

## X-RAY OBSERVATIONS OF THE HIGH MAGNETIC FIELD RADIO PULSAR PSR J1814–1744

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### ABSTRACT

PSR J1814–1744 is a 4 s radio pulsar with surface dipole magnetic field strength  $5.5 \times 10^{13}$  G, inferred assuming simple magnetic dipole braking. This pulsar’s spin parameters are very similar to those of anomalous X-ray pulsars (AXPs), suggesting that this may be a transition object between the radio pulsar and AXP population, if AXPs are isolated, high magnetic field neutron stars as has recently been hypothesized. We present archival X-ray observations of PSR J1814–1744 made with *ROSAT* and *ASCA*. X-ray emission is not detected from the position of the radio pulsar. The derived upper flux limit implies an X-ray luminosity significantly smaller than those of all known AXPs. This conclusion is insensitive to the possibility that X-ray emission from PSR J1814–1744 is beamed or that it undergoes modest variability. When interpreted in the context of the magnetar mechanism, these results argue that X-ray emission from AXPs must depend on more than merely the inferred surface magnetic field strength. This suggests distinct evolutionary paths for radio pulsars and AXPs, despite their proximity in period-period derivative phase space.

*Subject headings:* pulsars: individual (PSR J1814–1744) — stars: magnetic fields — stars: neutron — X-rays: stars

### 1. INTRODUCTION

Recently, PSR J1814–1744, an isolated radio pulsar with period  $P = 4$  s and large period derivative ( $\dot{P} = 7.4 \times 10^{-13}$ ), was discovered (Camilo et al. 2000) in an ongoing survey of the Galactic plane for radio pulsars using the 64 m Parkes telescope (Lyne et al. 2000). The pulsar’s surface magnetic field strength  $B$ , inferred under the assumption of a dipole rotating in vacuo (Manchester & Taylor 1977) from

$$B = 3.2 \times 10^{19} (P\dot{P})^{1/2} \text{ G}, \quad (1)$$

is  $5.5 \times 10^{13}$  G.

This pulsar’s properties are particularly interesting because they are similar to those of anomalous X-ray pulsars (AXPs). AXPs have spin periods  $P = 6$ –12 s and spin down regularly (see, e.g., Mereghetti & Stella 1995; Gotthelf & Vasisht 1998; Kaspi, Chakrabarty, & Steinberger 1999) with period derivatives  $10^{-12} < \dot{P} < 10^{-11}$ . The X-ray luminosities of AXPs are typically several orders of magnitude larger than their spin-down luminosities  $\dot{E} \equiv 4\pi^2 I \dot{P} / P^3$  (where  $I$  is the pulsar’s moment of inertia, assumed to be  $10^{45}$  g cm<sup>2</sup>) (see, e.g., Oosterbroek et al. 1998 and references therein). Strong observational evidence (see, e.g., Mereghetti, Israel, & Stella 1998) precludes accretion from a binary companion as the origin of the observed X-rays. Instead, the leading hypothesis to explain AXP properties is that they are isolated neutron stars with ultra-high magnetic fields, so-called magnetars (Duncan & Thompson 1992). In this model, the X-ray emission is powered either by decay of the large magnetic field (Thompson & Duncan 1996) or neutron star cooling enhanced by the presence of the strong field (Heyl & Hernquist 1997a). Assuming magnetic dipole braking,

AXPs have inferred surface dipole magnetic field strengths  $B = (0.6$ – $8) \times 10^{14}$  G.

While PSR J1814–1744 is a radio pulsar and hence an isolated neutron star, its spin parameters and hence inferred magnetic field are extreme in the pulsar population: its magnetic field is nearly 3 times larger than that of PSR B0154+61 (Arzoumanian et al. 1994), the pulsar with the previously known highest field strength.<sup>2</sup> Given that the spin parameters of PSR J1814–1744 are more typical of AXPs than radio pulsars, the possibility that this is a transition object between these two neutron star populations must be entertained. In particular, under the magnetar hypothesis, the mechanism responsible for the production of X-rays in AXPs should be present in PSR J1814–1744 if the inferred magnetic field is indeed the primary characteristic relevant to the observed magnetar properties.

The similarity in spin parameters between PSR J1814–1744 and the AXPs is readily seen in a “ $P$ - $\dot{P}$ ” plot. Figure 1 shows  $\dot{P}$  versus  $P$  for the radio pulsar population (*small dots*), with PSR J1814–1744 indicated. The figure also shows the candidate magnetar population, consisting of five AXPs and two soft gamma repeaters (SGRs). Immediately noticeable is the proximity of PSR J1814–1744 to the cluster of AXPs and SGRs at the upper right corner. It is especially close to 1E 2259+586, also indicated (Kaspi et al. 1999 and references therein). Table 1 compares the properties of these two neutron stars.

Here we present an analysis of archival *ROSAT* and *ASCA* X-ray observations that serendipitously include the location of PSR J1814–1744 within their respective fields of view. Emission from the pulsar position was not detected with either telescope. We note that X-rays from other

<sup>2</sup> The survey that discovered PSR J1814–1744 also discovered PSR J1119–6127, a radio pulsar with field  $B = 4.1 \times 10^{13}$  G (Camilo et al. 2000).

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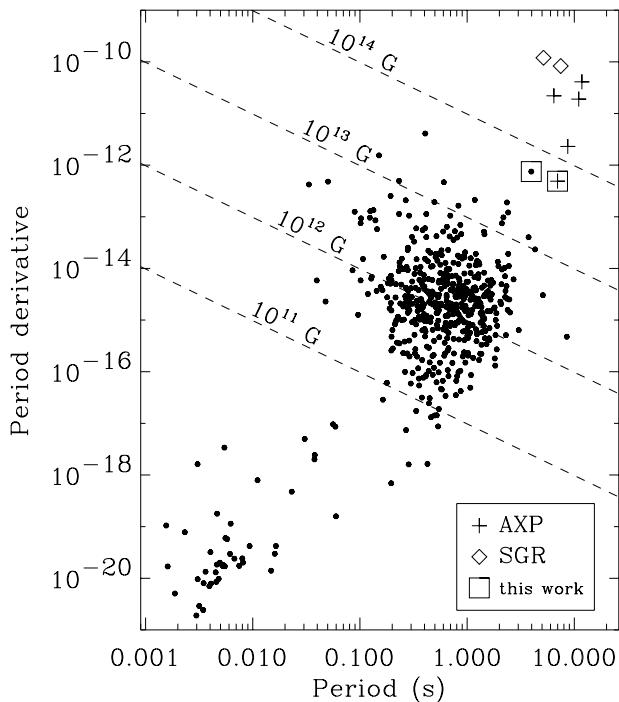


FIG. 1.— $P$ - $\dot{P}$  diagram. The small dots are the known radio pulsars. The crosses are the AXPs and the diamonds are the SGRs. Lines of constant magnetic field, derived from eq. (1), are shown by the dashed lines. Note the proximity of PSR J1814–1744 (boxed dot) to 1E 2259+586 (boxed cross). Pulsar references: Taylor et al. (1995; available at ftp://pulsar.princeton.edu/pub/catalog); Camilo et al. (2000); Young, Manchester, & Johnston (1999). SGR references: Kouveliotou et al. (1998, 1999). AXP references: see citations in the main text.

mechanisms (e.g., magnetospheric emission) are not expected to be observable from PSR J1814–1744. Given its spin-down luminosity of  $5 \times 10^{32}$  ergs  $s^{-1}$  and its probable distance of 10 kpc (estimated from the distance/dispersion measure relation of Taylor & Cordes 1993), its spin-down flux ( $\dot{E}/4\pi d^2$ ) implies that any rotation-powered high-energy emission should be too faint to detect (Seward & Wang 1988; Becker & Trümper 1997). Count rate limits from both observations are used to derive an upper limit on the X-ray luminosity from PSR J1814–1744 that is significantly smaller than those measured for the known AXPs. We then discuss the implications of the nondetection for current magnetar models.

## 2. ARCHIVAL DATA ANALYSIS

### 2.1. ROSAT

A field containing PSR J1814–1744 was observed with the Position Sensitive Proportional Counter (PSPC) instru-

ment aboard *ROSAT* (Trümper 1982) during 1992 April 2–8, as part of a study of the Galactic X-ray background (sequence RP900196N00). The radio timing position of PSR J1814–1744 (Camilo et al. 2000),  $\alpha(J2000) = 18^h14^m43^s.0(2)$ ,  $\delta(J2000) = -17^\circ44'47''(23)$ , is located  $34'$  from the optical axis. The total live time was 7.7 ks. A 0.1–2.4 keV broadband flat-field image was produced using an exposure map that accounts for vignetting and instrumental structure. The exposure map is a standard data product generated by the NASA-maintained HEASARC during its analysis of all *ROSAT* observations. No X-ray emission is present. To calculate an upper limit on the count rate, we compare the counts collected in an aperture of radius  $0.8$  centered on the radio position to those in a concentric annulus with radii  $4'$  and  $12'$ . The aperture radius represents the theoretical half-energy width for a point source located  $34'$  off-axis, calculated using the FTOOL PCRPSF v.2.0.7.

We define the signal-to-noise ratio  $S/N \equiv S/\sigma_s$ , with signal  $S \equiv N_s - b$ , and variance  $\sigma_s^2$ ,  $N_s$  is the number of counts in the circular aperture,  $b \equiv \beta N_b$ , where  $N_b$  is the number of counts in the annulus and  $\beta$  is the ratio of exposure areas of the aperture and annulus. This ratio accounts for the geometric size of the source aperture and background annulus as well as the effective exposure time of each sky element comprising the two regions. Using standard error propagation,  $S/N = S/[S + b(1 + \beta)]^{1/2}$ . Requiring  $S/N > 3\sigma$  yields a count rate upper limit in the 0.1–2.4 keV band of less than  $3.2 \times 10^{-3}$  counts  $s^{-1}$ .

### 2.2. ASCA

A field containing PSR J1814–1744 was observed with *ASCA* (Tanaka, Inoue, & Holt 1994) on 1996 April 9, as part of a Galactic plane survey (sequence 54005040). *ASCA* consists of four co-aligned telescopes, each of which has its own focal plane detector: two Gas Imaging Spectrometers (GIS2 and GIS3) and two Solid-State Imaging Spectrometers (SIS0 and SIS1). The pulsar position falls  $13'$  from the *ASCA* optical axis. This puts the source at the edge of the SIS detectors, limiting the utility of these data. We do not consider them further, focusing instead on the GIS instruments which have a much larger ( $25'$ ) FOV. The effective exposure time for the GIS is  $2 \times 11.5$  ks. The image obtained from combining data from both GIS cameras has been corrected for pointing offset<sup>3</sup> and exposure and rebinned with a  $45'' \times 45''$  boxcar function. To avoid the large instrument background at the edge of the detectors,

<sup>3</sup> This offset arises due to a systematic error with the *ASCA* star tracker. The correction was applied using the FTOOL offsetcoord and the look-up table available at <http://legacy.gsfc.nasa.gov/docs/asca/coord/updatecoord.html>.

TABLE 1  
COMPARISON OF PSR J1814–1744 AND 1E 2259+586

Parameter	PSR J1814–1744	1E 2259+586
Spin period, $P$ (s) .....	4.0	7.0
Period derivative, $\dot{P}$ .....	$7.4 \times 10^{-13}$	$4.9 \times 10^{-13}$
Surface magnetic field, $B$ (G) .....	$5.5 \times 10^{13}$	$5.9 \times 10^{13}$
Characteristic age, $P/2\dot{P}$ (kyr) .....	85	230
Spin-down luminosity, $\dot{E}$ (ergs $s^{-1}$ ) .....	$4.7 \times 10^{32}$	$5.7 \times 10^{31}$
Reference .....	1	2

REFERENCES.—(1) Camilo et al. 2000; (2) Kaspi et al. 1999.

we restricted the image to a circular FOV with 20' radius. The image is dominated by scattered flux from the nearby (34') bright low-mass X-ray binary (LMXB) GX 13+1 (Vrtilek et al. 1991). Because of its better mirror performance, *ROSAT* does not suffer from this contamination problem. A fanlike pattern, consistent with that from a bright point source located 34' from the optical axis (see, e.g., Gendreau 1995), and a shadow from a mirror quadrant boundary, fall where expected, given the satellite roll angle and the alignment of GX 13+1 with the optical axis.<sup>4</sup> No X-ray emission is present from the location of the radio pulsar.

An upper limit on flux from the pulsar is derived following the same prescription outlined in § 2.1, with an increase in the radius of the source aperture to 4.5 to accommodate the wider point-spread function (PSF) of *ASCA*. Fortunately, PSR J1814–1744 is situated in the middle of the boundary shadow, largely shielding the location of the pulsar from the scattered flux of GX 13+1. However, the contamination of nearly the entire GIS FOV from the LMXB complicates the choice of a background region. We considered using blank-sky data from the same region of the detectors that encompass the source aperture, which would account for the instrumental and cosmic X-ray backgrounds. However, the blank-sky background would not include contributions from the diffuse Galactic plane emission and most importantly, would not include the scattered flux from GX 13+1. Hence, we relied upon a relatively contamination-free region from this observation to calculate the background, selecting a circular region with 4' radius, located the same distance off-axis as PSR J1814–1744 and containing roughly the same amount of scattered light as the source aperture. Requiring  $S/N > 3\sigma$  yields a count rate upper limit in the 2–10 keV band of less than  $5.6 \times 10^{-3}$  counts  $s^{-1}$ . These calculations were performed on the unbinned data, and while our approach should mitigate most of the effects of the contamination from GX 13+1, we recognize it is impossible to fully account for it. The above upper limit represents a conservative estimate of the maximum count rate from PSR J1814–1744.

### 3. DISCUSSION

#### 3.1. The X-Ray Luminosity Upper Limit of PSR J1814–1744

The dependence of the magnetar hypothesis for AXP emission on the inferred magnetic field, coupled with the similarities in the spin parameters of PSR J1814–1744 and 1E 2259+586, suggests that PSR J1814–1744 may also share similar X-ray properties. Here we use the spectral properties of 1E 2259+586 as a template to convert the count rate upper limits from PSR J1814–1744 into an X-ray luminosity upper limit.

The spectrum of 1E 2259+586 is well studied (Iwasawa, Koyama, & Halpern 1992; Corbet et al. 1995; Rho & Petre 1997; Parmar et al. 1998) and best described by a two-component model consisting of a blackbody and power law. Rho & Petre (1997) combine data from *ROSAT*, *ASCA*, and *BXRT* (Serlemitsos et al. 1992) to determine best-fit parameters of  $\Gamma = 4.0$  for the power-law index and

$kT = 0.43$  keV for the blackbody temperature. See § 3.1 for the distribution of the spectral properties of all AXPs. The unabsorbed flux is  $F_{2-10 \text{ keV}} = 1.3 \times 10^{-11}$  ergs  $s^{-1} \text{ cm}^{-2}$  and  $F_{0.1-2.4 \text{ keV}} = 4.1 \times 10^{-9}$  ergs  $s^{-1} \text{ cm}^{-2}$ . The distance to 1E 2259+586 has been estimated to be  $d = 3.6\text{--}5.6$  kpc from the supernova surface brightness–distance ( $\Sigma$ - $D$ ) relationship (Gregory & Fahlman 1980; Sofue, Takahara, & Hirabayashi 1983; Hughes et al. 1984). While there is great uncertainty in the  $\Sigma$ - $D$  relation (see, e.g., Green 1984 and Berkhuijsen 1986), distances to stars in nearby H II regions are of similar value (Rho & Petre 1997), resulting in a commonly quoted distance of 4 kpc.

In order to scale the spectral model of 1E 2259+586 for PSR J1814–1744, we must first estimate the Galactic absorption (column density  $N_H$ ) and distance to the radio pulsar. There are two coarse, yet independent, methods for estimating  $N_H$ . The Seward & Wang (1988) approximation of 10 neutral hydrogen atoms per free electron, combined with the pulsar dispersion measure  $DM = 834 \text{ pc cm}^{-3}$  (Camilo et al. 2000), gives  $N_H = 2.6 \times 10^{22} \text{ cm}^{-2}$ . The FTOOL nh, which uses the H I maps of Dickey & Lockman (1990), predicts  $N_H = 1.8 \times 10^{22} \text{ cm}^{-2}$ . The DM- $d$  relationship of Taylor & Cordes (1993) predicts a distance of  $\sim 10$  kpc. At this distance, the unabsorbed X-ray flux of 1E 2259+586 would be reduced to  $F_{2-10 \text{ keV}} = 2.1 \times 10^{-12}$  ergs  $s^{-1} \text{ cm}^{-2}$  and  $F_{0.1-2.4 \text{ keV}} = 6.6 \times 10^{-10}$  ergs  $s^{-1} \text{ cm}^{-2}$ .

Figure 2 shows the expected count rates in both the *ROSAT* PSPC and the *ASCA* GIS as a function of  $N_H$ . The rates were calculated by using XSPEC (v. 10) to fold the spectrum of 1E 2259+586, normalized to a distance of 10 kpc, through the appropriate instrument response matrices. Calculations at several values of  $N_H$ , shown by the symbols, were used to interpolate the count rate as a continuous function of  $N_H$ . The dashed lines in each plot represent the measured upper limits. Even when  $N_H$  is allowed to exceed the maximum estimate, the predicted count rates are well above the measured upper limits. Assuming a reasonable compromise value for the column density of  $N_H = 2.2 \times 10^{22} \text{ cm}^{-2}$ , the expected *ROSAT* count rate is a factor of

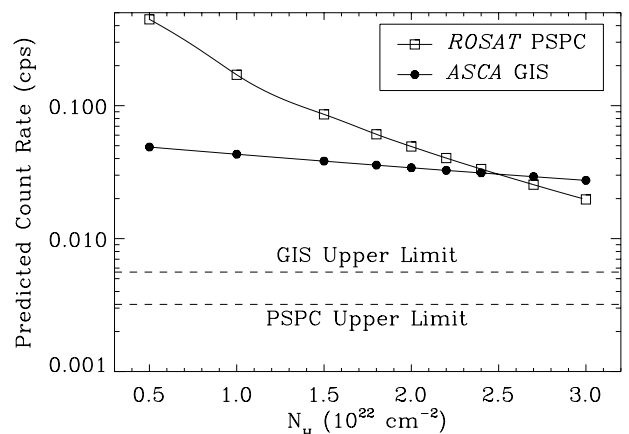


FIG. 2.—The diagram shows the count rates expected if PSR J1814–1744 had the same spectrum and luminosity as 1E 2259+586, as a function of  $N_H$ . Calculations at several discrete values of  $N_H$ , shown by the symbols, were used to interpolate the count rate as a continuous function of  $N_H$ . Distances of 10 and 4 kpc were assumed for PSR J1814–1744 and 1E 2259+586, respectively. The dashed lines represent the derived upper limit on count rate for the *ROSAT* PSPC (0.1–2.4 keV) and the *ASCA* GIS (2–10 keV). Assuming a reasonable estimate for the column density of  $N_H = 2.2 \times 10^{22} \text{ cm}^{-2}$ , the expected count rate exceeds the upper limit by factors of 13 (PSPC) and 6 (GIS).

<sup>4</sup> The interested reader is referred to Serlemitsos et al. (1995) for a detailed discussion of the stray light properties of *ASCA*.

13 higher than measured, and the expected *ASCA* count rate is a factor of 6 higher than measured. Scaling the flux by these ratios we find for PSR J1814–1744, *ROSAT* gives  $L_{0.1-2.4\text{ keV}} < 6.3 \times 10^{35} (d/10\text{ kpc})^2 \text{ ergs s}^{-1}$  and *ASCA* gives  $L_{2-10\text{ keV}} < 4.3 \times 10^{33} (d/10\text{ kpc})^2 \text{ ergs s}^{-1}$ . Extrapolating the *ROSAT*-derived upper limit to the *ASCA* band gives  $L_{2-10\text{ keV}} < 2.0 \times 10^{33} (d/10\text{ kpc})^2 \text{ ergs s}^{-1}$ , in good agreement with the *ASCA*-derived limit.

Next, we comment on the use of the spectral properties of 1E 2259+586 for calculating our luminosity upper limit for PSR J1814–1744. The spectral properties determined for AXPs are very similar, with power-law photon indices in the range  $\Gamma = 2.5-4$  and blackbody temperatures in the span  $kT = 0.39-0.71\text{ keV}$  (1E 2259+586: Rho & Petre 1997; 1E 1048.1–5937: Oosterbroek et al. 1998; 1E 1841–045: Vasisht & Gotthelf 1997; RX J170849.0–400910: Sugizaki et al. 1997; 4U 0142+61: White et al. 1996). Their X-ray luminosities (0.5–10 keV) differ significantly, however, varying by more than 2 orders of magnitude. Calculations identical to those described above show that if PSR J1814–1744 had properties like the other known AXPs, the expected count rates would all be greater than those predicted from assuming the spectrum and luminosity of 1E 2259+586. We note that only AXP 1E 1048.1–5937 (inferred surface magnetic field strength  $3.6 \times 10^{14}\text{ G}$ : Oosterbroek et al. 1998) nominally yields a lower expected count rate than the 1E 2259+586 model (although still higher than our upper limit), although the particularly large uncertainty in the distance of the former makes its true intrinsic luminosity difficult to know (Corbet & Mihara 1997).

Thus, if the measured spectral parameters for any of the other AXPs (with the possible exception of 1E 1048.1–5937) were used in interpreting the count rate upper limit for PSR J1814–1744, the difference between its X-ray luminosity upper limit and the luminosity expected from AXP-like emission would only increase.

### 3.2. Beaming and Source Variability

One scenario that must be considered for the lack of

emission from PSR J1814–1744 is that the magnetar mechanism is present and emitting X-rays that are beamed away from our line of sight. The small number of confirmed AXPs prevents any detailed statistical discussion of beaming. However, the pulsed fraction and pulse shape of the known AXPs can be used to motivate at least a rough characterization. For each AXP, Table 2 lists the pulsed fraction  $f$ , the passband, and the pulse shape. Here we follow Page (1995) and estimate the pulsed fraction using  $f = \frac{1}{2}(N_{\text{max}} - N_{\text{min}})/N_{\text{mean}}$ , where the subscript refers to the maximum, minimum, and mean counts in the pulse profile. All AXPs have large unpulsed components and have pulse profiles with smooth or sinusoidal shapes, independent of the number of X-ray pulses present. Another general trend is that, excepting 4U 0142+61, there is no evidence for appreciable pulse shape evolution with energy.

These properties are consistent with the predictions of both magnetar models: that pulsed emission from AXPs is best interpreted as smoothly modulated thermal emission from the surface of the neutron star (Thompson & Duncan 1996; Heyl & Hernquist 1997a). See § 3.3 for additional discussion. The pulsed high-energy component ( $E > 2\text{ keV}$ ), well-fit by a power-law model, raises the possibility that nonthermal magnetospheric processes may also contribute. The lack of AXP pulse evolution with energy, however, suggests that only a single X-ray emission mechanism is present in AXPs. This is in contrast to rotation-powered pulsars like the Vela pulsar, which has a soft, sinusoidal thermal component with a low pulsed fraction (Ögelman, Finley, & Zimmermann 1993) and a sharply peaked non-thermal component that extends above 100 MeV (Strickman, Harding, & de Jager 1999). Of course, AXPs and rotation-powered pulsars could have very different pulsed properties, given the uncertainty in the origin of high-energy magnetospheric emission or the effect that a high magnetic field would have on this mechanism. For example, distinct thermal and nonthermal components could be present, yet for reasons unexplained, are locked in phase, thus appearing to have a common origin.

In either magnetar model, the X-ray emission comes from

TABLE 2  
PULSE PROPERTIES OF KNOWN AXPs

Pulsar	$f^a$ (%)	Passband <sup>b</sup>	Shape	Reference
4U 0142+61 .....	7	0.5–1.5	Two broad symmetric peaks	1, 2
	13	4–10	Single peak	1, 2
1E 1048.1–5937 .....	70	0.5–1.5	Single sinusoidal peak	3
	70	1.5–4.0	Single sinusoidal peak	3
	70	4.0–8.0	Single sinusoidal peak	3
	70	0.5–10	Single sinusoidal peak	4
1E 1841–045 .....	15	1–10	Two broad overlapping peaks	5, 6
1E 2259+586 .....	30	0.1–2.4	Two broad asymmetric peaks	7
	35	1–10	Two broad asymmetric peaks	8
1RXS J170849.0–400910.....	38	0.1–2.4	Single sinusoidal peak	9
	50	2–4	Single sinusoidal peak	10
	50	4–10	Single broad peak	10

<sup>a</sup> See § 3.2 for the definition of  $f$ , the pulsed fraction. When not stated by the authors, we estimate  $f$  from the published pulse profiles. (Note that the previously reported value of 30% for 1E 1841–045 arises because of a different definition of  $f$ .)

<sup>b</sup> Units are keV.

REFERENCES.—(1) White et al. 1996; (2) Israel et al. 1999b; (3) Corbet & Mihara 1997; (4) Oosterbroek et al. 1998; (5) Vasisht & Gotthelf 1997; (6) Gotthelf, Vasisht, & Dotani 1999; (7) Rho & Petre 1997; (8) Corbet et al. 1995; (9) Israel et al. 1999a; (10) Sugizaki et al. 1997.

the hot neutron star surface. Thus, it seems improbable that PSR J1814–1744 would be oriented with respect to our line of sight as to make X-ray pulsations undetectable, especially considering that gravitational lensing can make much more than half of the neutron star surface visible (see, e.g., Page 1995 and Heyl & Hernquist 1998). Note, however, any magnetospheric emission would be too distant from the neutron star surface to undergo gravitational lensing and hence could be beamed.

But even if PSR J1814–1744 were aligned in such a way, considerable unpulsed X-ray emission would be present, as is the case of all the known members of the AXP population (see Table 2). For example, the unpulsed luminosity of 1E 1841–045 is  $\sim 85\%$  of the total observed luminosity (Vasisht & Gotthelf 1997). Even if half of the flux is present in pulsations directed away from our line of sight, the expected count rates from PSR J1814–1744 are still well above the upper limits derived from the archival data. We conclude that, even in the unlikely event that the X-ray emission is significantly beamed, PSR J1814–1744 should have been detectable as an X-ray point source under the magnetar hypothesis.

Finally, we discuss the ramifications of source variability in AXPs. Torii et al. (1998) report variations in flux greater than a factor of 10 in the AXP candidate AX J1844.8–0258. Recent observations by Vasisht et al. (2000) confirm the extreme variability of this object. If this source is firmly established as an AXP by an accurate  $\dot{P}$  measurement and PSR J1814–1744 has similar characteristics, there exists the possibility that both serendipitous observations of PSR J1814–1744 occurred during a low state and that it is, in fact, an X-ray source. If instead PSR J1814–1744 undergoes variability by a factor of 2–3, as witnessed in 1E 2259+586 (Corbet et al. 1995 and references therein) and 1E 1048.1–5937 (Corbet & Mihara 1997), X-ray emission still would have been detected.

### 3.3. Implications for Magnetar Models

X-ray emission from AXPs has been explained in the context of the magnetar model by either magnetic field decay (Thompson & Duncan 1996) or neutron star cooling (Heyl & Hernquist 1997a). Duncan & Thompson (1992) first posited the existence of magnetars to explain a subset of gamma-ray bursts, including those from the SGRs. Later (see, e.g., Duncan & Thompson 1994 and Thompson & Duncan 1995), they discuss how the 1979 March 5 event from SGR 0526–66, which released  $\sim 10^{44}$  ergs in  $\sim 0.2$  s (Cline et al. 1980 and Evans et al. 1980), could have been driven by a large-scale instability and subsequent readjustment of the neutron star’s magnetic field. For the timescale relevant to the system ( $\sim 10^4$  yr), they argue that the instability is best explained by ambipolar diffusion of the magnetic field out of the stellar core (Thompson & Duncan 1996). This process conducts energy from the core to the surface to produce X-ray luminosities in the range  $L_x \sim 10^{35}$ – $10^{36}$  ergs  $s^{-1}$ . The strong dependence of the surface heat flux on field strength concentrates flux in the polar regions. The modulation of this intensity gradient gives rise to the X-ray pulsations.

For 1E 2259+586, this mechanism can explain the observed X-rays if the neutron star’s characteristic age,  $P/2\dot{P} = 230$  kyr, is an overestimate, the true age being  $\sim 10$  kyr, that inferred for the proposed associated supernova remnant (SNR) CTB 109 (Wang et al. 1992). If this model is

correct, the difference of only 10% in the magnetic fields of 1E 2259+586 and PSR J1814–1744 seems unlikely to account for the large difference in their X-ray luminosities, given the similarity of the X-ray emission from the known AXPs, whose magnetic fields span a much larger range. Therefore, if the decay of magnetic fields leads to the observed emission from AXPs, that no X-rays are seen from PSR J1814–1744 argues that 1E 2259+586 is much younger, even though the characteristic ages indicate otherwise, consistent with the latter’s association with SNR CTB 109. This suggests that 1E 2259+586 has had a spin-down history inconsistent with simple dipole braking or that it was born with a long spin period.

Heyl & Hernquist (1997a) have suggested a second model, based on photon cooling, for the production of X-rays in AXPs. They extend into the magnetar regime ( $B = 10^{14}$ – $10^{16}$  G) the work of Shibano & Yakovlev (1996), who have shown that when the magnetic field of a neutron star exceeds  $10^{12}$  G, enhancements in the conductivity along the field lines due to electron energy quantization result in a net increase in heat flux (Heyl & Hernquist 1997b, 1998). In sufficiently young stars (ages of  $\sim 1$  kyr) this leads to a gradual increase in photon luminosity with increasing magnetic field. The composition of the neutron star envelope has an even more dramatic effect; the luminosity transmitted through a helium envelope is 6 times that transmitted through an iron envelope, while that transmitted through a hydrogen envelope is 10 times that for iron. They then argue that the total mass of an insulating low- $Z$  layer required for the observed AXP luminosity is modest and easily attained from either fallback following the supernova explosion or accretion from the interstellar medium, if the pulsar has a large birth velocity or the density is high enough. Heyl & Hernquist (1997b; 1998) consider how the flux varies across the surface of a magnetar and find a strong angular dependence caused by the anisotropic heat conduction in the outer layers of the neutron star. The temperature gradient, coupled with the limb darkening expected from magnetized atmospheres (see Heyl & Hernquist 1997b and references therein), results in a modulation of the thermal flux. The observed pulsed fraction may be reduced by gravitational lensing, which makes more than half of the neutron star surface visible at a given instance (see, e.g., Page 1995 and Heyl & Hernquist 1998) and effectively smooths the flux gradient discussed above in § 3.1.

This model accounts for both the intensity of the X-ray emission and the pulsed fractions from 1E 1841–045 and 1E 2259+586 (Heyl & Hernquist 1997a), assuming the pulsar ages are those of their associated SNRs, Kes 73 and CTB 109, respectively. The absence of X-rays from PSR J1814–1744 again argues that this neutron star must be much older than 1E 2259+586. Alternatively, PSR J1814–1744 could be equally as young as 1E 2259+586 and may not possess a light-element insulating layer, in spite of the ease with which Heyl & Hernquist (1997a) suggest them to be formed.

## 4. CONCLUSIONS

In summary, we have set an upper limit on X-ray emission from the newly observed high magnetic field radio pulsar PSR J1814–1744. The upper limit on the flux implies a luminosity in X-rays well below those of any known AXP. This conclusion is independent of any beaming given the low pulsed fraction of the known AXPs

and is robust to modest flux variability. This argues that any magnetar mechanism invoked to explain X-ray emission from AXPs must depend on more than observed  $P$  and  $\dot{P}$ , hence on more than a merely inferred  $B$  field. In the context of the two particular magnetar hypotheses discussed above, PSR J1814–1744 must be considerably older than any of the known AXPs, including 1E 2259 + 586, in spite of characteristic ages that indicate otherwise. This is consistent with 1E 2259 + 586 being a much younger object than its characteristic age suggests, in agreement with its association with CTB 109. In addition, it implies that its spin-down history has deviated significantly from dipole braking or that it had a large (few seconds) initial spin period. SGRs and AXPs may thus have markedly different evolutionary paths from radio pulsars, including even the

extreme members of the latter population. Thus, the proximity of SGRs and AXPs to any radio pulsar in  $P$ - $\dot{P}$  phase space must be considered merely coincidental and caution must be used when comparing the different classes of neutron stars.

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