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X-ray behaviour of the Supergiant Fast X-ray Transient: XTE J1739-302

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ABSTRACT

An INTEGRAL long-term monitoring of XTE J1739-302, considered as the prototype source of the Supergiant Fast X-ray Transients (SFXTs), is presented in detail. The source follows a more complex behaviour than expected. Far from presenting a regular variability pattern, XTE J1739-3021 shows periods of high, intermediate, and low flaring activity. The X-ray behaviour of the source is analysed in the context of the clumpy structure of the supergiant wind.

Key words. binaries: close, stars: supergiants, X-rays: binaries

1. INTRODUCTION

INTEGRAL (Winkler, C. et al. 2003) data have revealed a new class of Supergiant X-ray binary stars, characterised by very short (∼ hours) X-ray outbursts and long periods of quiescence. Most of these sources have obscured OB supergiants as optical counterparts and display similar X-ray properties, leading to the definition of new class of X-ray sources, called Supergiant Fast X-ray Transients (SFXTs) (Negueruela et al. 2006a). So far, about a dozen of SFXTs or related objects have been detected by INTEGRAL. Walter & Zurita-Heras (2007) have found many commonalities in the X-ray flaring behaviour of these sources:

- Very short outbursts, much shorter than those seen in other sources and clearly too short to be associated with the viscous timescale of an accretion disk.
- Very sharp outburst rises, reaching the peak of the flare in < 1 h. The decay is, in many cases, characterised by a complex structure, with two or three further flares.
- Hard X-ray spectra, similar to those typical of HMXBs with neutron stars, showing (in many cases, variable) moderate or high absorption
- Luminous OB star supergiant companions.

At present, four different models have been proposed to explain the behaviour of SFXTs: accretion onto a neutron star from a clumpy wind (Walter & Zurita-Heras (2007); Negueruela et al. (2008)); instabilities in the magnetosphere of a neutron star rotating close to its equilibrium spin period (Grebenev & Sunyaev 2007); transitions across the magnetic and/or centrifugal barriers with modest variations in the stellar wind velocity and/or density (Bozzo, Falanga & Stella 2008); and finally, encounters of the neutron star with a putative disk around the supergiant (Sidoli et al. 2007). Characterising the X-ray behaviour of SFXTs is the main tool we have to distinguish between different models.

The best characterised SFXT is XTE J1739-302, identified with an obscured O8 Iab(f) supergiant (Negueruela et al. 2006b). The source was discovered by RXTE in 1997 during a short outburst (Smith et al. 1998) and has been detected by INTEGRAL/ISGRI several times (Lutovinov et al. (2005); Sguera et al. (2005); Sguera et al. (2006); Walter & Zurita-Heras (2007)). The X-ray spectrum during the flares is generally very absorbed. Good fits can be achieved with either a power law with a high-energy cut-off or a thermal bremsstrahlung model with kT ∼ 20 keV. In quiescence, it has been detected by Chandra at a moderate luminosity $L_x \sim 10^{34} ergs^{-1}$ and not been detected by ASCA with an upper limit of $L_x < 10^{33} ergs^{-1}$.

2. OBSERVATIONS AND DATA ANALYSIS

The INTEGRAL data correspond to our AO-4 and AO-5 approved observations within the Key Programme of the Galactic Center Region, named KP1 and KP2 respectively. The covered time intervals during these observations are: 53990-54014 MJD (KP1), 54157-54184 MJD (KP1), 54337-54369 MJD (KP2) (already included in Blay et al. (2008)) and 54538-54563 MJD (KP2, new data).

Table 1. Frequency of outbursts for the activity periods defined during KP1 observations.

Period	Interval (MJD)	On-source time (d)	Num. outburst	Outburst Freq.(d^{-1})
E	53990.50 – 54001.50	5.5	21	3.8
F	54008.75 – 54014.00	3.1	13	4.2
G	54158.00 – 54163.25	3.0	8	2.7
H	54165.50 – 54169.00	1.8	8	4.4
I	54182.00 – 54184.00	1.3	3	2.3

The data have been reduced using the standard Off-line Analysis Software (OSA), version 7.0 *(http://isdc.unige.ch)*.

3. TIMING ANALYSIS: CHARACTERISING THE OUTBURST FREQUENCY

The 20-40 keV ISGRI lightcurve of XTE J1739-302 during our observations of KP1 is shown in Fig. 1. During these observations the source presents a clear flaring activity. However during the KP2 period the source is not detected significantly over a total on-source time of ~ 1000 ks, and only an upper limit flux of ~ 45 mCrab can be reported. For the sake of comparison, public data of the source from 2003-2005 are shown in Fig. 2.

KP1 data contain 5 periods of continuous coverage of the source, labelled as E, F, G, H and I in Fig. 1. This lightcurve can be divided in 26 activity or flaring periods, following the definition of flaring episode given by Walter & Zurita-Heras (2007).

The average duration of the activity period is ~ 6 h, with a maximum duration of 16 h and a minimum duration of 0.6 h. XTE 1739 shows two different kind of outbursts: the faint ones more numerous give an average flux of ~ 85 mCrab and the less frequent and the brighter ones with an average flux of ~ 500 mCrab, but reaching up to ~ 1.6 Crab flux. Both types of activity periods last on average very similar time span, but the brightest ones tend to last for longer than ~ 1h and the faintest ones can be as short as ~ 0.6 h.

The long-term monitoring of the source obtained with KP1 data, allows us to determinate the source characteristic outburst frequency. Following Walter & Zurita-Heras (2007), we define each flare with a clearly separated peak as an outburst. Table 1 summarises the outburst counting, showing the duration of the quasi-continuous observing period, the number of outbursts, as seen in Fig. 1 and the derived outburst frequency for each period, defined us the ratio between the number of outbursts and the time duration of a given period.

The obtained outburst frequency is much higher than previously expected (2-4 outburst d^{-1} as opposed to 0.14 outbursts d^{-1} given as average of INTEGRAL detections of SFXTs by (Walter & Zurita-Heras 2007)). This higher frequency is also seen in the active periods during the GCDE observations, such as the MJD 52877-78 and 53073-74 intervals in Fig. 2. However during the KP2 observations, no outburst have been detected. Nevertheless, we know that the absence of activity is not complete, as RXTE has detected at least an outburst during the long gap of KP2 observations. Taking a look to Fig. 2, we can see that long time intervals are characterised by low X-ray activity.

On the other hand, we have searched for pulsations in our data and we have not found any coherent modulation up to time scales of ~ 1000 s. The possibility of the presence of a very slow NS in the system can not be excluded.

4. DISCUSSION: ACCRETION FROM CLUMPY WIND ONTO NS

Giving the average outburst frequency for KP1, we can determinate the orbital period of a NS as the function of the radial distance as follow:

$$\nu_{\rm outb} = \frac{N(r)_{\rm c}^{\rm ring}}{P_{\rm orb}} \qquad (1)$$

where $N_{\rm c}^{\rm ring}$ is the number of clumps inside a ring at a distance r from the donor star. This quantity (continuous line Fig. 3 left panel) represents the number of clumps that a NS orbiting in a circular orbit of radius r will statistically be able to see and to accrete (Negueruela et al. 2008).

On the other hand, applying Kepler's third law, we can estimate the orbital period of a binary system formed by a canonical NS orbiting a O8I star, and express it as a function of the binary separation (see dashed line in left panel Fig. 3).

For the high frequency observed, the clumping parameter L_0 (Oskinova et al. (2007); Negueruela et al. (2008)) must be of ~ 0.2. Under this interpretation (see left panel Fig. 3) the system should have an orbital separation of $r \lesssim 3R_*$ and an $P_{\rm orb} \approx 8$ d (the outbursts seem to be regularly separated by an interval of ~ 8 d).

Assuming a distance to the source of 2.3 kpc (Negueruela et al. 2006b), we can estimate the source luminosity for the different intensity periods (fluxes values have been obtained from our spectral analysis – partially included in Blay et al. (2008)): flaring activity reaches ~ 5×10^{35} erg s^{-1}, outbursts ~ $\times10^{36}$ erg s^{-1} and the brightest outburst reaches ~ $\times10^{37}$ erg s^{-1}.

To validate our scenario, we have plotted the accretion luminosity of simple Bondi-Hoyle wind accretion versus the radial distance (see Fig. 3 right panel). At the distance to the system, the luminosity is the order of ~ 5×10^{35} erg s^{-1}, as observed in the flares. Relative changes in the density by a factor of 10 (plus or minus) can account for the outburst and quiescence luminosities.

The observed long spans of high activity of the source rule out the model proposed by Sidoli et al. (2007), where outbursts happen one or twice each orbital cycle. Meanwhile, the non-detection of spin periods below 1000s seems incompatible with Grebenev & Sunyaev (2007) model. Finally, the gating mechanism proposed by Bozzo, Falanga & Stella (2008) together with the clumpiness of the stellar wind may explain the very large luminosity swings of SFXTs with much milder density (or velocity) contrasts in the wind. Further studies are necessary to understand how much the magnetic field may contribute.

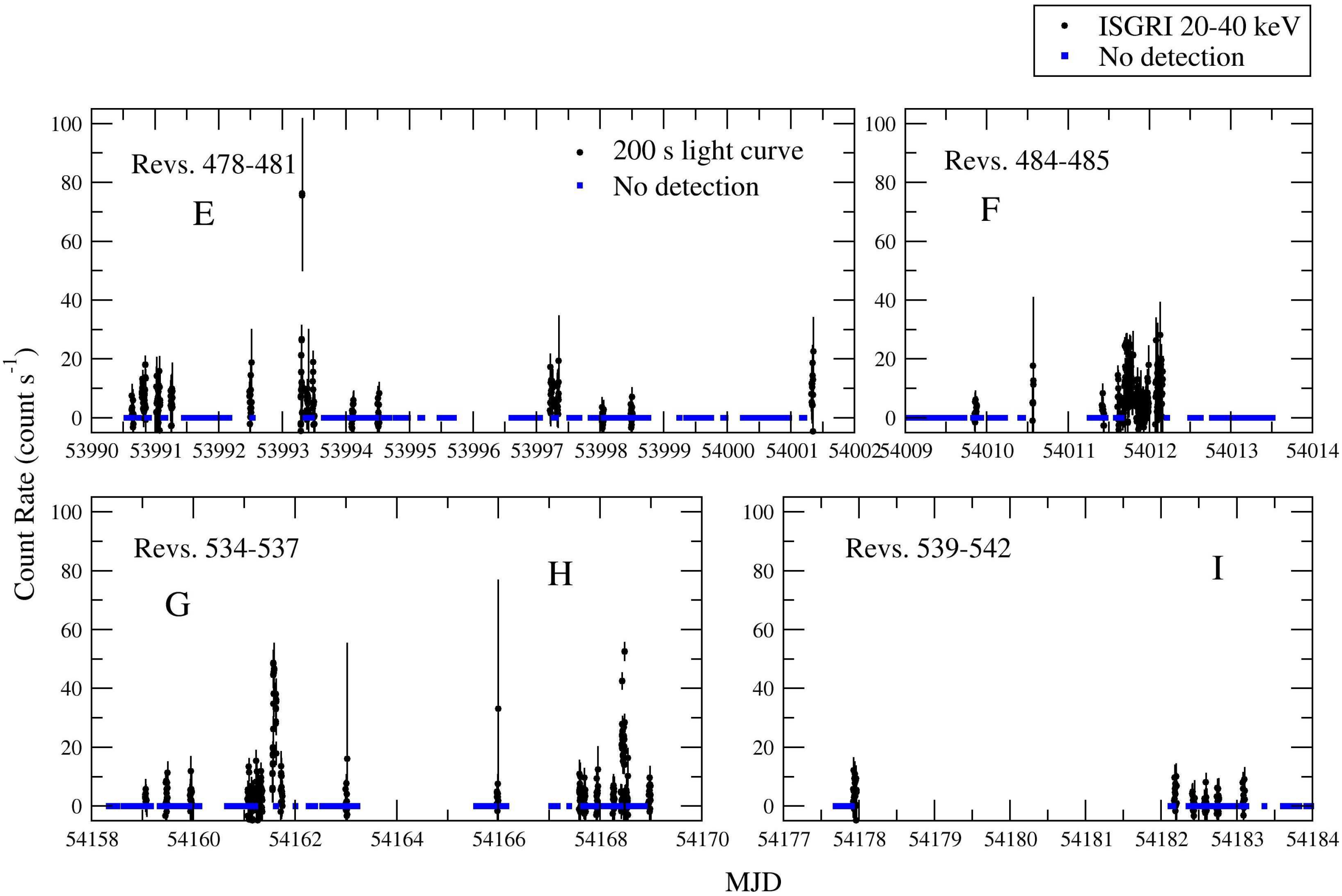

Fig. 1. Light curve of IGR J17391-3021 data from *INTEGRAL* Key Programme 1. In order to appreciate the number and structure of outbursts, a binning time of 200 s has been used. Blue squares represent times when INTEGRAL was staring towards the source direction but the source was not detected.

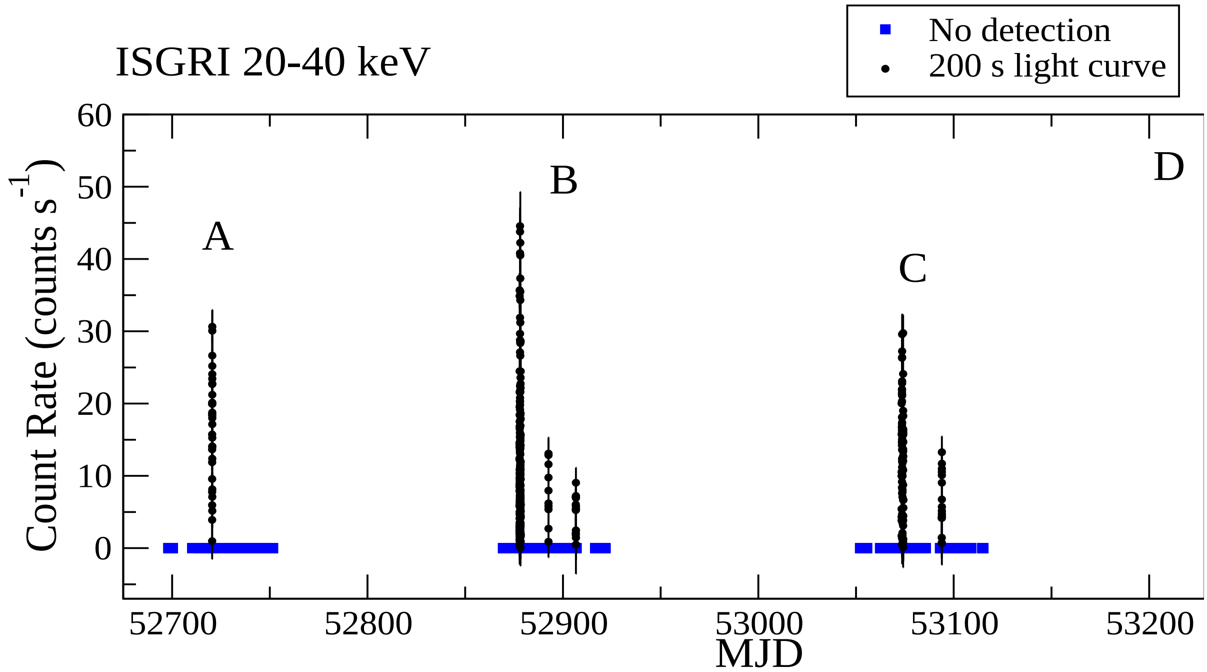

Fig. 2. Light curve of XTE J1739-302 data from *INTEGRAL* Galactic Center Deep Exposure (GCDE). In order to appreciate the number and structure of outbursts, a binning time of 200 s has been used.

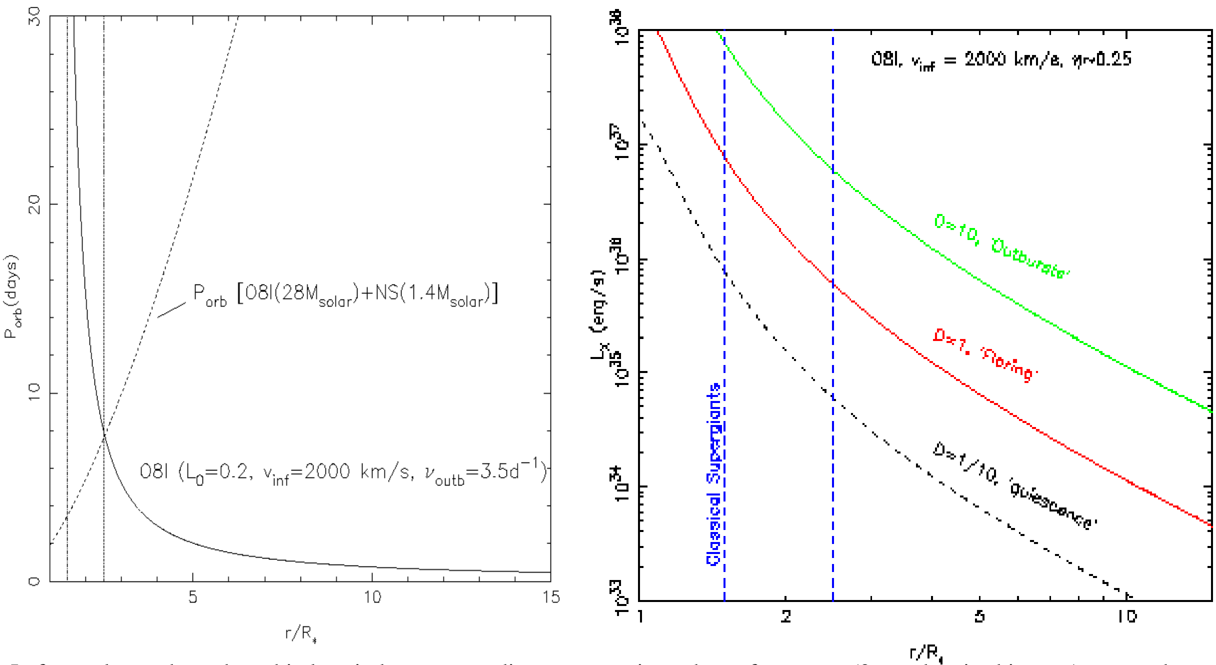

Fig. 3. Left panel: we show the orbital periods corresponding to a certain outburst frequency (3 per day, in this case) versus the radial distance (continuous line). The dashed lines represent the Kepler law for a NS and an O8I star. Vertical lines mark the smooth wind regime region, where the classical supergiants reside. For the observed frequency, the NS must lie close to the smooth region upper limit, at $r \lesssim 3R_*$. Right panel: Accretion luminosity versus radial distance. At the distance to the system, the luminosity is $\sim 5 \times 10^{35}$ erg s^{-1}, as observed in the flares. Relative changes in the density by a factor of 10 (plus or minus) can led to outburst or 'quiescence'.

5. CONCLUSIONS

XTE 1739-3021 has been observed with the INTEGRAL observatory during a long time span. In the period 2003-2005 the source showed moderate activity with an outburst frequency below 1 outburst d^{-1}. During our KP1 observations, the source increases its flaring level with an average characteristic outburst frequency of 3 outburst d^{-1}. Surprisingly, KP2 data reveal an unusually low activity state, and no outburst was detected with a flux above 45 mCrab. The behaviour during the first two periods can be explained well within the framework of the clumpy wind models. These models even predict an orbital periodicity around $\sim$ 8 d and will require the presence of a neutron star as the compact companion. To explain the low activity observed during KP2 period, geometrical considerations related to the eccentricity of the orbit, or a drop in the mass loss from the supergiant companion, need to be invoked to maintain consistency with the proposed model. This model would be the first consistent attempt to explain the observational propertiers of the SFXT and the classical wind-fed systems all together.

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