DEEP XMM-NEWTON OBSERVATIONS OF THE X-RAY EMISSION FROM PSR B1706-44

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PSR B1706-44 is a young, energetic pulsar which emits pulsed X-ray and gamma-ray emission at the 102 ms radio period. We present the first results from analysis of a 90 ks observation of PSR B1706-44 taken with XMM-Newton. The pulse profile is broad and single-peaked, with a pulse fraction of 22 ± 4 %. We find that the spectra can be well-described by a blackbody plus power law model with $N_H = 5.5 \times 10^{21}$ cm $^{-2}$, $kT = 0.157^{+0.007}_{-0.008}$ keV and $\Gamma = 1.77^{+0.11}_{-0.10}$. The emitting radius determined from the model fit is 1.2±0.1 km which indicates that the emission is from a hot spot, and not the whole neutron star.

1. Introduction

PSR B1706-44 is a 102 ms radio pulsar [1] which is known to display glitches [2]. Pulsed emission is seen at the radio period in gamma-rays [3,4] and in X-rays [5]. PSR B1706-44 is one of several sources with spin down ages 10^4–10^5 yrs which are referred to as Vela-like pulsars, due to their apparent similar emission properties. The pulse profile for PSR B1706-44 is broad and single peaked in both the gamma-ray and X-ray energy bands. We note that the light curve of Vela in the gamma-ray range shows two peaks [6], and at least three in the X-rays [7,8]. Particular characteristics of the Vela-like pulsars are that the pulse profiles at different energies are shifted in phase with respect to each other, and the high energy spectra differ from the non-thermal spectra of the Crab-like pulsars.

The spectrum of PSR B1706-44 from *Chandra* was found to be well-fit with a two component model, with a blackbody temperature of T $= 1.66 \times 10^6$ K and a power law index of $\Gamma = 2.0$ [5]. A blackbody radius of R = 3.6±0.9 km determined from the model parameters led Gotthelf *et al.* (2002) to suggest that the emission was from a hot spot, or that an atmospheric model was required to decrease the temperature and therefore increase the radius.

Archival *Chandra* data was also used to show that PSR B1706-44 has an X-ray pulsar wind nebula [9]. These data were combined with radio observations to argue that the pulsar is associated with the supernova remnant G343.1-2.3 [9]. Further evidence of which was presented by Bock & Gvaramadze (2002).

In this paper we report on *XMM-Newton* observations of PSR B1706-44. Results from the timing and spectral analyses are presented in the following sections.

2. Observations

PSR B1706-44 was observed by *XMM-Newton* for ~ 40 ks on 2002 March 12, and ~ 46 ks on 2002 March 13, as a part of the Guaranteed Time program. The following analysis utilises data from the EPIC PN and MOS detectors. The PN was operated in small window mode to minimize the effects of pile-up. MOS1 was operated in full window (imaging) mode, while MOS2 was operated in timing mode to obtain better temporal resolution.

Event files filtered on photon event pattern were used to maximise the signal-to-noise. The data were reduced using SAS v5.3.0 and XSPEC v11.1. For the temporal analysis we consider data within 0.2–15 keV, and 0.3–10 keV for the spectral analysis.

3. Temporal Analysis

We have derived a predicted pulse period at the epoch of our *XMM-Newton* observations for PSR B1706-44, using the radio measurements [11,5] and assuming a linear spin-down rate. It

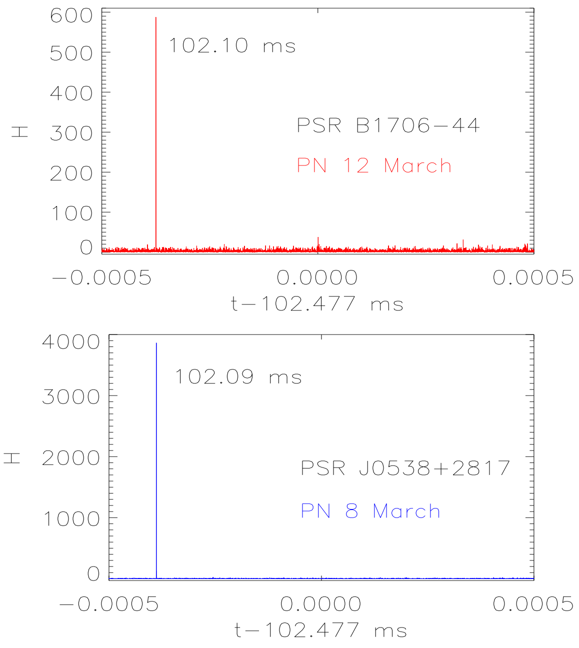

Figure 1. H-test periodograms for the PN data of PSR B1706-44 (top panel) and PSR J0538+2817 (bottom panel) showing the presence of a large peak at $\sim$ 102.1 ms.

is possible however that glitches could alter the period from the predicted value. Therefore we searched for a pulsed signal in the PN and MOS2 data over a wider frequency range centered on the predicted value of P $\sim$ 102.4776 ms.

The PN and MOS2 data were barycentrically corrected. We generated periodograms using the H-test [12]. The advantage of this test is that it makes no assumptions about the binning or the spectral shape of the light curve, and internally optimizes the number of harmonics to use.

A large peak at 102.10 ms was found in the H-test periodogram for the PN data of PSR B1706-44 (Fig. 1, *top panel*). However, the folded light curve indicated that this value did not represent a true periodicity. Analysis of PN data for another pulsar, PSR J0538+2817, revealed a similarly strong peak at 102.09 ms (Fig. 1, *bottom panel*). A study of the timing of the EPIC PN camera demonstrates that a number of aliases are produced due to dead time effects in the readout of the detector [13]. We conclude that the large

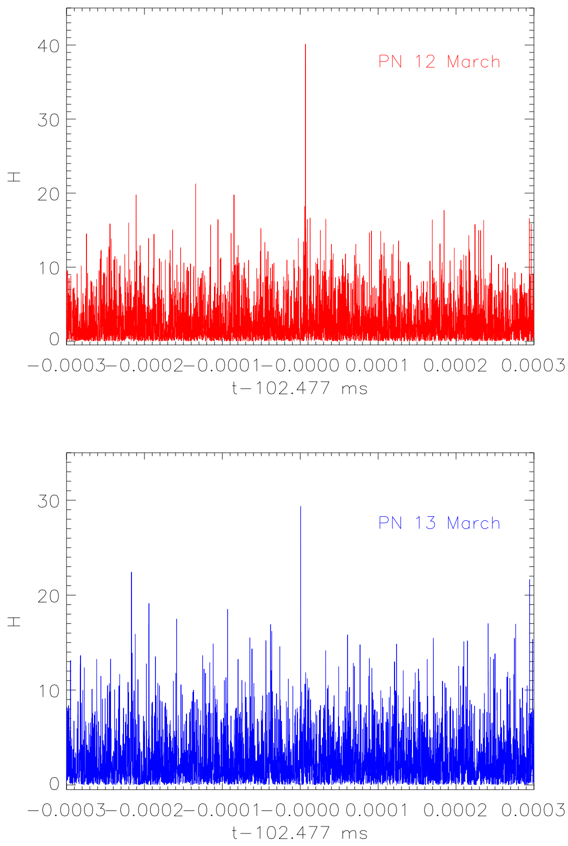

Figure 2. H-test periodograms for the PN data of PSR B1706-44 taken on 2002 March 12 (top panel) and 2002 March 13 (bottom panel). Both show a peak at $\sim$ 102.477 ms which is consistent with the predicted period.

peaks observed in the pulsar data are instrumental in origin. We therefore searched for periodicities in the data of PSR B1706-44 over a narrower frequency range.

We find a peak at P $= 102.477670^{+0.000759}_{-0.000600}$ ms (Fig. 2, *top panel*) in the PN data from 2002 March 12, and a peak at P $= 102.477603^{+0.000654}_{-0.000557}$ ms (Fig. 2, *bottom panel*) in the 2002 March 13 PN data. The periods found are consistent, within errors determined from the 68% uncertainty range, with each other and the predicted pulse period. We do not find a significant peak near the predicted period in the H-test peri-

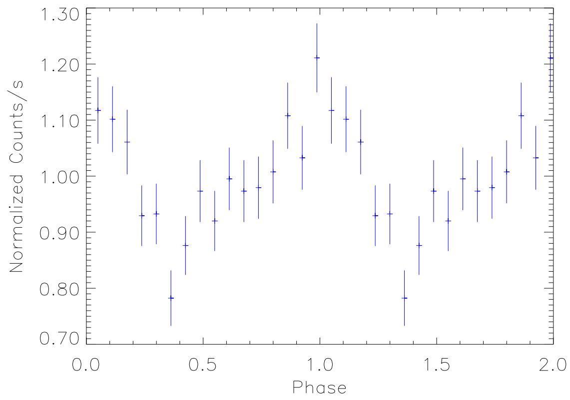

Figure 3. PN light curve of PSR B1706-44 from 2002 March 12 observation folded on the period found from the H-test for the same observation, P = 102.477670 ms. Phase zero corresponds to the epoch of the radio peak, $T_\circ$(MJD) = 2451585.3410392671.

odograms for the MOS2 data, the reason for which is uncertain at this time.

4. Folded Light Curve

We folded the PN data on the periods found from the H-test periodograms. We modelled the folded light curves with a sinusoid. We find χ^2_ν values of ~3 for the fits, indicating that the pulse profiles are asymmetric.

The light curve from the 2002 March 12 observation has a higher signal-to-noise than the 2002 March 13 observation, and the former is shown in Fig. 3. The pulse fraction for the 2002 March 12 light curve is $22 \pm 4\%$ which is in excellent agreement with the pulse fraction found from the *Chandra* data of $23 \pm 6\%$ [5]. As in Gotthelf *et al.* (2002), we find that the peak of our X-ray pulse is consistent with the radio pulse arrival time.

5. Spectral Analysis

We extracted spectra of PSR B1706-44 within a radius of 30″ from the MOS1 and PN data. The spectra were re-binned to ensure a minimum of 15 counts in each energy bin. The background spectra, which were subtracted from the source spectra, were extracted from an annulus around PSR B1706-44. We created the corresponding photon redistribution matrix (RMF) and ancillary region file (ARF). We modelled the spectra with XSPEC, fixing N_H at 5.5×10^{21} cm $^{-2}$, the value determined from the *Chandra* data [5].

The *Chandra* spectrum of PSR B1706-44 was found to require a two component model to be fit, with a blackbody temperature of $1.66^{+0.17}_{-0.15} \times 10^6$ K and a power law index of $\Gamma = 2.0 \pm 0.5$ [5]. We find that our *XMM-Newton* spectra can also be well-fit with a blackbody plus power law model, with $kT = 0.157^{+0.007}_{-0.008}$ keV and $\Gamma = 1.77^{+0.11}_{-0.10}$, with $\chi^2_\nu = 1.01$ for 884 d.o.f (Fig. 4).

From our model fits we find a blackbody temperature at infinity of T = $(1.82^{+0.08}_{-0.09}) \times 10^6$ K, which is consistent within errors to the *Chandra* results. As the distance to PSR B1706-44 is uncertain we have used a nominal distance of 2.5 kpc in our calculations. We find an X-ray luminosity of 1.2×10^{33} ergs s^{-1} in the 0.3–10 keV band, and a blackbody luminosity of 6.5×10^{32} ergs s^{-1}. The radius of the emitting region, corrected for the gravitational redshift parameter, assuming a mass and radius for the neutron star of 1.4 $M_\odot$ and 10 km respectively, is 1.2 ± 0.1 km.

It is difficult to reconcile this radius with the whole neutron star. While the uncertainty in the distance to PSR B1706-44 effects the determined radius, we would need to place the pulsar at an unacceptably large distance to have an emitting radius which is consistent with the expected neutron star radius.

It has been suggested that fitting with an atmospheric model could decrease the predicted temperature and lead to an increase in the area of the emitting region [5]. We note that taking into account the characteristic age of 1.75×10^4 yrs for PSR B1706-44 we find that our model temperature is higher than that predicted from the standard cooling curves for a neutron star [14,15].

We fit the MOS1 and PN spectra from 2002 March 12 and 13 with a pure-H, non-magnetised atmospheric model [16,17]. We fixed N_H = 5.5×10^{21} cm $^{-2}$, the mass and radius of the neutron star were fixed at 1.4 $M_\odot$ and 10 km, respectively. We find that the atmospheric model does not fit the spectra well with $\chi^2_\nu = 2.6$ for 886 d.o.f. While this suggests that the atmospheric model can be ruled out, we note that the model we have used is non-magnetised, and with B = 3×10^{12} G for PSR B1706-44 the applicability of this model

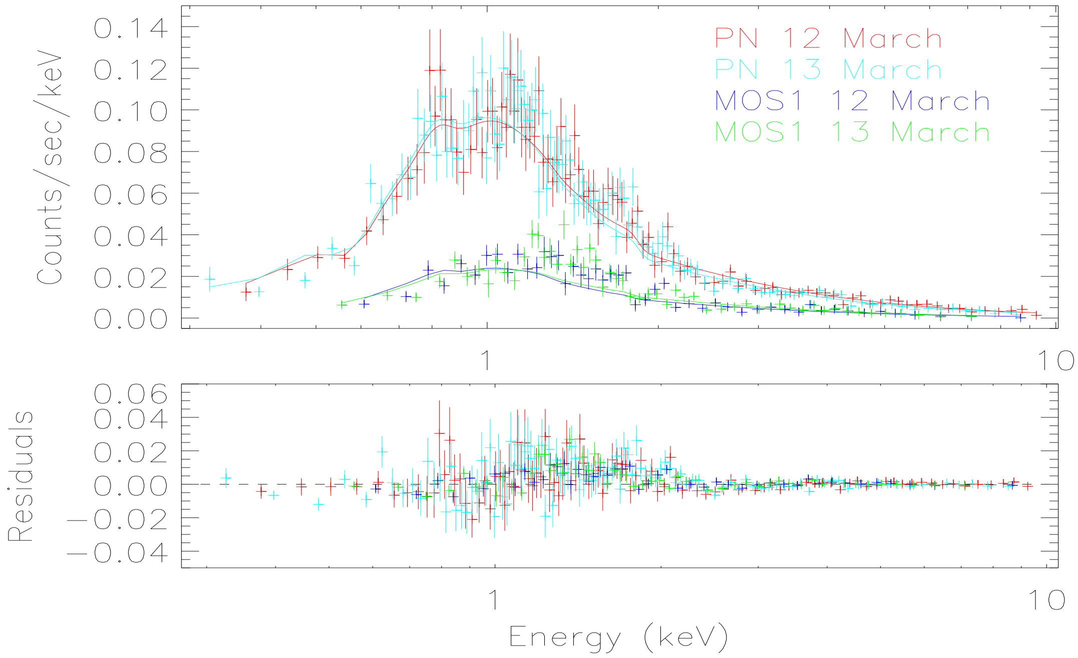

Figure 4. PN and MOS1 spectra of PSR B1706-44 (top panel). The solid line is the two component blackbody and power law model. The bottom panel shows the residuals of the model fit to the data.

is questionable. Further studies with a magnetic model must be performed to address this.

6. Phase Resolved Spectroscopy

To investigate whether or not PSR B1706-44 displays spectral variations as a function of phase we concentrated on the PN data from 2002 March 12 as a test case. We fit the spectrum with a blackbody plus power law model with N_H fixed at 5.5×10^{21} cm $^{-2}$. We then created source spectra in 4 phase intervals, and created the corresponding background spectra for each phase bin. We fit each spectra with the two component model above. All parameters were fixed at the best-fit values except the overall normalisation which was allowed to vary. We determined the ratio of the average spectral model to the spectrum in each phase interval.

The resulting ratios in the 4 phase intervals are shown in Fig. 5. It is clear that the average spectral parameters do not fit the phase binned spectra well at high and low energies. This suggests that the background spectra we extracted are not optimised for this analysis. If any spectral variations are present in the data they will be masked. A method in which the full background is utilised as opposed to the phase selected background will be investigated in a future work.

7. Summary

We find pulsed X-ray emission from PSR B1706-44 at a frequency consistent with the predicted period. The pulse profile is broad and single-peaked, with a pulse fraction of $22 \pm 4\%$. Pulsed X-rays can be emitted via one of two mechanisms: non-thermal emission due to relativistic particles produced either in regions above the polar caps of the neutron star or in the outer gaps. Thermal emission produced at the stellar surface due to the initial cooling of the neutron star, or reheating of the polar caps by backflowing particles. Our pulse profile does not rule out either model. The gamma-ray pulse profile is also broad and single peaked, further studies of

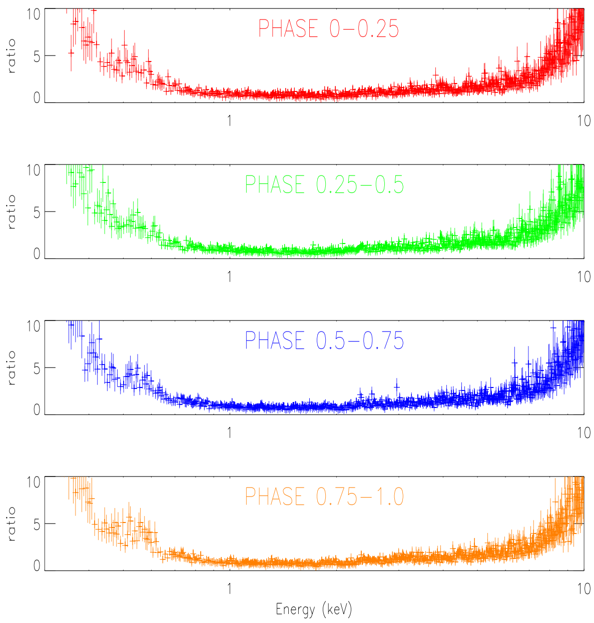

Figure 5. The ratio of the average model spectrum to the spectra of PSR B1706-44 in 4 phase bins.

this non-thermal emission and comparison with our X-ray measurements will help to determine the emitting region in PSR B1706-44.

We find that the spectra of PSR B1706-44 can be well-fit with a blackbody plus power law model with $kT = 0.157^{+0.007}_{-0.008}$ keV and $\Gamma = 1.77^{+0.11}_{-0.10}$. This is in good agreement with the values found from *Chandra* data [5]. We calculate an emitting radius of 1.2±0.1 km.

The temperature determined from our two component model fit is higher than that predicted from the standard cooling models [14,15]. In an attempt to decrease the fitted temperature, which would lead to an increase in the emitting radius, we fit our spectra with an atmospheric model. However, the poor fit determined indicates that our spectra are well-described by a blackbody plus power law model. The size of the emitting region indicates that the emission is from a hot spot, and not the whole neutron star.

The phase resolved spectroscopy results are inconclusive and more analysis is needed to determine whether the spectra vary as a function of phase.

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