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PSR J1124−5916: DISCOVERY OF A YOUNG ENERGETIC PULSAR IN THE SUPERNOVA REMNANT G292.0+1.8

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ABSTRACT

We report the discovery with the Parkes radio telescope of a pulsar associated with the ~1700 yr old oxygen-rich composite supernova remnant G292.0+1.8. The pulsar PSR J1124−5916 has a period of 135 ms and a period derivative of 7.4×10^{-13}, implying a characteristic age of 2900 yr, a spin-down luminosity of 1.2×10^{37} ergs s^{-1}, and a surface magnetic field strength of 1.0×10^{13} G. Association between the pulsar and the synchrotron nebula previously identified with *Chandra* within this supernova remnant is confirmed by the subsequent detection of X-ray pulsations by Hughes et al. The pulsar's flux density at 1400 MHz is very small, $S \approx 80$ μJy, but the radio luminosity of $Sd^2 \sim 2$ mJy kpc^2 is not especially small, although it is 1 order of magnitude smaller than that of the least luminous young pulsar previously known. This discovery suggests that very deep radio searches should be done for pulsations from pulsar wind nebulae in which the central pulsed source is yet to be detected and possibly from other more exotic neutron stars.

Subject headings: ISM: individual (G292.0+1.8) — pulsars: individual (PSR J1124−5916) — supernova remnants

1. INTRODUCTION

The supernova remnant (SNR) G292.0+1.8 is one of only three oxygen-rich SNRs known in the Galaxy. The other two (Puppis A and Cassiopeia A) have central compact objects, the nature of which, however, remains mysterious (e.g., Gaensler, Bock, & Stappers 2000a; Pavlov et al. 2000). At radio wavelengths, G292.0+1.8 has the appearance of a composite SNR, with a central peak and a shell ~10′ in diameter (Braun et al. 1986). *ASCA* X-ray observations (Torii, Tsunemi, & Slane 1998) detected a nonthermal nebula coincident with the central radio component. Recent *Chandra* ACIS-S observations have shown this nebula to be ~2′ in extent and to contain a resolved compact source located near its peak. This discovery, together with the energetics of the nebula, provides nearly incontrovertible evidence for the existence of a pulsar powering the nebula (Hughes et al. 2001).

The *Chandra* observations of G292.0+1.8 are a beautiful example of the recent flood of X-ray data with high spatial, temporal, and spectral resolution that is advancing dramatically our understanding of the varied outcomes of supernova explosions. In particular, X-rays provide an important complement to the radio band, the traditional hunting ground of pulsar studies.

In this Letter we report the discovery and the key parameters of the pulsar in G292.0+1.8 in a deep observation with the Parkes radio telescope. The characterization of this young and energetic pulsar is important for the analysis of existing X-ray and radio data on G292.0+1.8. Moreover, this discovery has significant implications for the concept of "radio-quiet neutron stars."

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2. OBSERVATIONS

The location of G292.0+1.8 was searched by the Parkes Multibeam Pulsar Survey of the inner Galactic plane ($260° < l < 50°$; $|b| < 5°$), which has discovered more than 600 pulsars (Manchester et al. 2001). The flux density limit at the location of the *Chandra* pulsar candidate was $S_\nu \approx 0.3$ mJy at a frequency of $\nu = 1374$ MHz. A similar limit was reached in a directed search of the SNR by Kaspi et al. (1996) at $\nu = 1520$ MHz. At a distance $d \sim 5$ kpc (see below), the corresponding luminosity limit is a not particularly constraining $L_{1400} \equiv S_{1400} d^2 \sim 7$ mJy kpc^2: about 25% of known pulsars have luminosities below this value (see Fig. 1).

On 2001 September 5 we searched the pulsar candidate position (see Table 1) at the Parkes telescope using the center beam of the multibeam receiver at a central frequency of 1374 MHz with a filter bank spectrometer having 96 channels spanning a total band of 288 MHz for each of two polarizations. Signals from each channel and polarization were square-law detected, high-pass filtered, and summed in polarization pairs. Each of the 96 channels was then integrated and 1 bit digitized at 1 ms intervals and recorded to magnetic tape for off-line analysis. The total observation time was 10.2 hr.

Standard search algorithms were used to reduce the data. First, strong narrowband radio interference was identified and removed by masking five offending frequency channels. Next, data from 2^{25} time samples (9.3 hr) were dedispersed at 325 trial dispersion measures (0 cm^{-3} pc $\leq$ DM $\leq$ 8800 cm^{-3} pc). Each of the 325 resulting time series was then searched for periodic signals over a range of duty cycles with a fast Fourier transform–based code (described in detail by Lorimer et al. 2000) identifying significant features in the fundamental amplitude spectrum as well as in spectra with two, four, eight, and 16 harmonics folded in. Finally, a limited but finer search in period and DM was made of the entire data set for the best dispersed candidates from this stage. A good pulsar candidate was found with a signal-to-noise ratio of S/N = 12.4, a barycenter-corrected period of $P = 135.3126$ ms, and DM = 330 cm^{-3} pc.

On 2001 October 3 we confirmed the pulsar with a detection of S/N = 8.8 in a 5 hr observation, with identical DM and $P = 135.3144$ ms, immediately implying a large period derivative of $\dot{P} = 7.4 \times 10^{-13}$. Following the initial radio detec-

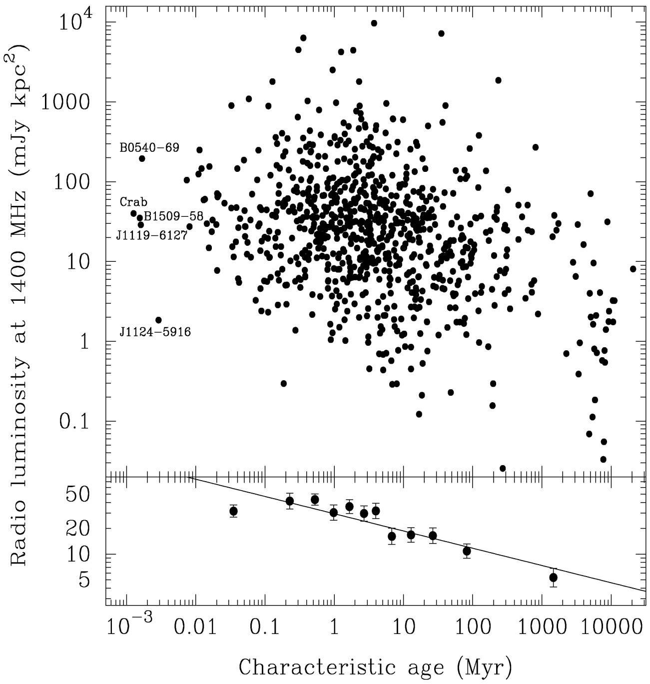

FIG. 1.—*Top*: Radio luminosities at 1400 MHz (L_{1400}) for 828 pulsars plotted vs. characteristic age τ_c. About 5% of known pulsars have L_{1400} below that of PSR J1124−5916. *Bottom*: Data from top panel binned into 12 groups of 69 pulsars each, with points representing the mean of L_{1400} and τ_c in each bin, and a straight-line least-squares fit to the binned points. The leftmost point ($\tau_c \lesssim 100$ kyr) suggests that young pulsars are not particularly luminous by comparison with middle-aged pulsars (100 kyr $\lesssim \tau_c \lesssim$ 5 Myr). Some luminosity decay for larger ages is suggested by the straight-line fit.

tion, new *Chandra* HRC data were searched for X-ray pulsations. As detailed by J. P. Hughes et al. (2002, in preparation), pulsations were found at a consistent period from the location of the previously identified pulsar wind nebula (PWN), ensuring beyond any doubt that we have discovered the pulsar near the center of SNR G292.0+1.8.

The measured DM, together with the Taylor & Cordes (1993) model for the Galactic distribution of free electrons, implies a pulsar distance of 11 kpc. However, the pulsar is located in the direction of the Carina spiral arm, where the model suffers from systematic errors. In fact, a new electron density/distance model (J. M. Cordes & T. J. Lazio 2002, in preparation) suggests a pulsar distance of 5.7 kpc (J. M. Cordes 2001, private communication). The SNR shows H I absorption to beyond the tangent point in this direction (Caswell et al. 1975), implying a lower limit on the distance of 3.2 kpc. Since the SNR shows absorption toward all more distant emission, no upper limit can be put on its distance from these data. A distance estimate is also available from the observed value of reddening, $d \sim 5.4$ kpc (Goss et al. 1979). In light of these various constraints on pulsar/SNR distance, we adopt hereafter the estimate $d = 5$ kpc.

We have begun regular timing measurements of the new pulsar at the Parkes Observatory, with 3–5 hr typically needed to obtain a satisfactory pulse profile and a corresponding time of arrival (TOA). The average pulse profile has a single approximately symmetric component with FWHM $\sim 0.1P$. Using the TOAs, the arcsecond-accuracy position measured with *Chandra*, and the TEMPO[6] timing software, we have obtained a phase-connected solution, with the resulting spin parameters

[6] See http://pulsar.princeton.edu/tempo.

TABLE 1
PARAMETERS OF PSR J1124−5916

Parameter	Value
R.A. (J2000.0)[a]	11 24 39.1
Decl. (J2000.0)[a]	−59 16 20
Period, P (s)	0.1353140749(2)
Period derivative, $\dot P$	$7.471(2) \times 10^{-13}$
Epoch (MJD)	52,180.0
Dispersion measure, DM (cm^{-3} pc)	330(2)
Data span (MJD)	52,157–52,214
Number of TOAs	10
rms timing residual (ms)	5.8
rms timing residual, "whitened" (ms)	0.4
Flux density at 1400 MHz, S_{1400} (mJy)	0.08(2)
Derived parameters:	
Characteristic age, τ_c (yr)	2900
Spin-down luminosity, $\dot E$ (ergs s^{-1})	1.2×10^{37}
Magnetic field strength, B (G)	1.0×10^{13}
Distance, d (kpc)[b]	∼5
Radio luminosity, L_{1400} (mJy kpc^2)	∼2

NOTE.—Numbers in parentheses represent 1 σ uncertainties in the least significant digits quoted.
[a] Position known with ∼1″ accuracy from *Chandra* data (Hughes et al. 2001). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[b] Distance of SNR G292.0+1.8 (see text).

listed in Table 1. The pulsar appears to suffer a large amount of "timing noise," with large and systematic residuals from the second-order fit listed in Table 1. Fitting of four spin-frequency derivatives removed the systematic component of this noise, leaving a final rms timing residual of 0.4 ms. The signal-to-noise ratios have remained constant when scaled by integration time, suggesting that the pulsar's flux is not greatly modulated by interstellar scintillation. We use this and the known observing parameters, telescope gain, and system temperature, including the contribution to the latter from the SNR (Lockhart et al. 1977), to estimate a flux density of 80 ± 20 μJy.

3. DISCUSSION

The measured P and $\dot P$ of PSR J1124−5916 imply that it is a very young and energetic pulsar. The implied characteristic age and surface magnetic dipole field strength are $\tau_c = P/2\dot P = 2900$ yr and $B = 3.2 \times 10^{19}(P\dot P)^{1/2} = 1.0 \times 10^{13}$ G, respectively. The spin-down energy loss rate is $\dot E = 4\pi^2 I\dot P/P^3 = 1.2 \times 10^{37}$ ergs s^{-1} (where a neutron star moment of inertia $I = 10^{45}$ g cm^2 has been used), in excellent agreement with the value predicted by Hughes et al. (2001) from the energetics of the PWN, if $d \sim 5$ kpc. In comparison with the sample of ∼1500 rotation-powered pulsars known, J1124−5916 ranks as the sixth youngest in terms of τ_c and the eighth most energetic in terms of $\dot E$.

The age of G292.0+1.8 is derived to be $\lesssim 1700(d/5\ \mathrm{kpc})$ yr from a measurement of the high radial velocity, oxygen-rich material positionally coincident with the central synchrotron nebula (Murdin & Clark 1979; Braun et al. 1983), while the pulsar characteristic age is a factor of nearly 2 larger than this. Assuming that the age estimate for the SNR represents the true age of the system, this discrepancy can be simply explained if the initial spin period of PSR J1124−5916 was $P_0 \gtrsim 90$ ms (e.g., Kaspi et al. 2001b; Murray et al. 2002). This is slower than for the six other young pulsars whose initial periods have been estimated, all of which have $P_0 < 60$ ms. Alternatively, the pulsar may spin down with a braking torque that is different from the usually assumed constant magnetic dipole. In a study

TABLE 2
Pulsars with Apparent Age of Less than 5 kyr

PSR	τ_c (kyr)	P (ms)	B ($\times 10^{12}$ G)	$\dot{E}$ ($\times 10^{36}$ ergs s^{-1})	SNR	d (kpc)	L_{1400} (mJy kpc^2)
J0537−6910	5.0	16	1	480	N157B	50 (LMC)	<150
B0531+21	1.3	33	4	440	Crab	2.0	40
B0540−69	1.7	50	5	150	0540−693	50 (LMC)	200
J0205+6449	5.4	65	4	27	3C 58	2.6	$\lesssim$2
B1509−58	1.6	150	15	18	G320.4−1.2	5.2	35
J1124−5916	2.9	135	10	12	G292.0+1.8	~5	~2
J1846−0258	0.7	323	48	8	Kes 75	~19	$\lesssim$50
J1811−1926	24	65	2	6	G11.2−0.3	5	< 2
J1119−6127	1.6	407	41	2	G292.2−0.5	~6	~30

Note.—We list in order of decreasing spin-down luminosity $\dot{E}$ all known pulsars for which the characteristic age $\tau_c < 5$ kyr or for which the pulsar is possibly associated with a historical supernova (J0205+6449: SN 1181; J1811−1926: SN 386).

of pulsar population dynamics, Cordes & Chernoff (1998) suggest alternative forms of braking torque (e.g., a braking index of 2.5 with a magnetic field decay time of ~6 Myr) that result in actual pulsar ages smaller than τ_c by a factor of $\lesssim$2. In the absence of a measured braking index for PSR J1124−5916, we tentatively regard a relatively large P_0 as a preferred explanation.

In Table 2 we summarize key parameters for the youngest rotation-powered pulsars known, ordered by decreasing $\dot{E}$. Heading the list are the three "Crab-like" pulsars, with extremely large $\dot{E}$. The remaining six young pulsars are varied in their properties and generally follow the trend of increasing P and B with decreasing $\dot{E}$ (with the pulsar in G11.2−0.3 a notable exception). Their spin-down luminosities are 20–200 times lower than that of the Crab pulsar's, and many are therefore difficult to detect: four were discovered just in the past 2 years (two each in radio and X-rays).

In its spin parameters, PSR J1124−5916 is most similar to PSR B1509−58 (see Table 2). It is interesting to note that their respective PWNe also have comparable luminosities. In the 0.2–4 keV X-ray band, we find for the PWN powered by J1124−5916[7] that $L_X = 6 \times 10^{34}$ ergs s^{-1} $= 0.005\dot{E}$ for a distance of 5 kpc (Hughes et al. 2001), while for B1509−58 we find $L_X = 2 \times 10^{35}$ ergs s^{-1} $= 0.01\dot{E}$ in the same energy range (Gaensler et al. 2002). For their respective radio PWNe, we find $L_R = 4 \times 10^{33}$ ergs s^{-1} $= 0.0003\dot{E}$ for J1124−5916 (Hughes et al. 2001), while $L_R \sim 5 \times 10^{33}$ ergs s^{-1} $= 0.0003\dot{E}$ for B1509−58 (Gaensler et al. 2002).

Thus, the efficiencies with which these pulsars power their X-ray nebulae differ by a factor of only ~2, while those for their radio nebulae are approximately equal. Although these pulsars have comparable spin parameters, we explain below that their PWNe have quite different environments and likely evolutionary histories. It is therefore surprising that the efficiencies with which they convert their spin-down into nebular flux are so similar.

In the radio band, it has been argued that a pulsar's initial parameters can make a crucial difference to the resultant luminosity of its PWN at later times (e.g., Bhattacharya 1990). If a pulsar is born spinning rapidly and has a high magnetic field, it will dump most of its spin-down energy into its surrounding nebula at the earliest stages, when adiabatic losses are most severe; this will result in a comparatively underluminous radio PWN (Bhattacharya 1990; Crawford et al. 2001). However, a pulsar that is otherwise similar but born spinning more slowly will not release its energy so quickly, so that its nebula will suffer less from expansion losses and will be correspondingly brighter at radio wavelengths. We have argued above that PSR J1124−5916 was possibly born with a comparatively long spin period, $P_0 \gtrsim 90$ ms, while PSR B1509−58 is generally assumed to have been born with a Crab-like spin period of $P_0 \approx 20$ ms (Bhattacharya 1990). The comparable values of L_R for their PWNe are therefore not easily explained.

Furthermore, that the radio and X-ray extents of the PWN powered by PSR B1509−58 are approximately equal indicates that synchrotron cooling does not yet dominate the nebula at high energies (Gaensler et al. 2002) and can account for this nebula's comparatively low X-ray efficiency (Chevalier 2000). However, for PSR J1124−5916 the X-ray nebula is noticeably smaller than its radio counterpart (Hughes et al. 2001; B. M. Gaensler & B. J. Wallace 2002, in preparation), indicating that the X-ray–emitting electrons are in this case efficient radiators. Thus, we expect the X-ray luminosity of the PWN around J1124−5916 to be much larger than observed, closer to the factor $L_X \approx 0.05\dot{E}$ seen for the Crab Nebula and other X-ray PWNe dominated by radiative losses (Chevalier 2000).

Thus, both L_R and L_X for the PWN powered by PSR J1124−5916 are much lower than expected through simple physical arguments. There are a variety of other factors that can affect the luminosity of a PWN: the pulsar braking index, PWN magnetic field, and nebular expansion velocity are all important parameters at radio wavelengths (Reynolds & Chevalier 1984; Crawford et al. 2001), while the Lorentz factor of the wind, the radius of the termination shock, and the magnetization parameter σ all have a strong bearing on the nebula's X-ray luminosity (Chevalier 2000). The unexpectedly similar nebular efficiencies for PSRs J1124−5916 and B1509−58, along with the large range of efficiencies among the other young pulsars in Table 2, emphasize that we still lack a detailed understanding of how a pulsar ultimately deposits its energy.

One particularly interesting young pulsar in this regard is PSR J1119−6127 (Camilo et al. 2000; Table 2), which has no known radio-bright PWN down to extremely constraining surface brightness limits (Crawford et al. 2001). It also has no confirmed X-ray–bright PWN (although a possible candidate was detected by Pivovaroff et al. 2001). This example, together with several relatively young and energetic pulsars that do not power detectable PWNe (Gaensler et al. 2000b), suggests that pulsar environments need not be good "calorimeters." Thus,

[7] The photon index of this source could not be measured from the *Chandra* observations of Hughes et al. (2001) because of contamination by thermal emission from the SNR. We assume a photon index of $\Gamma = 2$, as is typical for such sources.

some young pulsars may pass unnoticed unless their beamed radiation is favorably oriented so that pulsations may be detected.

The fact that radio pulsar beams do not in general sweep 4π sr is a fact of life. Although it is generally accepted that the beaming fraction f is period dependent, with short-period pulsars beaming to a larger fraction of the sky than their long-period counterparts, a consensus has yet to emerge on the form of $f(P)$. Pulse width analyses suggest that $f \approx 0.3$ for a pulsar with $P \sim 0.1$ s (Tauris & Manchester 1998), while from an analysis of pulsar-PWN associations, Frail & Moffett (1993) find $f \approx 0.6$. Since PWNe are regarded as unambiguous indicators that a young pulsar is present, the failure to detect pulsations toward such sources is usually ascribed solely to a misoriented pulsar beam. However, the case of G292.0+1.8 and its faint radio pulsar highlights an important caveat: the radio luminosity[8] limit implied by a nondetection should now be below at least $L_{1400} \sim 1$ mJy kpc^2, approximately the luminosity of PSR J1124−5916, and possibly as low as $\lesssim 0.1$ mJy kpc^2 (see Fig. 1), before one can invoke unfavorable beaming as an explanation.

Various analyses (e.g., Emmering & Chevalier 1989) have suggested that young pulsars have higher radio luminosities than older ones. Figure 1 shows that the basis for such arguments is weak in the case of very young pulsars. The least luminous radio pulsar previously detected for which $\tau_c < 10$ kyr had $L_{1400} \sim 30$ mJy kpc^2. The fact that some X-ray–detected pulsars have had much more constraining luminosity limits put on their radio emission (e.g., Crawford et al. 1998; Table 2) has usually been taken to imply that these pulsars have radio beams that are not directed toward us. However, the discovery of PSR J1124−5916 shows that very young pulsars can certainly have much lower radio luminosities than previously thought, due either to intrinsically low luminosity or to our line of sight cutting only low-level wings on the emitted beam.

The above discussion serves as a cautionary tale in the context of discussions of exotic sources, such as the "radio-quiet neutron stars" (RQNSs), "anomalous X-ray pulsars" (AXPs) and "soft γ-ray repeaters" (SGRs). While there is no question that these sources have properties that make them distinct from "normal" radio pulsars (e.g., Gotthelf, Petre, & Vasisht 1999; Pivovaroff, Kaspi, & Camilo 2000; Gaensler et al. 2000a; Kaspi et al. 2001a; Chakrabarty et al. 2001), the fact that none of these sources has been detected at radio wavelengths has been taken to imply that their radio pulse mechanism must be inactive (Baring & Harding 1998; Zhang & Harding 2000; Zhang 2001). However, the radio luminosity limits for many of these sources are not particularly stringent by the standard of radio pulsars, and there are so few of these objects known that they all could be radio luminous and yet all could still be beaming away from us (Gaensler et al. 2001). It may well be that the RQNSs, AXPs, and SGRs are all truly radio-silent, but this conclusion is difficult to justify until the luminosity limits available for such objects reach a level equivalent to at least the smallest radio luminosities observed for radio pulsars, $L_{1400} \sim 0.1$ mJy kpc^2 (Fig. 1), and in principle even smaller values.

With the discovery of PSR J1124−5916, G292.0+1.8 becomes the second example of an oxygen-rich SNR with a confirmed rapidly spinning pulsar (after 0540−693 in the Large Magellanic Cloud). The true nature of the compact sources in the other two Galactic oxygen-rich SNRs remains to be seen. This discovery also suggests that very deep searches for radio pulsations from known PWNe and possibly other more exotic neutron stars may be well worthwhile.

[8] The radio luminosities we discuss here are really "pseudoluminosities": they assume that the total luminosity is proportional to the integrated flux density of the observed cut across the radio beam. A realistic discussion of actual luminosities depends crucially on the generally unknown pulsar beam shape: e.g., for a beam with exponential roll off, the measured flux density—and therefore pseudoluminosity—can be arbitrarily low depending on the viewing impact angle, even for a large beam-averaged luminosity. Here primarily we are concerned with empirically determined "luminosities," i.e., with pseudoluminosities.

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