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CHANDRA X-RAY DETECTION OF THE HIGH MAGNETIC FIELD RADIO PULSAR PSR J1718−3718

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ABSTRACT

We report on the serendipitous X-ray detection, using the *Chandra X-Ray Observatory*, of the radio pulsar PSR J1718−3718. This pulsar has one of the highest inferred surface dipole magnetic fields in the radio pulsar population ($B = 7.4 \times 10^{13}$ G), higher than that inferred for one well-known anomalous X-ray pulsar (AXP). The X-ray emission for PSR J1718−3718 appears pointlike and has a purely thermal spectrum, with $kT = 0.145^{+0.053}_{-0.020}$ keV and absorbed 0.5–2 keV flux of (6.3–6.9) $\times\ 10^{-15}$ ergs s^{-1} cm^{-2}. We show that the pulsar's 2–10 keV luminosity is several orders of magnitude smaller than those of the nontransient AXPs and consistent with the predictions of standard models for initial cooling. The number of high magnetic field radio pulsars observed at X-ray energies now stands at five. All are X-ray faint, suggesting either that there is a significant physical distinction between high magnetic field radio pulsars and AXPs or that high magnetic field radio pulsars are, in fact, quiescent AXPs.

Subject headings: pulsars: general — pulsars: individual (PSR J1718−3718) — stars: neutron

1. INTRODUCTION

The existence of magnetars—young, isolated, high magnetic field neutron stars—is now well supported by a variety of independent lines of evidence. For recent reviews, see Woods & Thompson (2005) or Kaspi & Gavriil (2005). There appears to be at least two flavors of magnetar: soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Defining properties of both are their X-ray pulsations having luminosity in the range 10^{34}–10^{36} ergs s^{-1}, periods ranging from 6 to 12 s, period derivatives of 10^{-13} to 10^{-11}, and surface dipolar magnetic fields in the range (0.6–7) $\times\ 10^{14}$ G, assuming the vacuum dipole model formula for magnetic braking.[4] In the magnetar model, the pulsed X-rays are likely the combined result of surface thermal emission (e.g., Özel 2003; Lai & Ho 2003), with a nonthermal high-energy tail resulting from resonant scattering of thermal photons off magnetospheric currents (Thompson et al. 2002). The X-rays, in the magnetar model, are ultimately powered by an internally decaying very strong magnetic field. Despite numerous attempts, no magnetars have been detected at radio frequencies (Kriss et al. 1985; Coe et al. 1994; Lorimer et al. 1998; Gaensler et al. 2001), which has been suggested as implying that pair production ceases above some critical magnetic field (Zhang & Harding 2000).

An open issue in the magnetar model is the connection of these X-ray sources to radio pulsars. One might expect high-B radio pulsars to be more X-ray bright than low-B sources, and possibly exhibit magnetar-like X-ray emission. Pivovaroff et al. (2000) searched for enhanced X-ray emission from the high-B (5.5×10^{13} G) radio pulsar PSR J1814−1744 and placed an upper limit on its X-ray luminosity that was much lower than those of the five then-known AXPs (4U 0142+61, 1E 1048−9537, RXS 1708−4009, 1E 1841−045, and 1E 2259+586). Gonzalez et al. (2004) showed that the nearby radio pulsar PSR B0154+61 ($B = 2.1 \times 10^{13}$ G) has an X-ray luminosity 2–3 orders of magnitude lower than those of the same five AXPs. McLaughlin et al. (2003) reported on X-ray observations of PSR J1847−0130 ($B = 9.4 \times 10^{13}$ G), which has the highest inferred surface dipolar magnetic field of any known radio pulsar, and calculated an upper limit on its X-ray luminosity that was lower than those of all but one of the above five AXPs. Gonzalez & Safi-Harb (2003) studied PSR J1119−6127 ($B = 4.4 \times 10^{13}$ G), also finding it to be X-ray underluminous relative to the standard AXP group.

There are several possible ways to explain these results. There could exist a well-defined critical B-field above which the magnetar mechanism abruptly turns on. However, that would also require that B-fields inferred from spin-down are unreliable at the factor of $\gtrsim 2$ level, given the overlap in high-B radio pulsar fields and those of the AXPs (e.g., 1E 2259+586 has $B = 6 \times 10^{13}$ G). It could also be that AXPs and SGRs have higher order multipole moments that go undetected in spin-down, such that their true surface fields are orders of magnitude higher. The recently revealed strong X-ray variability seen in some AXPs (e.g., Ibrahim et al. 2004; Gavriil & Kaspi 2004) suggests that magnetar emission could be transient in many high-B neutron stars. Of course, which neutron stars become magnetars could depend on other, currently "hidden" neutron star properties besides the B-field, such as mass.

PSR J1718−3718 is a radio pulsar that was recently discovered in the Parkes Multibeam Survey (Hobbs et al. 2004). It has a spin period of $P = 3.3$ s and a spin-down rate of $\dot{P} = 1.5 \times 10^{-12}$, which imply a characteristic age $\tau_c \equiv P/2\dot{P} = 34$ kyr, spin-down luminosity $\dot{E} \equiv 4\pi^2 I\dot{P}/P^3 = 1.6 \times 10^{33}$ ergs s^{-1}, and a surface dipolar magnetic field of 7.4×10^{13} G. Its inferred magnetic field is the second highest of all known radio pulsars and is higher than that of the well-established AXP 1E 2259+586. Here we report on the first X-ray detection of this pulsar in a deep *Chandra X-Ray Observatory* observation of a nearby field.

2. OBSERVATIONS AND RESULTS

The position of PSR J1718−3718 was observed serendipitously by *Chandra* in an ACIS-S timed exposure obtained on 2002 May 13. The observation (PI: P. Slane, sequence 500235) had as its target the unrelated supernova remnant G347.7+0.2. The nominal telescope pointing was 7′.0 away from the pulsar's position derived from radio timing. As a result, the position of PSR J1718−3718 lies on chip 6, far from the optical axis,

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[4] Throughout the Letter, magnetic fields discussed are calculated via $B \equiv 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G, where P is the spin period and $\dot{P}$ the period derivative.

where the mirror point-spread function (PSF) is significantly extended and distorted asymmetrically.

We obtained the public data set using the *Chandra* Science Center's WebChaser facility and reduced the data with the CIAO software package (ver. 3.1), with calibration database CALDB version 2.28. After standard filtering using CIAO threads for ACIS-S data,[5] the effective integration time was 55.7 ks.

2.1. *Imaging*

The X-ray emission as seen by *Chandra* around the radio position of PSR J1718−3718 is shown in Figure 1. The source is identified with CIAO's CELLDETECT routine as having a signal-to-noise ratio of 6.4, for events in the energy range 0.5–3.0 keV. No source is apparent in images made with events having energies greater than 3.0 keV. Although the source appears extended (Fig. 1), given its large off-axis angle, its extent both in size and in morphology—including the angle of asymmetry—is consistent with the instrumental PSF at 1.5 keV, as determined using the CIAO MKPSF routine. Indeed, using counts in the range 0.5–3.0 keV, CELLDETECT run with default parameters reports a ratio of source to PSF size of 1.01. Given that the approximate 95% encircled energy radius for an object $7'.0$ off-axis is $\sim 7''$, we cannot rule out the presence of faint emission having an extent significantly smaller than this. However, as argued below, the spectrum strongly favors the emission originating from a point source.

The CELLDETECT routine reports a best-fit position for the X-ray source of R.A. = $17^{\rm h}18^{\rm m}9^{\rm s}.84 \pm 0.02$, decl. = $-37°18'51''.6 \pm 0.2$ (J2000.0). These (1 σ) uncertainties are statistical and do not include the systematic uncertainty in *Chandra*'s pointing. Note that for sources that are within $3'$ of the aim point, the 90% uncertainty circle of *Chandra*'s absolute pointing has radius[6] $0''.6$. For sources, such as ours, that are further off-axis, the absolute pointing uncertainty has not been well determined. This is an important caveat.

A timing analysis of the radio data (see Hobbs et al. 2004 for a description of the data and its analysis) yields a radio timing position of R.A. = $17^{\rm h}18^{\rm m}10^{\rm s}.162 \pm 0.194$, decl. = $-37°18'53''.75 \pm 10.0$ (J2000.0), where the quoted errors are formal 2 σ uncertainties as reported by TEMPO, and 10 months of additional timing data have been included since the most recently published result. Doubling the formal TEMPO uncertainties when reporting timing parameter errors is standard practice and is done to account for likely contamination from timing noise. Indeed, like most young pulsars, PSR J1718−3718 exhibits significant timing noise (rms 74 ms after fitting for position, P and $\dot{P}$), so the above-quoted uncertainties are likely to be good approximations to the true 1 σ uncertainties. The formal positional offset in declination is therefore $2''.2$, or $\sim 0.2\ \sigma$, while the R.A. offset is $0^{\rm s}.32$, or $\sim 1.6\ \sigma$. Note that these numbers do *not* include the unknown *Chandra* pointing uncertainty and so are lower limits only. We conclude that the source positions are consistent within the uncertainties.

However, given the slight possible positional offset, as well as the absence of unambiguous proof of the association via the detection of X-ray pulsations at the radio period (not possible with the ACIS-S data because it has an effective time resolution of 3.2 s), it is reasonable to question if the X-ray source is really associated with the radio pulsar. We can estimate the probability of chance superposition using a log N/ log S relationship for *Chandra* sources in the 0.5–2.0 keV band, appropriate for this source (Grindlay et al. 2003). In this relation, flux is the unabsorbed value; thus the probability of an X-ray source being near the pulsar position purely by chance depends strongly on the former's spectral parameters. As we show below, given only 110 source counts, these parameters are not well determined. However, even for the lowest plausible unabsorbed source flux for our source, the log N/ log S relation predicts $\sim$180 sources per square degree. With timing noise so strong in this pulsar, we would likely consider positional agreement within $\sim 10''$ to be a plausible association. In this case, the probability of a random source in this area of sky is only 1%. That the offset is smaller than $10''$, as well as that the unabsorbed flux is likely significantly larger than the lowest reasonable value (see below), make this 1% probability likely to be a large overestimate. Thus, the association appears extremely likely. We further note that the nearest optical counterpart in the uncalibrated plates of the Sloan Digital Sky Survey (Pier et al. 2003), with a limiting magnitude of $\sim$22, is more than $20''$ away, well outside of our *Chandra* error radius.

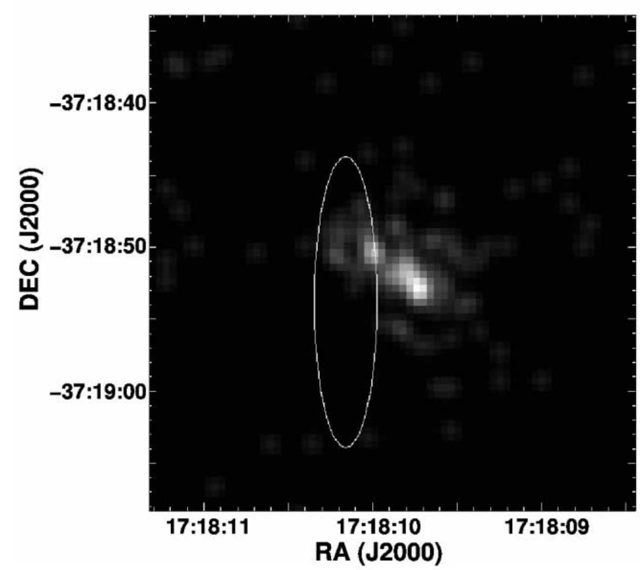

FIG. 1.—*Chandra* image of the PSR J1718−3718 field in the 0.5–3.0 keV band. The image has been smoothed with a Gaussian kernel having σ = 1 pixel. Although the source appears extended, its size and morphology, including angle of asymmetry, are consistent with the 1.5 keV PSF at this detector position. The formal TEMPO 2 σ error region of the radio timing position is shown with an ellipse. See text for details.

2.2. *Spectroscopy*

Counts from the pulsar were extracted using an elliptical extraction region having semimajor and semiminor axes of 26 and 18 pixels ($13''$ and $9''$), respectively, rotated to an angle 308° west of north. A nearby, nonoverlapping source-free region having the same elliptical shape and orientation, but with semimajor and semiminor axes of 40 and 32 pixels ($20''$ and $16''$), respectively, was used to estimate the background. The total number of source counts after background subtraction was 110, implying a count rate of 0.00197 ± 0.00019 counts s^{-1}.

RMF and ARF files were generated for the source and background using the CIAO script PSEXTRACT, and spectra grouped by a factor of 8 were fed into the spectral fitting

[5] See http://asc.harvard.edu/ciao/threads/index.html.
[6] See http://cxc.harvard.edu/cal/ASPECT/celmon.

TABLE 1
Spectral Results

Parameter	Value
N_h[a] ($\times 10^{22}$ cm^{-2})	$1.84^{+0.48}_{-0.77}$
kT[a] (keV)	$0.145^{+0.053}_{-0.020}$
Absorbed flux[b] ($\times 10^{-15}$ ergs s^{-1} cm^{-2})	6.3–6.9
χ^2 per degree of freedom	19.6/17
Unabsorbed flux[c] ($\times 10^{-14}$ ergs s^{-1})	7–200

[a] Range of uncertainties indicates 68% confidence intervals.
[b] Absorbed flux in 0.5–2 keV. Approximate 68% confidence interval.
[c] Unabsorbed flux in 0.5–2 keV.

package XSPEC (ver. 11.3.1). Spectral channels having energies below 0.5 keV and above 3.0 keV were ignored. The data were well described by an absorbed blackbody model; best-fit model parameters are given in Table 1, and the spectrum and best-fit model with residuals are shown in Figure 2. Although a power-law model yielded a statistically acceptable fit, the best-fit power-law index was ∼8–9, rendering such a model implausible. This is consistent with the absence of counts above ∼2 keV. Fitting for multicomponent models was unreasonable because of the small number of counts available. However, it is clear that the emission is dominantly thermal in origin. This argues strongly against our having detected any nebular component, as this should have a harder spectrum that is well characterized by a power-law model with photon index in the range ∼1–3 (see Kaspi et al. 2005 and references therein).

The absorbed flux of the source in the 0.5–2.0 keV range is $(6.3–6.9) \times 10^{-15}$ ergs s^{-1}, where the range quoted corresponds to that implied by the 68% limits of N_h and kT. Thus, the quoted flux range is an approximate but slightly overestimated 68% confidence range. With only 110 source counts, XSPEC is unable to more precisely constrain the true 68% confidence range for the flux while simultaneously fitting for N_h and kT. The low end of the flux range corresponds to higher values of N_h and lower values of kT; the high end corresponds to the reverse. The unabsorbed 0.5–2.0 keV flux is therefore relatively poorly constrained, ranging from $\sim 7 \times 10^{-14}$ ergs s^{-1} cm^{-2} for the high kT end to $\sim 2 \times 10^{-12}$ ergs s^{-1} cm^{-2} for the low kT end. We note that the maximum N_h in this direction is 1.81×10^{22} cm^{-2}, significantly lower than our upper 68% confidence limit (Dickey & Lockman 1990). This suggests that models having lower values of N_h, and hence higher values of kT and low values of unabsorbed flux, are slightly favored.

3. DISCUSSION

The dispersion measure toward the pulsar of 373 pc cm^{-3} implies a distance of 4.0–5.0 kpc (Cordes & Lazio 2001). We assume here a distance of 4.5 kpc. Dispersion measure distances are notoriously uncertain, and an independent distance estimate is obviously desirable. We do note that the Taylor & Cordes (1993) distance estimate for PSR J1718−3718 is 5.1 kpc, close to that obtained with the more recent Cordes & Lazio (2001) model, suggesting that our assumption of 4.5 kpc is not grossly incorrect.

Given the spectrum of the detected X-rays, the emission seems most likely to be coming from the neutron star surface. Thermal emission from the surface can be either from initial cooling, in which case X-rays are emitted from the entire surface, or from heated polar caps, a by-product of a higher energy magnetospheric process (see Kaspi et al. 2005 for a review). In the former case, the X-ray energy source is unrelated to the pulsar's spin-down. In the latter case, the spin-down powers it.

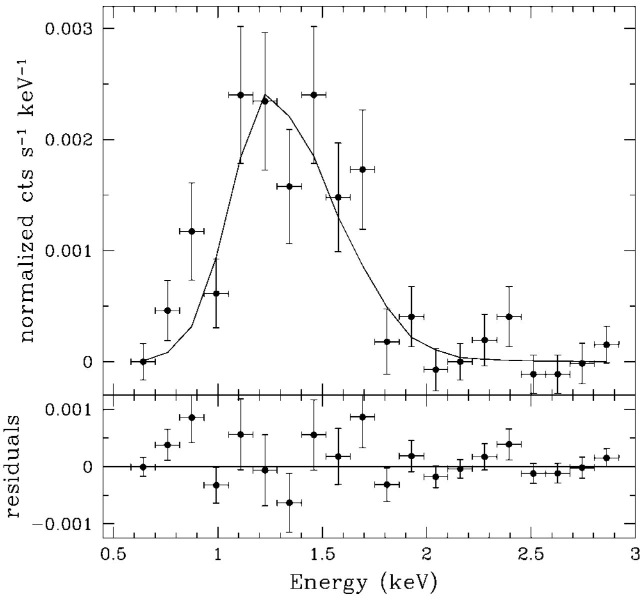

Fig. 2.—*Top panel*: Spectrum of the X-ray counterpart to PSR J1718−3718, with best-fit model plotted with a solid line (see Table 1 for best-fit parameters). *Bottom panel*: Residuals from the best-fit model.

Given the observed spectrum and flux of the X-ray source that we detect, we can ask which of these two mechanisms most likely accounts for the emission. First, we consider the high-temperature range of parameter space, $kT \simeq 0.2$ keV. In this case, the unabsorbed flux, given the distance, requires a source emitting radius of ∼1 km. This suggests heated polar caps, in which case the emission could be strongly pulsed. The implied bolometric isotropic luminosity would be 2.5×10^{32} ergs s^{-1} or $0.16\dot{E}$. This is uncomfortably high for polar cap reheating models (Harding & Muslimov 2001). Assuming 1.0 sr beaming, the efficiency drops to 0.013, still implausibly high for a pulsar having a characteristic age of 34 kyr (Harding & Muslimov 2001). At the low-temperature range of parameter space, we have $kT \simeq 0.12$ keV. In this case, for the observed unabsorbed flux at 4.5 kpc, an effective emitting radius of 22 km is required, too high for a neutron star even after correcting for the gravitational distortion (Lattimer & Prakash 2001). Thus, it seems likely on physical grounds that even though Table 1 quotes 68% confidence levels only, the true spectral parameters are indeed bracketed in this range.

For example, for $kT \simeq 0.13$ keV (corresponding to $N_h \simeq 2 \times 10^{22}$ cm^{-2}), the observations can be accounted for if the effective measured neutron star radius is ∼13 km. In this case, the unabsorbed bolometric luminosity would be $L_X \simeq 6 \times 10^{33}$ ergs s^{-1} (corresponding to $L_X \simeq 9 \times 10^{29}$ ergs s^{-1} in the 2–10 keV band) or $4\dot{E}$. This, to our knowledge, would be the first case of a radio pulsar having initial cooling emission that has X-ray luminosity comparable to or greater than its $\dot{E}$. Given that initial cooling is thought to be unrelated to spin-down, this is not necessarily surprising. More relevant is whether the effective temperature is plausible for initial cooling. For commonly assumed neutron star equations of state and modified Urca cooling with no exotica, a temperature as high as 0.13 keV at an age of 34 kyr is reasonable if the neutron star has accreted a $\sim 10^{-7}\ M_\odot$ hydrogen envelope (Yakovlev & Pethick 2004). In this case, however, because of the hydrogen envelope's effect on the outgoing radiation, a blackbody model as assumed here would be overestimating the true effective temperature by as much as a factor of ∼2 (see, e.g., Pavlov et al. 2001). Thus, the true effective temperature may be much smaller than 0.13 keV, very much in line with predictions for initial cooling of a neutron star of this age.

Even if $L_X > \dot{E}$, as seems likely in the case of PSR J1718−3718, L_X in the 2–10 keV band is $\gtrsim$3 orders of magnitude smaller than is observed for the five traditionally studied AXPs (see, e.g., Table 2 in McLaughlin et al. 2003). Its spectral properties are also quite different from those of the AXPs. This is consistent with the findings for other high-*B* radio pulsars (Pivovaroff et al. 2000; Gonzalez & Safi-Harb 2003; McLaughlin et al. 2003; Gonzalez et al. 2004). With X-ray observations of five high magnetic field radio pulsars revealing luminosities much smaller than those of the AXPs, it is becoming more difficult to appeal to small scatter in the true *B*-fields relative to those inferred from spin-down. Thus, it seems very plausible that the *B*-fields inferred from spin-down for AXPs and high-*B* radio pulsars are not reliable estimators of the true surface field, at least to within a factor of ∼2. Alternatively, there could be a “hidden” parameter, such as mass, that differentiates between the two populations.

Intriguingly, however, PSR J1718−3718’s X-ray luminosity is comparable to that of the recently identified transient AXP XTE J1810−197 when in quiescence (Ibrahim et al. 2004; Gotthelf et al. 2004). Moreover, the quiescent spectrum of XTE J1810−197 as observed in a serendipitous *ROSAT* observation (Gotthelf et al. 2004) is comparable to that seen for PSR J1718−3718, i.e., well described by a simple absorbed blackbody of temperature $kT \simeq 0.18$ keV. This raises the interesting possibility that PSR J1718−3718, and other high-*B* radio pulsars, may one day emit transient magnetar-like emission, and conversely that the transient AXPs might be more likely to exhibit radio pulsations. Both of these possibilities can be tested observationally.

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