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DISCOVERY OF A 136 MILLISECOND RADIO AND X-RAY PULSAR IN SNR G54.1+0.3

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ABSTRACT

We report the discovery of a pulsar with period P = 136 ms and dispersion measure 308 cm^{-3} pc in a deep observation of the supernova remnant (SNR) G54.1+0.3 with the Arecibo radio telescope. Timing measurements of the new pulsar, J1930+1852, reveal a characteristic age of $P/2\dot{P}$ = 2900 yr and spin-down luminosity $\dot{E}$ = 1.2×10^{37} erg s^{-1}. We have subsequently searched archival *ASCA* X-ray data of this SNR, and detect pulsations with a consistent period. These findings ensure that PSR J1930+1852 is the pulsar that powers the "Crab-like" SNR G54.1+0.3. Together with existing *Chandra* observations of the SNR, we derive an X-ray pulsed fraction (2–10 keV) of $\approx$ 27%. We also find that the cooling efficiency of the pulsar wind nebula (PWN) is intermediate between those of the Vela and Crab PWNe: L_X(2–10 keV) $\sim 0.002\dot{E}$. PSR J1930+1852 is a very weak radio source, with period-averaged flux density at 1180 MHz of 60 μJy. For a distance of 5 kpc, its luminosity, $\sim$ 1 mJy kpc^2, is among the lowest for known young pulsars.

Subject headings: ISM: individual (G54.1+0.3) — pulsars: individual (PSR J1930+1852) — supernova remnants

1. INTRODUCTION

The supernova remnant (SNR) G54.1+0.3 is a close analogue of the Crab Nebula in several respects. At radio wavelengths it has a filled-center morphology, a flat spectrum, and shows significant polarization (Reich et al. 1985; Velusamy & Becker 1988). Its X-ray spectrum is non-thermal, and the X-ray and radio extents are comparable ($\lesssim 2'$; Lu, Aschenbach, & Song 2001). It is a classic compact synchrotron nebula powered by its putative energetic pulsar, with no evidence for a thermal component corresponding to shocked ISM or stellar ejecta. Using the *Chandra* X-ray Observatory, Lu et al. (2002) have recently identified the central compact source (pulsar candidate) and imaged with $\sim$ arcsecond resolution beautiful coherent structures (e.g., a ring) that are a manifestation of the relativistic pulsar wind interacting with the ambient medium.

The morphological and spectral properties of G54.1+0.3 revealed by *Chandra* leave no room for doubt as to the presence of a central pulsar. It is nevertheless of considerable interest to detect actual pulsations, and to measure the period of rotation P and its derivative $\dot{P}$. Because the SNR is powered entirely by the pulsar, knowledge of the input energy source (pulsar spin-down) luminosity ($\dot{E} = 4\pi^2 I\dot{P}/P^3$, where $I \equiv 10^{45}$ g cm^2 is the neutron star moment of inertia) would improve our understanding of the energetics of the nebula. Also, the pulsar characteristic age $\tau_c = P/2\dot{P}$ is a useful (if sometimes crude) measure of the SNR age, especially in cases like G54.1+0.3 where no independent reliable age estimate exists. Finding radio and/or X-ray pulsations is also important because a significant sample of well-studied SNRs and their pulsars provides a window into the distribution of initial spin periods and magnetic fields of neutron stars. Finally, detection of pulsations addresses the poorly constrained luminosity distribution, "beaming fraction", and hence Galactic population of young neutron stars.

The SNR G54.1+0.3 was searched for a radio pulsar by Gorham et al. (1996) with the "pre-upgrade" Arecibo telescope. At a frequency of 1408 MHz, their 30 min observation of a 40 MHz-wide band reached a claimed sensitivity of 300 μJy for a pulsar with period $P \sim 0.1$ s of duty-cycle 10% and dispersion measure DM ~ 300 cm^{-3} pc (based upon their assumptions, we find their limiting sensitivity to be $\sim 100\,\mu$Jy). Following the striking *Chandra* observations of G54.1+0.3 (Lu et al. 2002), we attempted the most sensitive search currently possible at Arecibo. In this Letter we report the discovery of a 136 ms radio pulsar which, through a subsequent detection in archival *ASCA* X-ray data, is confirmed to be the neutron star powering SNR G54.1+0.3.

2. RADIO SEARCH

On 2001 August 29 we collected data for a full source transit of 2.7 hr[6] at a center frequency of 1175 MHz. However these data were too corrupted by radio-frequency interference to be searched, and the observations were redone on 2002 April 29.

The incoming signals from the telescope were recorded using the Wide-band Arecibo Pulsar Processor (WAPP), a fast-dump digital correlator (Dowd, Sisk, & Hagen 2000) currently capable of sampling a band of either 50 or 100 MHz and determining either 3- or 9-level correlation functions. All observations for this search utilized the 100 MHz 3-level mode of the WAPP in which raw auto-correlation functions (ACFs) for each of the two polarizations (IFs) were written to disk as either 32- or 16-bit numbers. Data from 2001 August were collected in 32-bit mode recording 256 lags every 570 μs with the two IFs summed on-line. Data from 2002 April were collected in 16-bit

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[6] Because the source declination is very close to the observatory latitude, there is a "hole" at |zenith angle| $< 1^\circ\!.06$ within which it cannot be tracked; nevertheless we continued data (noise) collection during this 8 min interval in order to maintain phase coherence of the data set.

mode recording 256 lags every 295 μs separately for each of the two IFs at a frequency of 1180 MHz.

Off-line preparation of WAPP data for search processing proceeded by applying the van Vleck correction (see, e.g., Hagen & Farley 1973) to each set of 256 ACFs to remove unwanted 3-level quantization effects. The resulting unbiased ACFs were then Fourier transformed to produce spectral channels so that the data following this step are, in effect, equivalent to power streams from a filter bank with 2×256 spectral channels. Since the search targeted a young ($P \gtrsim 30$ ms) pulsar, the ideal sampling interval for our observations would have been ~ 1 ms. However the slowest sample time of the WAPP (determined by the size of the registers used to store accumulated correlation values) is $\approx 400\,\mu$s in 16-bit, 2-IF mode, and the faster-sampled data recorded were instead decimated off-line by adding every 8 time samples before further processing. At this point summing of the 2 IFs and reduction in precision to 8-bit quantities were also performed. The data reduction tools used for this stage of the analysis are described by Lorimer (2001)[7].

The data from 2002 April were reduced thereafter in standard fashion. The 256 time series of 2^{22} samples, each decimated to a resolution of 2.36 ms, were de-dispersed at 1001 trial DMs in the range 0–1000 cm^{-3} pc. Finally, these 1001 time series were each searched for periodic signals over a range of duty cycles with an FFT-based code (see Lorimer et al. 2000 for details).

An unmistakable periodic and dispersed signal with $P \approx$ 136.8 ms was detected with maximum signal-to-noise ratio of 20.7 at DM ≈ 308 cm^{-3} pc. Nine days later we confirmed this signal in a shorter observation, by which time the barycentric period had increased by $\sim 0.6\,\mu$s, indicating a period derivative $\dot{P} \sim 8 \times 10^{-13}$. At this stage, we searched archival X-ray data for (and found) pulsations (§ 3). We have begun timing observations of the pulsar and so far have obtained times-of-arrival (TOAs) on 5 occasions spanning 24 days. In addition we reduced, and obtained TOAs from, the 2001 August data. We have used the TEMPO[8] timing software and the TOAs, along with the pulsar position known to $\sim 0\farcs6$ accuracy from *Chandra* data (Lu et al. 2002), to derive the P and $\dot{P}$ listed in Table 1. We regard this as a preliminary ephemeris because of the 8 month gap between the first TOA and the recent set.

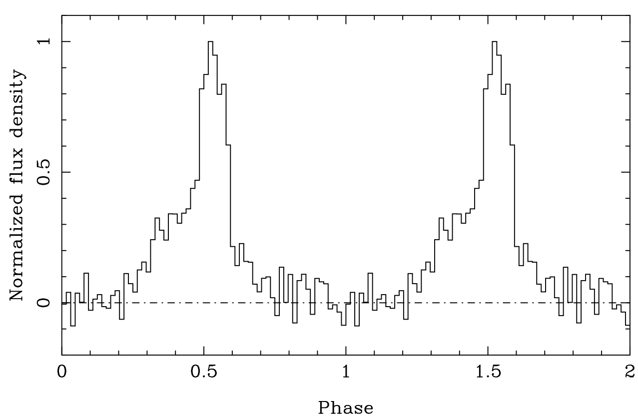

FIG. 1.— Average radio pulse profile of PSR J1930+1852 at 1180 MHz, based on 8.75 hr of Arecibo data. Notice the broad "wings" of emission. Phase zero is arbitrary.

The average pulse profile at a frequency of 1180 MHz is displayed in Figure 1, and was obtained by phase-aligning and summing the profiles obtained on each day according to the ephemeris given in Table 1. We have measured the area under each of the individual profiles, and their baseline offsets, and used these, together with the known telescope gain and system temperature (including their dependencies on zenith angle and the contribution from Galactic synchrotron and SNR emission), to estimate the average flux density of the pulsar. We obtain $S_{1180} = 60 \pm 10\,\mu$Jy, where the uncertainty is the addition in quadrature of the standard deviation of the 6 measurements (6 μJy) and a $\sim$ 10–15% contribution accounting for imperfectly known system parameters.

3. X-RAY PULSAR

The field containing G54.1+0.3 was observed in the X-ray band on 1997 April 27–28 with the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*; Tanaka, Inoue, & Holt 1994) to search for a Crab-like pulsar. This observation was designed to allow temporal studies with the two gas scintillation imaging spectrometers (GISs) at a time resolution of 0.488 ms throughout the exposure. To ensure consistent (high) temporal resolution, during periods when real-time telemetry was not available, data were taken at a reduced (1/4) spatial resolution at the slower (medium) bit-rate and stored on board. Although the spatial resolution of the GIS ($\sim 2'$) is insufficient to resolve the pulsar from the surrounding nebula, the moderate ($\approx$ 5–10%) energy resolution in the 0.5–10 keV bandpass allows some measure of energy discrimination of the instrumental and X-ray background. To search for pulsations, we combined GIS data from both instruments and from data sets taken in different spatial modes. The latter necessitated rebinning the sky pixels of the high bit-rate data to match the medium bit-rate data set. All data were edited to exclude times of high background contamination using the standard (REV2) screening criteria. The resulting effective observation time was 22.7 ks spanning 43.1 ks. Photon arrival times were corrected to the solar system barycenter using the JPL DE200 ephemeris and the known pulsar position (Table 1).

Arrival times were obtained for 2210 photons extracted from a $3'$ radius aperture centered on the peak of X-ray emission from G54.1+0.3 and restricted in energy to 2–10 keV to optimize the signal-to-noise ratio. We generated a periodogram using the χ^2 statistic by folding the extracted photons over a range of test frequencies centered on the extrapolated radio measurement, using a crude spin-down rate based on the discovery and confirmation observations. We detected a single $\approx 6\,\sigma$ signal with a narrow pulse profile near the predicted period. Using the Z_n^2 test to gain sensitivity to n harmonics of the fundamental frequency (Buccheri et al. 1983), we obtained a best signal with $Z_3^2 = 47.8$. While not significant in a blind search (probability of chance occurrence is 1.3×10^{-8} per trial, or 0.13 in a 0–20 Hz search range with 2 μHz resolution), this is the strongest signal in the search range. Impressively, the barycentric period of $P = 136.74374(5)$ ms on 50566.0 MJD differs by only $(0.15 \pm 0.05)\,\mu$s from the period extrapolated back to this epoch with the preliminary radio timing ephemeris obtained 5 yr later (§ 2). This confirms that the X-ray signal represents a bona fide detection of pulsations from the radio pulsar. As there is no X-ray source in the *Chandra* field other than the point-source pulsar candidate that could generate the pulsed X-ray emission detected by *ASCA*, we conclude unambiguously that we have in

[7] Available at http://www.jb.man.ac.uk/∼drl/sigproc.

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

fact detected radio and X-ray pulsations from PSR J1930+1852 at the center of SNR G54.1+0.3.

The X-ray pulse profile, shown in Figure 2, is similar in shape to the radio profile (Fig. 1), with a single narrow peak of $\sim 20\%$ duty-cycle. The pulse width is slightly larger than that found in the radio, but is limited by the statistics of the observation. The measured pulsed fraction, defined as the ratio of counts in the light-curve above the mean baseline in the off-pulse interval to the total counts, is 9.5%. However this result is contaminated by emission from the nebula. Using all available data (*ASCA* GIS and *Chandra* ACIS-S3) together we can constrain further the properties of the pulsar.

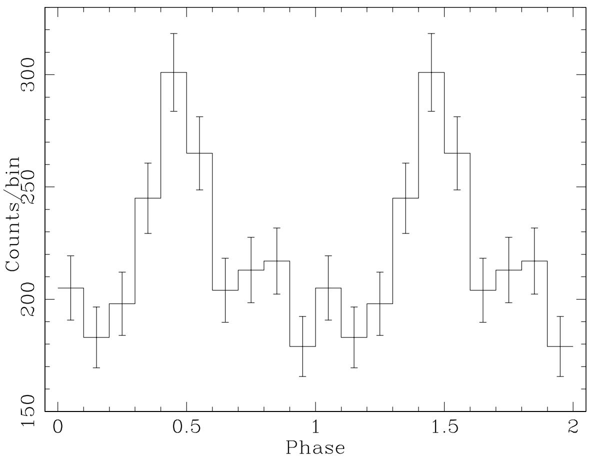

FIG. 2.— X-ray pulse profile of PSR J1930+1852 in the 2–10 keV band from *ASCA* GIS. Accounting for diffuse emission resolved with a *Chandra* observation (see text), pulsed fraction is $\approx 27\%$. Phase zero is arbitrary.

With a count rate of $0.064 \pm 0.002\,\mathrm{s}^{-1}$, the point source in the *Chandra* observation of Lu et al. (2002) was significantly affected by pile-up (Davis 2001). We have used a new version of the spectral analysis software XSPEC that accounts for this, obtaining a corrected pulsar photon index $\Gamma = 1.35^{+0.06}_{-0.10}$ (uncertainties are 90% confidence levels) and measured flux in the 2–10 keV band of $1.7 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The absorbing column density was fixed at $N_H = 1.6 \times 10^{22}\,\mathrm{cm^{-2}}$ (Lu et al. 2002), for which the unabsorbed pulsar flux is $1.9 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. This spectrum corresponds to a count rate in the 2–10 keV *ASCA* GIS band of $0.044\,\mathrm{s}^{-1}$, computed with WPIMMS[9] for a $6'$ radius aperture. The pulsed rate measured within this aperture is $0.012\,\mathrm{s}^{-1}$, implying a pulsed fraction of $\approx 27\%$. This compares to a fraction of $\approx 7\%$ for the Vela pulsar (Helfand, Gotthelf, & Halpern 2001), and $\gtrsim 75\%$ for PSR J2229+6114 (Halpern et al. 2001), two young pulsars with values of $\dot{E}$ within a factor of 2 of PSR J1930+1852's. The absolute phase alignment of the X-ray and radio profiles (to be determined from scheduled *RXTE* and planned radio observations) will provide a further diagnostic of the emission mechanism(s).

Pulsars such as this one are known to emit a substantial fraction of their spin-down luminosity in magnetospheric γ-rays. PSR J1930+1852 lies $1^\circ\!.4$ from the high energy (> 100 MeV) EGRET γ-ray source 3EG J1928+1733 (Hartman et al. 1999). This is slightly outside the 99% confidence-level error box, but given its weakness and the possibility of an extended or multiple source, an association is not out of the question.

4. DISCUSSION

The P and $\dot{P}$ measured for PSR J1930+1852 imply a large spin-down luminosity $\dot{E} = 1.2 \times 10^{37}\,\mathrm{erg\,s^{-1}}$, small characteristic age $\tau_c = 2900$ yr, and surface magnetic dipole field strength $B = 3.2 \times 10^{19}(P\dot{P})^{1/2} = 1.0 \times 10^{13}$ G (Table 1). These parameters are virtually identical to those of PSR J1124–5916 in SNR G292.0+1.8, and place it in the group of ~ 10 pulsars with the highest values of $\dot{E}$ and smallest apparent ages known, all of which are associated with SNRs (see Camilo et al. 2002a). However its parameters are substantially different from those of the Crab pulsar, which remains the only Galactic neutron star known with $P < 50$ ms and $\dot{E} > 10^{38}\,\mathrm{erg\,s^{-1}}$.

The pulsar's characteristic age allows for a useful estimate of its actual age (and that of the SNR), given by $\tau = 2\tau_c[1-(P_0/P)^{n-1}]/(n-1)$ under the assumption of constant magnetic moment, where P_0 is the initial period and n is the braking index of rotation (Manchester & Taylor 1977). For magnetic dipole braking, $n = 3$, and measured values span $2 \lesssim n \lesssim 3$ (see, e.g., Camilo et al. 2000). Initial periods of rotation are thought to range from ≈ 10 ms, to perhaps $\gtrsim 90$ ms (for PSR J1124–5916; Camilo et al. 2002a). Considering the extremes of $n \approx 2$ and $P_0 \approx 90$ ms in turn, the age of J1930+1852/G54.1+0.3 likely lies in the range 1500–6000 yr.

The distance of SNR G54.1+0.3 has been estimated from a measurement of the X-ray absorption column density, which is found to be about half the total Galactic absorption in this direction. As the Galaxy here extends to ~ 10 kpc from the Sun, Lu et al. (2002) consider $d \sim 5$ kpc. Assuming the SNR to be associated with the star-forming region G53.9+0.3, Velusamy & Becker (1988) obtain $d \sim 3.2$ kpc. The dispersion measure of PSR J1930+1852 (Table 1) provides an independent estimate: the Taylor & Cordes (1993) free electron density/distance model suggests $d \sim 12$ kpc. A newer model incorporating, among other improvements, discrete regions of enhanced ionized material (J. M. Cordes & T. J. Lazio 2002, in preparation), yields $d \lesssim 8$ kpc (T. J. Lazio 2002, private communication), consistent with the estimate derived from X-ray measurements. While the distance to this SNR/pulsar pair remains uncertain, we here retain $d \sim 5$ kpc as a plausible estimate.

We now comment on some features of the pulsar wind nebula (PWN). A composite *Chandra* image of G54.1+0.3 (Fig. 3) demonstrates the trend of X-ray spectral softening from the inner to the outer regions of the nebula (as first indicated in the analysis of Lu et al. 2002). This is likely caused by a combination of synchrotron cooling and adiabatic expansion of the shocked wind material. The 2–10 keV luminosity of the PWN/pulsar combination is $L_X = 2.2 \times 10^{34}(d/5\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}} \sim 0.002\dot{E}$. This is a factor of ~ 2 lower than that of the PWN surrounding PSR J1124–5916, a pulsar with identical spin parameters to PSR J1930+1852 (Camilo et al. 2002a)[10]. By contrast, the cooling efficiencies ($L_X/\dot{E}$) of the PWNe surrounding the Vela (Pavlov et al. 2001) and J2229+6114 (Halpern et al. 2001) pulsars, with similar $\dot{E}$, are much lower: $L_X \lesssim 10^{-4}\dot{E}$; while that of the Crab Nebula is ~ 25 times higher (e.g., Helfand & Becker 1987). The extent

[9] See http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html.

[10] Likewise the radio luminosity (10^7–10^{11} Hz) of G54.1+0.3, $L_R \sim 1 \times 10^{33}(d/5\,\mathrm{kpc})^2\,\mathrm{erg\,s^{-1}} \sim 0.0001\dot{E}$ (Velusamy & Becker 1988), is half that of the PWN powered by PSR J1124–5916. However, in one significant respect these two pulsar/SNR systems are different: PSR J1124–5916 and its PWN are part of the text-book composite SNR G292.0+1.8, embedded in a large and bright shell of stellar ejecta (Hughes et al. 2001; Park et al. 2002), whereas to date no thermal emission has been detected surrounding G54.1+0.3.

to which these differences are due to different ambient media, energy spectra of the injected pulsar wind (including the time evolution thereof), and ages, among other variables, is not clear.

FIG. 3.— *Chandra* ACIS-S3 image of SNR G54.1+0.3, color-coded by energy: 1.0–2.0 keV (red), 2.0–3.5 keV (green), and 3.5–8.0 keV (blue). The X-ray images in individual bands were adaptively smoothed in identical manner with a Gaussian filter in order to achieve a count-to-noise ratio of ≈ 6 in the final 1–8 keV image. North is to the top and East is to the left.

With the discovery of PSR J1930+1852, four very young and energetic pulsars have been uncovered in the past year, all with luminosities of ~ 1 mJy kpc^2 in the 1400 MHz radio band (Halpern et al. 2001; Camilo et al. 2002a, b; this Letter). These are well below the luminosities of previously known young pulsars (see Camilo et al. 2002a), and it is now clear that such pulsars can be extremely faint. Determining their intrinsic luminosity distribution requires disentangling observed "pseudo-luminosities" from beam-averaged values. For example, do the broad wings of emission in PSR J1930+1852 visible in Figure 1 indicate nearly aligned rotation and magnetic axes with an impact angle grazing the outer boundary of a radio beam with possibly large averaged luminosity? Studies of polarized emission may provide important clues to constrain the beaming geometry of individual pulsars.

Naturally, a large sample of young pulsars is also desirable, together with upper limits from the most sensitive searches possible of well-selected targets. In this regard, it is significant that new and upgraded radio telescopes are now available. The discovery of PSR J1930+1852 is an excellent example, as it could only barely have been made with the Arecibo telescope prior to its upgrade in the late 1990s: in addition to the increased bandwidth, we can now sample a lower-frequency band (1175 vs. 1400 MHz), where pulsars are brighter and the telescope's gain is higher. Planned improvements in system temperature and bandwidth at Arecibo, the new Green Bank Telescope, and the remarkably productive Parkes telescope, along with the continued availability of the superb *Chandra* X-ray Observatory, offer the prospect of yet further progress in studies of faint young neutron stars.

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TABLE 1
PARAMETERS OF PSR J1930+1852

Parameter	Value
R.A. (J2000)	$19^{h}30^{m}30\overset{s}{.}13$
Decl. (J2000)	$+18^{\circ}52'14\overset{''}{.}1$
Period, P (ms)	136.855046957(9)
Period derivative, $\dot{P}$	$7.5057(1) \times 10^{-13}$
Epoch (MJD [TDB])	52280.0
Dispersion measure, DM (cm^{-3} pc)	308(4)
Flux density at 1180 MHz (μJy)	60 ± 10
Pulse FWHM at 1180 MHz (ms)	15 ± 2
Pulse FWHM at 2–10 keV (ms)	~ 25
Distance of SNR G54.1+0.3, d (kpc)	~ 5
Derived parameters:	
Characteristic age, τ_c (yr)	2900
Spin-down luminosity, $\dot{E}$ (erg s^{-1})	1.2×10^{37}
Magnetic field strength, B (G)	1.0×10^{13}
Luminosity at 1400 MHz (mJy kpc^2)	~ 1