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OUT OF THE FRYING PAN: A YOUNG PULSAR WITH A LONG RADIO TRAIL EMERGING FROM SNR G315.9–0.0

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ABSTRACT

The faint radio supernova remnant SNR G315.9–0.0 is notable for a long and thin trail that extends outward perpendicular from the edge of its approximately circular shell. In a search with the Parkes telescope we have found a young and energetic pulsar that is located at the tip of this collimated linear structure. PSR J1437–5959 has period $P = 61$ ms, characteristic age $\tau_c = P/(2\dot{P}) = 114$ kyr, and spin-down luminosity $\dot{E} = 1.4 \times 10^{36}\,\mathrm{erg\,s^{-1}}$. It is very faint, with a flux density at 1.4 GHz of about $75\,\mu$Jy. From its dispersion measure of $549\,\mathrm{pc\,cm^{-3}}$, we infer $d \approx 8$ kpc. At this distance and for an age comparable to τ_c, the implied pulsar velocity in the plane of the sky is $V_t = 300\,\mathrm{km\,s^{-1}}$ for a birth at the center of the SNR, although it is possible that the SNR/pulsar system is younger than τ_c and that $V_t > 300\,\mathrm{km\,s^{-1}}$. The highly collimated linear feature is evidently the pulsar wind trail left from the supersonic passage of PSR J1437–5959 through the interstellar medium surrounding SNR G315.9–0.0.

Subject headings: ISM: individual (G315.9–0.0) — pulsars: individual (PSR J1437–5959) — stars: neutron

1. INTRODUCTION

Pulsars convert their prodigious rotational energy into relativistic winds of particles and fields. When significantly confined by ambient pressure, a portion of this outflow, or of shocked surrounding medium, may be detected as a pulsar wind nebula (PWN). PWNe are observed across the electromagnetic spectrum in enormous diversity, reflecting differences in, and serving as probes of, the properties of the pulsars and their winds, and of their environments (for a review, see Gaensler & Slane 2006).

After pulsars escape the confines of their expanding supernova remnant (SNR) shells, into media with relatively small sound speed, they typically move supersonically. Confinement by ram pressure of the ISM leads to characteristically elongated bow shock PWNe. These are observed at radio or X-ray wavelengths, when the shocked pulsar wind emits synchrotron radiation, and/or in the Hα emission of collisionally excited ISM. Among some 15 known pulsar bow shock nebulae, two-thirds are in the former category (see Chatterjee & Cordes 2002), of which the best-studied example is the "Mouse" (Gaensler et al. 2004). Given the variety of pulsar properties and environmental conditions, it is desirable to increase the small sample of pulsar bow shock nebulae available for detailed study.

SNR G315.9–0.0 is a little-studied faint radio shell, approximately $15'$ in diameter and incomplete in the north-east, with a peculiar collimated jet-like protrusion extending radially outward from the north-west quadrant of the shell for approximately $8'$ (Kesteven et al. 1987). Figure 1 (left) shows an 843 MHz radio image of SNR G315.9–0.0, from the Molonglo Observatory Synthesis Telescope (MOST) survey of Whiteoak & Green (1996)[6]. Whiteoak & Green noted that the protruding linear feature does not have an infrared counterpart in 60 μm *IRAS* data, suggesting that the radio emission from this source is non-thermal. The overall SNR morphology is reminiscent of a frying pan.

Such long collimated structures are rare (see, e.g., Gaensler et al. 1998; Kargaltsev & Pavlov 2008), and we considered it likely that this one could be generated by the trailing wind of a fast-moving pulsar. In this Letter we report the discovery of PSR J1437–5959, which is highly likely to be responsible for this remarkable feature and to be associated with SNR G315.9–0.0.

2. OBSERVATIONS AND RESULTS

We observed the tip of the linear feature in SNR G315.9–0.0 (see left panel of Figure 1) with the ATNF Parkes telescope on 2008 June 17. The 6.1 hr observation used the central beam of a multibeam receiver at a frequency of 1374 MHz, spanning a bandwidth of 288 MHz, with the total radio power sampled in each of 96 polarization-summed channels every 1 ms and recorded to disk. The data were searched for periodic dispersed signals using standard techniques implemented in PRESTO (Ransom 2001; Ransom et al. 2002), similarly to other deep searches for young pulsars (e.g., Camilo et al. 2006). We identified in these data a pulsar with period $P = 61$ ms and dispersion measure DM = $549\,\mathrm{pc\,cm^{-3}}$ (Figure 2). The distance is estimated from the DM and the Cordes & Lazio (2002) NE2001 electron density model to be 8 kpc, which we parameterize by $d_8 = d/(8\,\mathrm{kpc})$. We attempted to obtain a precise position using a pulsar-gated observation with the Australia Telescope Compact Array (ATCA) on 2008 July 23 (project CX156), but the pulsar was too faint to be detected.

We have made regular timing observations of PSR J1437–5959 at Parkes since discovery. Typically we observe the pulsar for approximately 1 hr at a frequency of 1.4 GHz. From each such observation we obtain one time-of-arrival (TOA). We have used TEMPO[7] and 23 TOAs spanning 1 yr to obtain a phase-connected timing solution that yields high-precision measurements of P, $\dot{P}$, R.A., and decl. (see Table 1, where we also gather some important derived parameters). The residuals from this fit are featureless, and any unmodeled rotational

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[6] Obtained from http://www.physics.usyd.edu.au/astrop/wg96cat/msc.a.html .
[7] http://www.atnf.csiro.au/research/pulsar/tempo

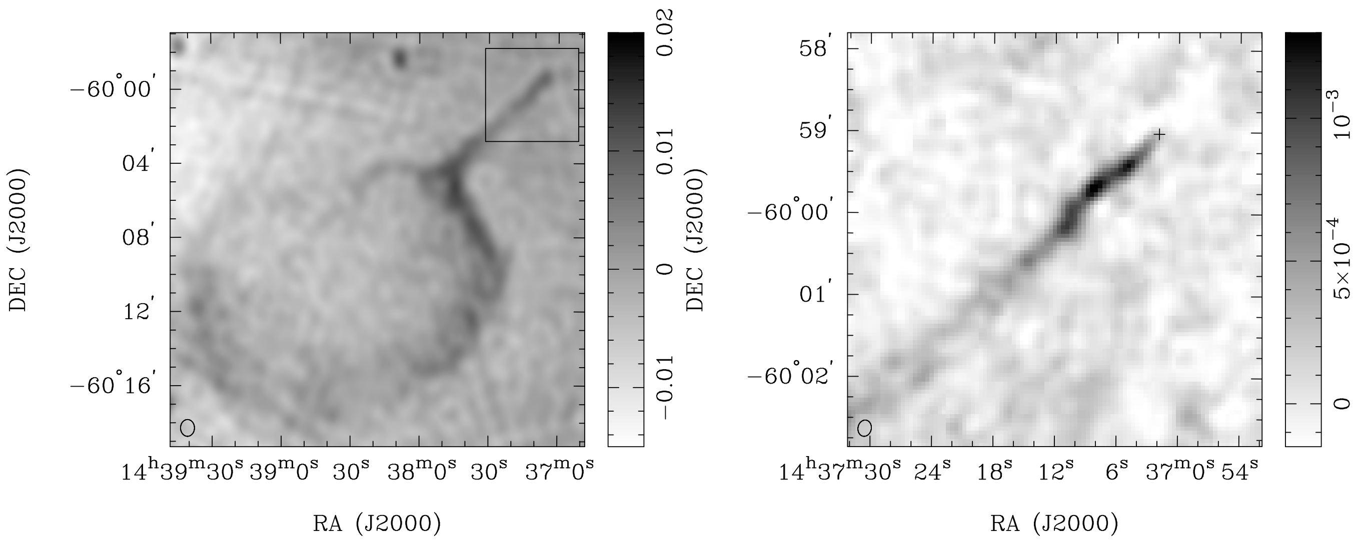

FIG. 1.— Left: MOST image of SNR G315.9–0.0 at 843 MHz (data from Whiteoak & Green 1996). The beam size (shown at lower left) is $54'' \times 45''$, the rms noise is 1.1 mJy beam^{-1}, and the grey scale is linear, ranging from –15 mJy beam^{-1} to 20 mJy beam^{-1}. The area bounded by a square is shown on the right panel at higher resolution. Right: ATCA 2.4 GHz image of G315.9–0.0, zoomed in near the tip of the linear trail, with the position of PSR J1437–5959 marked by the cross. The pulsar positional uncertainty is ~ 10 times smaller than the cross (see Table 1). The image has beam size $12'' \times 10''$, rms of 0.13 mJy beam^{-1}, and a linear scale ranging between –0.15 mJy beam^{-1} and 1.3 mJy beam^{-1}.

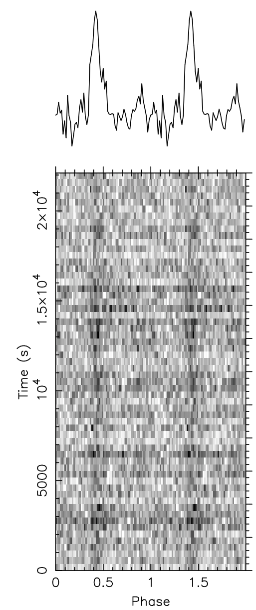

FIG. 2.— Discovery observation of PSR J1437–5959 at the Parkes telescope at 1.4 GHz. The pulse profile (shown twice; $P = 61$ ms) is displayed as a function of time in the grey scale and summed at the top.

TABLE 1
MEASURED AND DERIVED PARAMETERS FOR PSR J1437–5959

Parameter	Value
Right ascension, R.A. (J2000)	$14^h37^m01\overset{s}{.}91(3)$
Declination, decl. (J2000)	$-59°59'01\overset{''}{.}4(3)$
Galactic longitude, l (deg)	315.783
Galactic latitude, b (deg)	0.227
Spin period, P (s)	0.0616961234035(9)
Period derivative, $\dot{P}$	$8.5870(5) \times 10^{-15}$
Epoch (MJD)	54827.0
Post-fit rms timing residual (ms)	0.7
Data span (MJD)	54634–55018
Dispersion measure, DM (pc cm^{-3})	549.6(11)
Rotation measure, RM (rad m^{-2})	-700 ± 25
Flux density at 1.4 GHz, $S_{1.4}$ (μJy)	≈ 75
Pulse FWHM (P)	0.11
Characteristic age, τ_c (kyr)	114
Spin-down luminosity, $\dot{E}$ (erg s^{-1})	1.4×10^{36}
Surface dipole magnetic field strength (Gauss)	7.4×10^{11}
Distance, d (kpc)[a]	≈ 8
Radio luminosity, $S_{1.4}d^2$ (mJy kpc^2)	~ 5

NOTE. — Values in parentheses represent $1\,\sigma$ TEMPO uncertainties.
[a] Distance is inferred from the DM and the Cordes & Lazio (2002) model.

instability contributes a systematic uncertainty to celestial coordinates of no more than $\sim 1''$.

We also made one polarimetric observation, using a digital filterbank to record all four Stokes parameters for 5.8 hr on 2008 September 27. These data were analyzed with PSRCHIVE (Hotan et al. 2004). The emission is approximately 50% linearly polarized throughout the pulse profile, with a fairly flat position angle of linear polarization that does not constrain the geometry. Faraday rotation is measured to be RM = (-700 ± 25) rad m^{-2}; along with the DM, this implies an average Galactic magnetic field along the line of sight, weighted by the local free electron density, of 1.6 μG, directed away from us. The pulse profile shows a hint of an interpulse (see Figure 2), while the main pulse appears slightly asymmetric. The possible one-sided exponential tail of width ≈ 5 ms could be caused by multipath propagation through the ISM (this is half the value expected for this location and DM from the NE2001 model). From this flux-calibrated observation we measure a 1.4 GHz period-averaged flux density of $S_{1.4} \approx 75\,\mu$Jy.

SNR G315.9–0.0 has been observed with the ATCA at frequencies of 1.4 GHz and 2.4 GHz. We have reprocessed the archival 2.4 GHz data taken on 1998 July 5, 1999 March 25 and April 20 with the 750E, 1.5B and 1.5C array configurations, respectively. Each observation had 12 hr integration time, and PKS 1934–63 and PKS 1251–71 were observed as the primary and secondary calibrators to determine the flux density and antenna gains. Our data reduction was carried out in MIRIAD[8]. We excluded any baselines longer than 2 km to provide a uniform u-v sampling and to boost the signal-to-noise ratio. After flagging the bad data points and scans dur-

[8] http://www.atnf.csiro.au/computing/software/miriad

ing poor atmospheric phase stability, we applied the multifrequency synthesis technique with uniform weighting to form the images. This can improve the *u*-*v* coverage and minimize the sidelobes. The resulting image was then deconvolved using a maximum entropy algorithm (Sault et al. 1996) and restored with a Gaussian beam of FWHM $12'' \times 10''$. Figure 1 (right) shows the image zoomed in near the pulsar position.

The position of PSR J1437–5959 was observed with the *Swift* X-ray telescope (in PC mode) on 2008 July 5 for a total of 9.6 ks. We detect only one photon within $5''$ of the pulsar position, and consider five photons to represent a flux upper limit. Using PIMMS[9] with the total Galactic neutral hydrogen column density in this direction, $N_H = 1.6 \times 10^{22}\,\mathrm{cm}^{-2}$, and a typical power-law model with photon index $\Gamma = 1.5$, the unabsorbed flux in the 2–10 keV range is $f_X < 4.5 \times 10^{-14}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$. The resulting X-ray luminosity is $L_X < 3.5 \times 10^{32}\,d_8^2\,\mathrm{erg\,s^{-1}}$, or $L_X/\dot{E} < 2.5 \times 10^{-4}\,d_8^2$. This limit is somewhat below the "usual" X-ray luminosities from pulsars (or their PWNe) with comparable $\dot{E}$, which however have a large spread (see, e.g., Possenti et al. 2002).

3. DISCUSSION

We have discovered PSR J1437–5959, a young pulsar with $\tau_c = 114$ kyr that is located precisely at the tip of an unusual collimated linear feature (right panel of Figure 1), suggesting a physical association. In turn the linear feature seamlessly connects with the shell SNR G315.9–0.0, which is brightest in the area near the point of apparent contact (left panel of Figure 1), suggesting a physical connection. By analogy with well-studied examples of pulsars and their bow shock PWNe (e.g., Gaensler et al. 2004), we infer that the long non-thermal nebula trailing PSR J1437–5959 is caused by its shocked relativistic wind as the pulsar moves supersonically through the local ISM and away from SNR G315.9–0.0.

The pulsar/SNR association is located in the direction of the Crux spiral arm. At a distance of 8 kpc (according to the NE2001 model of Cordes & Lazio 2002), this system is on the inside edge of the arm. The RM = $-700\,\mathrm{rad\,m^{-2}}$ measured for PSR J1437–5959 is typical for this part of the Galaxy (Brown et al. 2007). Many high-DM pulsars known within the Crux arm have $-900 < \mathrm{RM}/(\mathrm{rad\,m^{-2}}) < -500$, and are located at $d \sim 6$ kpc (Han et al. 2006). If the NE2001 model Crux arm has a smaller electron density than the real arm or does not extend as far in width, it is entirely possible that the true pulsar distance is as small as 6 kpc. We consider it reasonable that the NE2001 fractional distance uncertainty for this system is about 25%, i.e., $d_8 = 1 \pm 0.25$.

PSR J1437–5959 is located $15'$ ($= 35\,d_8$ pc) from the geometric center of the shell G315.9–0.0, its putative place of birth. For a true age τ, parameterized as $\tau_{114} = \tau/\tau_c$, the pulsar velocity in the plane of the sky is $V_t = 300\,d_8/\tau_{114}\,\mathrm{km\,s^{-1}}$, which is a perfectly reasonable velocity for a young neutron star (e.g., Arzoumanian et al. 2002). For almost any ISM phase, this is also a highly supersonic velocity.

While $\approx 300\,\mathrm{km\,s^{-1}}$ is a plausible velocity for a young pulsar, we now consider the possibility that for PSR J1437–5959 the true velocity may be substantially larger. We know little about the ISM density near SNR G315.9–0.0, but it seems reasonable to question whether the age of the SNR really is as large as 114 kyr, especially in view of its relatively undisturbed, if incomplete, circular symmetry. Also, the SNR shell radius, $R_{\mathrm{SNR}} = 17\,d_8$ pc, may be small for such a large age: for adiabatic expansion, the Sedov solution implies $\tau \approx 22\,d_8^{5/2}(n_0/E_{51})^{1/2}$ kyr, for a hydrogen ambient medium of density $n_0\,\mathrm{cm}^{-3}$ and SN explosion kinetic energy of $10^{51}\,E_{51}$ erg (a search for thermal X-rays from the SNR could provide useful constraints on its age). In addition, for the nominal age, the long pulsar wind trail (of length $17\,d_8$ pc) must have remained remarkably collimated for about 50 kyr. A detailed study of the PWN (now underway using the ATCA) may find whether this is reasonable. If on the other hand $\tau_{114} \ll 1$, these possible difficulties disappear. In that case, the pulsar age is $\ll \tau_c$. For instance, if $\tau = 0.2\,\tau_c$, the implied initial spin period of the neutron star is $P_0 \approx 55$ ms. Such relatively large initial periods, close to their current periods, are inferred for other pulsars (e.g., Camilo et al. 2006; Kaspi et al. 2001), and this could be the case as well for PSR J1437–5959. And if $\tau_{114} \approx 0.2$, then $V_t \approx 1500\,\mathrm{km\,s^{-1}}$. The expected proper motion for the pulsar (or, as its proxy, for the head of the bow shock nebula) is $\mu = 8/\tau_{114}\,\mathrm{mas\,yr^{-1}}$. If indeed $\tau_{114} \ll 1$, this could be measurable with the ATCA. Thus, multiwavelength observations of SNR G315.9–0.0, its associated PSR J1437–5959, and its bow shock PWN, may usefully constrain the properties of this newly identified system, and put it into context in the zoo of young neutron stars and their environments.

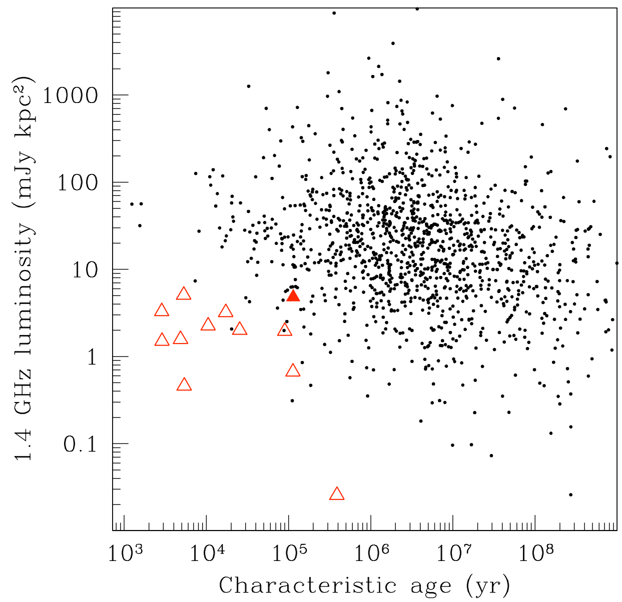

FIG. 3.— Radio luminosity at 1.4 GHz ($L_{1.4}$) vs. characteristic age (τ_c) for 1259 pulsars in the Galactic disk with $\tau_c < 10^9$ yr. The pulsars denoted by red triangles (PSR J1437–5959 is the filled one) were discovered in directed searches of PWNe/energetic targets (see § 3). All other information is from the ATNF pulsar catalog (Manchester et al. 2005).

PSR J1437–5959 has a very small flux density, and it is not surprising that it was not identified previously in relatively shallow undirected surveys. Its location was observed in the Parkes multibeam survey of the Galactic plane (e.g., Manchester et al. 2001), and although we do detect the pulsar faintly in archival data from 1997 October 26, it is not significant in an unbiased search. Its luminosity, $L_{1.4} \equiv S_{1.4}d^2 \approx 5\,d_8^2\,\mathrm{mJy\,kpc^2}$, is low by historical standards, but following numerous young pulsar discoveries in recent years is now unremarkable. We update the current state of play in Figure 3

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

(using data from the ATNF pulsar catalog[10] along with revised and unpublished fluxes in some cases), where we highlight the radio pulsars discovered in deep directed searches of PWNe/high-energy targets (Camilo et al. 2002a,b,c,d, 2006, 2009a,b; Gupta et al. 2005; Halpern et al. 2001; Keith et al. 2008; Roberts et al. 2002, and this work). The most sensitive searches possible with Parkes, in the absence of significant scattering (see Camilo et al. 2009a; O'Brien et al. 2008), reach threshold $L_{1.4} \sim 1$ mJy kpc^2 at $d \sim 5$ kpc. Figure 3 then suggests that while the faint tail of the population remains out of reach in a significant Galactic volume (even at more sensitive telescopes like the GBT), there is also a substantial population of young pulsars with $L_{1.4} \sim 5$ mJy kpc^2 that is detectable to great distances, given a maximum effort on carefully selected targets, exemplified here by PSR J1437–5959 and SNR G315.9–0.0.

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Facilities: ATCA, Molonglo, Parkes (PDFB, PMDAQ), Swift (XRT)

[10] http://www.atnf.csiro.au/research/pulsar/psrcat

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