Flaring activity of the SFXT IGR J16418−4532

D Poliakov1,2†, V Aitov2 and N Ikhsanov1,2,3∗
1Pulkovo Observatory, St. Petersburg, Russia
2Saint Petersburg State University, St. Petersburg, Russia
3Special Astrophysical Observatory, Nizhnij Arkhyz, Russia
E-mail: †polyakovdmi93@gmail.com, ∗ikhsanov@gaoran.ru

Abstract. Supergiant fast X-ray transients (SFXTs) are a sub-class of wind-fed High Mass X-ray Binaries (HMXB) in which the normal companion is a supergiant. These systems were collected in a sub-class because of short flares (a few hours duration) in which the X-ray luminosity increases by a few orders of magnitude. One of the members of SFXTs is the X-ray 1212s pulsar IGR J16418−4532, which is characterized by a high quiescent X-ray luminosity and flaring on a short timescale. We show that the degenerate component of the system is either a magnetar which accretes matter from a Keplerian disk of quasi-spherical flow, or a regularly magnetized neutron star which rotates near spin equilibrium and accretes matter from a non-Keplerian magnetic disk.

1. Introduction
IGR J16418−4532 is a High Mass X-ray Binary system (HMXB) with a short eclipsing orbit of \( P_{\text{orb}} \sim 3.7 \) days [1] which belongs to the Supergiant fast X-ray transients SFXTs subclass of wind-fed HMXBs [2, 3]. The optical component of this system is an O8.5I supergiant of the mass \( M_{\text{OB}} = 3.15M_\odot \), radius \( R_{\text{OB}} = 21.4R_\odot \), luminosity \( L_{\text{OB}} = 4.47 \times 10^{35}L_\odot \), and the effective temperature \( T_{\text{eff}} = 32274K \) [4], which underfills its Roche lobe [3]. A distance to the system is \( \sim 13 \) kpc [5]. The neutron star (NS) in this system manifests itself as an X-ray pulsar with the period \( 1212 \pm 6s \) [6]. The X-ray luminosity of the system in the quiescence, \( L_{\text{qt}} \sim 10^{36} \) erg s\(^{-1}\), is unusually high for SFXTs.

2. Flaring activity
The X-ray luminosity of the system in 18 – 100 keV during outbursts lies in the range \( (2 – 40) \times 10^{36} \) erg s\(^{-1}\) [6]. The orbital phase distribution of the outbursts is uniform, apart the eclipse region where no outbursts were detected. The duration of the outbursts varies from a few minutes up to a few hours [3, 7]. The total duration of these outbursts places the active duty cycle of IGR J16418−4532 at 6.14% [3]. The raising/decline time of the outbursts lies in the range 100 – 1000s [3].

3. Equilibrium rotation
As recently shown by Ikhsanov & Mereghetti [8], the equilibrium period of a NS in a wind-fed HMXB lies within the range \( P_{\text{eq}}^{\text{min}} \leq P_{\text{eq}} \leq P_{\text{eq}}^{\text{max}} \), where

\[
P_{\text{eq}}^{\text{min}} \simeq 14s \times \mu_{30}^{6/7} \Omega_{15}^{-3/7} m^{-5/7},
\]

(1)
is the minimum possible equilibrium period, which corresponds to the case of accretion from a Keplerian disk, and

\[ P_{\text{max}}^{\text{eq}} \approx 20 \, \text{s} \times P_{\text{orb(d)}}^{15/7} \xi_{0.2}^{-15/7} \beta_{0}^{-12/7} c_{6}^{24/7} m^{-8/7} \]  

(2)

is the maximum possible equilibrium period corresponding a situation in which the angular velocity of the accreting matter is smaller than the Keplerian angular velocity at the magnetospheric radius \( \omega_{s}(r) < \omega_{k}(r_{m}) = (GM_{\text{ns}}/r_{m}^{3})^{1/2} \). Here \( \xi_{30} \) is the dipole magnetic moment \( (\mu = (1/2)B_{\text{ns}}R_{\text{ns}}^{2}) \) of a NS with the surface magnetic field \( B_{\text{ns}} \) and the radius \( R_{\text{ns}} \) in units \( 10^{30} \, \text{G} \, \text{cm}^{3} \) and \( m \) is its mass, \( M_{\text{ns}} \), in units \( 1.4 \, M_{\odot} \). The parameter \( \mathcal{M}_{15} \) represents the mass accretion rate onto the surface of the NS in units \( 10^{15} \, \text{g} \, \text{s}^{-1} \), which can be evaluated from the observed X-ray luminosity, \( L_{x} \), of the pulsar as \( \mathcal{M} = \dot{L}_{x}R_{\text{ns}}/GM_{\text{ns}} \). \( P_{\text{orb(d)}} \) is the orbital period of the binary system measured in days. \( \xi = \xi/0.2 \) is the dimensionless parameter accounting for dissipation of angular momentum due to density and velocity gradients in a gas with no magnetic field which is falling free towards the NS in a quasi-spherical fashion [9]. \( c_{6} \) is the speed of sound, \( c_{s,0} \), in the gas captured by neutron star from the stellar wind of its massive companion at the Bondi radius, \( r_{c} = 2GM_{\text{ns}}/v_{\text{rel}}^{2} \), in units \( 10^{6} \, \text{cm} \, \text{s}^{-1} \) (here \( v_{\text{rel}} \) is the velocity of NS in the frame of surrounding material). Finally, \( \gamma_{0} = \beta(r_{c}) = 8\pi \rho_{0} c_{s,0}^{2}/B_{0}^{2} \) is the ratio of thermal to magnetic pressure in the material of the density \( \rho_{0} \) which the NS captures at its Bondi radius, and \( B_{0} = B_{1}(r_{c}) \) is the magnetic field of the accreting matter itself.

The lines \( P_{\text{min}}^{eq} = P_{\text{min}}^{eq}(P_{\text{orb}}) \) and \( P_{\text{max}}^{eq} = P_{\text{max}}^{eq}(P_{\text{orb}}) \) are shown in Figure 1, which is the \( P_{\text{s}} \) vs. \( P_{\text{orb}} \) diagram. The position of IGR J16418–4532 on the diagram is marked by an asterisk. It is located well above the line of the minimum possible period and is rather close to the maximum period of a NS which accretes from a magnetized non-Keplerian disk (a so-called the Magnetic Levitating disk, or ML-disk) in which the material is confined by its own magnetic field. Formation of the ML-disk can proceed if \( R_{\text{sh}} > \max\{r_{A}, r_{\text{circ}}\} \), where \( r_{\text{circ}} \) is the circularization radius, \( r_{A} \) is the Alfvén radius. This is valid if the NS velocity relative to wind of its optical companion satisfies the inequality \( v_{\text{kd}} < v_{\text{rel}} < v_{\text{ma}} \), where

\[ v_{\text{ma}} \approx 550 \, \text{km} \, \text{s}^{-1} \times \beta_{0}^{-1/5} \xi_{30}^{-6/35} m^{12/35} \mathcal{M}_{15}^{3/5} c_{6}^{2/5} \]  

(3)

and

\[ v_{\text{kd}} \approx 430 \, \text{km} \, \text{s}^{-1} \times c_{6}^{3/7} \beta_{0}^{1/7} m^{3/7} P_{\text{orb(d)}}^{-3/7} c_{6}^{-2/7}. \]  

(4)

This indicates that the accretion process in IGR J16418–4532 can unlikely be explained in terms of the Keplerian disk accretion scenario. For this scenario to realize the surface magnetic field of the neutron star should satisfy the condition \( B_{\text{ns}} \geq B_{\text{kd}} \), where

\[ B_{\text{kd}} \sim 3 \times 10^{14} \, \text{G} \times R_{6}^{-3} m^{5/6} \mathcal{M}_{15}^{1/2} \left( \frac{P_{\text{s}}}{1000 \, \text{s}} \right)^{7/6}, \]  

(5)

is the solution of equation \( P_{\text{s}} = P_{\text{orb}}^{eq} \) for the parameters of IGR J16418–4532. Also, one can obtain similar condition \( B_{\text{ns}} \leq B_{\text{ml}} \) for the Magnetic Levitation accretion scenario, where

\[ B_{\text{ml}} \sim 3.4 \times 10^{12} \, \text{G} \times R_{6}^{-3} m^{2} \mathcal{M}_{15}^{1/2} c_{6}^{7/3} \left( \frac{v_{\text{rel}}}{500 \, \text{km} \, \text{s}^{-1}} \right)^{-35/6} \beta_{0}^{-7/6}, \]  

(6)

is the solution of equation \( R_{\text{sh}} = r_{A} \) for the parameters of IGR J16418–4532. Here \( R_{\text{sh}} \) is the Shvartsman radius [10]. These conditions indicate that accretion process in this pulsar should be constructed with the quasi-spherical or Magnetic Levitation accretion scenarios. A possibility for the NS in IGR J16418–4532 is far from the equilibrium rotation can be rather rejected since the spin-up time of the NS in this case will be less than 30 years.
Figure 1. $P_s$ vs. $P_{orb}$ diagram. The solid line corresponds the minimum equilibrium period, $P_{eq}^{\text{min}} = P_{eq}^{\text{min}}(P_{orb})$, for $\mu = 10^{30}\text{G cm}^3$ and $\mathcal{M} = 5 \times 10^{15}\text{g s}^{-1}$. The dash-dotted lines indicate the maximum equilibrium period, $P_{eq}^{\text{max}} = P_{eq}^{\text{max}}(P_{orb})$, for $\beta_0 = 1$ and $c_{s,0} = 20\text{ km s}^{-1}$. The position of IGR J16418$-$4532 is marked by the asterisk, the crosses denote several other of presently known pulsing SFXTs.

4. Flaring timescale
The observed flaring in SFXTs is associated with the sporadic variations of the mass accretion rate onto the surface of NS. This can be a reason of variations of the mass capture rate by the NS from the wind of its companion or/and instabilities of the accretion flow inside the Bondi radius or/and variations of the rate at which the accreting material enters the magnetic field of the NS at its magnetospheric boundary. All of these possibilities implies variations of the radius of the magnetosphere of the NS. The magnetospheric radius decreases during flares and increases to its initial value as the mass-transfer rate towards the magnetospheric boundary decreases and the system switches back to the quiescence.

The characteristic time on which the system can change its state from quiescence to flaring within this approach is limited to $t_{\text{rf}} \geq \tau_a(r_m)$, where $\tau_a(r_m) = r_m/\nu_a(r_m)$ is the Alfvén time, $\nu_a(r_m) = 2\mu/r_m^3\sqrt{4\pi\rho(r_m)}$ is the Alfvén velocity and $\rho(r_m)$ is the density of matter in the magnetopause at the magnetospheric boundary. If a NS accretes matter from a quasi-spherical flow or/and from a hot turbulent envelope [11], then the Alfvén time in the magnetopause is comparable to the dynamical time $t_{\text{ff}}(r) = r^3/(2G\text{M}_{\text{ns}})^{1/2}$, which under the conditions of interest is only a fraction of a second. The raise time of flares in this case reflects the characteristic time of variations of the mass-transfer rate in the accretion flow beyond the magnetospheric boundary.

If a NS accretes matter form a disk the Alfvén velocity in the magnetopause is comparable with the speed of sound in the plasma at the magnetospheric boundary, which is significantly smaller than the dynamical (free-fall) velocity. This indicates that the characteristic time on which the system can switch into flaring is limited to $t_{\text{rf}} \geq r_m/c_{s}(r_m)$. The magnetospheric radius of a NS accreting from a disk can be limited as $r_{\text{ma}} < r_m < r_\Lambda$, where (see [8] and
references therein)

\[ r_{ma} = 2 \times 10^8 \text{ cm} \times \alpha_B^{2/13} \mu_30^{6/13} L_{36}^{-4/13} m_3^{5/13} R_6^{-4/13} T_6^{-2/13} \]  

(7)

is the radius of the magnetosphere of a NS accreting from the ML-disk, and

\[ r_A \simeq 6 \times 10^8 \text{ cm} \times \mu_30^{4/7} m_3^{1/7} L_{36}^{-2/7} R_6^{-2/7} \]  

(8)

is the Alfvén radius which is defined by equating the magnetic pressure of the dipole magnetic field of the NS with the ram pressure of the free-falling spherical flow. Here \( \alpha_B \) is the efficiency parameter, \( L_{36} \) is the X-ray luminosity of the pulsar in units of \( 10^{36} \text{ erg s}^{-1} \), and \( T_6 \) is the temperature of material in the magnetopause at the magnetospheric boundary in units \( 10^6 \text{ K} \), which is normalized following Hickox et al [12]. Consequently, if the NS in IGRJ16418–4532 accretes matter from a disk, then the raising time of flares can hardly be less than a minute and about 100\,s if the temperature of material in the disk at its inner radius is about \( 10^4 \text{ K} \).

5. Conclusion
Assuming that the NS in IGRJ16418–4532 rotates close to the equilibrium period we showed that accretion in this system can hardly be explain by the accretion from Keplerian disk since this scenario requires supercritical NS magnetic field. Obtained restrictions of the characteristic time on which the system can switch into flaring are consistent with observed flaring properties. This allows to investigate the mechanism of flaring formation within Magnetic Levitation accretion scenario in IGRJ16418–4532.

Acknowledgments
VA thanks organizers for kind hospitality and financial support. NI acknowledges support of the Russian Scientific Foundation under the grant no. 14-50-00043.

References
[1] Levine A M, Bradt H V, Chakrabarty D, Corbet R H D and Harris R J 2011 The Astrophysical Journal Supplement 196 6
[2] Romano P 2015 Journal of High Energy Astrophysics 7 126–36
[3] Drave S P, Bird A J, Sidoli L, Sguera V, McBride V A, Hill A B, Bazzano A and Goossens M E 2013 MNRAS 433 528–42
[4] Martins F, Schaerer D and Hillier D J 2005 Astron. Astrophys. 436 1049–65
[5] Rahoui F, Chaty S, Lagage P O and Pantin E 2008 Astron. Astrophys. 484 801–13
[6] Sidoli L, Mereghetti S, Sguera V and Pizzolato P 2012 MNRAS 420 554–61
[7] Ducci L, Sidoli L and Paizis A 2010 MNRAS 408 1540–50
[8] Ikhsanov N R and Mereghetti S 2015 MNRAS 454 3760–5
[9] Ruffert M 1999 Astron. Astrophys. 346 861–77
[10] Shvartsman V F 1971 SvA 15 377
[11] Ikhsanov N R 2001 Astron. Astrophys. 375 944–9
[12] Hickox R C, Narayan R and Kallman T R 2004 ApJ 614 881–96