Deep Searches for Young Pulsars

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Abstract. By 2000 there were only 10 established Galactic pulsar–supernova remnant associations. Two years later there are 16 such associations known. I discuss the work leading to this substantial increase. In particular I summarize an ongoing search project that has resulted in the detection of several young pulsars with a very low radio luminosity of about 1 mJy kpc\(^2\) at 1.4 GHz, and comment on future prospects.

1. Introduction

Young pulsars are objects of interest for a variety of reasons: inferring the initial period, velocity, and magnetic field distributions of neutron stars may inform the physics of core collapse; measuring their “beaming fraction”, luminosities, and spectra is crucial for making a census of the Galactic population and determining the birthrate of pulsars; also, they frequently exhibit period glitches, and emit substantial amounts of X- and \(\gamma\)-rays — these can be observed to learn about the internal composition of neutron stars, and their emission mechanisms. In addition, many young neutron stars are embedded in compact non-thermal radio and/or X-ray pulsar wind nebulae (PWNe) where the ambient medium confines the relativistic pulsar wind, or otherwise interact with their host supernova remnants (SNRs); they are therefore unique probes of their immediate environment and the local interstellar medium (ISM).

A natural location to search for young pulsars is the Galactic plane and more specifically SNRs. However, establishing bona fide associations between Galactic pulsars and SNRs has been a painfully slow-going business: two were known by 1970 (those of the Crab and Vela), five by 1985, and only 10 by 2000 (see compilation by Kaspi & Helfand 2002), despite more than 200 SNRs and 1400 pulsars known. It is instructive to consider how those associations were established: in four cases the pulsars were discovered in undirected searches, even if the respective SNRs were already known (B0531+21/Crab; B0833–45/Vela; B2334+61/G114.3+0.3; J0538+2817/S147); in a further three cases the pulsars were detected in directed searches of known point/X-ray sources (B1509–58/G320.4–1.2; B1951+32/CTB 80; J1811–1925/G11.2–0.3); while in only three cases the pulsars were discovered in unbiased searches of (sometimes large) SNRs (B1757–24/G5.4–1.2; J1341–6220/G308.8–0.1; B1853+01/W44).

Clearly the wholesale search of SNRs has not been immensely productive in this regard — indeed, a survey of 88 (77 entire) SNRs in the 1990s netted zero associated pulsars (Kaspi et al. 1996; Gorham et al. 1996; Lorimer, Lyne, & Camilo 1998). One problem is that the large total area to be searched limits the integration time used per telescope pointing. More recently the Parkes
multibeam pulsar survey, using a 13-beam receiver system at a frequency of 1.4 GHz with a bandwidth of 0.3 GHz and individual 35 min pointings, covered a very large area ($|b| < 5^\circ; 260^\circ < l < 50^\circ$) with sensitivity broadly comparable to that of the previous best SNR surveys. While extraordinarily successful, discovering more than 600 pulsars (e.g., Manchester et al. 2001), this survey to date has yielded only one new pulsar–SNR association (see Fig. 1 left). I now describe a far more efficient method for detecting young pulsars.

Figure 1. (Left): PSR J1119–6127 (cross; Camilo et al. 2000) centered on the shell SNR G292.2–0.5 (ATCA image; Crawford et al. 2001). PSR J1846–0258, with very similar spin parameters, was discovered serendipitously in the composite SNR Kes 75 by Gotthelf et al. (2000). (Right): VLA contours of 25% polarized, flat spectrum source overlaid on Chandra image of PWN G106.6+2.9. PSR J2229+6114 is coincident with the central point source (Halpern et al. 2001).

2. Deep Searches

The certain existence of a PWN by definition points to the presence of an energetic and reasonably young pulsar. PWNe also have the virtue of being compact (usually smaller than the primary beam size of a large telescope at 1.4 GHz, or 3–15 arcmin). Thus it is eminently reasonable to search all PWNe as deeply as possible. (Despite arguments to the contrary there is no credible evidence suggesting that young pulsars have higher radio luminosity than their older brethren — see Fig. 4. If true, this would obviate the need to search deeper than some threshold luminosity.) Alas, not all that glitters is a PWN. (Some “SNRs” listed in the Green 2001 catalog are not even clearly SNRs.) However, with the Chandra X-ray Observatory and its superb resolving power, one can for the first time often identify unambiguously a PWN and its embedded pulsar even when pulsations are not detected. These are then targets worthy of the utmost efforts at radio wavelengths in pursuit of pulsations, as I now demonstrate.

Energetic and young pulsars are the only substantial established class of Galactic point $\gamma$-ray sources detected with EGRET on the CGRO satellite. Understanding the remaining unidentified EGRET sources presents a considerable
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challenge owing to their large positional uncertainties. In an exhaustive multi-wavelength study of 3EG J2229+6122, Halpern et al. identified all but one of the X-ray sources within its error box. Its high ratio of X-ray-to-optical flux, particularly when combined with a coincident polarized and flat-spectrum radio source, strongly suggested a pulsar interpretation. Finally, a Chandra observation resolved a ring of emission surrounding a point source (Fig. 1 right), much as for the Vela PWN/pulsar, clearly indicating a PWN. Pursuing this trail we detected the pulsar in a 2 hr observation using the 76 m telescope at Jodrell Bank, subsequent to which pulsations were detected in X-rays. PSR J2229+6114 has period $P = 51$ ms, dispersion measure $\text{DM} = 205 \text{cm}^{-3} \text{pc}$, characteristic age $\tau_c = P/2\dot{P} = 10$ kyr, and spin-down luminosity $\dot{E} = 4\pi^2 I \dot{P} / P^3 = 2.2 \times 10^{37} \text{erg s}^{-1}$, where $I \equiv 10^{45} \text{g cm}^2$. There is no plausible alternative counterpart, and the pulsar is virtually certainly the source of 3EG J2229+6122's $\gamma$-rays (Halpern et al. 2001). In all respects it appears to be similar to the Vela pulsar/PWN, at $\sim 10$ times the distance. It also has a low radio luminosity: with a flux density at 1.4 GHz of $S_{1400} = 0.25 \text{mJy}$, the luminosity is $L_{1400} \equiv S_{1400} d^2 \sim 2 \text{mJy kpc}^2$.

Figure 2. (Left): Chandra image of SNR G292.0+1.8 (Hughes et al. 2001) with position (arrow) and mean pulse profile of PSR J1124–5916 (Camilo et al. 2002a) indicated. (Right): Chandra image of SNR G54.1+0.3 (Lu et al. 2002). PSR J1930+1852 (Camilo et al. 2002c) is coincident with the central point source seen in inset.

Figure 2 (left) shows a beautiful Chandra observation of the oxygen-rich $\sim 1700$ year-old composite SNR G292.0+1.8 (Hughes et al. 2001). Although not clear in this representation, the data clearly resolve a $\sim 2'$ PWN within which is located a point source. While this SNR had been searched previously (as had many of these targets), the Chandra results encouraged new efforts. In a 10 hr integration at Parkes using the multibeam system, we detected PSR J1124–5916 (Camilo et al. 2002a), with $P = 135$ ms, $\text{DM} = 330 \text{cm}^{-3} \text{pc}$, $\tau_c = 2900$ yr, and $\dot{E} = 1.2 \times 10^{37} \text{erg s}^{-1}$. It is a very weak source, with $S_{1400} = 80 \mu \text{Jy}$ and $L_{1400} \sim 2 \text{mJy kpc}^2$. Figure 2 (right) once again shows a spectacular Chandra image, of the “Crab-like” SNR G54.1+0.3 (that is, a PWN, with no evidence for stellar ejecta or thermal emission from interaction with the ambient ISM). In a 3 hr observation at Arecibo using a frequency of 1.2 GHz and bandwidth of 0.1 GHz, we detected the pulsar coincident with the central point source visible
in the image. PSR J1930+1852 has spin parameters that are virtually identical to those of PSR J1124–5916, and is an even fainter radio source (Camilo et al. 2002c). X-ray pulsations were detected in both of these objects subsequent to the radio discoveries.

3C58 is a Crab-like SNR thought to be the remnant of SN 1181. After 20 years of searching at X-ray and radio wavelengths, PSR J0205 +6449 was finally discovered with the Chandra and RXTE telescopes (Murray et al. 2002). Its spin parameters \( P = 65 \text{ ms}, \tau_c = 5400 \text{ yr}, \) and \( E = 2.7 \times 10^{37} \text{ erg s}^{-1} \) can be reconciled with the 1181 AD explosion if the initial spin period was a relatively large \( \sim 60 \text{ ms} \). Subsequent to this we detected the pulsar with the Green Bank Telescope in individual 8 hr integrations at frequencies of 0.8 and 1.4 GHz: it is the weakest of all (so far) known young pulsars, with \( S_{1400} = 50 \mu\text{Jy} \) and \( L_{1400} \sim 0.5 \text{ mJy kpc}^{-2} \), and has DM = 141 cm\(^{-3}\)pc (Camilo et al. 2002b).

![Figure 3](image_url)

Figure 3. (Left): Large scale view of G359.23–0.82 (“The Mouse”), showing its bright head and long tail, and two unrelated SNRs (0.8 GHz MOST image). (Right): Detailed view of the Mouse’s head from VLA observations at 8.4 GHz. The ellipse denotes the current positional uncertainty of PSR J1747–2958 (Camilo et al. 2002d).

The fifth of our recent young pulsar discoveries is located near the “Mouse”, an axisymmetric non-thermal nebula with a polarized tail, long thought to be caused by a fast-moving pulsar (see Fig. 3). PSR J1747–2958, discovered in a 9 hr observation at Parkes, has \( P = 98 \text{ ms}, \) DM = 101 cm\(^{-3}\)pc, \( \tau_c = 25 \text{ kyr}, \) and \( E = 2.5 \times 10^{36} \text{ erg s}^{-1} \) (Camilo et al. 2002d). Its distance, determined from the DM to be \( \sim 2 \text{ kpc} \), implies a luminosity \( L_{1400} \sim 1 \text{ mJy kpc}^{-2} \). The probability of chance coincidence between the Mouse’s head and the pulsar, considering its current positional uncertainty, is only \( \sim 5 \times 10^{-5} \); the distance constraints to both objects are consistent; and the (ROSAT) X-ray energetics of the Mouse’s head are compatible with being powered by the pulsar. We thus feel confident in associating both objects: the Mouse is a PWN powered by PSR J1747–2958, with the morphology of the head expected to be shaped by ram-pressure balance between the pulsar wind and the ISM. Future measurements in this system should be quite valuable to characterize the local ISM.
We have detected these five young pulsars associated with PWNe in the course of searching a total of 20 PWNe. We expect to search seven additional PWNe shortly. Also, we have made deep searches of five other young neutron stars with no surrounding PWNe: the four well known “radio-quiet neutron stars” in SNRs G260.4–3.4, G266.2–1.2, G296.5+10.0, and G332.4–0.4 (reaching luminosity limits $L_{1400} \sim 0.2 \text{ mJy kpc}^2$), and RX J1836.2+5925 in 3EG J1835+5918 (Halpern et al. 2002). We have no confirmed detections of pulsations from any of these objects, although we have a very intriguing candidate from G296.5+10.0 at the X-ray period observed by Pavlov et al. (2002).

3. Discussion

Figure 4. $L_{1400}$ versus $\tau_c$ for 833 pulsars. Filled circles represent the nine Galactic radio pulsars known by 2000 to be associated with SNRs, and PSR B0540–69 in the LMC (at $\sim 200 \text{ mJy kpc}^2$ and 1600 yr). Open squares indicate the recently discovered pulsars described here (PSR J1119–6127 is at $\sim 30 \text{ mJy kpc}^2$).

The work summarized here indicates clearly that many young pulsars beam towards the Earth, although what exact fraction is still unclear. What is abundantly clear is that many of them are very weak radio sources (see Fig. 4). When this project is completed, a careful analysis of the sensitivity and selection effects relevant to the search of the $\sim 25$ PWNe under study should yield useful constraints on the combination of luminosity distribution and beaming fraction of young pulsars. In the meantime we may consider the following: nearly half of all well-established PWNe already have pulsations detected; the least luminous young radio pulsar known has $L_{1400} \sim 0.5 \text{ mJy kpc}^2$; and few of the searches

\footnote{It is important to note that the radio luminosities discussed here are really “pseudo-luminosities”: they assume that 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.}
done to date (including ones described here) reach this low level of luminosity. I am forced to conclude, optimistically, that from a purely observational viewpoint nearly all remaining PWNe could contain a pulsar beamed at us, and that several most certainly do. The lesson is clear: one should be discerning in choosing targets (often pointed to by Chandra or XMM), and then (the wisdom of time-assignment committees permitting) use maximum effort in both time and bandwidth to pursue them. Also, multi-path propagation cannot be neglected for some distant objects: at $\sim 10$ kpc along the Galactic plane, some lines-of-sight have a predicted “scattering timescale” of $\sim 20$ ms at 1.4 GHz. In these cases, sensitive $\sim 3$ GHz systems with large bandwidth may be appropriate. It is hoped that several planned improvements at Parkes, Arecibo, and GBT will be pushed to fruition soon, making possible even more sensitive searches.

I conclude with one possibly important concern. Nearly 200 of the 231 SNRs listed in the Green (2001) catalog are shells. Could a substantial number harbor pulsars? I think yes: two of six associated pulsars discovered in undirected searches are located in shell SNRs, and have high $L_{1400} \sim 20$ mJy kpc$^2$. They also have spin parameters rather different from those of most associated pulsars. Thus we neglect these SNRs at our peril. But how to go about searching them?

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