BeppoSAX observations of GRO J1744–28

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ABSTRACT

We present an analysis of BeppoSAX observations of the unique transient bursting X-ray pulsar GRO J1744–28. The observations took place in March 1997 during the decay phase of the outburst. We find that the persistent broadband X-ray continuum of the source is consistent with a cutoff power law typical for the accreting pulsars. We also detect the fluorescence iron line at 6.7 keV and an absorption feature at ~ 4.5 keV, which we interpret as a cyclotron line. The corresponding magnetic field strength in the line forming region is ~ 3.7 × 1011 G. Neither line is detected in the spectra of the bursts. However, additional soft thermal component with kT ~ 2 keV was required to describe the burst spectrum. We briefly discuss the nature of this component and argue that among other possibilities it might be connected with thermonuclear flashes at the neutron star surface, which accompany the accretion-powered bursts in the source.

Key words: pulsars: individual: stars: neutron stars: binaries

1 INTRODUCTION

The peculiar transient X-ray source GRO J1744–28 also known as the bursting pulsar, was discovered on December 2, 1995, with the Burst and Transient Source Experiment (BATSE), on board the Compton Gamma Ray Observatory (CGRO) (Fishman et al. 1995; Kouveliotou et al. 1996). Three major outbursts have been observed since the discovery. The first lasted from the end of 1995 until the beginning of 1996, the second from December 1996 until April 1997, and the third from January to May 2014 (Degenaar et al. 2014; Younes et al. 2015; D’Ai et al. 2015). The peak outburst luminosity in X-rays reaches Lx ~ 1037 – 1038 erg s⁻¹ (Woods et al. 1999), while the quiescent luminosity is ~ Lx ~ 1033 erg s⁻¹ (Wijnands & Wang 2002; Daigle et al. 2003; Degenaar et al. 2012). The source exhibits coherent pulsations with a period of ~ 0.467 s, associated with the rotation of the neutron star i.e. is an accreting X-ray pulsar in a binary system. Finger et al. (1996) determined the orbital period and semimajor axis to be Porb = 11.8 days and a ~ 1.12 R⊙ (~ 7.8 × 10¹⁰ cm) respectively. The mass function was estimated to be f(M) = 1.36 × 10⁻³ M☉ implying, for the canonical neutron star mass of MNS = 1.4 M☉, accretion via Roche lobe overflow from a strongly evolved red giant remnant with mass about 0.2 – 0.7 M☉ (Daumerie et al. 1996; Miller 1996; Sturmer & Dernier 1994; Bildsten & Brown 1997; Rappaport & Joss 1997). The photoelectric absorption does not change significantly during the outbursts and is comparable with interstellar absorption NHI ~ (5 – 6) × 10²² cm⁻² in the direction of the Galactic center where the source is thought to be located at distance of ~8 kpc (Dotani et al. 1996; Nishiuchi et al. 1996).

Probably the most unusual property of GRO J1744–28 is the relatively short ~ 10 s bursts observed from the source. Since the discovery, several thousands of bursts have been detected, all at high luminosity (Nishiuchi et al. 1999). During the bursts the flux increases by an order of magnitude, and it is often followed by a drop to below the pre-burst level for several tens of seconds to minutes depending on the burst fluence (Lewin et al. 1994; Nishiuchi et al. 1999; Younes et al. 2015). Pulsations are observed during the bursts, although with a phase shift of ~ 5% with respect to the persistent emission (Kouveliotou et al. 1994; Strickman et al. 1996).

A similar bursting activity has been observed only in another source the transient LMXB MXB 1730–335, usually referred to as the Rapid Burster (RB) (Lewin et al. 1976; Lewin et al. 1993). For both sources, it has been suggested that the origin of the bursts could be due to accretion flow instabilities which intermittently enhance the accretion rate onto the neutron star (so-called Type II bursts). However details are still unclear. For instance, unlike the RB, Type I bursts, associated with thermonuclear flashes on the surface of neutron star, are generally thought not to occur in GRO J1744–28. On the other hand, contrary to the RB case, the duration of the GRO J1744–28 bursts is remarkably stable (~ 10 s), and a large fraction of the bursts exhibit a temporal profile characterized by a fast rise followed by an exponential decay typical of classical bursters. Type II bursts in RB have rather irregular profiles. These differences are likely related to the different magnetic field strengths of the neutron star companion, which is expected, given the presence of pulsations, to be stronger in GRO J1744–28. In the case of GRO J1744–28, Finger et al. (1996) reported an upper limit on the magnetic field strength of B ≤ 6 × 10¹¹ G. This estimate is based on the requirement that the plasma at the inner edge of the ac-
creatin disk (disrupted by the magnetosphere) moves faster than the magnetic field lines as otherwise the accretion would be centrifugally inhibited (so-called “propeller” regime, Il’’inov & Sunyaev 1973). Later Cui (1997) found a possible transition to the “propeller” regime in RXTE data at lower luminosity, which allowed for an estimate of the the magnetic field at ~ 2.4 × 10^{11} G. Recently D’Ai et al. 2015 reported the observation of an absorption feature at E∼4.7 keV, during the 2014 outburst of the source. Interpreting the line as due to cyclotron resonance scattering, the authors estimated a magnetic field of ~ 5.3 × 10^{11} G in good agreement with earlier estimates.

In this paper we report on independent discovery of the same feature in BeppoSAX observations carried out during the outburst in 1997 (Sect. 3.2) We analyze three BeppoSAX observations of GRO J1744–28 carried out during the outburst in 1996–1997 and present a detailed spectral and timing analysis of the persistent flux and the bursts. We also briefly discuss the origin of the bursts in GRO J1744–28. The instruments and methods of the analysis are described in Section 2. Results from the timing and spectral analysis are summarised in Section 3. In Section 4, we discuss the observational results and finally provide a summary of the paper in Section 5.

2 OBSERVATIONS

BeppoSAX was an Italian X-ray astronomy satellite, with Dutch participation, which operated from 1996 to 2002 (Boella et al. 1997). It covered a broad energy band 0.1–300 keV with four Narrow Field Instruments (NFIs) and two Wide Field Cameras (Jager et al. 1997). The NFIs included the Low-Energy Concentrator Spectrometer (LECS, 0.1–10 keV, Parmar et al. 1997), three identical Medium-Energy Concentrator Spectrometers (MECS, 2–10 keV, Boella et al. 1997), and two collimated high energy detectors with good energy resolution and low instrumental background: the High Pressure Gas Scintillation Proportional Counter (HPGSPC, 4–120 keV, FWHM energy resolution of 8% at 10 keV and 5.5% at 20 keV, Manzo et al. 1997) and the Phoswich Detection System (PDS, 15–300 keV, FWHM energy resolution of 24% at 20 keV, and 14% at 60 keV, Frontera et al. 1997).

GRO J1744–28 was observed by BeppoSAX several times from March 1997 to April 1998 (Table 1). In Figure 1 the long term source light curve observed by the All Sky Monitor onboard the Rossi X-ray Timing Explorer (ASM RXTE, Bradt et al. 1993) with superimposed BeppoSAX observations is presented. The first three observations of BeppoSAX were performed in the declining edge of the 1997 outburst, with a total exposure time for MECS of approximately 270 ks. In our work we use LECS, MECS, and PDS in 0.7 – 4 keV, 2 – 10 keV and 15 – 120 keV energy ranges respectively. The HPGSPC was, unfortunately, not operating during the first three observations. In the last three observations, the source was in quiescence and below the sensitivity thresholds of BeppoSAX, so it was not detected. The data from the quiescence, however, proved very useful for the background subtraction of the outburst PDS data.

The standard BeppoSAX pipeline was used for the processing of the data. HPGSPC and PDS were operated in rocking mode to monitor local background and its variation along the orbit. The source counts for LECS and MECS were extracted from source centered circles with radii of 4 arcmin, while the background from an annulus with outer radius of 18 arcmin. A detailed description of BeppoSAX data reduction procedures can be found in the handbook for BeppoSAX.

3 DATA ANALYSIS AND RESULTS.

3.1 Timing analysis.

The 2–10 keV MECS light curve of the first observation (MJD 50528) is presented in Figure 2. Bursts are clearly visible in the first two observations, whereas none is detected in the last observation. The inter-burst to burst fluence ratio in the energy range 2-20 keV is between 3 and 18, i.e. compatible with earlier reports (Lewin et al. 1998, Jahoda et al. 1997). The burst profiles exhibit variety of shapes: most are rather symmetric and in this respect are similar to Type II bursts observed in RB (Lewin et al. 1976). However, about twenty percent (for example, the next to last

Table 1. Observations of the X-ray source GRO J1744-28 by BeppoSAX. Luminosity is estimated using unabsorbed flux in the energy range 2–10 keV (MECS) for the distance D = 8 kpc.

| MJD | Exposure time, ks | Period, s | L_x, 10^{37} erg s^{-1} 2–10 keV | Orbital phase$^a$ |
|-----|------------------|-----------|---------------------------------|-----------------|
| 50528 | 117.5 | 0.467044(1) | 2.8 | 0.9 |
| 50534 | 101.9 | 0.467044(1) | 1.8 | 0.4 |
| 50550 | 51.6 | 0.46705(1) | 0.46 | 0.8 |
| 50905 | 62.5 | source in | 0.8 | 0.8 |
| 50911 | 34.5 | quiescent state | 0.3 | |
| 50913 | 67.5 | | 0.5 | |

$^a$Ephemeris from Kouveliotou et al. (1996)

Figure 1. The light curve of GRO J1744-28 observed by the ASM onboard RXTE. Dashed lines mark the BeppoSAX observations (Table 1).
one in Fig. 2 exhibit the characteristic exponential decay typical of thermonuclear Type I bursts. The source also exhibited a few “smaller” bursts, a factor of ∼ 6 less luminous than the major bursts. These have already been reported by Nishiuchi et al. (1999) based on the ASCA data. We confirm the presence of the low luminosity bursts, although the statistical quality of the data is not sufficient for any detailed analysis.

As reported earlier by several authors (Lewin et al. 1996; Younes et al. 2015), a flux drop following the burst is a relative common feature in GRO J1744−28. Such a drop is observed in more than half of the bursts in our sample. In Fig. 2 a fragment of the light curve in the 2–10 keV is presented. The decrease of the mean flux from the source after the burst, for about 100 sec, is evident. Note that a similar flux depression is observed after Type II bursts of the RB and is usually associated with the depletion of the inner edge of the accretion disk after the bursting event due to enhanced accretion (Lewin et al. 1996).

To study coherent pulsations, we corrected the photon arrival time for Doppler delays due to the orbital motion of the spacecraft and the pulsar (using the orbital ephemeris of Kouveliotou et al. 1996). Using the phase-connection technique (see for instance Doroshenko et al. 2010) we measure the spin period to be $P = 0.467044(1)$ s, $P = 0.467050(1)$ s and $P = 0.46705(1)$ for the March and the two April 1997 observations (all uncertainties are for 90% confidence level unless stated otherwise). Folding the light curves reveals sinusoidal, single-peaked pulse profiles (Fig. 3). We find that the phase of the pulsed profiles during the bursts is shifted by ∼ 5% relative to the persistent state, which is consistent with earlier reports by Kouveliotou et al. (1996); Strickman et al. (1996). The morphology of the pulse profiles appears to be consistent between the two observations and shows no apparent dependence on luminosity.

The fraction of pulsed emission defined as the ratio $(F_{\text{max}} - F_{\text{min}})/(F_{\text{max}} + F_{\text{min}})$, where $F_{\text{max}}$ and $F_{\text{min}}$ are the maximum and minimum source flux does change with energy. To estimate it we assumed standard backgrounds for all instruments and also took the contamination from the nearby sources to the PDS data (see Section 3.2). We found that the pulsed fraction increases between 2 and 10 keV from about 5% to 20% (with a notable exception of a region close to the fluorescent iron line, see also D’Ai et al. 2013), and then remains fairly constant between ∼ 10% and ∼ 30% for the first two observations and between 20 – 80% for the third one. From 0.1 to 2 keV, the pulse fraction decreases from 20 – 30% to 5% although our findings are at the lowest energies and for the third observation are hampered by low statistics (Fig. 5).

3.2 Spectral analysis.

GRO J1744−28 is located in crowded Galactic Center region and a number of sources fall into the field of view of the telescope. This might potentially affect the spectral analysis, particularly for non-imaging instruments. Even the LECS and MECS observations could be affected as the deep Chandra observation of the field reveals ∼ 40 sources within the standard 4′ extraction region. However, GRO J1744−28 is by far the brightest among these sources even in quiescence, so for the imaging instruments MECS and LECS source confusion is not an issue. We followed, therefore, standard analysis procedure.

The situation for the non-imaging instruments is more complicated. The MECS image reveals at least two sources besides GRO J1744−28 within the field of view of collimating instruments. These are detected irrespective of the brightness of the pul-
Figure 3. Light curves of all burst of the pulsar GRO J1744−28 in 1997-03-21 (top) and 1997-03-27 (bottom), MECS.

sar (see Fig. 6) and are plausibly identified as 1E 1743.1-2843 and Sgr A*. To account for the in-orbit instrumental background which is rapidly changing and the for the contribution of the sources contaminating the PDS data, we extracted the background-subtracted spectra for all observations (including those in quiescence) using the standard pipeline. The standard pipeline allows to account for instrumental in-orbit background. Then we subtracted quiescent spectra (obtained during the 1998 observations) from the source spectra obtained for the first three observations. Apparently, an important assumption here is that the flux of the contaminating
sources remains constant. To verify that we compared the soft X-ray fluxes measured by the MECS which indeed remained constant.

For spectral fitting, we used the XSPEC package (version 11.3.2, Arnaud 1996). We found that the observed broadband continuum spectrum can be described with several phenomenological models generally used for the spectra of accreting X-ray pulsars:

1) a power law plus a high-energy cutoff model, where the transition is smoothed with a Gaussian

\[ PHC \sim E^{-\Gamma} \begin{cases} 1 \\ e^{-(E-E_{\text{cut}})/E_{\text{fold}}} \end{cases} \begin{cases} (E \leq E_{\text{cut}}) \\ (E > E_{\text{cut}}) \end{cases} \]

2) a power law with Fermi-Dirac cutoff:

\[ \text{FDCO} \sim E^{-\Gamma} (1 + e^{E-E_{\text{cut}}}/E_{\text{fold}})^{-\frac{1}{\alpha}}; \]

3) the Negative and Positive power law EXponential model (Mihara 1993, Makishima et al. 1999):

\[ \text{NPEX} = (A_1 E^{-\alpha_1} + A_2 E^{\alpha_2}) e^{-E/E_{\text{fold}}}; \]

4) the CompTT model by Titarchuk (1994) describing the comptonization of soft photons with temperature \( kT_e \) in a hot electron plasma with \( kT_e \) and a hot electron optical depth \( \tau_e \).

In all cases the inclusion of the fluorescent iron \( K_{\alpha} \) line at \( \sim 6.7 \text{keV} \) (modelled with a simple Gaussian profile) was also required. All continuum models give a reasonably good \( \chi^2_{\text{red}} \) (from 0.94 for the \( PHC \) model to 1.25 for \( CompTT \) model, see Table 2). To demonstrate the evolution of the parameters with the luminosity we used \( PHC \) based on the formal statistical quality and stability of the fit (Table 3). Regardless of the assumed continuum model, some residuals below 1 keV and around 4–5 keV (Fig. 8) were clearly observed. The absorption-like feature at \( \sim 4 \text{keV} \) was modelled with a multiplicative line with either a gaussian or lorentzian profile. This significantly improved the fit (see residuals of Fig. 8). The parameters of the line for the gaussian profile are presented in Table 2. For the lorentzian profile (CYCLABS in XSPEC) we get comparable values, i.e. \( E_{\text{fold}} = 4.0 \pm 0.2 \text{ keV} \), \( \sigma = 1.3 \pm 0.2 \text{ keV} \). The chance probability for fit improvement based on the \( f \)-test is marginal \( \leq 10^{-30} \) (see, however, Protassov et al. 2002). The feature also appeared in the phase resolved spectra (see Fig. 9). Our findings nicely agrees with the absorption-like feature recently reported by D’Ai et al. (2015) based on XMM-Newton and INTEGRAL observations of the 2014 outburst. We note that Younes et al. (2015) detected an absorption feature at 10 keV which is not observed in our data, although the lack of HPGSPC data makes it difficult to draw a definitive conclusion.

We have also performed a pulse phase resolved spectral analysis to study the variation of spectral parameters with the angle of view to the neutron star. Only data from the observation on March 21, 1997 with highest luminosity and best counting statistics was considered. To describe the phase resolved spectra, we used the same model as for the phase averaged spectrum, i.e. a power law

**Figure 5.** MECS image centered at GRO J1744–28 in quiescence on 1998-04-02 overlaid with contours from an observation in bright state (taken on 1997-03-21). Two additional sources detected in the MECS field of view contaminate also the PDS spectrum.

**Figure 6.** Pulse fraction of the pulsar GRO J1744–28 for 1997-03-21 - solid black line, 1997-03-27 - dashed red line, 1997-04-12 - dashed dotted blue line.

**Figure 7.** The best-fit residuals for spectra derived from the observation 1997-03-21 modeled as described in the main text. The best residuals obtained with the power law plus high-energy cutoff model, \( PHC(E) \), at the top panel.
The best fit spectrum of the bursts modelled with energies and line widths are given in keV. The continuum is also presented together with the residuals for the observation 1997-03-21.

Table 2. Spectral parameters of the persistent spectrum of GRO J1744–28 observed by BeppoSAX in 1997-03-21 for various spectral models. All energies and line widths are given in keV.

| Parameter | PHC | PHC no CRSF | FDCO | NPEX | CompTT |
|-----------|-----|-------------|------|------|--------|
| $N_H$    | 5.7(2) | 5.23(2) | 5.55(8) | 5.16(6) | 5.84(3) |
| $\Gamma$  | 1.26(7) | 1.14(7) | 1.09(4) | 1.10(4) | 1.15(4) |
| $E_{cut}$ | 18.4(1) | 18.1(1) | 15.1(1) | 15.3(1) | 15.6(1) |
| $E_{fold}$ | 11.7(4) | 11.7(7) | 10.2(2) | 6.1(1) | 6.5(1) |
| $\alpha_1$ | -0.48(4) | -0.50(4) | -0.52(4) | -0.53(4) | -0.54(4) |
| $\alpha_2$ | -2.0 | -2.1 | -2.2 | -2.3 | -2.4 |
| $kT_H$ | 0.18(3) | 0.17(3) | 0.16(3) | 0.15(3) | 0.14(3) |
| $kT_X$ | 5.82(3) | 5.85(3) | 5.88(3) | 5.91(3) | 5.94(3) |
| $\tau$ | 13.1(1) | 13.2(1) | 13.3(1) | 13.4(1) | 13.5(1) |
| $E_{Fe}$ | 6.69(2) | 6.71(2) | 6.70(2) | 6.68(2) | 6.72(2) |
| $\sigma_{Fe}$ | 0.28(3) | 0.38(2) | 0.26(3) | 0.23(3) | 0.34(3) |
| $N_{Fe}$ | 7.26(6) | 10.24(4) | 5.85(5) | 5.86(5) | 8.85(5) |
| $E_{cyc}$ | 4.3(2) | 4.47(9) | 4.55(5) | 4.6(3) | 4.7(3) |
| $\alpha_{cyc}$ | 1.2(3) | 1.1(2) | 1.2(1) | 0.7(5) | 0.8(5) |

$\chi^2_{red}$/dof 0.94 / 549 1.28 / 552 0.95 / 551 1.04 / 551 1.25 / 553

Table A. Spectral parameters of the persistent spectrum low mass X-ray pulsar GRO J1744–28 observed by BeppoSAX modeling by the PHC with smoothing gaussian continuum model. All the energies and the line widths are given in keV.

| Parameter | 1997-03-21 | 1997-03-27 | 1997-04-12 |
|-----------|------------|------------|------------|
| $N_H$    | 5.7(2) | 5.7(2) | 5.4(1) |
| $\Gamma$  | 1.26(7) | 1.29(5) | 1.24(3) |
| $E_{cut}$ | 18.1(1) | 19.3(8) | 24(4) |
| $E_{fold}$ | 11.7(4) | 13.3(5) | 12(3) |
| $E_{Fe}$ | 6.69(2) | 6.71(3) | 6.68(5) |
| $\sigma_{Fe}$ | 0.28(3) | 0.27(4) | 0.24(7) |
| $N_{Fe}$ | 7.2(7) | 4.9(6) | 1.2(2) |
| $E_{cyc}$ | 4.3(2) | 4.3(1) | 4.3(1) |
| $\sigma_{cyc}$ | 1.2(3) | 1.1(1) | 1.1(1) |
| $F_c$ | 10.1 | 6.5 | 1.2 |
| $F_{unab}$ | 13.0 | 8.3 | 1.6 |

$\chi^2_{red}$/dof 0.94 / 549 1.04 / 531 1.06 / 487

*in units 10^{22} atoms cm^{-2}

$^b$ $K_0$ line normalization in units 10^{-3} ph cm^{-2} s^{-1}

$^c$ Absorbed and unabsorbed fluxes in units 10^{-9} erg cm^{-2} s^{-1} and in 0.1–120 keV range.

Figure 8. The best-fit unfolded average persistent spectrum, modelled with the PHC continuum is shown in the top panel. We also present the best fit residuals without and with the inclusion of a cyclotron line at ~4.5 keV. The best fit spectrum of the bursts modelled with PHC and a black body continuum is also presented together with the residuals for the observation 1997-03-21.

3.2.1 Analysis of the burst spectra

To investigate the burst spectra we aligned and stacked all observed bursts using the rising edge as a reference to improve statistics. We also subtracted the contribution of the persistent emission. We found that the shape of the combined spectrum of the bursts departs significantly from that of the non-bursting spectrum (Fig. 8).

We first described the burst spectrum with the PHC and CompTT models. Both models give formally acceptable results (see Table 4). The spectral parameters of the PHC model are similar to those reported recently by Younes et al. (2015) for the burst spectrum ($\Gamma = 0.2 \pm 0.1$ and $E_{fold} = 7.6 \pm 0.5$ keV). Such a hard power law together with a soft cut-off are rather peculiar and not typical of X-ray pulsars. This might suggest that the model describes a bump-like feature at soft energies. In addition, the best-fit results for the bursts spectrum using the CompTT model reveals a significant change, with respect to the persistent spectrum, of both the seed photon temperature and the absorption column (see Table 5), which is difficult to understand. On the other hand, the apparent change of the seed photon temperature might suggest an additional soft component in the burst spectrum. Indeed, including a blackbody component in either model allows to achieve comparable (or, in fact, slightly better) fit statistics while the other parameters of the continuum remain close to ones measured for the persistent spectrum. In other words, we find that the burst spectrum significantly differs from the persistent one at soft energies, and this change is well accounted for by adding a soft blackbody-like component to the spectrum with high-energy cut-off (see Fig. 8). We divided the data in 10 equally spaced phase bins. We fixed the absorption component at the average value $N_H = 5.7_{-0.2}^{+0.2}$ atoms cm^{-2}. The emission iron line at ~6.7 keV and the absorption-like feature at ~4.5 keV were also included in the phase resolved analysis. We can see the clear anti-correlation of the photon index with phase flux. The parameters of the absorption-like and iron lines (line centroid and width) did not exhibit any significant phase variation. The cut-off and folding energies appeared to be anti-correlated with each other.
the unchanged continuum of the persistent spectrum. The blackbody component has a temperature about 2.1 – 2.2 keV and a size close to a neutron star radius (for an assumed distance of 8 kpc). A Fe-K line is also marginally significant in the burst spectra of the observation on 1997-03-27. We have summarised the fit results for the 1997-03-21 data in Table 4.

To investigate the pulse phase dependence of the black body and power law components we carried out the phase resolved analysis of the burst spectrum. Unfortunately, the statistics was insufficient to constrain all model parameters, so we kept most of the parameters fixed to the best-fit phase average values, and only allowed the normalizations of the continuum components to vary. The results are shown in Fig. 10. The pulse fraction for the soft and hard components are 6.5% ± 3.4% and 13.8% ± 1.9% respectively, i.e. the hard component varies with pulse-phase stronger than the soft one.

To explore the time evolution of both components along the burst, we performed also time-resolved spectral analysis using the stacked data of all bursts. It is interesting to note, that both the temperature and normalization of the blackbody component (and thus the size of the emitting region) change along the burst as shown in Figure 11.

Figure 9. Spectral parameters of the pulsar GRO J1744–28 in 1997-03-21 with the PHE continuum model as function of pulse phase. Phase: 0-0.2-0.4-0.6-0.8-1. Dashed lines are the MECS and PDS pulse profiles, they are the same.

Figure 10. Changing normalizations of the soft (top) and hard (bottom) part of the bursts spectrum with phase for the GRO J1744–28 in 1997-09-21. $\chi^2_\text{red}$ lies in region from 0.97 to 1.45.

Figure 11. Cooling of the soft component, during the bursts. The probability that the observed temperatures are due to a statistical fluctuation is $\leq 1.7 \times 10^{-6}$ (from Kolmogorov-Smirnov test), so the trend is significant.
We incidentally observe that there are no systematic errors in the model. By interpreting an absorption-like feature observed at around 406 keV, we find that the gravitational redshift (see Pottschmidt et al. (2012), for pulsars, e.g. by an absorbed power law with cut-off at around 18 keV. In addition, a line-like absorption feature at 5 keV from the continuum at cyclotron resonance scattering feature (CRSF). Our result is in excellent agreement with these findings. The strongest argument against the thermonuclear origin of the soft component as well. The effective temperature of the irradiated surface $T_{\text{eff}} \approx (L_*/4\pi r^2/\sigma_{\text{SB}})^{1/4} \approx 2$ keV is, in fact, comparable with the observed. On the other hand, strong gravitational separation of chemical elements in the neutron star atmospheres (Hameury et al. 1983) implies that the upper atmospheric layers consist almost exclusively of fully ionized hydrogen plasma which reflects most of the incident flux due to electron scattering. Therefore, the fraction of thermalized emission is likely to be less than 10% (see a detailed argumentation in Poutanen et al. 2013), in contrast with the $30\%$ observed. It is also hard to explain the observed pulsation of the soft component if it originates in the inner regions of accretion disk, although the even softer component with $kT \sim 0.5$ keV reported recently by Younes et al. (2015); D’Ai et al. (2015) might indeed be related to irradiation of the accretion disk by the pulsar.

Finally, taking into consideration the observed cooling of the thermal component along the burst (see Fig. 17) very similar to that observed in classical pulsars (Lewin et al. 1993) thermonuclear flashes on the NS surface could be also responsible for the observed soft emission. In fact, several authors have already considered the possibility that some of the bursts in GRO J1744–28 might be Type I bursts. Based on the BATSE observations, Lewin et al. (1996) concluded that this is unlikely because the amount of matter accreted between the bursts is insufficient to explain the observed burst fluence if bursts are powered by thermonuclear burning. Indeed, the inter-burst to burst fluence ratio $\alpha \sim 4$ deduced from BATSE observations was found to be much smaller than $\alpha \geq 40$ typical of thermonuclear hydrogen burning (Lewin et al. 1993).

On the other hand, Jahoda et al. (1997), based on the RXTE observations close to the peak of the outburst, found significantly higher $\alpha \sim 34$. Moreover, we found that the flux of the thermal component constitutes only about $30\%$ of the total flux and, therefore, of the burst fluence. If this is taken into account, even at lower luminosities such as during the BeppoSAX observations, when we estimate $\alpha \sim 5 – 15$ for the bolometric flux, the same ratio calculated for the thermal component alone is factor of three higher, i.e. still comparable with that observed in classicalbursters. Therefore the argument by Lewin et al. (1994) clearly does not always hold.

The strongest argument against the thermonuclear origin of...
the soft component in burst spectrum of GRO J1744–28 is that it is an accreting pulsar. Indeed, the temperature and pressure of matter funneled by the magnetic field to the polar areas are usually sufficient for stable thermonuclear burning, so no unburned matter accumulates at the surface and thus no Type-I bursts are observed from accreting pulsars. In fact, Bildsten & Brown (1997) did consider the possibility of unstable thermonuclear burning in GRO J1744–28, and concluded that under the most favourable assumptions it should not be possible. In particular, Bildsten & Brown (1997) argue that to escape the accretion flow and spread over the NS surface (where it can be accumulated and subsequently ignite as a thermonuclear flash), the accreted plasma must overcome the magnetic pressure and turn the magnetic field lines parallel to the neutron star surface. This implies a pressure of $P \approx 10^{22}$ erg cm$^{-3}$ while the hydrogen/helium mixture burns in the stable regime at $P \approx 10^{25}$ erg cm$^{-3}$.

In other words, accreting matter remains confined at the polar caps where it burns steadily as expected. However, in our opinion, this key assumption of Bildsten & Brown (1997) is probably too conservative, and, in fact, corresponds to the case when the plasma is not confined to polar areas at all. This would basically imply that GRO J1744–28 is an ordinary burster, which clearly it is not. On the other hand, the magnetic pressure at the poles of the neutron star can be estimated based on the observed CRSF energy and turns out to be $B^2 / 8\pi \approx 10^{23}$ erg cm$^{-3}$ comparable with the pressure required for stable thermonuclear burning. Therefore, the magnetic field is unlikely to confine plasma at significantly higher pressures and part of accreted matter probably leaves the polar areas before burning, thereby creating conditions for thermonuclear flashes. We note also that, if realised, the onset of a such flash could in principle disrupt the inner parts of the accretion disk triggering the instabilities responsible for the enhanced accretion rate and most of the observed burst emission.

In conclusion, we fully agree that there is no doubt that the mass accretion rate does increase during the bursts GRO J1744–28 and is responsible for the bulk of the observed emission. However, some fraction of the flux in principle could still be due to unstable thermonuclear burning at the NS surface.

5 SUMMARY AND CONCLUSIONS

We presented the results of the analysis of three BeppoSAX observations, with a total exposure time 270 ks, carried out in the declining phase of the 1997 outburst of the unique bursting pulsar GRO J1744–28.

Pulsations with a period of 0.4670 s with a stable pulse profile were detected in all observations. The pulsed fraction was found to vary with energy, reaching a minimum of 10–20% in the energy range 5–40 keV and increasing for higher and lower energies, especially at lower luminosities. Several tens of bursts with typical durations of about 10 s were detected as well. Depletion in the light curve is observed at least after some of the bursts. The source luminosity typically increases by factor of ten during the bursts, although a number of dimmer bursts are also observed.

The non-bursting broad band X-ray spectrum was found to be well described by several phenomenological models typically used for accreting pulsars. An iron line at ~6.7 keV and an absorption feature at ~4.5 keV were also required to fit the data. We interpret the absorption feature as a cyclotron line which implies a magnetic field of the neutron star of $B \approx 3.7 \times 10^{11}$ G. This value is in good agreement with earlier predictions and with the recent observations of the 2014 outburst with XMM-Newton and INTEGRAL. D’Ai et al (2013) have detected the same feature at $E \sim 4.7$ keV in agreement, within uncertainties, with our measurement.

The average burst spectrum could be represented as a combination of the harder non-bursting spectrum and an additional soft thermal component with temperature of about 2 keV. The burst spectrum requires that neither the iron 6.7 keV line nor the absorption feature at 4.5 keV. Both components are pulsed although the amplitude is smaller for the soft component, ~6.5% vs ~13.8%.

We discussed a possible nature of the thermal component and speculate that it could be caused by thermonuclear flashes which possibly trigger the accretion rate enhancement responsible for the bursts observed in the source. This hypothesis is based on several similarities between typical Type I bursts and the thermal component, namely, the burst duration of 10 s, the inter-burst to burst fluence ratio and cooling as a burst progresses. There are some observational and theoretical arguments that disfavor this hypothesis. These cannot be verified with the existing data, however, additional data from current or future missions like LOFT (in’t Zand et al. 2015) might provide decisive insights on this puzzling source.

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