ELSEVIER

Nuclear Physics B (Proc. Suppl.) 69/1-3 (1998) 216–219

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

A Search for Cyclotron Lines in the Bursting Pulsar, GRO J1744-28

W. Heindl, P. Blanco, D. Gruber, M. Pelling, R. Rothschild [a] and K. Jahoda [b]

[a]Center for Astrophysics and Space Sciences, UCSD, La Jolla, CA, USA

[b]NASA/Goddard Space Flight Center, Greenbelt, MD, USA

We report a search for cyclotron line absorption in the pulsed spectrum of the "Bursting Pulsar", GRO J1744-28 using the Proportional Counter Array (PCA) and the High Energy X-ray Timing Experiment (HEXTE) on the Rossi X-ray Timing Explorer (*RXTE*). We focus on data obtained around the peak of the 1996-1997 outburst. Improvements made in these analyses include the use of more accurate PCA and HEXTE detector response matrices, data with a larger overlapping energy band, and a continuum model especially well suited to cyclotron line searches. We find that the spectrum can be adequately fit with a smooth continuum model typical of other X-ray pulsars, with no modification for cyclotron absorption required. In fact, the data are inconsistent with cyclotron features with depths greater than a few percent of the continuum.

1. Introduction

Bright hard X-ray bursts from GRO J1744-28 (commonly known as the "Bursting Pulsar") were discovered in *CGRO*/BATSE data from 1995 December 2 [1]. Subsequently, a new persistent source near the Galactic center was seen in BATSE occultation data. Finger *et al.* [2] using BATSE pulsar monitoring data discovered coherent hard X-ray pulsations at a period of 467 ms associated with this source, and the detection of pulsations in the bursts unambiguously identified the pulsar with the burster. Furthermore, they found that GRO J1744-28 was spinning up, indicating the presence of torques due to an accretion disk. Its pulse frequency was also modulated with an 11.8 d period from the orbital motion of the pulsar and its binary companion. Despite intensive searches, no optical or infrared counterpart for GRO J1744-28 has been confirmed (although one has been suggested) (see e.g. [3,4]).

After it began bursting, the GRO J1744-28 persistent flux continued to increase until 1996 mid-January. By 1996 early June, it was only weakly detectable (see figure 1). However, in late June, a weak outburst began, lasting until mid-August. After this small maximum, the source was inactive until 1996 December 2, when it once again began bursting and started a second major outburst. Unfortunately, GRO J1744-28 was too close to the sun to be observed by *RXTE* during the start of the second outburst, so the properties of the initial rise are unknown. While the peak flux of the second outburst was only about half that of the initial event (not shown on figure 1), it's decay after the peak was quite similar.

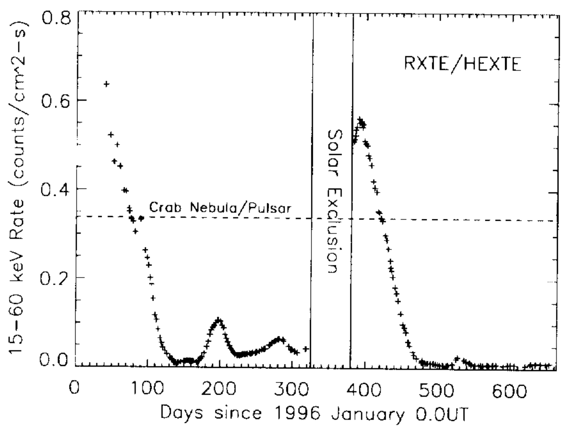

Figure 1. The HEXTE light curve of GRO J1744-28 from *RXTE* pointed observations. The flux level of the Crab Nebula/Pulsar is shown for comparison.

PII S0920-5632(98)00211-4

Several authors have discussed the nature of the system and its evolution [5–9]. The system is most likely a low mass X-ray binary accreting via Roche lobe overflow and viewed nearly face on. With the exception of Lamb, Miller, & Taam (1996), these evolutionary pictures favor a low dipole magnetic field (B $\lesssim$ *few* $\times 10^{11}$ G). If the field is this low, then the associated cyclotron absorption energy ($\lesssim$ 5 keV) would fall at or below the bottom of the *RXTE* bandpass. If, however, the field is as strong as Lamb, Miller, & Taam suggest (B $\sim 10^{13}$ G, $E_{cyc} \sim 100$ keV), a cyclotron line may appear in the *RXTE* data.

We present here a search for cyclotron features in the pulsed X-ray spectrum of GRO J1744-28 from eight observations near the peak of the second outburst.

Table 1
Observations and their exposures. The HEXTE live times are the sum of both clusters and are smaller than the PCA live times due to a ~40% instrumental deadtime.

	Live Time (s)	
Time (1997 UT)	PCA	HEXTE
Jan. 19.864–19.895	2031	1235
Jan. 20.929–20.968	2555	1561
Jan. 21.930–21.965	1328	746
Jan. 22.997–23.038	3271	1265
Jan. 24.160–24.237	1395	1113
Jan. 25.101–25.172	2668	1275
Jan. 25.865–25.905	2215	1391
Jan. 27.068–27.106	3026	1408

2. Observations and Analysis

With the exception of solar viewing exclusions from mid-November to mid-January, *RXTE* has observed the bursting pulsar on at least a weekly basis (and at times much more frequently) since 1996 January. The *RXTE* pointed instruments consist of the Proportional Counter Array (PCA)[10] and the High Energy X-ray Timing Experiment (HEXTE) [11]. They cover a combined energy range of 2–250 keV. There have been nearly 250 observations. In this work, we concentrate on eight observations made at the peak of the second outburst. Table 1 summarizes the observation details.

To avoid possible spectral variability during bursts, we excluded 500 seconds of data beginning ~30 seconds before each large burst and lasting ~470 seconds after. This is generally enough time for the light curve to recover its pre-burst flux level and hopefully spectrum. This is a conservative approach, as the spectra of the bursts seem to be quite similar to the persistent emission.

Because the Galactic center region has a high density of X-ray sources and a bright diffuse component, we analyzed only the GRO J1744-28 pulsed emission. By subtracting the pulse minimum data from the pulse maximum, we effectively remove all sources of background (which do not vary with the pulsar period). In future work, we will investigate the possibility of phase averaged and resolved analyses of the total spectrum using detailed estimates of the sky background.

The pulsar period for each observation was determined from the HEXTE data by a maximum χ^2 search of folding periods. PCA and HEXTE spectra were then accumulated in 20 phase bins. Figure 4 shows folded light curves from the counting rates in these 20 spectra for observation 1. The pulsed-flux spectrum for each observation was formed by subtracting the "off-pulse" spectrum from the "on-pulse" spectrum. For the off-pulse and on-pulse spectra, we summed the five phase bins at the pulse minimum and maximum, respectively. The eight observations were then combined to form the single pulsed-flux spectrum which is shown in figures 2 and 3.

We fit the pulsed spectrum to two different continuum models, both including interstellar absorption at low energies. Both continuum models represent power law photon spectra which are exponentially cut off at high energies. The first, the so-called "Pulsar Spectrum"[12], is given by equations 1 and 2:

$$P(E < E_{cut}) = KE^{-\Gamma} \quad (1)$$

$$P(E > E_{cut}) = KE^{-\Gamma} e^{-(E-E_{cut})/E_{fold}} \quad (2)$$

This model has been successful at fitting pulsar spectral data of modest statistical quality. However, it has the undesirable property of a discontinuous first derivative at the cutoff energy (E_{cut}). The second model which we use is a power law times a "Fermi-Dirac" cutoff function:

$$P(E) = KE^{-\Gamma} \times \frac{1}{1 + e^{(E-E_{cut})/E_{fold}}} \quad (3)$$

In this case, the power law is modified at all energies; however, the first derivative is continuous for all positive energies. To this spectral form, we also allowed cyclotron absorption features described by a multiplicative term:

$$C(E) = e^{-\frac{A(WE/E_a)^2}{(E-E_a)^2+W^2}} \quad (4)$$

where W is the line width, A the depth, and E_A the energy. Our spectra showed no indication of multiple harmonics, so only the fundamental line was included.

Because cyclotron line searches are very sensitive to errors and uncertainties in instrument response matrices, we added systematic uncertainties to our spectra to account for residuals obtained in fitting the phase average Crab Nebula and Pulsar spectrum. These residuals are as large as a few percent of the model and are the primary limit to the sensitivity of our line search.

3. Results and Discussion

Figure 2 shows the best fit "pulsar spectrum" model to the joint PCA/HEXTE data. The best fit parameters are: $N_h = (7.7 \pm 0.4) \times 10^{22}$ cm^{-2}, $\Gamma = 0.92 \pm 0.03$, $E_c = 13.9 \pm 0.2$ keV, and $E_f = 11.2 \pm 0.2$ keV, with $\chi_r^2 = 4$ for 135 degrees of freedom. While these are fairly typical parameters for X-ray pulsars, the fit is clearly poor. Furthermore, the strong residuals near 15 keV could easily masquerade as a cyclotron absorption line. They are in fact due to the discontinuous nature of the model's first derivative at E_c, which cannot match the presumably smooth true spectrum. While this model has been useful for pulsar work on data of moderate statistical quality, it is clearly inadequate for the high quality data available with *RXTE*.

Figure 3 shows the best fit to a Fermi-Dirac cutoff power law. Here the residuals are all well within the combined statistical and systematic uncertainties. The best fit parameters are: $N_h = (4.8 \pm 0.5) \times 10^{22}$ cm^{-2}, $\Gamma = 0.24 \pm 0.09$, $E_c = 7 \pm 2$ keV, and $E_f = 8.0 \pm 0.1$ keV, with $\chi_r^2 = 1.0$ for 135 degrees of freedom. This fit describes the spectrum well with no modification. No iron line emission is indicated, which is not surprising, considering that this is the pulsed component only. The only part of the measured spectrum where a cyclotron absorption feature might fit is near 35 keV. However, the residuals in this region are almost certainly due to imperfect knowledge of the HEXTE response matrix near the iodine K edge. We therefore conclude that there is no evidence for cyclotron absorption in the pulsed X-ray spectrum of GRO J1744-28.

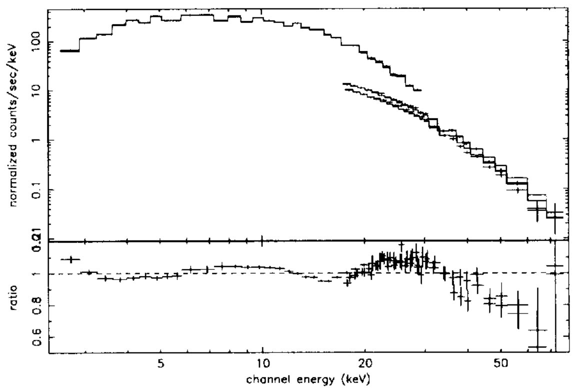

Figure 2. The *RXTE* spectrum of GRO J1744-28 from 1997 January fit to a model with interstellar absorption and a high energy cutoff times a power law.

Similar analyses of *RXTE* observations made in 1996 March during the first outburst were inconclusive [13]. In that case, some improvement to the Fermi-Dirac cutoff model fits was obtained by the addition of an absorption line near 25 keV. However, 25 keV was just at the overlap of the instrumental energy bands for those observations, and the statistical improvement was

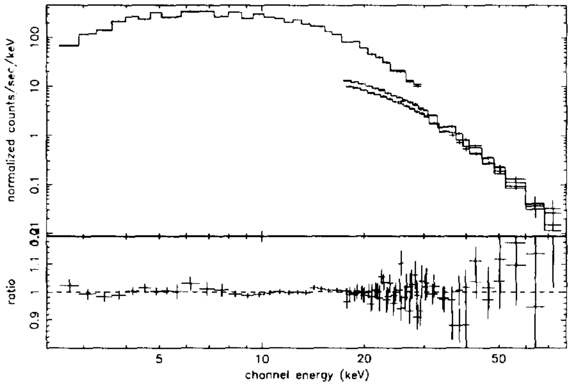

Figure 3. The pulsed spectrum of GRO J1744-28 from *RXTE* during 1997 January 19–27. The best fit model (interstellar absorption and a Fermi-Dirac cutoff times a power law) and the ratio of the data to the model are shown.

questionable. The model fits were otherwise similar to what we report here. We expect, therefore, that there was no cyclotron absorption present in 1996 March either. The absence of cyclotron absorption in the *RXTE* band is in agreement with evolutionary models which favor low dipole fields ($\lesssim 10^{11}$ G). While fields greater than $\sim 10^{13}$ G are not ruled out, the lack of absorption is evidence against field components in the emission region with strengths around 10^{12} G . Of course, these conclusions are only applicable to the *pulsed spectrum*, and total spectrum results await further analysis.

Figure 4 shows the PCA and HEXTE cluster A light curves folded on the pulsar period ($P =$ 0.46702817, not barycenter corrected) from observation 1. As noted by Finger *et al.* (1996), the pulse shape is unusually sinusoidal. The pulsed fraction (defined as $(mean - minimum)/mean$) is greater at higher energies, with values of 13% (PCA) and 22% (HEXTE). This latter is slightly lower than the 24.6% measured by BATSE in the 20–40 keV band during the first outburst [2]. This is not unexpected, as the HEXTE data encompass a lower energy range, and is consistent with an unchanged pulsed fraction between the first and second outbursts.

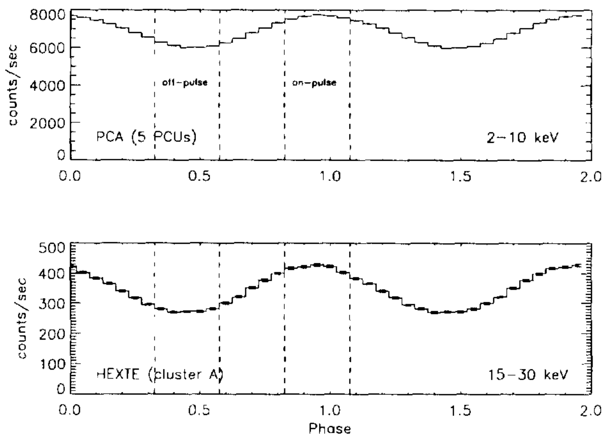

Figure 4. The PCA and HEXTE folded light curves for observation 1.

REFERENCES

1. C. Kouveliotou, *et al.,* Nat. 379 (1996) 799.
2. M.H. Finger, *et al.,* Nat., 381 (1996) 291.
3. T. Augusteijn, *et al.,* Ap.J., 486 (1997) 1013.
4. D.M. Cole, *et al.,* Ap.J., 480 (1997) 377.
5. P. Daumerie, V. Kalogera, F.K. Lamb, and D. Psaltis, Nat., 382 (1996) 141.
6. D.Q. Lamb, M.C. Miller, and R.E. Taam, preprint, (1996).
7. S.J. Sturner and C.D. Dermer, Ap.J., 465 (1996) L31.
8. S. Rappaport and P.C. Joss, Ap.J., 486 (1997) 435.
9. L. Bildsten and E.F. Brown, Ap.J., 477 (1997) 897.
10. K. Jahoda, *et al.,* SPIE 2808 (1996) 59.
11. D.E. Gruber, *et al.,* A&A Supp., 120 (1996) 641.
12. N.E. White, J.H. Swank, and S. Holt, Ap.J., 270 (1983) 711.
13. W.A. Heindl, *et al.,* BAAS 28 (1996) 1394.