## The dark side of the bursting pulsar

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### 1. Abstract

GRO J1744−28 is a unique source which appears as a transient accreting pulsar and a peculiar X-ray burster. This unusual combination of properties is thought to be due to the magnetic field strengh of the neutron star, which being $B \sim 5 \times 10^{11}$ G is both significantly higher than in accreting millisecond pulsars but lower than those of normal X-ray pulsars. Given the estimated field, it has been suggested that outside of the outbursts the source shall switch to the so-called "propeller" regime when the accretion is centrifugally inhibited, and only non-pulsed thermal emission from neutron stars surface could still be observed. However, several serendipuous detections of GRO J1744−28 in quiescence revealed a spectrum fully compatible with that observed during the outbursts rather than much softer spectrum expected from a pulsar in "propeller" regime. It is unclear, therefore, whether accretion is indeed inhibited and, if not, how the accreted plasma overcomes the centrifugal barrier. We propose a 50 ks XMM observation of the source in quiescence to investigate the physical origin of the observed X-ray emission.

### 2. Description of the proposed programme

*A) Scientific Rationale:*

GRO J1744−28, also known as the bursting pulsar was discovered in 1995 during a major outburst, one of the three observed to date. The peak outburst luminosity reaches $\sim 10^{38}\,\mathrm{erg\,s^{-1}}$, while quiescent flux is much lower at $10^{33-34}\,\mathrm{erg\,s^{-1}}$ (Wijnands & Wang 2002; Daigne et al. 2002; Degenaar et al. 2012). At high luminosities the source appears as an X-ray pulsar with period of $\sim 0.467$ s orbiting a low mass (0.2-0.7 $M_\odot$) companion in a circular $\sim 11.8$ d orbit (Rappaport & Joss 1997). The photoelectric absorption does not change significantly during the outbursts and is comparable with interstellar absorption $N_H \sim (5-6) \times 10^{22}\,\mathrm{cm^{-2}}$ in the direction of the Galactic center where the source is located at a distance of $\sim$8 kpc (Nishiuchi et al. 1999). The distance estimate is, however, rather uncertain, and the source can be as close as $\sim$3.5 kpc (Sanna et al. 2017).

Probably the most unusual property of GRO J1744−28 are the short $\sim 10$ s bursts of X-ray emission with hard spectrum which are thought to be due to a rapid increase of the accretion rate triggered by magnetospheric instabilities. We have recently shown, however, that besides the hard component, the bursts contain a time-dependent thermal component similar to that observed in normal X-ray bursters (Doroshenko et al. 2015). We also independently discovered a narrow absorbtion feature at $\sim 4.7$ keV, which is interpreted as a cyclotron line (D'Aì et al. 2015; Doroshenko et al. 2015) and implies surface field of $\sim 5 \times 10^{11}$ G. This is significantly lower than those of normal X-ray pulsars, yet higher than in accreting millisecond pulsars. Such a low field is probably related to the peculiar observed properties of the pulsar, and in particular the short bursts.

Magnetic fields can also be estimated from the observed spin-up rate. However, the situation is complicated by the uncertainties in distance, spin-down torque, and coupling radius between the disc and magnetosphere. On the other hand, assuming the field strengh is known, Sanna et al. (2017) concluded that to explain the observed spin-up the source must be relatively close (i.e. $\sim 3.5$ kpc), and that accretion disc must push comparatively deep into the magnetosphere ($\sim 0.2 - 0.4 R_A$, where $R_A$ is the Alfvén radius).

Another estimate of the field has been obtained based on the claimed transition to the so-called "propeller" regime at the end of 1996 outburst (Illarionov & Sunyaev 1975; Cui 1997). Rotating magnetosphere of the pulsar expands as the accretion rate drops, so linear velocity of field lines must exceed local Keplerian velocity at some stage, and the accretion is inhibited. Transition to this regime has been recently detected by our group in several accreting pulsars (Tsygankov et al. 2016a), and accreting magnetars (Tsygankov et al. 2016b, 2017a). We have found, however, that in some cases instead of the "propeller" regime, a stable low level accretion state sets in, which we have interpreted as accretion from a cold, non-ionized accretion disc (Tsygankov et al. 2017b,c; Doroshenko et al. 2014).

Whether a given source enters the "propeller" regime or low-ionized accretion disc accretion at low accretion rates depends on the inner disc temperature at the time of the expected "propeller" transition, and depends only on fundamental parameters of the neutron star (Tsygankov et al. 2017b). It is expected that pulsars with periods shorter than $P = 36.6k^{6/7}B_{12}^{0.49}M_{1.4}^{-0.17}R_6^{1.22}$ s shall end up in the propeller regime (Tsygankov et al. 2017b). Here $k \sim 0.5$ is inner disc radius expressed in units of Alfvén radius $R_{disc} = kR_A$, and $B_{12} = B/10^{12}, M_{1.4} = M/1.4M_\odot, R_6 = R/10^6$ are neutron star parameters. For GRO J1744−28 we find $P_* \sim 6-13$ s, as illustrated in Fig. 1, i.e. it is expected to switch to the propeller below $10^{35-36}$ erg/s (depending on the assumed value of $k$), in line with suggestion by Cui (1997). Note that it must also be the case if the disc for some reason pushes deeper into the magnetosphere than usually assumed (D'Aì et al. 2015; Sanna et al. 2017). Below this luminosity accretion must be centrifugally inhibited. Indeed GRO J1744−28 has only been detected in quiescence at much lower level at $L_x \sim 10^{33}$ erg/s (Daigne et al. 2002; Wijnands & Wang 2002) comparable with luminosity observed in other "propeller" sources.

Closer inspection of the quiescent spectrum suggests, however, that the source might continue to accrete even at this luminosity. Indeed, in the "propeller" regime only relatively soft ($kT \sim 0.5$ keV) thermal emission from the neutron star surface is expected to be observed, which is consistent with the observed spectra of V 0332+53 and 4U 0115+53 at low luminosities (Tsygankov et al. 2016a). On the other hand, observed spectrum of GRO J1744−28 in quiescence is significantly harder as illustrated in Fig. 1. In fact, it appears to be fully consistent with the spectrum of the source observed during the outbursts implying that the observed X-ray emission is likely to be accretion powered also in quiescence. The centrifugal inhibition appears thus to be ineffective for yet unknown reason. This, if true, will have a profound impact on our understanding of the accretion mechanisms at low accretion rates and of the spin evolution of magnetized neutron stars. It is essential, however, to prove that the accretion indeed continues, which is the main goal of the proposed investigation.

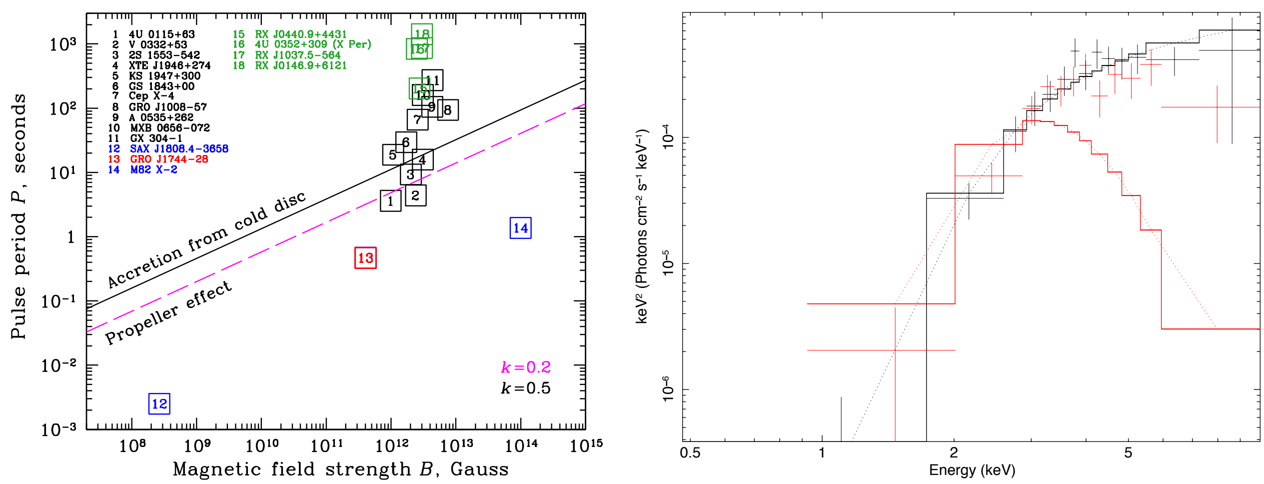


Figure 1: *Left:* Collection of some known NS XRBs on the B−P plane. Binaries with Be-type donor star are shown in black and green (weak persistent sources). We also show GRO J1744−28 (red), the unique accreting millisecond pulsar SAX J1808.4-3658, and the accreting magnetar M82 X-2 (both blue). The solid and dashed lines correspond to model prediction by Tsygankov et al. (2017b) separating the parameter space for the "propeller" and cold disc accretion for $R_{disc} = 0.2/0.5R_A$. *Right:* Unfolded spectrum of GRO J1744−28 in quiescence as observed with *XMM-Newton* (obs. 0506291201, colors correspond to two MOS cameras). A cutoff power law model with parameters fixed to those reported in Doroshenko et al. (2015) for outburst spectrum with only normalization adjusted, and a blackbody with temperature fixed to 0.5 keV similar to that observed in other propeller sources are also shown for reference. GRO J1744−28 appears to be significantly harder $kT \sim 1.2$ keV, however, the statistics is insufficient to discriminate between the models.

*B) Immediate Objective:*

With the proposed observation is aimed to unveil the origin of the quiescent emission of the bursting pulsar. In particular, we will verify whether the source indeed continues to accrete through 1) variability analysis; 2) detection of the pulsations; and 3)comparison of a high quality X-ray spectrum with that observed

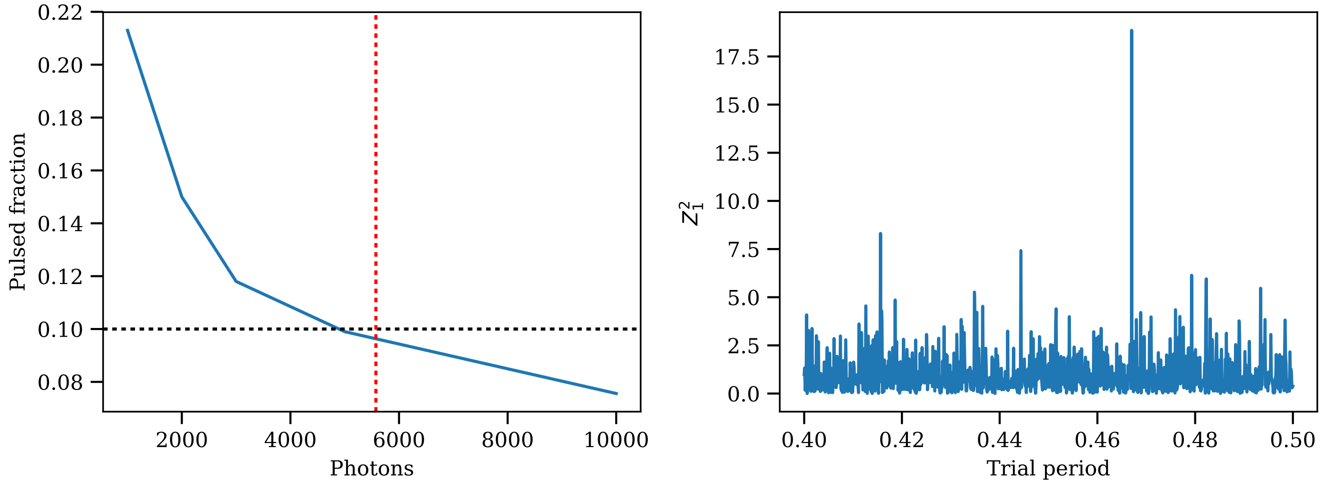


Figure 2: *Left:* minimum pulsed fraction detectable at $3\sigma$ significance as function of number of photons. The horisontal and vertical lines indicate the expected pulsed fraction and number of photons in the proposed obervation respectively. *Right:* A periodogram computed using the Rayleigh test ($Z_1^2$) and a simulated 50 ks lightcurve containing sinusoidal pulsations with 0.467 period and 10% pulsed fraction (main peak in the periodogram).

in outburst and with spectra of other accreting and "propelling" sources. Furthermore, comparison of the observed pulse period with the values reported during the recent outburst of the source will allow to measure the observed rate of spin frequency change in quiescence. Comparison with the spin evolution of the source during the outburst can then be used to put additional constrains on distance to the source and effective magnetospheric radius (Sanna et al. 2017).

## 3. Justification of requested observing time, feasibility and visibility

GRO J1744−28 has alredy been observed in quiescence a number of times with *XMM-Newton*, and *Chandra*, however, none of the observations are suitable to achieve our goals. Most of the observations are short (1-5 ks) monitoring pointings of the Galactic centre not targeting specifically the source. The two longer XMM observations in quiescence (0506291201, 38 ks, and 0794580301, 25 ks) were performed in modes unsuitable to search for the pulsations in GRO J1744−28. The former was devoted to study another transient GRS 1741.9−2853, so GRO J1744−28 was only observed with MOS with insufficient time resolution. On the other hand, quality of X-ray spectrum in this observation is hampered by relatively high soft-proton background and the position of the source at the very edge of the field of view.

The second observation (0794580301) was likely triggered by an increased activity from GRO J1744−28 in *Swift/BAT* data and targeted at GRO J1744−28 in anticipation of a new outburst. All EPIC cameras were thus operating in timing mode. The outburst, however, did not set in and the source was not detected due to a high background in timing mode.

Finally, it appears that neither observation was actually sensitive enough to allow detection of pulsations at the expected flux level of $\sim 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. Indeed, from the observed MOS spectrum (obs. 0506291201, see Fig. 1) we estimate 0.5-10 keV flux at $\sim 1.3\times10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$, which corresponds to a combined countrate of $\sim 0.1$ from all three EPIC cameras. The exposure required to significantly detect pulsations at this countrate can be estimated for instance using the bootstrap method. The pulsed fraction in the soft X-ray band was reported to be almost constant throughout the outbursts at $\sim 10\%$, so similar value can be anticipated in quiescence. To estimate sensitivity to pulsations we simulated $10^4$ pulsed and unpulsed lightcurves containing the expected number of source and background photons ($\sim 5000$ and 2000 respectively), and compared the distributions of $Z_1^2$ statistics (de Jager et al. 1989) at the input pulse frequency. For each countrate we then determined the minimal pulsed fraction such that for $\geq 99.7\%$ realisations the $Z_1^2$ value of pulsed lightcurve exceeds that of the unpulsed. The results are presented in Fig. 2 and imply that $\sim 50$ ks XMM observation is required to robustly detect the pulsations. Given the low source countrate, the observation must be performed in full-frame mode for PN and small-window mode for MOS cameras to ensure effective background rejection and sufficient time resolution. The resulting accuracy of pulse period determination $\Delta P \sim 10^{-7}$ s is comparable with reported uncertanties from *Fermi/GBM*, so meaningful comparison will be also possible.

The 50 ks exposure will yield also an energy spectrum of sufficient quality to confidently rule out thermal origin of the observed emission and constrain emission region size. With the available 29 ks exposure (obs. 0506291201 after screening of high background periods, two MOS cameras only), the best-fit blackbody temperature of $kT = 1.2(1)$ (at $1\sigma$ confidence) is already significantly higher than reported for other sources $kT < 0.55$ keV. However, the spectrum can still be described with a blackbody/atmosphere model. The proposed observation will almost triple the total exposure, which, together with the addition of PN data, will allow easy discrimination between the cutoff power law and a blackbody like spectrum and decrease the uncertainty for spectral parameters by factor of five.

We have verified that the target is observable multiple times within the AO17 period (Aug-Oct 2018, and March-Apr 2019).

### 4. Report on the last use of XMM-Newton data

Recently granted observations include the 50ks XMM-Newton observation of another accreting pulsar (1A 0535+262) in quiescence (AO10, proposal id: 067418, Accreting pulsars in quiescence, PI: Doroshenko, V.), and two joint NuSTAR/XMM observations of another pulsar V 0332+53 (AO14, 35ks each, proposal id 076347). The results of both investigations are published. The data obtained in 30 ks observation of the SNR G 96.0+2.0 (AO16, proposal id 08034502, PI: Klochkov, D.) are currently being analyzed by VD and a publication is being prepared.

### 5. Most relevant proposer's publications

Doroshenko, R.; Santangelo, A.; Doroshenko, V.; Suleimanov, V.; Piraino, S.; 2015, MNRAS, 452, 3: *"BeppoSAX observations of GRO J1744−28: cyclotron line detection and the softening of the burst spectra"*
Doroshenko, V.; Santangelo, A.; Doroshenko, R.; Caballero, I.; Tsygankov, S.; Rothschild, R.; 2014, A&A, 561, A96: *"XMM-Newton observations of 1A 0535+262 in quiescence"*

Tsygankov, S. S.; Lutovinov, A. A.; Doroshenko, V.; Mushtukov, A. A.; Suleimanov, V.; Poutanen, J.; 2016, A&A, 593, A16: *"Propeller effect in two brightest transient X-ray pulsars: 4U 0115+63 and V 0332+53"*

Tsygankov, S. S.; Mushtukov, A. A.; Suleimanov, V. F.; Doroshenko, V.; Abolmasov, P. K.; Lutovinov, A. A.; Poutanen, J.; A&A (accepted, arXiv:1703.04528): *"Stable accretion from a cold disc in highly magnetized neutron stars"*

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