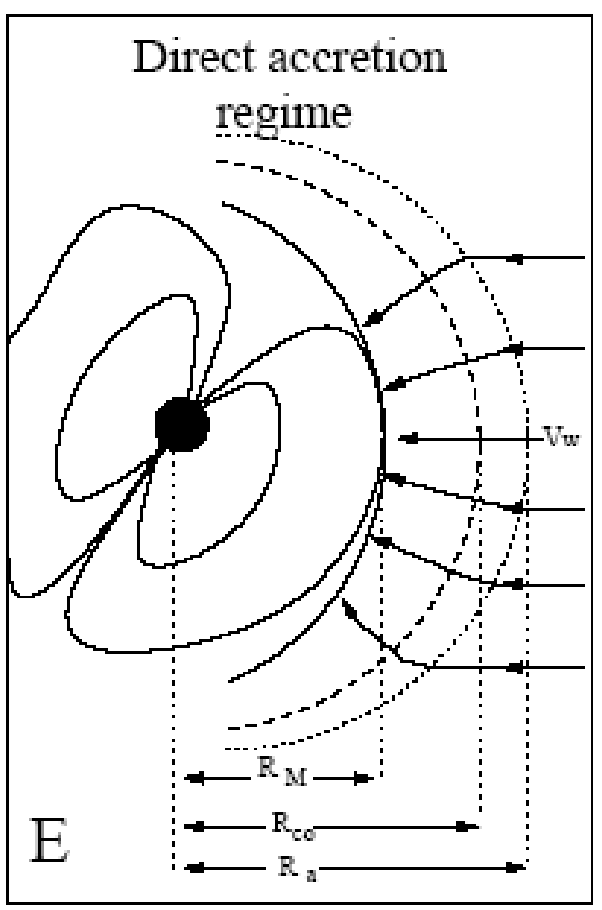


Corbet (1986) was the first who noted that these groups of HMXBs occupy different areas in the Ps-Po diagram. He pointed the possible reason for such different behaviour: all the pulsars have periods close to their «equilibrium» periods Ps*, separating phases of direct accretion and the «propeller» regime.

Why the «equilibrium» periods ?



Rc<Rh (Ps<Peq)



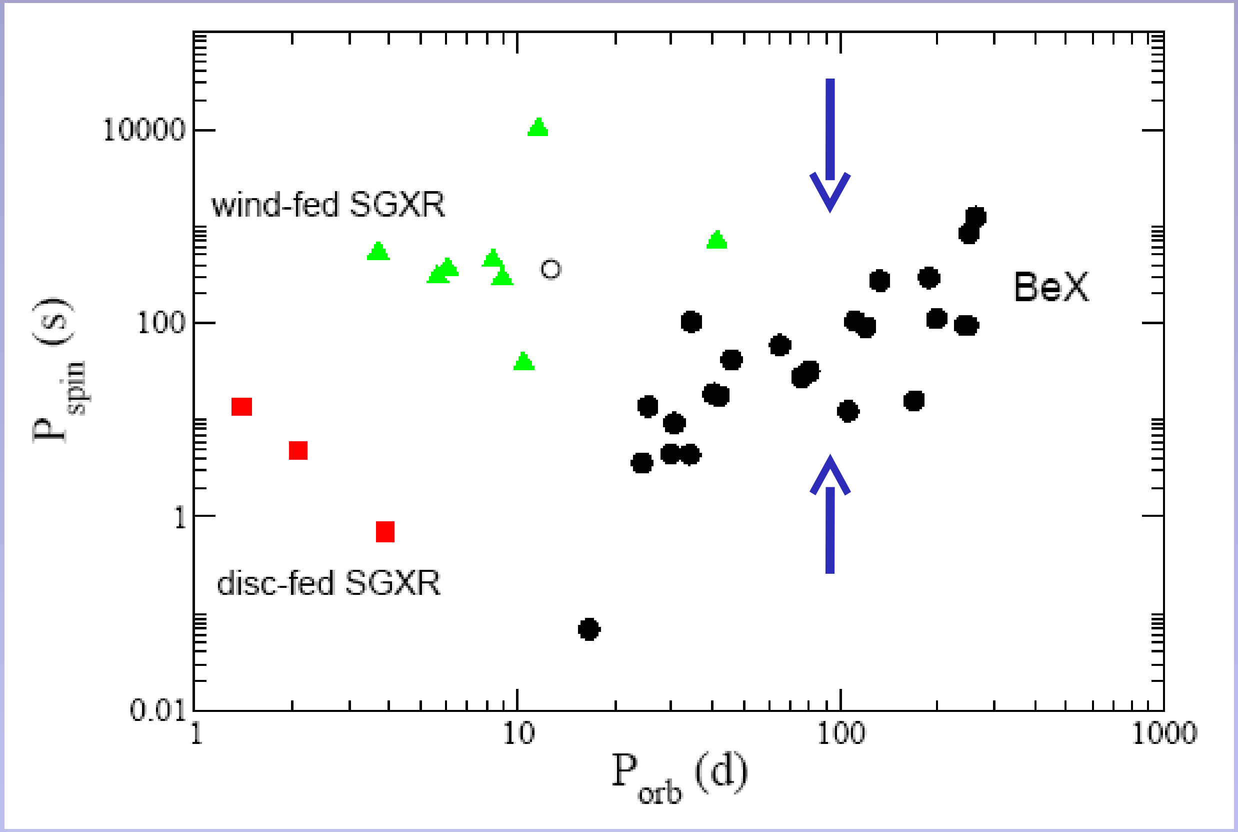
Rc>Rh (Ps>Peq)

Pulsars at the “propeller “ stage are spinning down thus their periods Ps will increase and approach to Ps*.

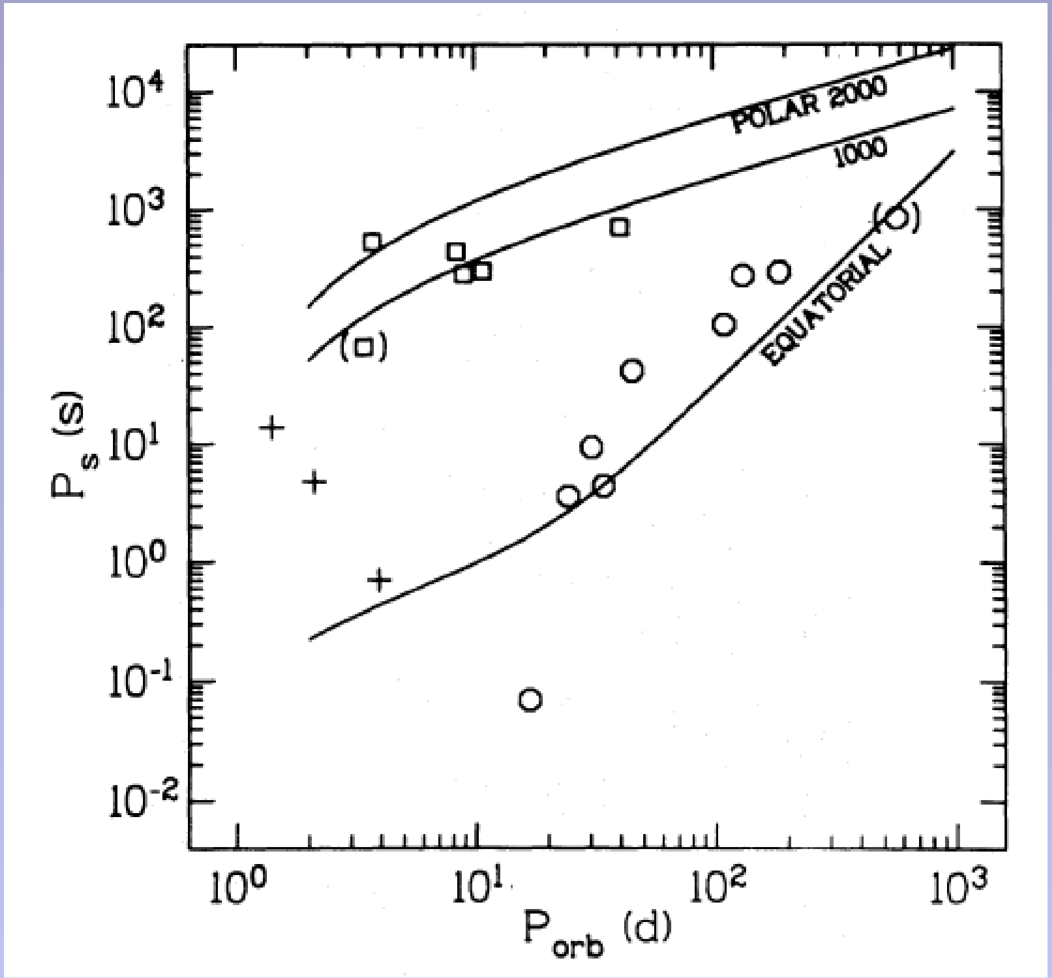
During the direct accretion stage they are spinning up thus their periods will decrease and again approach to Ps*.

Thus they should have Ps ~ Ps* (be near equilibrium)

Why the «equilibrium» periods ?



Ps-Po diagram



«Propeller» regime assumes

the Ps* ~ Po dependence (for the wind with the density decreasing as r $^{-2}$). This does not agree with observations of the Be-binaries.

Waters & van Kerwijk (1989) explained the observed dependence by the wind in the decreting disk with the density falling as r $^{-3.25}$ (v_0 =10 km/s).

The systems with supergiants agree with the observations very poorly too – they require either magnetic fields of ~10 ^{13} G, or the wind ejection rate ~10 $^{-9}$ $M_{\odot}$/yr that can not provide the observed level of X-

«Propeller» effect

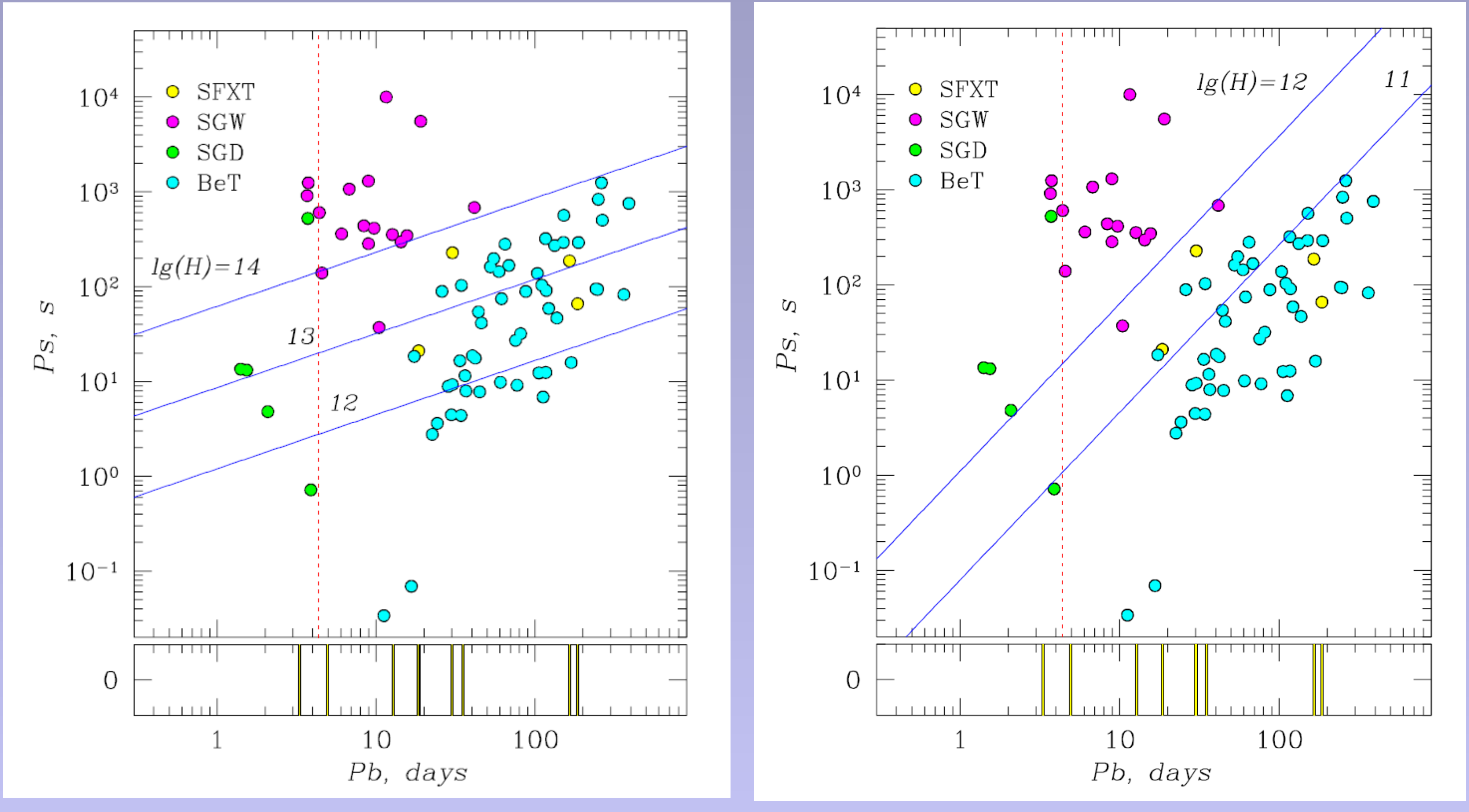
- first proposed by Illarionov & Sunyaev (1975) to explain the small observed number of X-ray binaries with supergiant companions – the majority of such systems do not emit X-rays because the accreting matter is stopped or even ejected from the system by rapidly spinning magnetosphere of a neutron star.
- is realized when the velocity ΩR of the magnetosphere (its surface) exceeds $v_2 = (2GM/R)^{1/2}$ (escape or “the 2nd cosmic” velocity) – the matter is ejected
- or when it exceeds $v_1 = (GM/R)^{1/2}$ (Keplerian or “the 1st cosmic” velocity), that is, when the magnetospheric radius Ra exceeds its corotation radius $R_c = (GM/\Omega^2)^{1/3}$ - matter is stopped and accumulated forming some quasi-static convective envelope. The wind will flow round the envelope if it extends to the Bondi radius

«Propeller» effect

- Angular momentum of matter captured from the stellar wind is ~Ra^2/Po and usually much smaller than the Keplerian one (Illarionov, Sunyaev 1975, Illarionov, Kompaneets 1990, Bisnovatyi-Kogan 1991).
- “Propeller” effect is formally realized when the velocity of the magnetosphere (its surface) exceeds the Keplerian velocity, but actually - when the accreting matter has velocity smaller than that of the magnetosphere.
- Thus the effect works if the magnetospheric radius exceeds $Rc = (0.5\ Ps/Po)^{1/2}\ Ra$, where $Ra = 2GM/v^2$ is the radius of the gravitational capture and Po is the orbital period.

- The valid dependence is Ps ~ Po (Grebenev 2009)

Ps-Po diagram



Standard dependence for the «propeller regime» (left) and that taking into account the smallness of momentum of accreting matter Ps* ~ $Po^{37/21}$ (right)

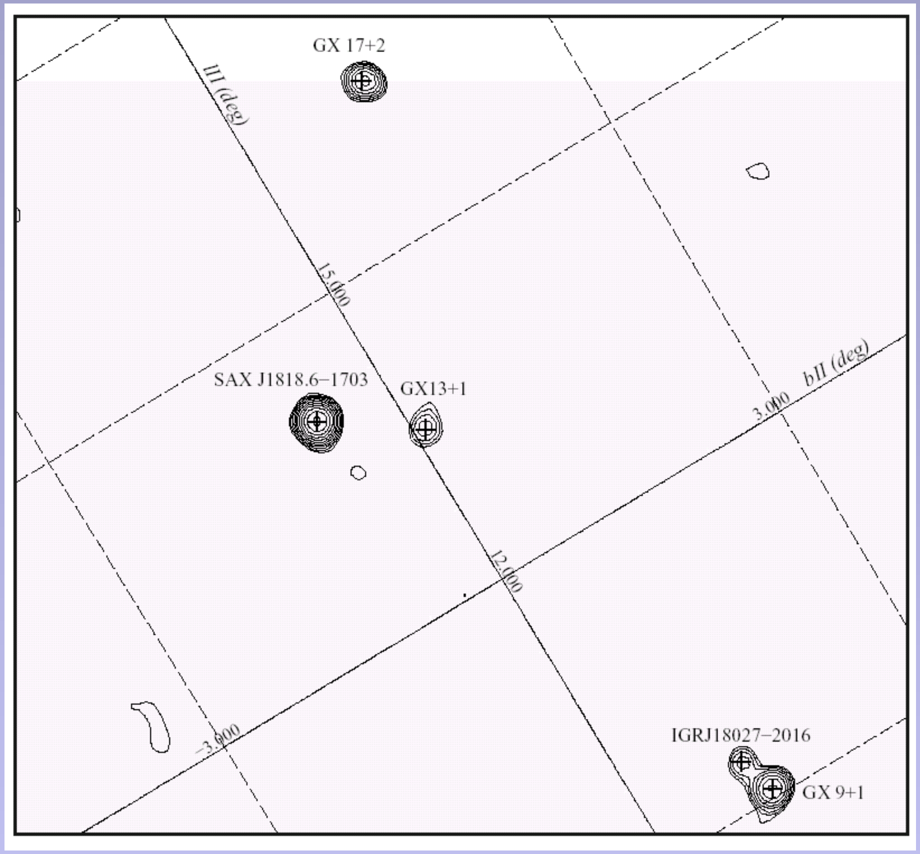
HMXBs in Galaxy with INTEGRAL

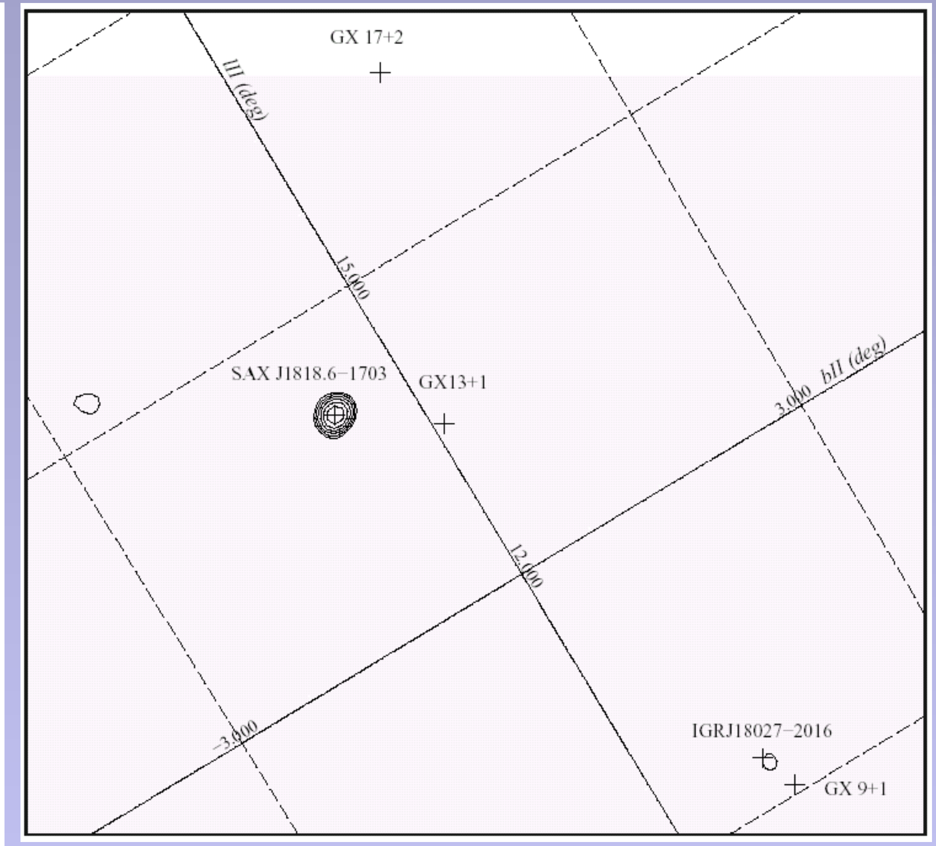
More than 50% increase in the number of HMXBs

New populations of HMXBs were discovered:

- strongly absorbed (enshrouded) sources (~25 objects)
- supergiant fast X-ray transients (>12 objects)

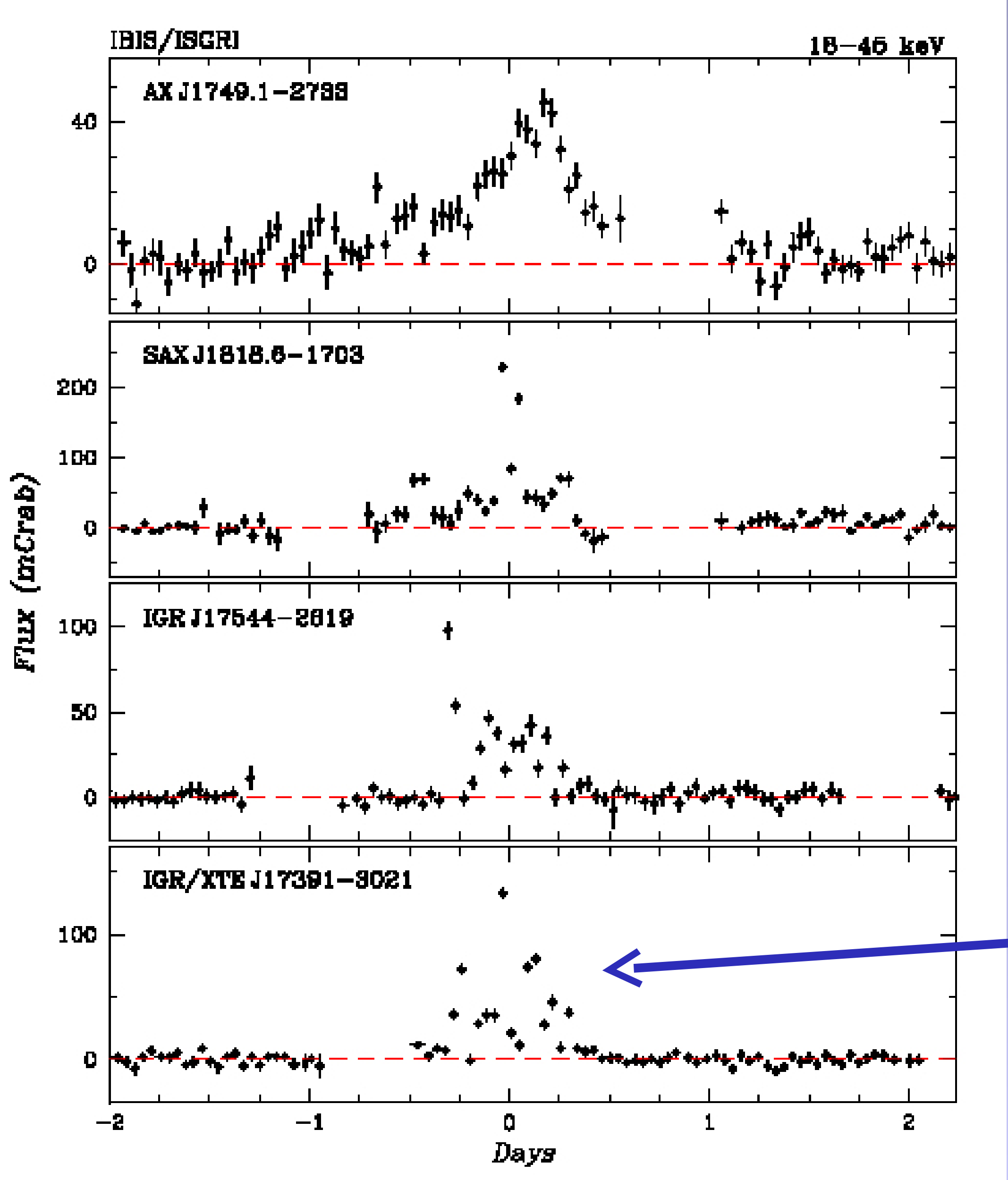
Outburst of SAX J1818.6-1703 in 2003 September





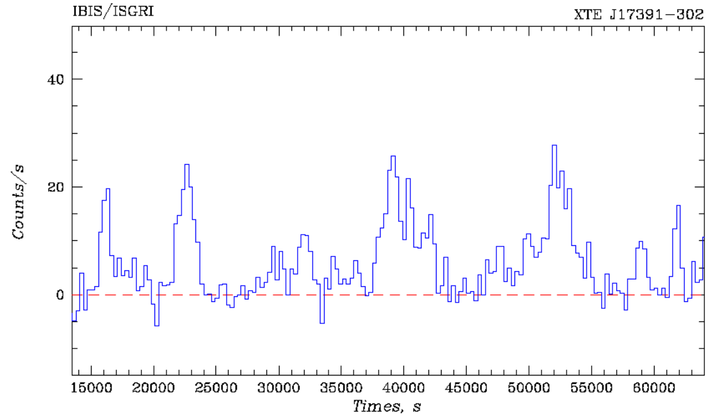
INTEGRAL IBIS/ISRGI 18-45 keV 45-70 keV

Typical light curves of SFXTs measured with IBIS/ISGRI

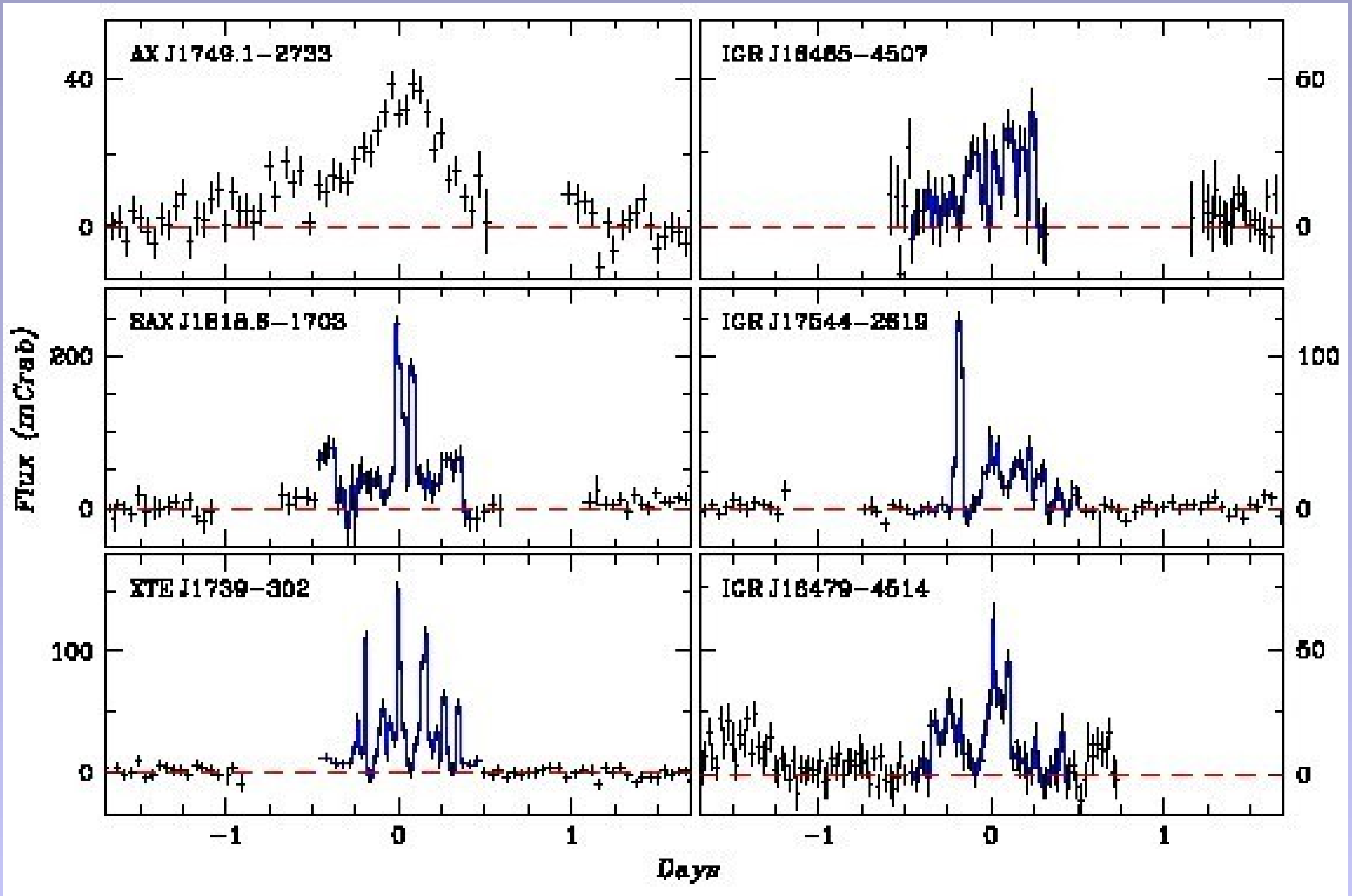


September 2003

- Duration <1 day
- Main peak is usually shorter the overall duration and there is some complex structure in the profile

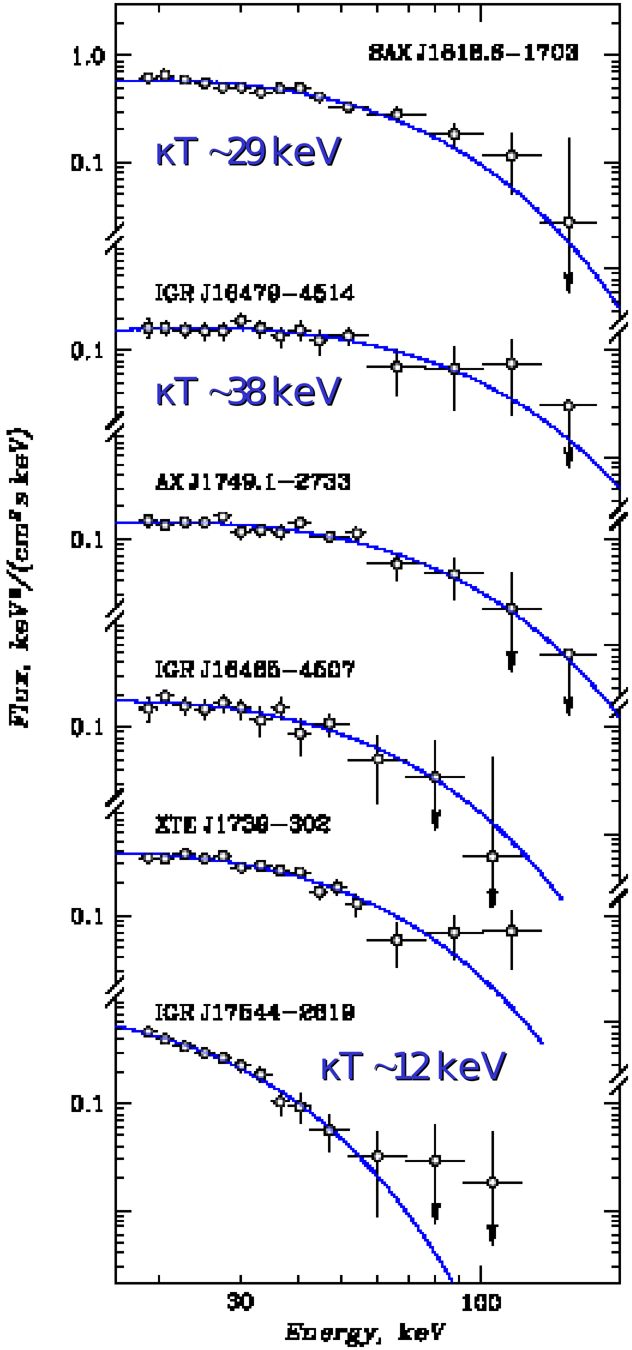


Typical light curves of SFXTs from IBIS/ISGRI

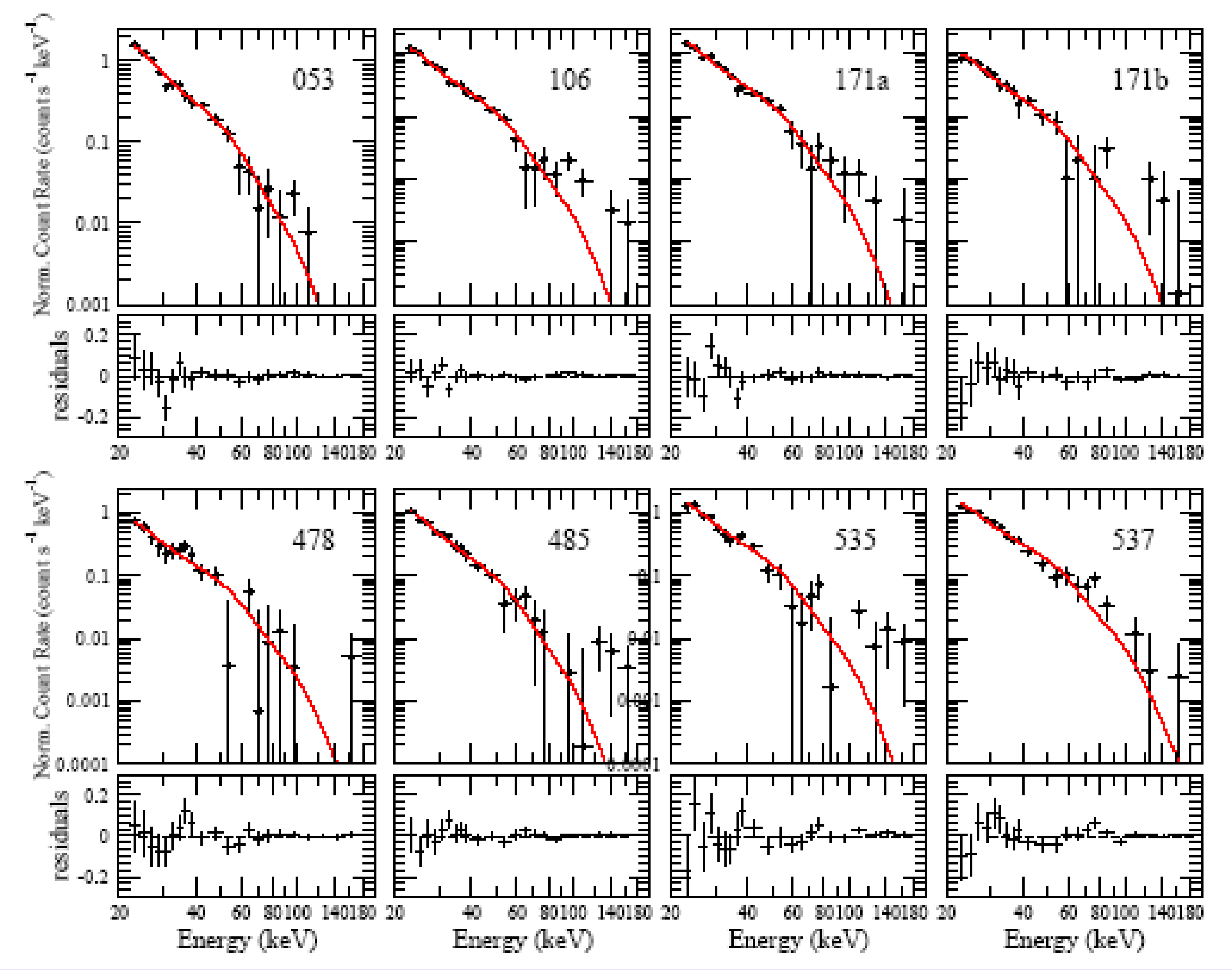


Typical X-ray spectra of SFXTs according to IBIS/ISGRI

Spectra measured in 2003-2004 during the first detected outbursts of the SFXTs and their approximation by thermal optically thin bremsstrahlung.



XTE J1739-302

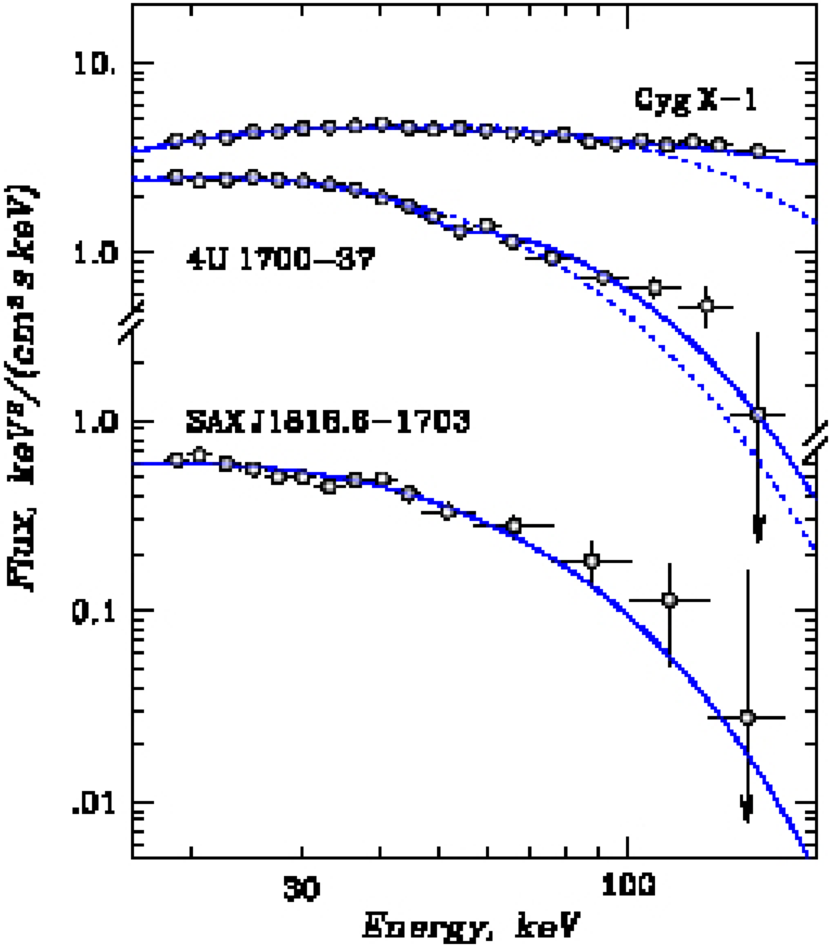


kT~20 keV

Spectra are changing slightly in various outbursts of the same source.

INTEGRAL IBIS/ISGRI

Comparison with spectra of other accretors

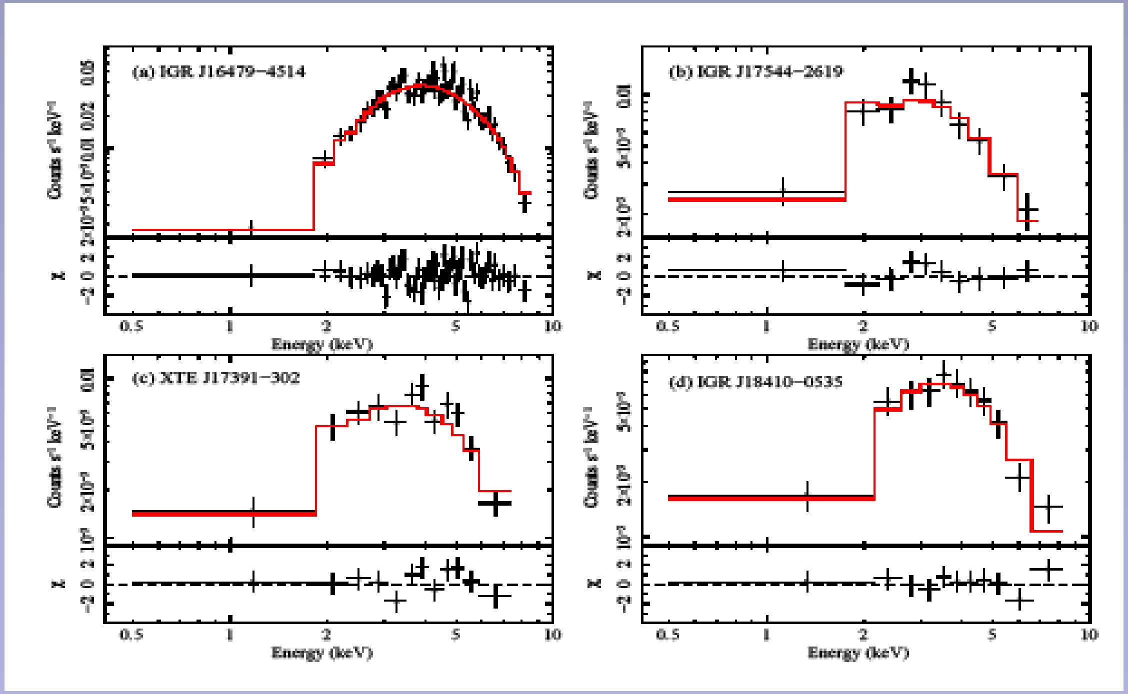


They are softer than those of black hole X-ray binaries and are similar to those of binaries with neutron stars accreting from the supergiant’s stellar wind (if neutron stars have strong magnetic field).

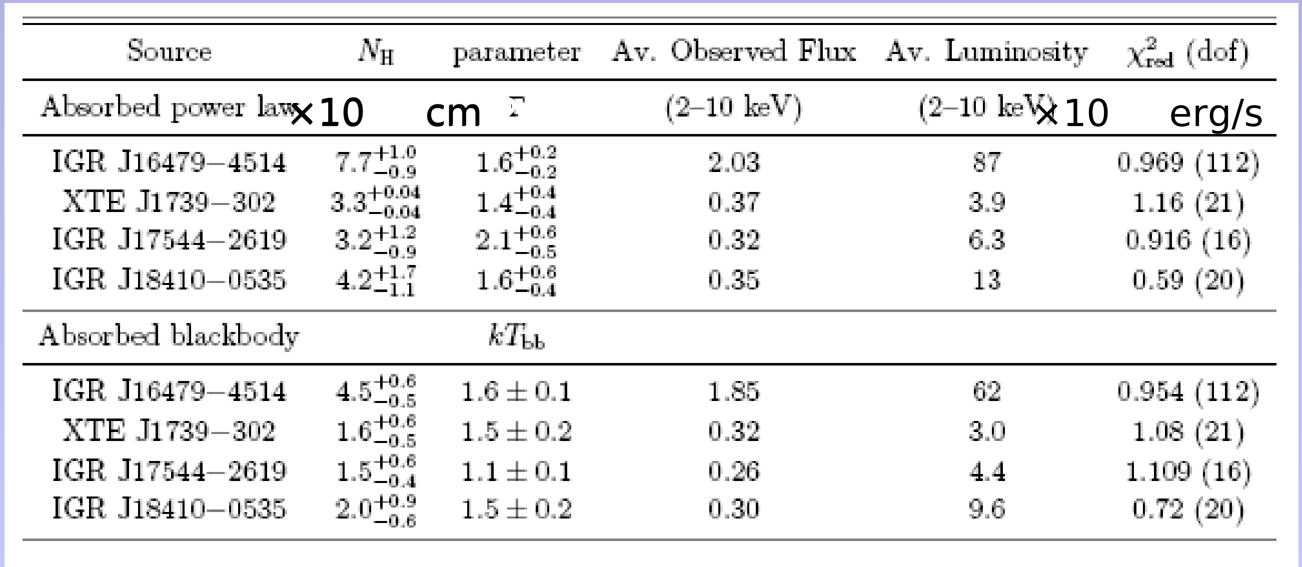
kT>100 keV for Cyg X-1

kT~30 keV for 4U1700-37

SFXTs in the off (quiescent) state

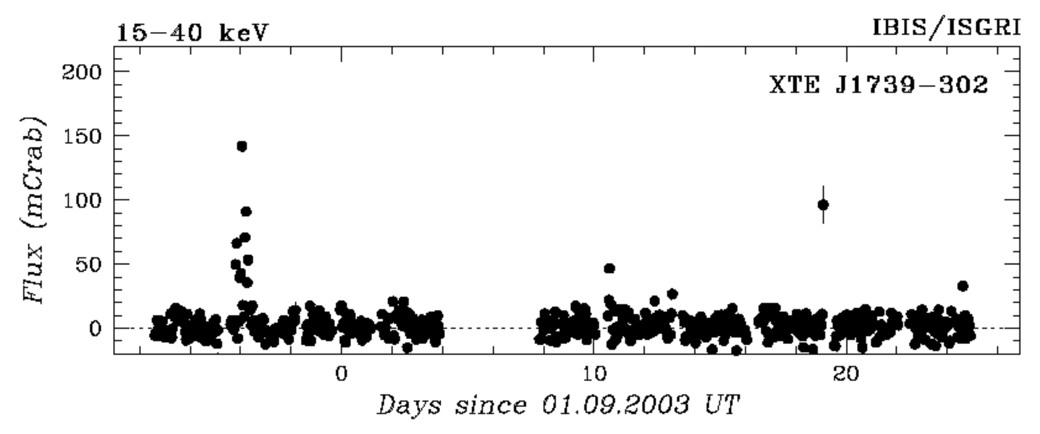


The luminosity rises and falls in ~10 4 times during very short time (minutes).



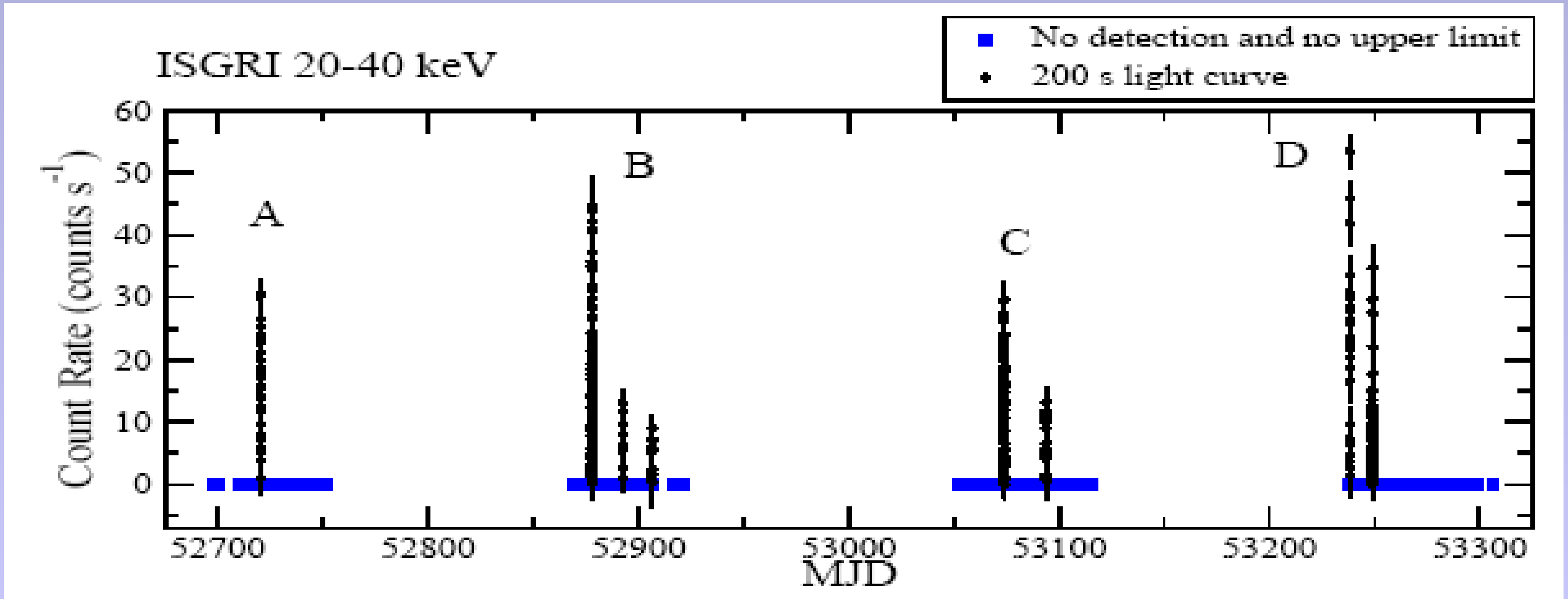
Source	N_H	parameter	Av. Observed Flux	Av. Luminosity	χ^2_{red} (dof)
Absorbed power law	×10 cm	Γ	(2–10 keV)	(2–10 keV) ×10 erg/s	
IGR J16479−4514	$7.7^{+1.0}_{-0.9}$	$1.6^{+0.2}_{-0.2}$	2.03	87	0.969 (112)
XTE J1739−302	$3.3^{+0.04}_{-0.04}$	$1.4^{+0.4}_{-0.4}$	0.37	3.9	1.16 (21)
IGR J17544−2619	$3.2^{+1.2}_{-0.9}$	$2.1^{+0.6}_{-0.5}$	0.32	6.3	0.916 (16)
IGR J18410−0535	$4.2^{+1.7}_{-1.1}$	$1.6^{+0.6}_{-0.4}$	0.35	13	0.59 (20)
Absorbed blackbody		kT_{bb}			
IGR J16479−4514	$4.5^{+0.6}_{-0.5}$	1.6 ± 0.1	1.85	62	0.954 (112)
XTE J1739−302	$1.6^{+0.6}_{-0.5}$	1.5 ± 0.2	0.32	3.0	1.08 (21)
IGR J17544−2619	$1.5^{+0.6}_{-0.4}$	1.1 ± 0.1	0.26	4.4	1.109 (16)
IGR J18410−0535	$2.0^{+0.9}_{-0.6}$	1.5 ± 0.2	0.30	9.6	0.72 (20)

Recurrence intervals



Intervals between outbursts vary from tens of days to months and years.

The outbursts are irregular in most of sources.



Known SFXTs and their periods

Source name	Companion type	Ps (s)	Pb (days)	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.	30.2	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		66.	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			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

Summary of properties of SFXTs

1. flare up only for a short time, less than or about one day;
2. usually have long recurrence periods (months and years);
3. have quiescent luminosities 10^{3}-10^{4} times smaller than those during the outbursts and the luminosity rises by 100-10000 times during already the first minutes of the outburst;
4. provide radiation up to $\sim 10^{42}$ ergs during the outburst, which corresponds to mass accretion of $\sim 10^{22}$ g with a 20%-efficiency;
5. most of them contain a neutron star with strong magnetic field, others have a hard X-ray spectrum typical for X-ray pulsars;

1. The outburst one day duration – longer than free-fall time-scale but shorter that viscous time (for disc accretion) – wind accretion

Fast X-ray transients

should be bright sources of persistent X-ray emission due to Bondi stellar wind accretion

$$L_X \simeq 6 \times 10^{36}\ m_*^3\ \dot{m}_*\ r_*^{-1}\ v_*^{-4}\ p_*^{-4/3}\ \mathrm{erg\ s^{-1}}$$

The relative velocity of components, mass and radius of the neutron star, rate of the wind outflow and binary period are

$$v_* = v_{\mathrm{rel}}/10^3\ \mathrm{km\ s^{-1}},\ m_* = M_1/1.4\, M_\odot,$$
$$\dot{m}_* = \dot{M}_{\mathrm{w}}/10^{-5}\, M_\odot\ \mathrm{yr^{-1}},\ r_* = R_1/10\ \mathrm{km},$$

$$p_* = P_{\mathrm{b}}/5\ \mathrm{days}$$

Pb should exceed 3.5 days in order to prevent overflow of the Roche lobe

Models to explain unsteady accretion

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

1. 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 (i’nt Zand 2005, Negueurela, Walter, Ducci),
2. 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 (Sidoli et al. 2007). But the long recurrence periods requires extreme eccentricityies,
3. Overcoming of a centrifugal barrier at the magnetospheric boundary of the neutron star which stops steady accretion onto its surface (the “propeller effect” , the overcoming may occur due to even small increase in the wind density or decrease in its velocity (Grebenev, Sunyaev 2007),
4. 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 (Bozzo 2008).

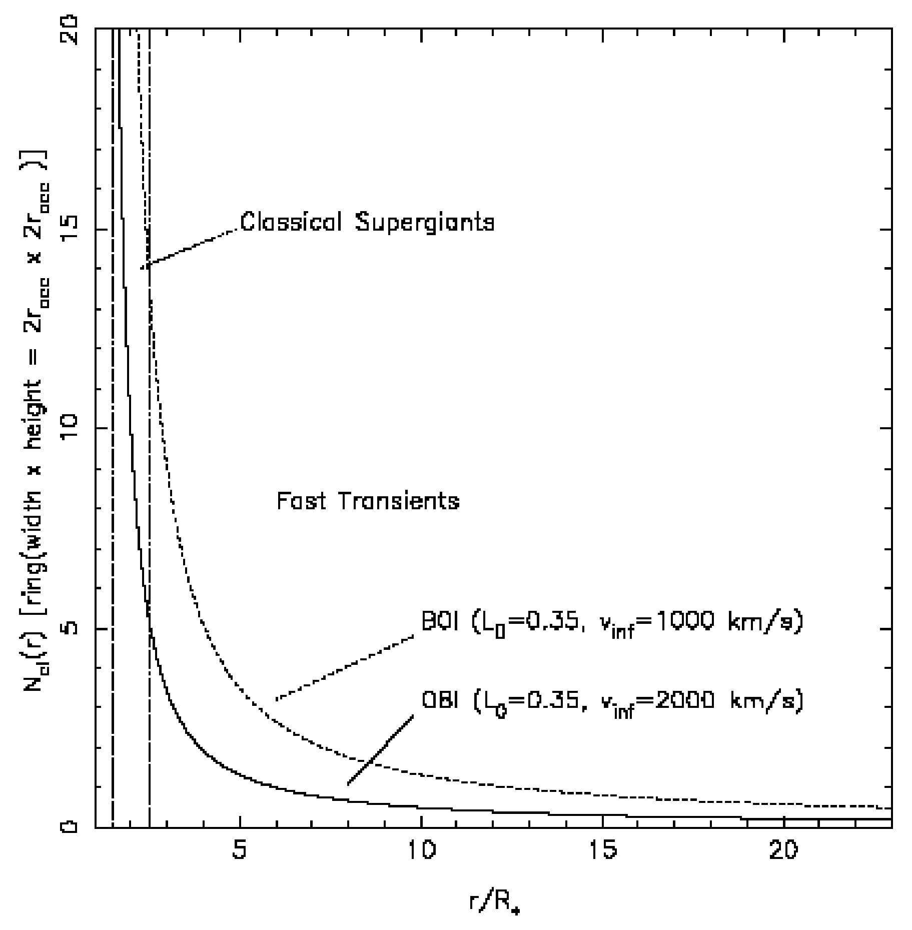
Model 1 (of Clumpy Stellar Wind)

Wind is accelerating (e.g. due to radiation pressure in lines).

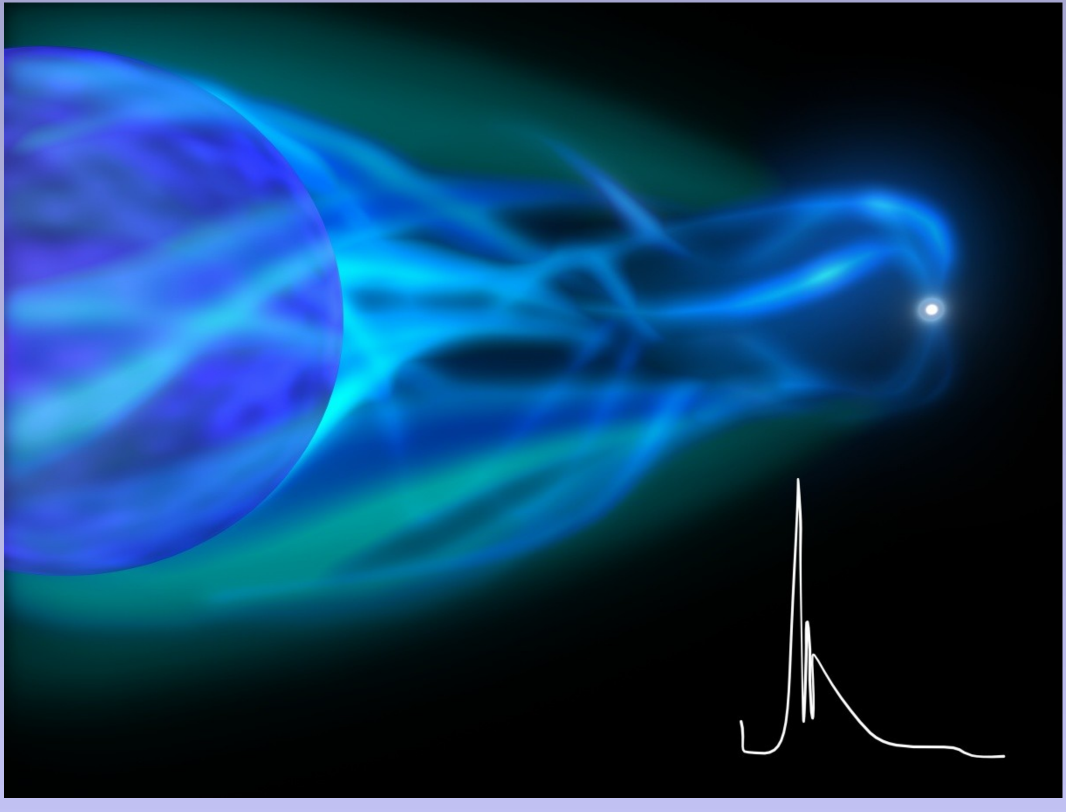
$$v_w(r) = v_\infty \left(1 - \frac{R_*}{r}\right)^\beta$$

HMXB is observed as SFXT if its separation exceeds ~5 R_* (when probability to meet a clump becomes small).

From Negueruela et al. 2008



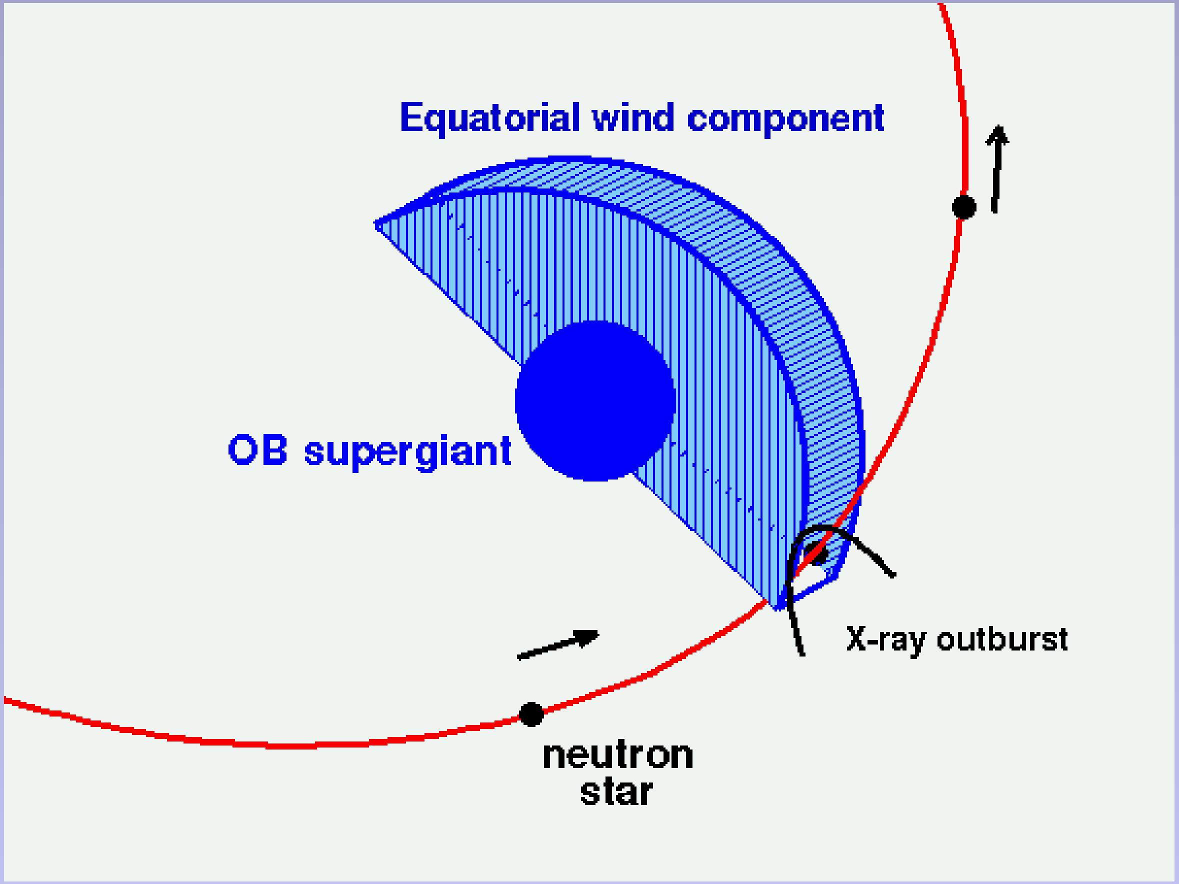
Model 1 (of Clumpy Stellar Wind)



The problems:

- Wind should consist of clumps with a density contrast of 10^{3}-10^{4} and low filling factor
- The outburst is observed when a clump passes the region of gravitational attraction of the compact object. However such a clump will be accreted with a free-fall time that is much smaller (<500 s) than the duration of SFXT’s outbursts.

Model 2: Be-type system



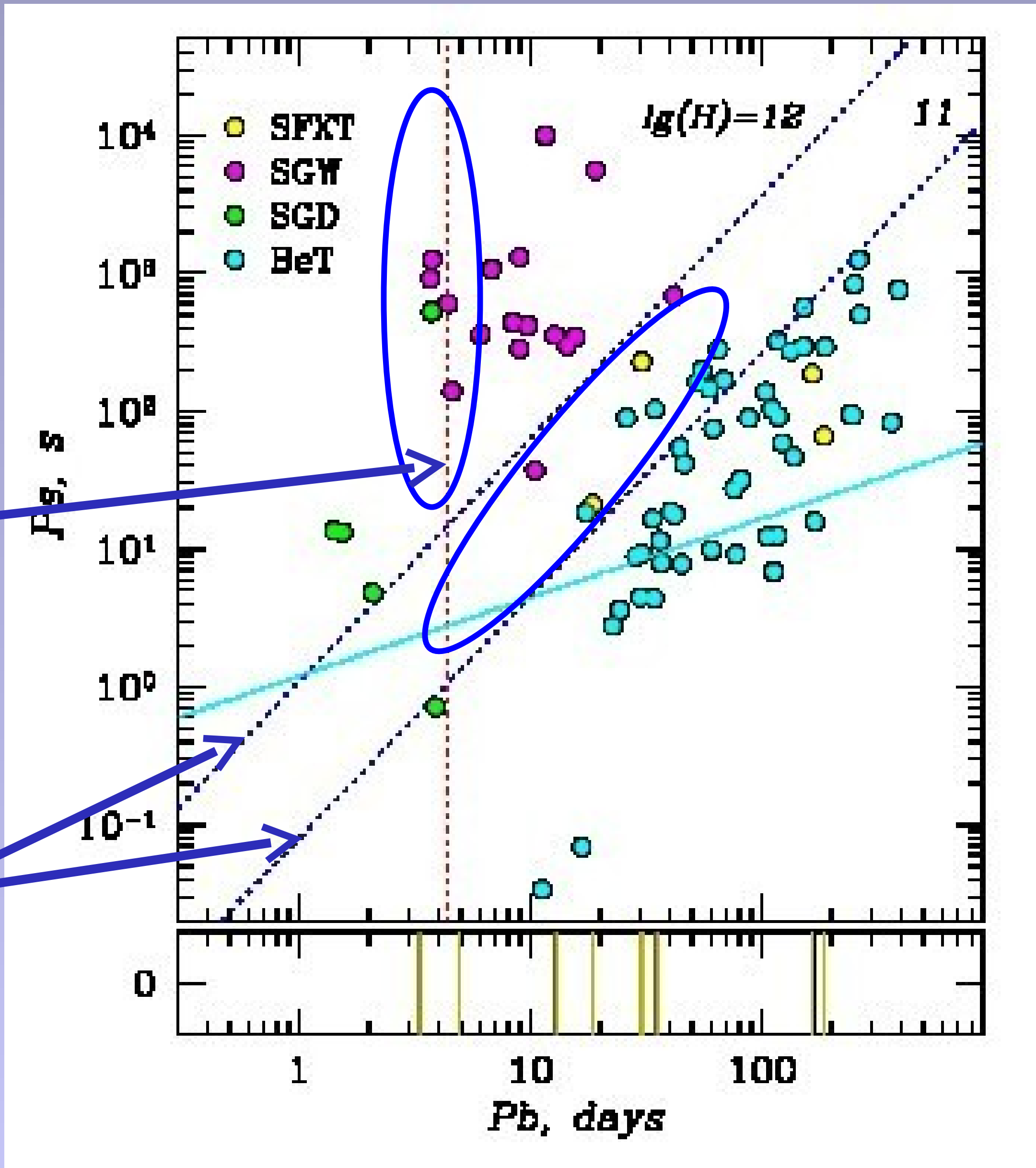
X-ray outburst is observed when the neutron star crosses the equatorial disk inclined with respect to the orbital plane

(from Sidoli 2008).

Model 3: Overcoming the centrifugal barrier

- SFXTs form a new class of wind-fed X-ray binaries with OB supergiants as optical counterparts with periods only slightly less than the critical one Ps*. Thus SFXTs are only slightly differ from usual accreting pulsars.
- They could become transients when local density of the wind is exceeded in $\sim(Ps^*/Ps)^{7/3}$ times (Grebenev, Sunyaev 2007). The density excess may be rather small (e.g. tens of percents). Then the magnetospheric radius decreases below the corotation radius and the accretion process is starting.
- The duration of the outburst (<1 days) could reflect the time necessary for the compact object to pass through the region of enhanced density of the stellar wind :
  - temporal increase in rate of the wind,
  - clump (low density and large/with high filling factor) or
  - perigee passage (no equatorial disk but at certain level of density)

SFXTs at the Ps-Pb diagram



Red dotted line indicates Pb at which the supergiant with $R = 20\,R_\odot$ and $M = 22\,M_\odot$ fills its Roche lobe

Black lines – Ps 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).

Blue line – critical Ps for the disc accretion

Fast transients vs. normal pulsars

- SFXTs only slightly differ from usual accreting pulsars which also demonstrates transitions between active and off (quiescent) states.

- But normal pulsars are switching off when their Ps decreases below Ps* due to spinning up.

- SFXTs are flaring up when Ps* decreases below Ps due to changes in the accretion rate (density or velocity of the stellar wind).

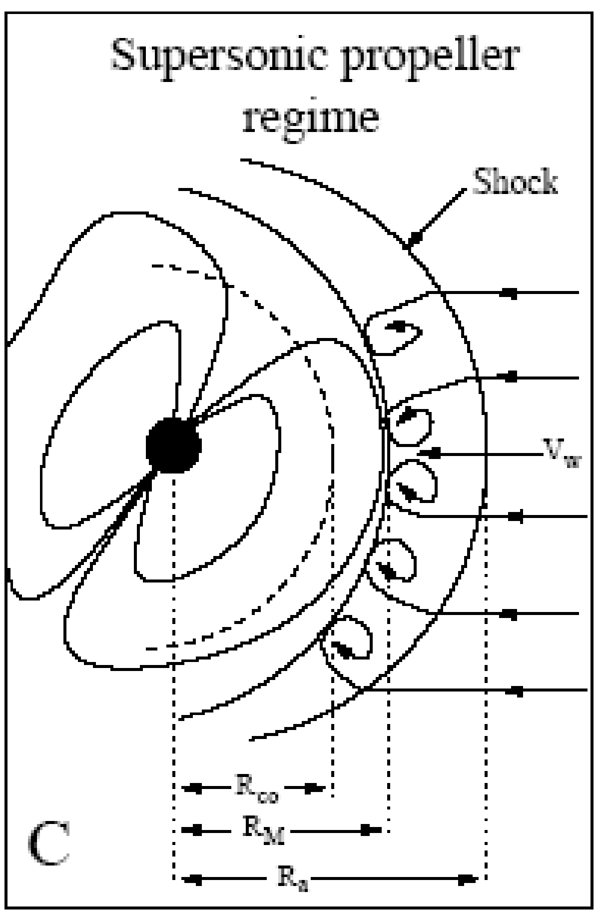
Conclusions

The “propeller effect” allows us to explain all difficulties existing in the clumpy wind model (large density contrast ~10^4 in clumps, too short duration <1000 s needs to accrete a clump or too large size of clumps – much larger than the accreting radius or even comparable with the supergiant radius). It allows ones as well to explain the quiescent emission at the observed level.

The “propeller” model puts SFXTs in one line with normal pulsars (directly accreting from the wind) explaining the difference between them by slightly different spinning periods. The “propeller” effect should work independently on the wind structure depending only on magnetic field strength of a neutron star and the wind rate (or its local density).

Thank you

“Propeller effect”

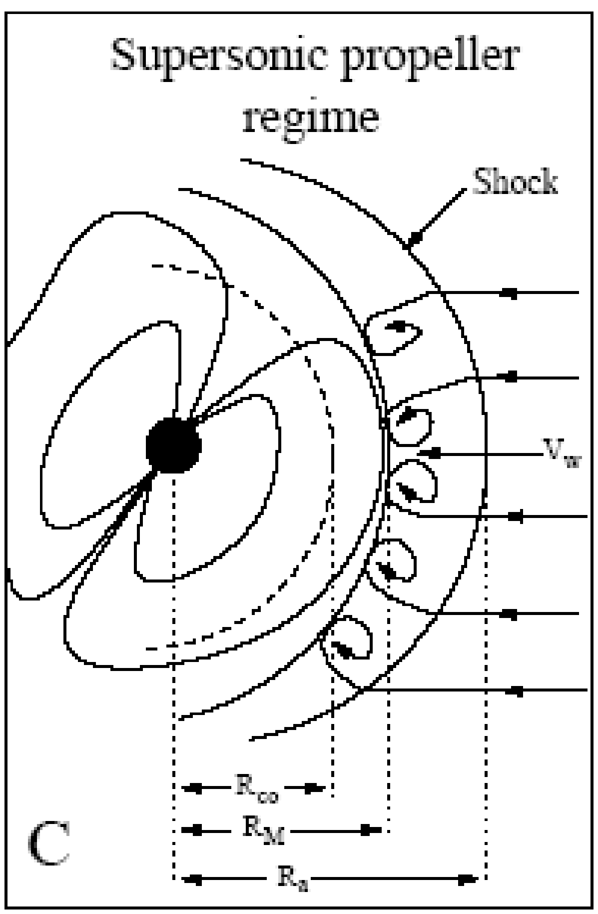


Davies & Pringle (1981) have shown that neutron stars at the propeller stage are enshrouded by a quasi static envelope with low luminosity < 10^{33} erg/s thermal emission. This emission can be that observed at the quiescent stage of SFXTs.

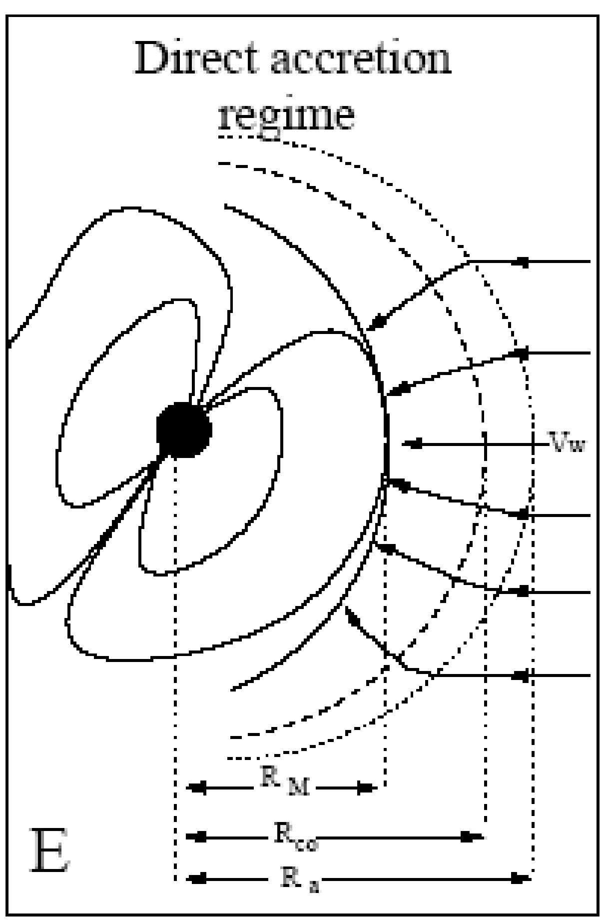
The transition to direct accretion near Rh ~ Rc will be realized with help of the Kelvin-Helmholtz instability (rotation energy realise is too high in the envelope to allow simple accretion). Thus the light-curve should be very irregular and pulsations could be difficult to observe in X-rays.

Rc<Rh
(Ps<Peq)

“Propeller effect” to stop accretion



Rc<Rh
(Ps<Peq)



Rc>Rh
(Ps>Peq)

The pulsars at the propeller stage are spinning down thus Ps will increase and approach to Ps*.

During the direct accretion stage they are accelerating thus active pulsars should have Ps ~ Ps* (be near equilibrium). This is fully in line with observations !

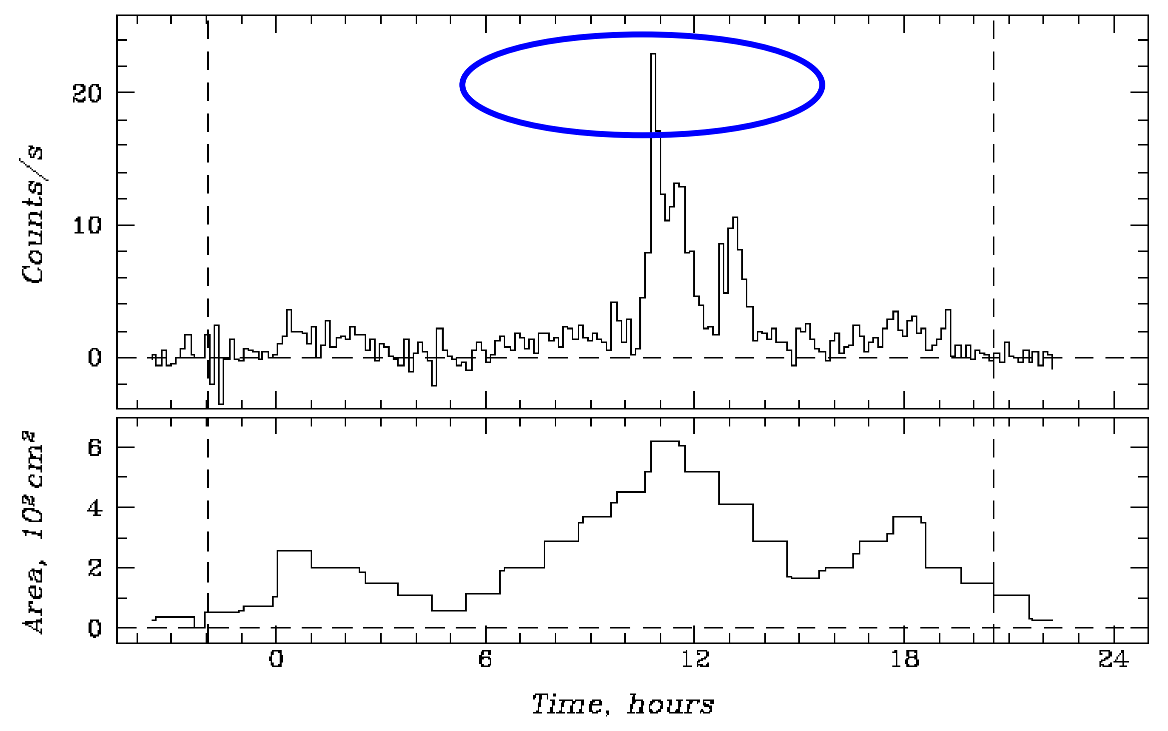
Почему SFXTs открыты именно ИНТЕГРАЛом?

- большие поля зрения телескопов
- долгие непрерывные наблюдения галактического диска и центральных областей
- высокая чувствительность в жестком рентгеновском диапазоне

Большинство SFXTs были открыты в первые годы наблюдений.

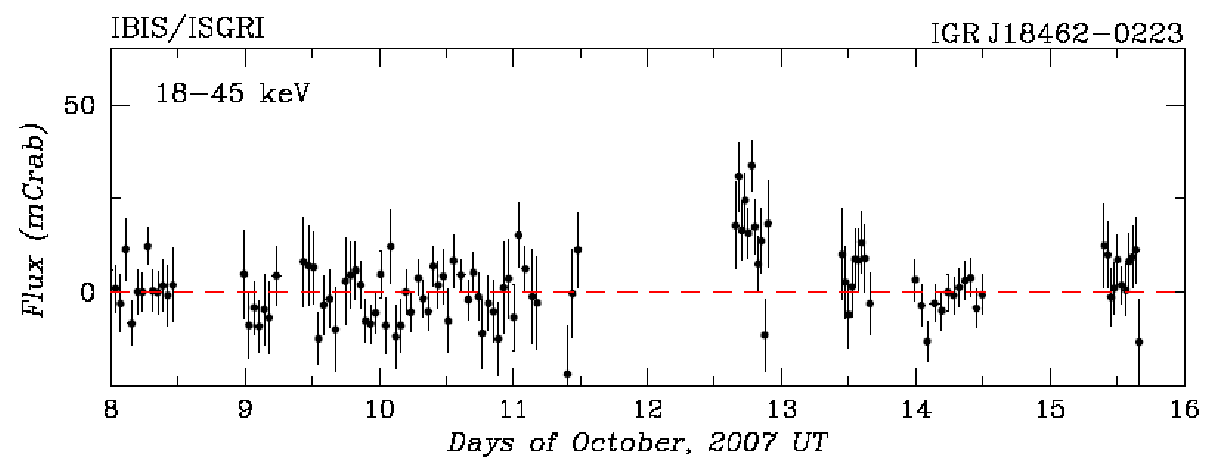
Каковы шансы обнаружить других представителей группы ?

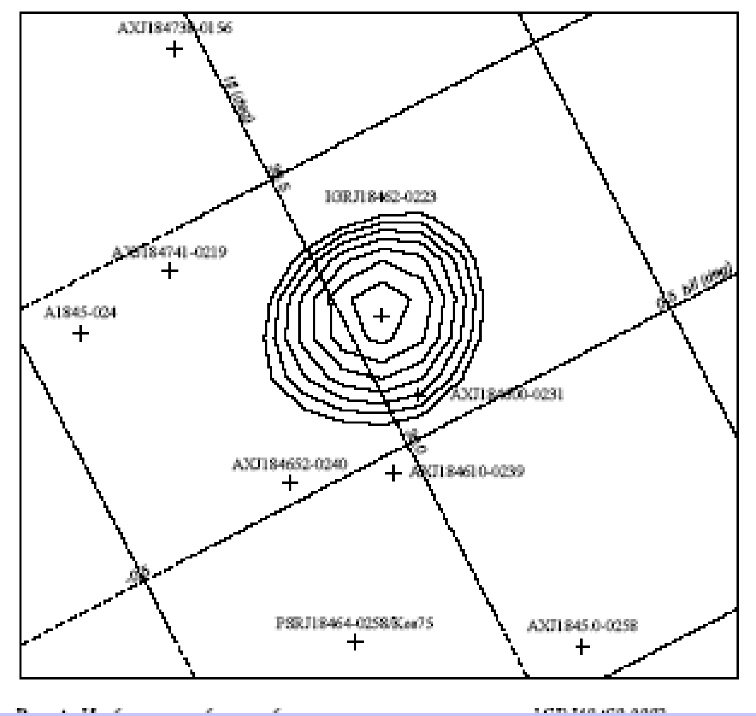
Короткие и слабые SFXTs

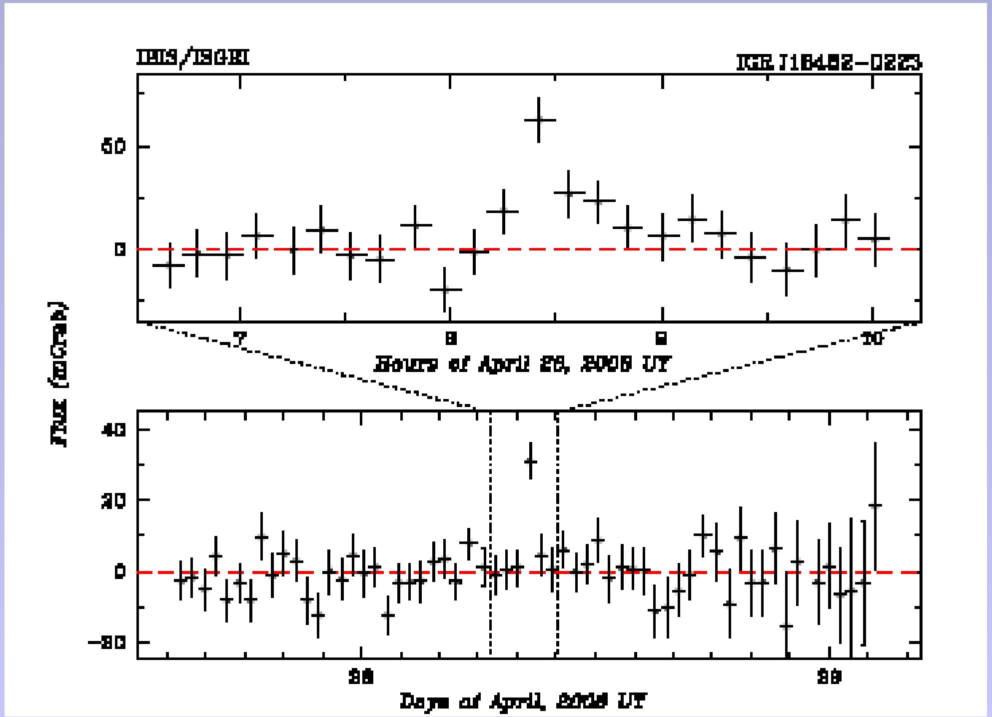


Для удаленных и слабых SFXTs мы можем наблюдать лишь короткие пики во время их вспышек – они могут иметь длительность порядка часов или даже десятков минут.

Очень короткие вспышки – слабые SFXTs ? (IGRJ18462-0223)



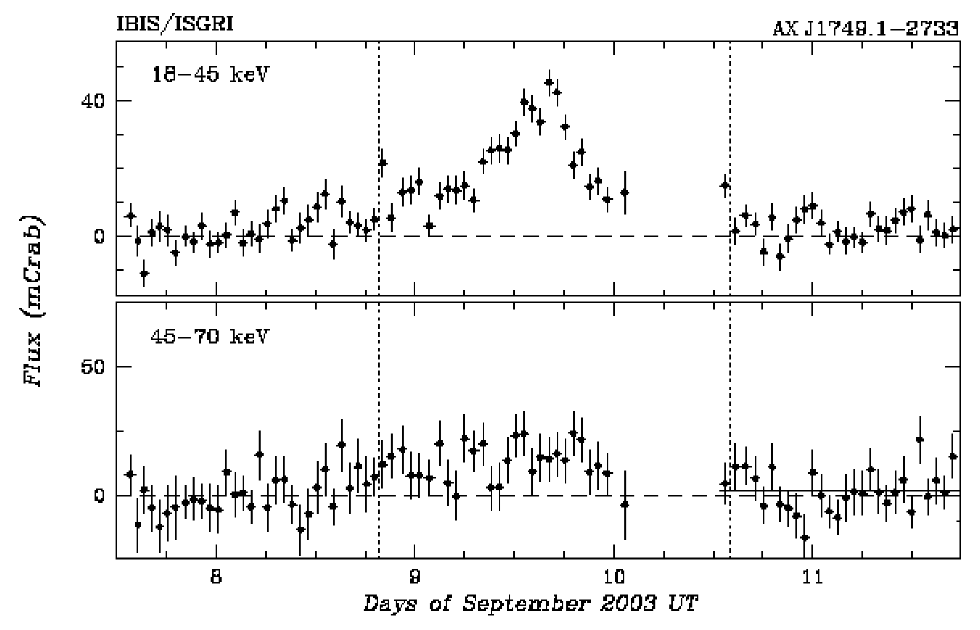


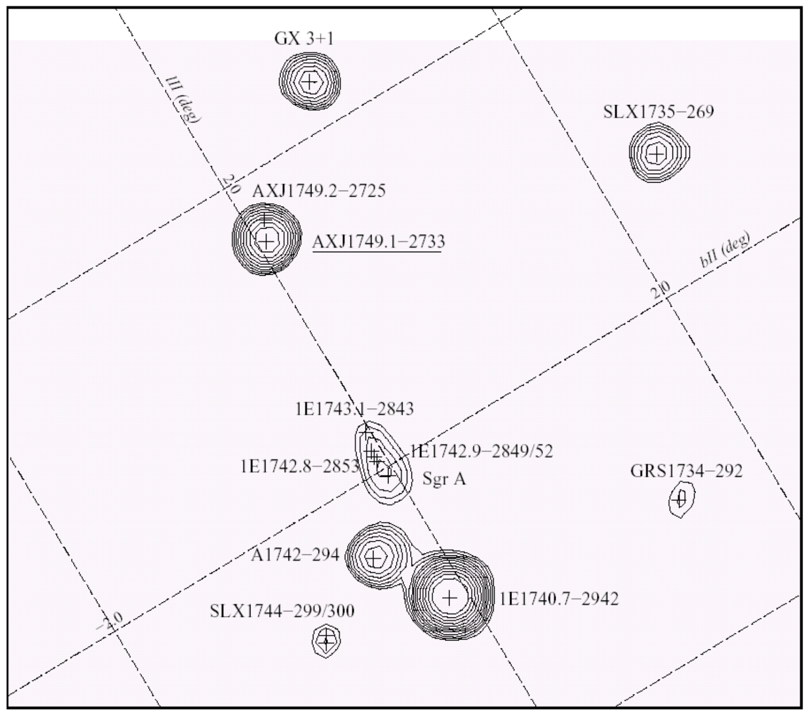


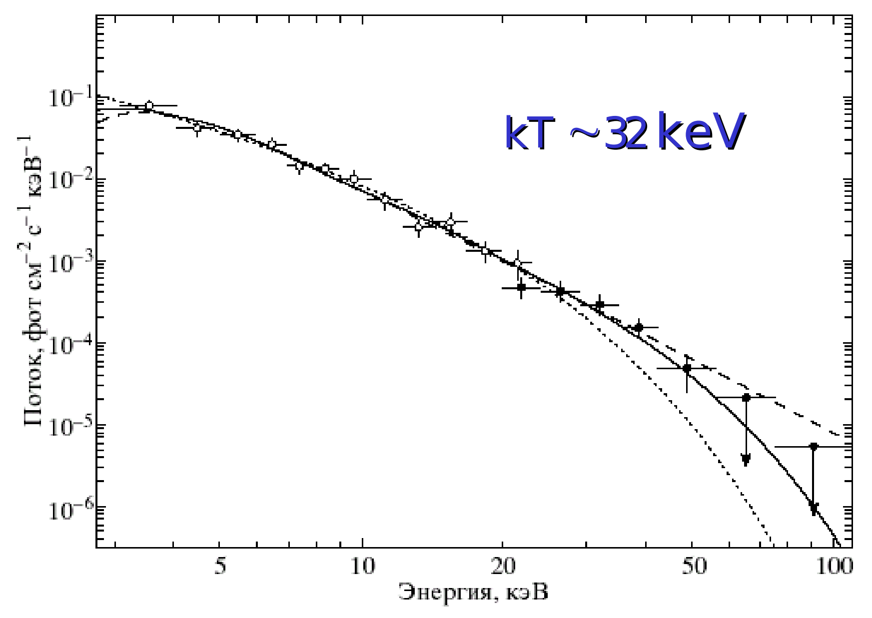
AX J1749.1-2733

It was first detected in the bright (~45 mCrab) X-ray state with INTEGRAL in September, 2003.

Its luminosity was at the level of ~10^{34} erg/s (0.04 mCrab) during 3 years of observations with ASCA.







kT ~32 keV

“Propeller effect” to stop accretion

Simulations show that amount of OB binaries could be essentially higher than we observe, the reason for their absence in the case of neutron star accretors was pointed out by Illarionov, Sunyaev (1975) - “propeller effect"

T heric radius of NS

$$r_{\rm h} \simeq \left(\frac{1}{8}\frac{H^4 R_1^{12}}{G M_1 \dot{M}^2}\right)^{1/7} \simeq 0.0050 h_*^{4/7} r_*^{12/7} \times$$

$$\times\, m_*^{-5/7} \dot{m}_*^{-2/7} v_*^{8/7} p_*^{8/21} R_\odot$$

$$H = 10^{12}\, h_*\ {\rm G}$$

where

$$r_{\rm c} \simeq \left(\frac{G M_1}{\Omega^2}\right)^{1/3} \simeq 0.0024 P_{\rm s}^{2/3} m_*^{1/3} R_\odot,$$

exceeds the corotation radius

that is when the NS spin period

$$P_{\rm s} < P_{\rm s}^* \simeq 3.0\, h_*^{6/7}\, r_*^{18/7}\, m_*^{-11/7}\, \dot{m}_*^{-3/7}\, v_*^{12/7}\, p_*^{12/21}\ {\rm s}.$$

“Propeller effect” to stop accretion

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 and the corotation radius

$$R_c = (0.5 P_s/P_b)^{1/2} R_a \simeq 0.00041\, P_*^{-1/2} P_s^{1/2} v_*^{-2}\, R_\odot$$

while the equilibrium period

$$P_s^{\,*} \simeq 258\, P_*^{37/21} h_*^{8/7} v_*^{44/7} \dot{m}_*^{-4/7}\ \mathrm{s}$$

This dependence Ps^* on Pb is much steeper than in the case of disc accretion

$$Ps^* \sim Pb^{\,4/7}\ \mathrm{s}$$