

PSR J1847–0130: A RADIO PULSAR WITH MAGNETAR SPIN CHARACTERISTICS

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ABSTRACT

We report the discovery of PSR J1847–0130, a radio pulsar with a 6.7 s spin period, in the Parkes Multibeam Pulsar Survey of the Galactic plane. The slowdown rate for the pulsar, $1.3 \times 10^{-12} \text{ s}^{-1}$, is high and implies a surface dipole magnetic field strength of $9.4 \times 10^{13} \text{ G}$. This inferred dipolar magnetic field strength is the highest by far among all known radio pulsars and over twice the “quantum critical field” above which some models predict radio emission should not occur. The inferred dipolar magnetic field strength and period of this pulsar are in the same range as those of the anomalous X-ray pulsars, which have been identified as being “magnetars” whose luminous X-ray emission is powered by their large magnetic fields. We have examined archival ASCA data and place an upper limit on the X-ray luminosity of J1847–0130 that is lower than the luminosities of all but one anomalous X-ray pulsar. The properties of this pulsar prove that inferred dipolar magnetic field strength and period cannot alone be responsible for the unusual high-energy properties of the magnetars and create new challenges for understanding the possible relationship between these two manifestations of young neutron stars.

Subject headings: pulsars: individual (PSR J1847–0130) — stars: magnetic fields — stars: neutron — X-rays: stars

1. INTRODUCTION

According to the standard model, neutron stars spin down according to $\dot{\nu} \propto -\nu^n$, where ν is the rotation frequency, $\dot{\nu}$ is the frequency derivative, and n is the “braking index.” If the spin-down is due to energy loss from electromagnetic dipole radiation, then $n = 3$. Magnetic field strengths at the neutron star surface are then conventionally inferred using the relation

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

where $P = 1/\nu$ is the pulsar spin period, $\dot{P} = -\dot{\nu}/\nu^2$, and a dipolar field structure, a neutron star radius of 10^6 cm , and moment of inertia 10^{45} g cm^2 are assumed (e.g., Manchester & Taylor 1977). As a number of authors have pointed out (e.g., Shapiro & Teukolsky 1983; Usov & Melrose 1995), this relation gives the field strength at the magnetic equator, whereas the perhaps more relevant field strength at the magnetic poles is a factor of 2 higher. However, for consistency with earlier work, we use the conventional value in this Letter. We note that no direct observational confirmation has been made of inferred fields, so they should be considered rough estimates only. In particular, they are completely insensitive to higher order multipoles at the stellar surface.

The spin parameters measured for neutron stars reveal in-

ferred dipolar magnetic field strengths ranging from 10^8 G for the “recycled” millisecond pulsars to 10^{15} G for the anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs). These so-called magnetars have spin periods ranging from 5.2 to 11.8 s and inferred surface dipole magnetic field strengths ranging from 5.9×10^{13} to $1.8 \times 10^{15} \text{ G}$. Their X-ray and gamma-ray luminosities are too great to be powered by the neutron star spin-down and are attributed to the decay of their ultrastrong magnetic fields (Thompson & Duncan 1995; Kouveliotou et al. 1998; Kouveliotou et al. 1999; Gavriil, Kaspi, & Woods 2002; Kaspi et al. 2003). Despite numerous attempts, and aside from a radio detection of SGR 1900+14 by Shitov et al. (2000) that has not been confirmed (Lorimer & Xilouris 2000), these objects have not yet been detected at radio frequencies (Kriss et al. 1985; Coe et al. 1994; Lorimer et al. 1998; Gaensler et al. 2001). This was explained by the suppression of pair production above the quantum critical field $B_{\text{cr}} = m_e^2 c^3 / e\hbar \approx 4.4 \times 10^{13} \text{ G}$, at which the cyclotron energy is equal to the electron rest-mass energy. Above this field, it was expected that pair production would cease due to ineffective competition with the quantum electrodynamical process of magnetic photon splitting (Baring & Harding 1998).

Prior to the Parkes Multibeam Pulsar Survey, the largest dipolar magnetic field strength inferred for any radio pulsar was $2.1 \times 10^{13} \text{ G}$ for PSR B0154+61 (Arzoumanian et al. 1994). The above paradigm held, and a clear division in inferred dipolar magnetic field strength between the radio pulsars and magnetars was possible. This was challenged by the Parkes discoveries of PSR J1744–3333 and PSR J1814–1733 with implied dipole field strengths of 5.2×10^{13} and $5.5 \times 10^{13} \text{ G}$ (Morris et al. 2002; Camilo et al. 2000). In this Letter, we present the discovery of PSR J1847–0130, a radio pulsar with a $9.4 \times 10^{13} \text{ G}$ implied dipolar magnetic field strength.

2. RADIO OBSERVATIONS AND ANALYSIS

PSR J1847–0130 was discovered in the Parkes Multibeam Pulsar Survey of the Galactic plane (e.g., Manchester et al. 2001), which has thus far discovered over 680 new pulsars. The instrumental setup used for search and timing observations

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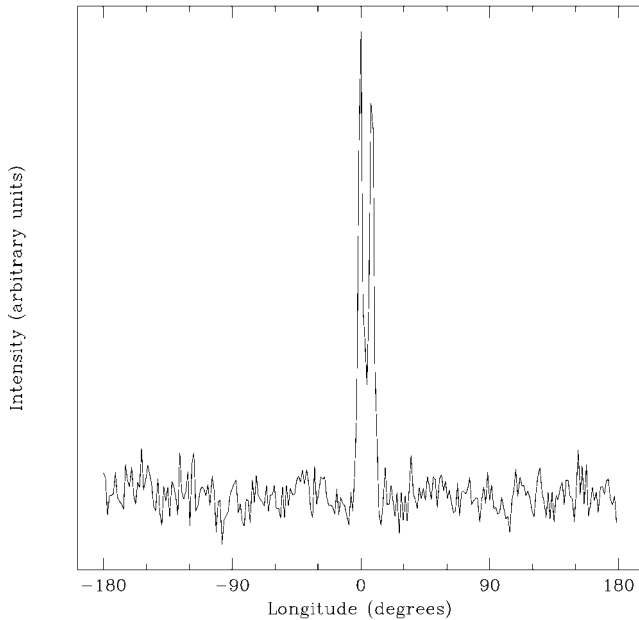


FIG. 1.—Integrated pulse profile of J1847–0130 at 1374 MHz. This profile was formed from roughly 2 hr of data taken over 11 epochs. The profile is double-peaked with a 3% duty cycle, measured as the full width of the profile at half the maximum pulse intensity.

is described in detail in Manchester et al. (2001). The 6.7 s period of this pulsar is the second-longest known; Figure 1 shows the mean pulse profile. Following the calibration procedure described by Manchester et al. (2001), we calculate the flux density at 1374 MHz to be 0.25 mJy, which for the distance of ~ 8.4 kpc translates to a radio luminosity of 18 mJy kpc². This distance is calculated from the dispersion measure and a model for the Galactic electron density (Cordes & Lazio 2002). Because of systematic uncertainties and the possibility of unmodeled interstellar medium features, both of which effects are greater for objects like this pulsar which lie deep in the Galactic plane, we estimate that the distance may be in error by as much as 30%.

Timing observations since 2001 August 14 have resulted in the measurement of 22 times of arrival. We fitted these using the TEMPO software package⁹ to derive the timing model given in Table 1. The postfit timing residuals are featureless, with no evidence for a binary companion, timing noise, or period glitches. The surface dipole magnetic field strength inferred from equation (1) is 9.4×10^{13} G, the largest by far among known radio pulsars. The pulsar is apparently young, with a characteristic age (assuming magnetic dipole spin-down) of 83 kyr. There is no cataloged supernova remnant associated with this pulsar (Green 2002).

In Figure 2, we plot the period and period derivative of J1847–0130 along with those of radio pulsars, all five known AXP, and the two SGRs with measured period derivatives. In Table 2, we give the periods and inferred dipolar magnetic field strengths of J1847–0130 and the AXP. The similarity of the spin parameters of this pulsar to the AXP, in particular, 1E 2259+586 and 4U 0142+61, is obvious.

⁹ See <http://pulsar.princeton.edu/tempo>.

TABLE 1
MEASURED AND DERIVED PARAMETERS OF PSR J1847–0130

Parameter	Value
Measured	
Right ascension (J2000)	18 ^h 47 ^m 35 ^s .18(6)
Declination (J2000)	−01°30′44″.0(16)
Galactic longitude (deg)	31.15
Galactic latitude (deg)	+0.17
Barycentric period, P (s)	6.7070459454(5)
Period derivative, \dot{P} ($\times 10^{-15}$ s s ^{−1})	1274.9(2)
Epoch (MJD)	52353
Timing data span (MJD)	52135–52571
Postfit rms timing residual (ms)	3.2
Dispersion measure (cm ^{−3} pc)	668(7)
Flux density at 1374 MHz, S (mJy)	0.25(4)
Width of pulse at 50%, W_{50} (ms)	210
Derived	
Distance, d (kpc)	~ 8.4
Surface dipole magnetic field, B ($\times 10^{14}$ G)	0.94
Characteristic age, τ_c (kyr)	83
Spin-down luminosity, \dot{E} (ergs s ^{−1})	1.7×10^{32}
Radio luminosity at 1374 MHz, Sd^2 (mJy kpc ²)	18
2–10 keV X-ray luminosity, L_x (ergs s ^{−1})	$< 5 \times 10^{33}$

NOTE.—Values in parentheses represent 1σ uncertainties in least-significant digits quoted. Distance derived from Cordes & Lazio 2002. The characteristic age is calculated using the standard magnetic dipole formula (Manchester & Taylor 1977) $\tau_c = P/2\dot{P}$. The spin-down luminosity $\dot{E} = 4\pi^2 I \dot{\nu}$, where the moment of inertia I is assumed to be 10^{45} g cm².

3. X-RAY OBSERVATIONS AND ANALYSIS

Unlike all of the known AXP, this pulsar is not detected as a point source in the *ROSAT* All-Sky X-Ray Survey (Voges et al. 1999). In the best *ROSAT* data set obtained with the Position Sensitive Proportional Counter instrument (sequence RP900402N00), the pulsar is 51′ off-axis, precluding a stringent upper limit calculation. However, a field containing the

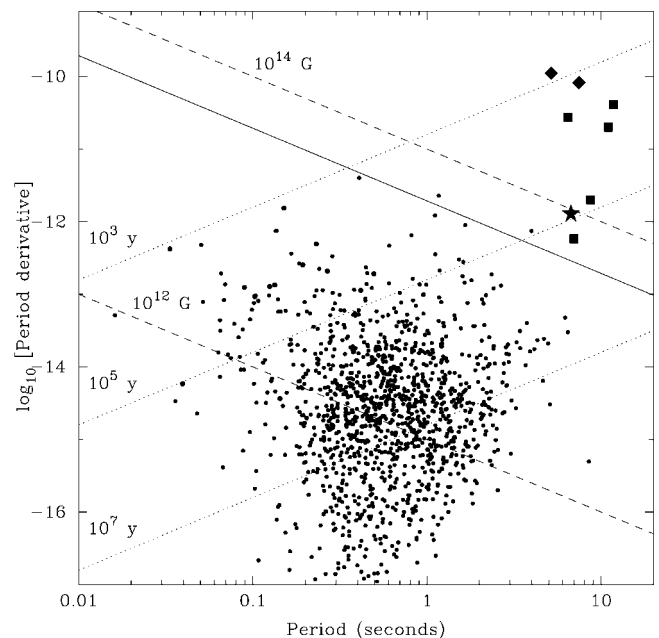


FIG. 2.—Period-period derivative for radio pulsars (dots), SGRs (diamonds), and AXP (squares). PSR J1847–0130 is marked with a star. Pulsars with periods less than 10 ms and/or period derivatives less than 10^{-17} s s^{−1} are not shown. Lines of constant inferred dipolar magnetic field strength (dashed line) and constant characteristic age (dotted line) are labeled. The solid line indicates the quantum critical field of 4.4×10^{13} G.

TABLE 2
COMPARISON WITH AXP SPIN PARAMETERS, DISTANCES, AND X-RAY LUMINOSITIES

Name	P (s)	B ($\times 10^{14}$ G)	\dot{E} (ergs s^{-1})	Distance (kpc)	$L_x(2-10 \text{ keV})$ (ergs s^{-1})
AXPs:					
1E 1048.1–5937	6.5	5.0	5.4×10^{33}	≥ 2.7	$\geq 5 \times 10^{33}$
1E 2259+586	7.0	0.59	5.6×10^{31}	4–7	$4 \times 10^{34} - 1 \times 10^{35}$
4U 0142+61	8.7	1.3	1.1×10^{32}	≥ 1.0 or ≥ 2.7	$\geq 1 \times 10^{34}$ or $\geq 7 \times 10^{34}$
RXS J1708–40	11.0	4.6	5.6×10^{32}	~ 8	$\sim 5 \times 10^{35}$
1E 1841–045	11.8	7.1	1.0×10^{33}	5.7–8.5	$2 \times 10^{34} - 5 \times 10^{34}$
PSR J1847–0130	6.7	0.94	1.7×10^{32}	6–11	$< 3 \times 10^{33} - 8 \times 10^{33}$

pulsar was observed with the ASCA telescope (Tanaka et al. 1994) on 1998 October 7 as part of a Galactic plane survey. In this 6 ks observation (sequence 56000000), the pulsar position is 13' from the pointing direction. Given this offset, only the two Gas Imaging Spectrometer instruments (GIS2 and GIS3), which have a 25' field of view, are of use. Starting with the archived screened event files, we first corrected for a known star tracker problem.¹⁰ We then considered a circular aperture of radius 4.5 around the pulsar position, as well as a neighboring region of the same area in order to estimate the background, using the FTOOL *xselect*. No significant emission above the background level was seen at the pulsar position. We use the method described by Pivovarov et al. (2000) to establish a 90% confidence level upper limit on the source count rate in the 2–10 keV band of 6×10^{-3} counts s^{-1} .

In order to convert this upper limit on the count rate to a luminosity upper limit, we assume isotropic emission and an equivalent neutral hydrogen column density (Dickey & Lockman 1990) of $3 \times 10^{22} \text{ cm}^{-2}$. All the AXP spectra can be fitted by a model consisting of a power-law and blackbody component, with spectral indices and blackbody temperatures in the ranges 2.4–3.6 and 0.41–0.65 keV, respectively (Gotthelf & Vasisht 1997; Tiengo et al. 2002; Patel et al. 2001, 2003; Rea et al. 2003). As shown in Table 2, AXPs 1E 2259+586 and 4U 0142+61 have the spin-down parameters most similar to J1847–0130. The spectrum of 1E 2259+586 can be described by a power-law index of 3.6 and blackbody temperature of 0.412 keV, with the power law contributing roughly 50% of the unabsorbed flux (Patel et al. 2001). The spectrum of 4U 0142+61 can be described by a power-law index of 3.35 and blackbody temperature of 0.458 keV, with the power law contributing roughly 60% of the unabsorbed flux (Patel et al. 2003). Assuming either of these spectra and a distance of 8.4 kpc results in a 90% confidence upper limit of $\sim 5 \times 10^{33}$ ergs s^{-1} for the 2–10 keV unabsorbed luminosity L_x of J1847–0130.

In Table 2, this upper limit, taking into account the 30% distance uncertainty, is compared with luminosities measured for the AXPs (Patel et al. 2001, 2003; Tiengo et al. 2002; Gotthelf et al. 2002; Rea et al. 2003), where AXP distances from Özel et al. (2001) have been adopted. The derived upper limit on the 2–10 keV luminosity of J1847–0130 is less than the luminosity of all of the AXPs except 1E 1048–5937. In Table 2, we also list the spin-down luminosities (i.e., $\dot{E} = 4\pi^2 I \nu \dot{\nu}$, where I is the moment of inertia) of J1847–0130 and the AXPs. Becker & Trümper (1997) find that, for radio pulsars that also are detected at X-ray energies, $L_x/\dot{E} \sim 10^{-3}$. Our upper limit for X-ray emission for J1847–0130 is still 2 orders of

magnitude higher than the X-ray luminosity expected given that relation.

4. DISCUSSION

Despite the remarkable similarity between the spin-down properties of J1847–0130 and the magnetars, their emission properties are apparently very different. As discussed in § 1, searches for radio pulsations from magnetars have so far been unsuccessful or unconfirmed. On the other hand, unlike all of the known AXPs, J1847–0130 does not appear to be a strong X-ray source. However, because of the large uncertainties in calculating X-ray luminosities for J1847–0130 and the AXPs, X-ray observations of higher sensitivity are necessary to determine if the luminosity does indeed lie well below those of all of the AXPs.

The discovery of J1847–0130 challenges those radio pulsar emission models that depend on pair-production cascades above the magnetic poles and hence on the strength of the magnetic field. This pulsar's inferred dipolar magnetic field lies more than a factor of 2 above the quantum critical field above which some models predicted the cessation of radio emission (Baring & Harding 1998). As discussed in § 1, magnetic field strengths calculated at the poles are a factor of 2 greater than the conventionally quoted surface field value, exacerbating this discrepancy. The radio luminosity at 1374 MHz of 18 mJy kpc^2 is typical for observed radio pulsars, indicating that photon splitting does not inhibit radio emission at these magnetic field strengths.

A newer model (Zhang & Harding 2000) argues that high magnetic field radio pulsars and magnetars are all rotating high-field neutron stars but that their magnetic axes have different orientations with respect to their rotation axes. This model predicts that radio pulsars should not have surface dipole magnetic field strengths (inferred via eq. [1]) greater than 9.5×10^{13} G, close to the field of J1847–0130. However, this boundary is uncertain because it depends on roughly the square of the unknown neutron star temperature, with the model assuming a typical value of 3×10^6 K. Another possibility (Baring & Harding 2001) is that only photons from one polarization split, allowing photons of the other polarization to produce pairs. Alternatively, the very different properties of the magnetars and the high-field pulsars could be due to the two populations having similar dipolar magnetic field configurations, but with the magnetars also having quadrupole or other multipole components (Gavriil et al. 2002). Yet another possibility is that neutron stars spin down under the combined effects of magnetic dipole spin-down and spin-down due to a propeller torque applied by a surrounding fallback disk, as suggested by Alpar et al. (2001). This model predicts a small population of pulsars with long spin periods, high inferred surface dipole

¹⁰ Performed using the FTOOL *offsetcoord* and coordinate offsets determined using a lookup table available at <http://legacy.gsfc.nasa.gov/docs/asca/coord/updatecoord.html>.

magnetic fields, and small characteristic ages. As these pulsars would actually have conventional (i.e., $\sim 10^{12}$ G) magnetic fields and be very old, independent age estimates could distinguish between propeller spin-down and pure magnetic dipole spin-down.

To understand the possible relationship between radio pulsars and magnetars and to determine the physics responsible for their emission mechanisms, it is essential to find more radio pulsars like J1847–0130. While it is currently the only known radio pulsar with inferred dipolar magnetic field strength and period as high as those of the magnetars, there are significant survey selection effects acting against the detection of long-period radio pulsars, which are therefore likely to be under-represented in the known population. These effects include high-pass filtering to increase the robustness of searches to radio frequency interference and software cutoffs at long periods. This is evidenced by our initial detection of J1847–0130 at half its true period and the detection of the 8.5 s pulsar J2124–3933 at a third of its period (Young et al. 1999). Furthermore, the empirically determined relationship between pulse width and pulse period (Rankin 1993) implies that long-period pulsar beams are narrower and hence less likely to sweep across the Earth. This is of course somewhat balanced by the fact that narrower pulses have more detectable harmonics. Additionally, assuming magnetic dipole spin-down, such pulsars may be visible only for the relatively short time that they are young ($\sim 10^5$ yr) and in the magnetar-like region of Figure 2.

The discovery of this pulsar, with spin-down properties in-

distinguishable from those of some AXPs, strengthens the conclusion of Pivovarov et al. (2000) that the X-ray emission properties of some AXPs must depend on more than their inferred surface dipole magnetic field strengths. Similarly, there is no reason based on period and period derivative why magnetars cannot be radio emitters. The nondetections of radio emission should not be taken as proof that magnetars are radio-silent, as is evidenced by recent detections (Camilo 2003) of very faint pulsars with luminosities of 0.5–3 mJy kpc², resulting from deep targeted searches. Alternatively, the magnetars may be strong radio emitters whose radio beaming fractions are small. To determine whether J1847–0130 and the magnetars are different manifestations of the same source population would require the detection of radio emission from an AXP or SGR or the detection of magnetar-like high-energy emission from a high-field radio pulsar.

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