DETECTION OF PULSED X-RAY EMISSION FROM PSR B1706–44
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ABSTRACT

We report the first detection of pulsed X-ray emission from the young, energetic radio and gamma-ray pulsar PSR B1706–44. In a 47 ks observation with the High Resolution Camera on-board the Chandra X-ray Observatory we find a pulsed signal at a frequency consistent with the radio ephemeris, \( f = 9.7588081 \pm 0.0000027 \) Hz (at epoch 51585.34104 MJD). The broad, single-peaked pulse profile has a pulsed fraction of 23\% \pm 6\%; this is not in conflict with a ROSAT PSPC upper limit of < 18\% because this instrument could not resolve the pulsar from a surrounding synchrotron nebula. The probability that this pulsed detection is a chance occurrence is \( 1.8 \times 10^{-4} \) as judged by the Rayleigh test. We also fitted Chandra spectroscopic data on PSR B1706–44, which require at least two components, e.g., a blackbody of \( T_\infty = (1.66^{+0.17}_{-0.15}) \times 10^8 \) K and a power-law of \( \Gamma = 2.0 \pm 0.5 \). The blackbody radius at the nominal 2.5 kpc distance is only \( R_\infty = 3.6 \pm 0.9 \) km, indicating either a hot region on a cooler surface, or the need for a realistic atmospheric model that would allow a lower temperature and larger area. Because the power-law and blackbody spectra each contribute more than 23\% of the observed flux, it is not possible to decide which component is responsible for the modulation in the spectrally unresolved light curve.

Subject headings: pulsars: individual (PSR B1706–44) — stars: neutron — X-rays: stars

1. INTRODUCTION

PSR B1706–44 is a 102 ms radio pulsar discovered by Johnston et al. (1992) and possibly associated with the supernova remnant G343.1–2.3 (McAdam, Osborne, & Parkinson 1993). It is a young neutron star with characteristic age \( P/2\dot{P} = 17,500 \) yr and spin-down luminosity \( \dot{E} = 3.4 \times 10^{36} \text{ ergs s}^{-1} \). Its distance is 1.8 kpc according to the Taylor & Cordes (1993) free electron model of the Galaxy; but Koribalski et al. (1995) find a kinematic distance in the range 2.4–3.2 kpc from H I absorption. Originally detected as the high-energy \( \gamma \)-ray source 2CG342–02 by the COS B satellite (Swanenburg et al. 1981), it is one of approximately eight rotation-powered pulsars that are responsible for some of the brightest gamma-ray sources in the sky. Thompson et al. (1992; 1996) showed that photons detected from the direction of PSR B1706–44 by the EGRET instrument on board the Compton Gamma-Ray Observatory are pulsed at the radio period. All of the known gamma-ray pulsars are well observed at X-ray energies between 0.1 and 10 keV, where both surface thermal emission and magnetospheric synchrotron emission can be studied. However, PSR B1706–44 carries the dubious distinction of being the only gamma-ray pulsar in which pulsed X-ray emission has not been detected despite several searches. This failure has hindered attempts to understand its X-ray emission mechanism(s).

Using an observation of PSR B1706–44 by the ROSAT PSPC, Becker, Brazier, Trumper (1995) placed an upper limit of 18\% on the pulsed fraction. They attributed this negative result to the diluting effect of an as-yet unresolved synchrotron nebula, recalling the history of Vela (Ögelman, Finley, & Zimmerman 1993), a pulsar of similar age and spin-down luminosity. Finley et al. (1998), using data from the ASCA GIS, placed an upper limit of 22\% on the pulsed fraction in the 2–10 keV band, although their image was severely contaminated by stray light from the bright low-mass X-ray binary 4U1705–44 just outside the field of view. Finley et al. also analyzed a ROSAT HRI observation, from which they concluded that 57 \pm 12\% of the photons associated with PSR B1706–44 actually come from a compact nebula with an exponential scale length of \( \approx 27'' \). When folding only the photons from the HRI point source at the radio period, they derived an upper limit of 29\% on its pulsed fraction. An observation by the non-imaging Rossi X-ray Timing Explorer performed during a low state of 4U1705–44 also failed to detect pulsations in the 9 – 18.5 keV band. (Ray, Harding, & Strickman 1999). Here we report on Chandra X-ray Observatory observations of PSR B1706–44 in which we detect its pulsed emission for the first time in X-rays.

2. OBSERVATIONS

The field of PSR B1706–44/G343.1–2.3 was observed by Chandra twice, once with each of the two types of cameras at the focal plane of the telescope. Herein we analysis data from these observations, made available through the Chandra public archive. Timing data on PSR B1706–44 was acquired on 2000 Feb 11 with the imaging High Resolution Camera (HRC-I; Murray et al. 1997), a multichannel plate detector with an effective time resolution reduced to \(~4\) ms due to a known timing error. The HRC is sensitive to X-rays in the energy range 0.1 – 10 keV over a 0.5 \times 0.5 square field-of-view; no useful spectral information is available. The target was placed near (\(~28\)\') the optical axis where the telescope mirror point-spread function (PSF) has a half power radius (the radius enclosing 50\% of the total source counts)
of \( \sim 0.5' \) for energies \( E < 6 \) keV. The HRC-I oversamples the PSF with pixels \( 0.1318' \) on a side, which allows the pulsar to be isolated from any surrounding emission such as the pulsar wind nebulae (PWNe) typically found associated with young pulsars observed by Chandra (e.g., see Gotthelf 2001).

Complimentary to the HRC observation, the data from the Advanced CCD Imaging Spectrometer (ACIS; Burke et al. 1997) has a resolution of \( \Delta E / E \sim 0.1 \) at 1 keV scaling as \( 1/\sqrt{E} \) over its 0.2–10 keV active band-pass. The pulsar was observed on 2000 Aug 14 and positioned on the back-illuminated S3 chip of the ACIS-S array, offset by 0.5' from the aim-point, where the PSF is undersampled by the \( 0.04920 \times 0.04920 \) CCD pixels. Data were collected in the nominal timing mode, with 3.241 s exposures between CCD readouts, and in “FAINT” spectral mode. In the following analysis, data from the ACIS and HRC instruments are used exclusively for spectroscopy and timing analysis, respectively, while images from both sensors are examined.

The standard Chandra screening criteria produced a total usable exposure time of 46.8 ks and 14.3 ks for the HRC and ACIS data sets, respectively. Given the relative sensitivity of the two instruments, the two exposures resulted in a similar number of detected photons from the source, and the sky images made from the two instruments are found to be consistent. The ACIS image, restricted to the \( \sim 0.3 - 8 \) keV energy band to reduce the instrumental background, reveals a point-like X-ray source near the radio pulsar position and four faint X-ray sources that are coincident with nearby USNO stars to sub-arcsecond accuracy. The Chandra position of PSR B1706−44 is \( \alpha = 17^h 09^m 42^s .73, \delta = -44^\circ 29' 08'' .4 \) (J2000.0) with RMS error \( 0.5' \). This is in agreement with the precise radio timing position of Wang et al. (2000), \( \alpha = 17^h 09^m 42^s .728, \delta = -44^\circ 29' 08'' .24 \). Thus, we conclude that the point source is the X-ray counterpart of the radio pulsar.

To look for evidence of extended emission from PSR B1706−44 we examined its radial profile, the distribution of counts in the HRC as a function of distance from the pulsar, normalised by area. For comparison, we similarly analyzed a 23 ks HRC observation of the millisecond pulsar PSR J0437−4715 observed by Chandra just two days later (Zavlin et al. 2002). The latter is an isolated point source with a spectrum similar to that of PSR B1706−44 (as shown in §4) observed at the HRC aimpoint, and thus providing a realistic example of the in-orbit point-spread function. Figure 1 displays the two radial profiles after adjusting for the relative background rate, estimated using the mean (area normalized) count rate in an annulus of \( 30'' < r < 60'' \), where the background is flat. We then normalized the two profiles to the peak emission within \( r < 1.5'' \). While the majority of the emission is point-like, there is clearly diffuse emission out to a radius of \( \sim 20'' \). There is also evidence for a bump of enhanced emission between \( 11'' < r < 23'' \). This result is consistent with the analysis of these data by Dodson & Golap (2002) who found extended emission out to \( \sim 10'' \), and is marginally consistent with the decomposition of the ROSAT HRI image deduced by Finley et al. (1998). In order to make a direct comparison with the ROSAT energy band, we also extracted photons from the ACIS image in the range \( 0.2 - 2.0 \) keV. After background subtraction, we find 513 photons in the ACIS from the point source (radius \( 1.5'' \)), and 383 nebular photons in the annulus between \( 1.5'' \) and \( 20'' \).

3. Timing Analysis

We searched for a pulsed signal from PSR B1706−44 in the HRC data using time-tagged photon events extracted from an \( 1.5'' \) radius aperture centered on the X-ray pulsar position. This aperture effectively excludes diffuse emission from the putative surrounding synchrotron nebula; furthermore, less than 1% of the photons in this aperture are background events. The arrival times of the 685 selected photons were corrected to the solar system barycenter using the JPL-DE405 ephemeris and the radio timing position of Wang et al. (2000). We then generated a periodogram using the \( Z_2^2 \) statistic (Rayleigh test) on a range of test frequencies centered on the predicted pulsar frequency as extrapolated from the radio ephemeris (epoch MJD 51945 − 52225) in the “Australian Pulsar Timing Data Archive” (cf. Wang et al. 2000).

The resulting periodogram is shown in Figure 2. We find a statistically significant peak at \( f = 9.7588081 \pm 0.0000027 \) Hz (epoch 51585.34104 MJD) which, within the quoted 68% uncertainty range, agrees with the extrapolated radio frequency, \( f = 9.7588096 \) Hz. The \( Z_2^2 \) statistic for this peak is 17.24, which has a probability of chance occurrence of \( 1.8 \times 10^{-8} \). The pulse profile, shown in Figure 3, is broad and single peaked with a pulsed fraction of \( 23\% \pm 6\% \). According to convention, the pulsed fraction is defined as the ratio of counts above the minimum in the light curve to the total counts. This detection is consistent with the previous upper limits of \(< 29\% \) from the ROSAT HRI (Finley et al. 1998) and \(< 18\% \) from the ROSAT PSPC (Becker et al. 1995). The latter did not resolve the pulsar from the nebula, therefore, it represents a true upper limit of \(< 31\% \) given the contribution of diffuse photons measured in the Chandra ACIS image as described in §2. Based on the statistical significance of the HRC signal and its near coincidence with the expected period, we regard it as the first detection of X-ray pulsations from this well-known radio and gamma-ray pulsar.

4. Spectroscopy

To characterize the energy dependence of the emission from the pulsar and its putative wind nebula, we analyzed spectral data obtained with the ACIS detector. Pulsar and PWN source counts spectra were extracted from two concentric regions, a circle of radius \( 1'' \) and an annulus of radii \( 2'' < r < 10'' \), respectively. An annular background region centered on the pulsar was extracted from radii \( 30'' < r < 60'' \), which appears to be pure background (see Fig. 1). We verified that background is a negligible contribution to the pulsar spectrum and a 10% contribution to the PWN spectrum over their respective extraction regions. To be specific, there are 561(486) source counts and an estimated 1(54) background count(s) for the pulsar(PWN) regions in the 0.5 − 8.0 keV spectral fitting range. From the radial profile (Fig. 1) it is clear that there is negligible cross-contamination between the pulsar.

Available at www.atnf.csiro.au/research/pulsar/archive
and PWN extraction regions.

The ACIS pulse-height data were corrected for gain and resolution degradation due to CCD charge transfer inefficiencies (CTI) using the correctit software (Townesley et al. 2001) applied to the Level 1 event file. We selected the ASCA-like 0.2,3,4,6 grades only and used the Townesley et al. instrument response matrix appropriate for the CTI corrected data. Since the location of the target on the CCD straddled regions covered by two response files, we generated a count-weighted mean response to match the data. The CIAO tool mknxrtf were used to generate a point-source mirror response matrix for the pulsar and PWN source regions. The extracted photons were binned in pulse-height channel space to match the response matrices and regrouped such that each fitted spectral bin contained a minimum of 20 counts. The resulting spectra were then fitted with the X-ray spectral analysis package XSPEC (version 11) using three different models, a power law, a simple blackbody, and a sum of both, each with interstellar absorption.

Initial fits to the pulsar spectrum using blackbody or power-law models were unacceptable, with $\chi^2 = 115$ and $\chi^2 = 60$ for 23 degrees-of-freedom (DoF), respectively. We next determined, as is often the case for young pulsars, that a blackbody plus power-law fit provides an adequate description of the spectrum. The intrinsic parameters of this multicomponent model are rather unconstrained and strongly correlated with the fitted value of the interstellar absorption column density, $N_H$. To remove an unnecessary degree of freedom, we fixed the column density at the value obtained from a simple fit to the PWN, $N_H = 5.5 \times 10^{21} \text{ cm}^{-2}$, since we expect the intervening column density to be the same. The PWN is well characterized by a single absorbed power-law with $\chi^2 = 13$ for 20 DoF. The results of these fits are given in Table 1, and the counts spectrum of the pulsar, with the model components superposed, are shown in Figure 4.

The fitted blackbody component yields effective temperature $T_\infty = (1.66^{+0.17}_{-0.13}) \times 10^6 \text{ K}$, bolometric luminosity $L_\infty = 6.8^{+0.8}_{-1.1} \times 10^{32} \text{ ergs s}^{-1}$, and effective radius $R_\infty = 3.5 \pm 0.9 \text{ km}$ in the observed frame. Here we adopt a distance of 2500 pc as a compromise between the smaller DM distance of 1.8 kpc, and the H I kinematic distance of 2.4 – 3.2 kpc. While $T_\infty$ is consistent with some standard neutron star cooling curves (Umeda, Tsuruta, & Nomoto 1994), the associated $R_\infty$ is significantly smaller than theoretical neutron star radii. As has been found frequently for other pulsars, e.g., Vela (Pavlov et al. 2001), such an outcome could have either of two implications. First, the thermal X-rays could be coming from a smaller hot region on the surface of a cooler neutron star, the substantial interstellar $N_H$ making it difficult to measure softer X-rays coming from the full surface. Second, a more realistic atmosphere model, especially if dominated by hydrogen or helium, would require a lower effective temperature and larger effective radius, perhaps becoming consistent with emission from the full neutron star surface.

5. DISCUSSION AND CONCLUSIONS

There are at least two mechanisms for the emission of broad-band pulsed X-rays from young rotation-powered pulsars like PSR B1706–44. One is non-thermal magnetoospheric synchrotron from relativistic electrons and positrons created either in regions above the neutron star polar caps or in outer gaps. The second is thermal emission from the hot surface, a result of initial cooling of the hot neutron star or reheating of the polar caps by backflowing accelerated particles. Sometimes the shape of the pulse sheds additional light on the X-ray emission mechanism. Sharp, narrow pulses of high amplitude can only be produced by a highly beamed, thus relativistic population of electrons, while quasi-sinusoidal pulses of low amplitude such as describe PSR B1706–44 can be produced by either mechanism. For those intermediate-age pulsars ($10^4 - 10^6 \text{ yr}$) that are also EGRET sources, the presence of both types of X-ray source is usually discovered when spectrally resolved timing data are available (e.g., Wang et al. 1998; Pavlov et al. 2001). Unfortunately, in this case, the Chandra HRC has little or no energy resolution. Since each spectral component fitted to the ACIS spectrum contributes more than 23% of the flux in the total energy band to which the HRC is sensitive (60% from blackbody, 40% from power law), the pulsed fraction alone does not reveal the source of the pulsed X-rays. Either or both components may contribute to the modulation. Additional clues, such as the absolute phase relationship of the X-ray pulse to the radio and $\gamma$-ray peaks cannot be examined yet due to our lack of a closely contemporaneous radio observation of this noisy, glitching pulsar (Johnston et al. 1995; Wang et al. 2000). Future spectrally resolved X-ray observations with high throughput and moderate time resolution, such as with XMM-Newton, could be effective in resolving this ambiguity.

The $> 100 \text{ MeV}$ luminosity of most $\gamma$-ray pulsars is a significant fraction of their spin-down power. In the case of PSR B1706–44 this fraction is $\approx 0.20$ if isotropic, while its $0.5 - 8 \text{ keV}$ non-thermal X-ray luminosity is only $1.3 \times 10^{34} \text{ ergs s}^{-1}$ including both pulsar and nebula, similar to that of other pulsars. Thompson et al. (1996) parameterized the EGRET spectrum of PSR B1706–44 as a broken power law, with photon index $\Gamma = 1.27 \pm 0.09$ from 50 MeV to 1 GeV, breaking to $\Gamma = 2.25 \pm 0.13$ above 1 GeV. Since there is no evidence for any unpulsed $\gamma$-ray emission, the EGRET spectrum can be compared directly with the power-law component of the pulsar point source in the Chandra ACIS spectrum. When extrapolated back to 10 keV, the EGRET spectrum nearly matches the X-ray flux, although the power-law X-ray slope itself, with $\Gamma = 2.0 \pm 0.5$, is somewhat steeper than the EGRET value. The non-thermal X-rays are not likely to be emitted by the same population of electrons/positrons as produce the $\gamma$-rays, but may instead originate from a much less energetic population, such as secondary pairs from the inward emitted $\gamma$-rays converting on the strong $B$-field near the neutron star surface. Wang et al. (1998) predicted $L_\gamma$ ($2 - 10 \text{ keV}$) $\approx 2 \times 10^{31} \text{ ergs s}^{-1}$ and $\Gamma = 1.5$ from this process, similar to the non-thermal X-ray component of PSR B1706–44. If its thermal luminosity comes partly from a small surface area, then inward flowing primary electrons impacting the polar caps may be responsible. Wang et al. predicted $L_\gamma \approx 1 \times 10^{33} \text{ ergs s}^{-1}$ of thermal emission from this process, not far from the observed thermal luminosity of PSR B1706–44.
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REFERENCES

McAdam, W. B., Osborne, J. L., & Parkinson, M. L. 1993, Nature, 361, 516
Murray, S. S., et al., 1997, SPIE, 3114, 11

Table 1
Spectral Fits to PSR B1706−44 and its PWN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pulsar</th>
<th>Nebula</th>
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<tr>
<td>(N_H (10^{21}\text{ cm}^{-2}))</td>
<td>5.5 (fixed)</td>
<td>5.5^{+2.5}_{-2.1}</td>
</tr>
<tr>
<td>(\Gamma)</td>
<td>2.0^{+0.5}_{-0.5}</td>
<td>1.34^{+0.24}_{-0.30}</td>
</tr>
<tr>
<td>(C_{pl}^{b})</td>
<td>4.3^{+1.1}_{-1.6}</td>
<td>5.5^{+2.6}_{-1.8}</td>
</tr>
<tr>
<td>(F_{pl}(\text{absorbed})^{c})</td>
<td>(1.2 \times 10^{-13})</td>
<td>(3.4 \times 10^{-13})</td>
</tr>
<tr>
<td>(L_{pl}(\text{unabsorbed})^{d})</td>
<td>(1.45^{+0.48}_{-0.48} \times 10^{32})</td>
<td>(3.1^{+1.5}_{-1.5} \times 10^{32})</td>
</tr>
<tr>
<td>(T_{\infty} (\text{K})^{e})</td>
<td>1.66^{+0.15}_{-0.15} \times 10^{6}</td>
<td>\ldots</td>
</tr>
<tr>
<td>(R_{\infty} (\text{km})^{f})</td>
<td>3.6 \pm 0.9</td>
<td>\ldots</td>
</tr>
<tr>
<td>(L_{\infty} (\text{ergs s}^{-1})^{g})</td>
<td>(6.8^{+0.8}_{-1.1} \times 10^{32})</td>
<td>\ldots</td>
</tr>
<tr>
<td>(\chi_{v}^{2} [\text{DoF}])</td>
<td>1.4 [21]</td>
<td>0.61 [21]</td>
</tr>
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</table>

\(a\)Uncertainties are 68% confidence for two interesting parameters.
\(b\)Power-law normalization in units of \(10^{-5}\) photons cm\(^{-2}\) s\(^{-1}\) keV\(^{-1}\) at 1 keV.
\(c\)Power-law flux (ergs cm\(^{-2}\) s\(^{-1}\)) in the 0.5–8 keV band.
\(d\)Power-law luminosity (ergs s\(^{-1}\)) in the 0.5–8 keV band for \(d = 2500\) pc.
\(e\)Spherical blackbody parameters for \(d = 2500\) pc.
Fig. 1.— X-ray intensity of PSR B1706−44 as a function of radius (histogram). The error bars are 1σ. For comparison is shown the HRC response to a point source (solid line; see text). The radial profile shows clear evidence for extended emission between 1.5″ and 20″.

Fig. 2.— Evidence for pulsed X-ray emission from PSR B1706−44 using a $Z^2_1$ periodogram. The arrow indicates the frequency expected according to the extrapolated radio ephemeris (see text). The inset is an expanded view around the peak. The peak value $Z^2_1 = 17.24$ at $f = 9.7588081$ Hz has a $1.8 \times 10^{-4}$ probability of occurring by chance.

Fig. 3.— The light curve of PSR B1706−44 from the Chandra HRC folded at the best fitted X-ray period, showing a nearly sinusoidal modulation with pulsed fraction of 23% ± 6%. The error bars are 1σ.

Fig. 4.— Chandra ACIS-S3 spectrum of the point source coincident with PSR B1706−44. Top panel: Data (crosses) and best-fit model (dark line) for the parameters given in Table 1; thin lines show the contribution of the power-law (PL) and blackbody (BB) components of the fit. Lower panel: Difference between the data and model, in the same units as the top panel.