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Frequent bursts from the 11 Hz transient pulsar IGR J17480-2446

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Abstract. Accreted matter falling on the surface of the neutron star in a Low Mass X-ray Binary (LMXB) system gives rise to intense X-ray bursts originating from unstable thermonuclear conflagration and these bursts can be used as a tool to constrain the equation of state. A series of such X-ray bursts along with millihertz (mHz) quasi-periodic oscillations (QPOs) at the highest source luminosities were observed during the 2010 outburst of the transient LMXB pulsar IGR J17480–2446. The quite diverse burst properties compared to typical type-I bursts suggested them to be the type-II bursts originating from accretion disc instability. We show that the bursts are indeed of thermonuclear origin and thus confirm the quasi-stable burning model for mHz QPOs. Various properties of the bursts such as, peak flux, fluence, periodicity and duration, were highly dependent on the source spectral states and their variation over a large accretion rate range revealed the evolution of the burning process at different accretion rate regimes.

Keywords : accretion, accretion discs – stars: neutron – stars: individual: IGR J17480-2446

1. Introduction

The transient LMXB IGR J17480–2446 in the globular cluster Terzan 5 was discovered in outburst by *INTEGRAL* on Oct 10, 2010. This source is an unique one because of its few interesting properties- it is an unusually slowly rotating (11 Hz) accreting X-ray pulsar, shows a series of highly recurrent X-ray burst, shows burst oscillation at such low frequencies, shows mHz QPOs, accretion disk wind is detected from it and it is only the second source to show atoll-Z transition. An X-ray burst was observed from this source by the *RXTE* PCA on October 13, 2010 and following that a series of recurrent bursts were observed at short intervals (shortest till date) (Papitto et al. 2011; Motta et al. 2011; Chakraborty & Bhattacharyya 2011; Linares, Chakrabarty & van der Klis 2011). The burst frequency increased with source intensity and at

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the outburst peak, the bursts disappeared and milliHertz (mHz) quasi-periodic oscillations (QPOs) appeared. The highly frequent bursts and the lack of cooling during the decay of weaker bursts led Galloway & in't Zand (2010) to propose these bursts to be the type-II bursts occurring due to accretion instability. Type-II bursts are fed by gravitational potential energy rather than nuclear energy and thus these bursts being Type-II renders the existing model of quasi-stable nuclear burning for mHz QPOs invalid. Thus, here we carry out a detailed study of these bursts in order to understand their unique nature and origin, to test the mHz QPO model and to probe the variation of burst properties with accretion and spectral states.

2. Observation and data analysis

The source was observed by *RXTE* PCA during its outburst from October 13, 2010 to November 19, 2010. The total time observed by PCA was $\approx$ 297 ks (proposal no. 95437; 46 obsIds: 95437-01-01-00 to 95437-01-14-00).

2.1 Bursts

We found $\sim$ 400 bursts in the PCA data of this source and analysed all of them to understand their origin. For this purpose we have used the event-mode/ good-Xenon files because of the high time and spectral resolution offered by them. In order to perform a time -resolved spectroscopy of these bursts, we have divided the bursts into time segments with significant statistics and created a dead-time corrected spectrum from each of them. The background for spectral modelling was generated from the pre-burst emission. Each such spectrum was modelled with an absorbed blackbody model within 3–15 keV with the neutral hydrogen column density N_H fixed at 3.8×10^{22} cm^{-2} (Galloway & in't Zand 2010; Kuulkers et al. 2003). The dead-time corrected pre-burst spectra was created from the standard-2 mode files (van der Klis 1989) and the corresponding background from the *RXTE* PCA data analysis tool `PCABACKEST`. From various combinations of thermal and non-thermal models, the `phabs*(bbodyrad+powerlaw+Gaussian)` gave the best fit for the pre-burst spectra within 3–15 keV. The fit results were used to calculate α– the ratio of the non-burst to burst fluence.

2.2 Color-color (CD) and hardness-intensity diagrams (HID)

For constructing CD and HID we have used the entire top layer PCU-2 standard-2 mode data after excluding the bursts and data gaps. The background-subtracted detector counts were calculated in the 4 energy bands– 2.6-3.9, 3.9-5.7, 5.7-9.2, 9.2-18.9 keV and the soft color (SC) and the hard color (HC) were calculated taking the ratio of the first two and last two respectively. The intensity is given as the total background subtracted count rate within 2.6 – 18.9 keV. In order to track the source spectral state evolution we have segmented the data into 11 temporal segments each marking a distinguishable position in the HID. In the 5th segment all the data from

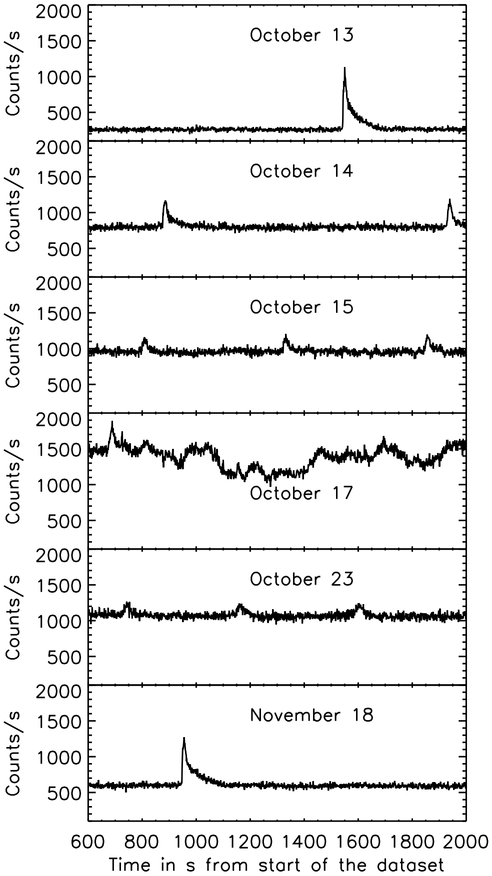

Figure 1. Burst lightcurves of 1 s resolution of data from 6 days from different regions of the outburst of IGR J17480–2446 (Chakraborty & Bhattacharyya 2011)

October 17-21 were combined as in those times the bursts could not be distinguished from the non-burst. Except in segment 5 the source most probably traces out the 'banana' state of an atoll source. The source showed a clear hysteresis in HID between the rise and the decay of the outburst. To investigate further, the CD/ HID were created for each day in segment 5 (5a, 5b, 5c, 5d and 5e) and 'Z' like tracks with secular motion were observed in them (Chakraborty et al. 2011).

3. Results and discussion

The burst properties evolved with the source intensity during the outburst and a few examples are shown in Fig. 1 and Table 1. The first burst observed by *RXTE* PCA on October 13, 2010 is a typical thermonuclear burst because of its characteristic

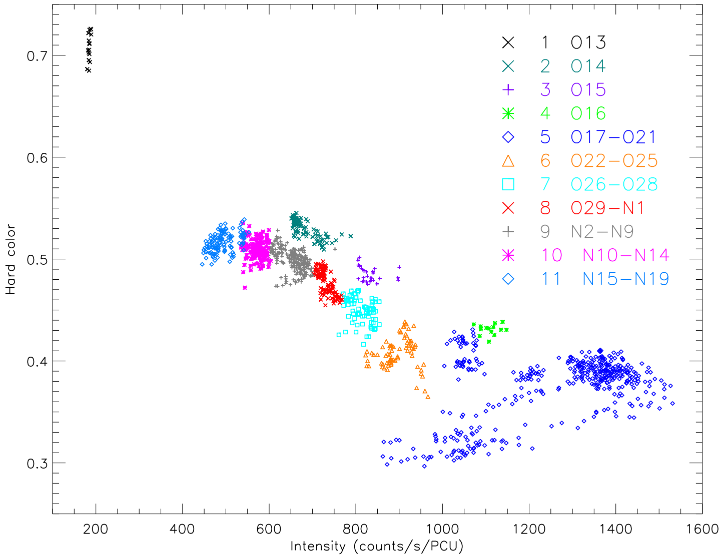

Figure 2. Hardness-Intensity Diagram of 2010 outburst of IGR J17480–2446 using the RXTE PCA data. Different temporal segments are shown using different plotting symbols and segment numbers. The dates corresponding to the different segments is shown. Here, 'O' stands for 'October' and 'N' stands for 'November'. (For CCD and detailed plots of the 'Z' tracks see Chakraborty et al. (2011).)

profile, temperature cooling during decay and presence of burst oscillations (Cavecchi et al. 2011). We conclude that the following bursts were also powered by nuclear energy rather than gravitational from their properties on the basis of the following reasons: 1) For a thermonuclear burst the value of α is theoretically expected to be ~40. Therefore the calculated values of α ($\sim 50-90$) throughout the outburst is consistent with a thermonuclear origin. 2) Though most of the weaker bursts do not exhibit a cooling trend during the decay, the stronger bursts during the early and late phases of the outburst do show cooling. The absence of the cooling is probably due to lower statistics for the weaker bursts. 3) The burst and the non-burst spectra fitting require different models suggesting different origins for them. 4) Burst peak flux, fluence and recurrence time are anti-correlated with non-burst flux 5) Bursts do not show "ringing" or "flat-top" like the type-II bursts rather the burst profiles were similar to the October 13 burst and varied smoothly during the outburst 6) No clear evidence of dips, which is a signature of type-II bursts, was obtained.

After establishing this bursts to thermonuclear, we proceeded to examine their evolution during the outburst and for this purpose we studied the source persistent spectra and spectral state evolution. The source took a month to trace out the entire 'banana' state in the HID (Fig. 2). The soft and hard color decreased with intensity and at the peak of the outburst at the highest intensities the 'Z' like tracks appear in

Table 1. Properties of burst and non-burst emissions

Date^1	$F_{b,peak}{}^2$	τ^3	$T_{rec}{}^4$	$F_p{}^5$	$E_b{}^6$	α^7	$n_b{}^8$
Oct 13	$9.89^{+0.73}_{-0.78}$	120	-	$2.58^{+0.01}_{-0.02}$	$26.70^{+0.52}_{-0.54}$	-	1
Oct 14	$5.36^{+0.48}_{-0.56}$	105	1034	$8.62^{+0.04}_{-0.04}$	$15.35^{+0.61}_{-0.67}$	$58.11^{+2.32}_{-2.55}$	3
Oct 15	$2.73^{+0.02}_{-0.23}$	72	512	$10.65^{+0.04}_{-0.04}$	$6.60^{+0.22}_{-0.29}$	$82.62^{+2.76}_{-3.59}$	5
Oct 23	$2.70^{+0.29}_{-0.39}$	56	434	$11.81^{+0.05}_{-0.06}$	$6.72^{+0.37}_{-0.44}$	$76.38^{+4.25}_{-4.99}$	6
Oct 26	$4.21^{+0.27}_{-0.31}$	60	722	$10.55^{+0.04}_{-0.05}$	$11.21^{+0.31}_{-0.35}$	$67.94^{+1.92}_{-2.15}$	5
Oct 31	$4.18^{+0.38}_{-0.42}$	90	1016	$9.54^{+0.04}_{-0.04}$	$10.31^{+0.37}_{-0.42}$	$93.96^{+3.43}_{-3.81}$	3
Nov 05	$4.56^{+0.41}_{-0.46}$	100	1273	$8.92^{+0.04}_{-0.04}$	$12.50^{+0.35}_{-0.38}$	$90.83^{+2.58}_{-2.82}$	3
Nov 08	$4.92^{+0.54}_{-0.60}$	120	1488	$8.35^{+0.04}_{-0.04}$	$17.62^{+0.42}_{-0.46}$	$70.48^{+1.72}_{-1.85}$	2
Nov 15	$7.65^{+0.59}_{-0.63}$	130	2137	$7.26^{+0.03}_{-0.03}$	$26.85^{+0.55}_{-0.59}$	$57.80^{+1.20}_{-1.30}$	2
Nov 18	$9.17^{+0.61}_{-0.65}$	135	2391	$6.62^{+0.02}_{-0.02}$	$36.41^{+0.65}_{-0.70}$	$43.49^{+0.79}_{-0.85}$	2

Notes: (1) Observation date (for detailed time ranges see Table 1 of Chakraborty & Bhattacharyya (2011)); (2) Mean burst peak flux (in 10^{-9} ergs cm^{-2} s^{-1}) within 3 – 15 keV; (3) Mean duration (in s) of a burst (from ∼ 5% of peak count rate during rise to ∼ 5% of peak count rate during decay); (4) Mean burst recurrence time; (5) Mean persistent (non-burst) flux (in 10^{-9} ergs cm^{-2} s^{-1}) within 3 – 15 keV; (6) Mean burst fluence (in 10^{-8} ergs cm^{-2}) within 3 – 15 keV; (7) $\alpha = F_p T_{rec}/E_b$ (8) Number of bursts observed within the chosen time

the CD and HID indicating transition between 'atoll' and 'Z' state (Chakraborty et al. (2011)). This is one of the transient sources to have shown large scale hysteresis as observed in sources like Aquila X-1, EXO 1745–248, 4U 1608–52. Though the peak outburst luminosities of these sources are similar, the widely different tracks traced out by them in the HID suggests that the spectral evolution during an outburst is not dependent on its peak luminosity.

The variation of hard color, soft color, blackbody and powerlaw parameters with source intensity as shown in Fig. 5 of Chakraborty et al. (2011) can give indications as to the emission mechanism and the emission geometry evolutions during the outburst. The blackbody temperature and the powerlaw index were somewhat correlated suggesting same origin for these two components- most likely the magnetic pole. As the source entered the high-soft state the the contribution of the thermal component dominated that of the non-thermal one. The blackbody+powerlaw model is well expected of a neutron star low mass X-ray binary pulsar with the blackbody originating from the neutron star surface and the powerlaw indicating a comptonized component.

4. Conclusions

Burst properties were found to be highly correlated with spectral states and the mHz QPOs occurred during the 'Z' regime. The burst properties and their gradual variations during the outburst as depicted before suggests that the bursts are of thermonuclear origin (Chakraborty & Bhattacharyya 2011; Motta et al. 2011; Linares et al. 2011). Theoretically it is expected that with increase in accretion rate (which is related to the non-burst emission), the thermonuclear burning on the neutron star surface approaches stability and bursting frequency increases and finally at very high accretion rate stable burning starts to set in with appearance of mHz QPOs. Therefore these bursts and hence mHz QPOs, caused by the quasi-stable nuclear burning, can be used as a tool to measure the various neutron star parameters. Compared to other periodic bursters like EXO 0748-676 this source showed highly periodic bursts with shortest recurrence times observed till date which may be related to the fact that it is a pulsar and thus matter is initially accreted onto smaller area. The variation of the burst recurrence was modelled using $T_{rec} \propto F_p^{-\beta}$ (T_{rec} is burst recurrence time and F_p is persistent flux) and β was obtained to be 2.53 ± 0.13, 2.52 ± 0.06 and 2.91 ± 0.07 for the rise, the decay and the whole of the outburst respectively. The value of β deviated from the expected value 1 indicating the set in of different burning regimes for different accretion rates (Linares et al. 2012). Thus this source provides a perfect laboratory for studying the mechanism of thermonuclear bursts at high accretion regime and the physics of highly recurrent bursts.

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