# Part 3

# Pulsars: Surveys and Galactic Distribution

## Searches for Young Pulsars

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**Abstract.** I review the results of radio and X-ray searches for pulsations from young neutron stars, emphasizing work accomplished in the last five years. I cover undirected searches, as well as directed searches of pulsar wind nebulae, EGRET $\gamma$-ray sources, and also the search for pulsations from "isolated neutron stars" and "central compact objects".

## 1. Introduction

With one supernova occurring in the Galaxy every $\sim 100$ years, it follows that young neutron stars are rare. Because of the manifold applications of their study, however, considerable effort continues to be devoted to detecting young neutron stars. In the age of *Chandra* and *XMM*, the existence of a young magnetospherically active neutron star can often be taken for granted even in the absence of the detection of pulsations, most spectacularly via the imaging and spectroscopy of the beautiful structures that form when the relativistic pulsar winds are confined by the ambient pressure — a point source surrounded by such a pulsar wind nebula (PWN) is proof enough. Still, proceeding to extract maximum understanding from the multi-wavelength observations of such systems requires knowledge of the neutron star spin period $P$, its derivative, and derived quantities: the spin-down luminosity $\dot{E} = 4\pi^2 I \dot{P}/P^3$, which ultimately is the energy source for all that we detect from most pulsars/PWNe, where the neutron star moment of inertia is $I \equiv 10^{45}\,\mathrm{g\,cm^2}$; the characteristic age $\tau_c = P/2\dot{P}$, usually considered to be an upper limit on the real age, although because of unknown braking indices of rotation $n$ (where $\dot{\nu} \propto -\nu^n$ and $\nu = 1/P$), the real age can easily be up to about twice this value; and an estimate of the surface magnetic dipole field strength, $B = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G. For this reason, this review will emphasize searches for *pulsations* from young neutron stars, summarizing efforts made in this area in the past five years.

## 2. How to Search for Pulsars

In principle, pulsations can be searched throughout the entire electromagnetic spectrum, from radio to $\gamma$-ray wavelengths. In practice, for reasons having to do both with the spectral energy distribution of pulsed emission and the available instrumentation, only radio and X-ray have been successful bands for such searches (see, e.g., Chandler et al. 2001, for a search for $\gamma$-ray pulsations).

The original discovery of pulsars relied on the detection of individual radio pulses with no need to account for their dispersive propagation. Since the early days few pulsars have been discovered via detection of single pulses (see Nice 1999 for an exception). Nevertheless it is important to keep in mind the case of the Crab pulsar, discovered via its "giant pulses". The important point here is that giant (dispersed) pulses can be exceptionally bright, detectable at up to $\sim$ Mpc distances! See McLaughlin & Cordes (2003), Johnston & Romani (these proceedings) and Cordes (these proceedings) for a discussion of giant pulses.

The standard modern method to search for pulsars relies on the use of Fast Fourier Transform-based techniques to analyze time series of up to several million pulses. Also, for long observations, "acceleration search" techniques can be be employed (e.g. Ransom 2001) to partially correct for a changing pulse period caused by binary motion or a large $\dot{P}$ from a young pulsar. The above applies to both radio and X-ray searches. For radio searches, in addition, dispersive propagation must be corrected for by "de-dispersing" the time samples from many narrow frequency channels at a large ($\sim$ 100–1000) number of trial dispersion measures before searching the one-dimensional time series for periodic signals.

## 3.   Where to Search for Pulsars

Search efforts consist of undirected/"all-sky" surveys and directed searches of promising objects. The most successful undirected surveys for young pulsars cover the Galactic plane (see Fig. 1 left), of which the Parkes multibeam survey represents the state-of-the-art (see §4). However, even high-latitude searches can uncover nearby or high-velocity young pulsars (e.g., McLaughlin et al. 2002).

Directed searches include those of the following targets:

1. PWNe: by definition these contain young pulsars; whether the pulsars are beaming toward the Earth or are luminous enough for pulsations to be detected is a question to be addressed by sensitive searches (see §5.2).

2. Supernova remnants (SNRs): obviously a good place to look for young pulsars — but some are rather large, and not all contain neutron stars (see, e.g., Kaplan et al., these proceedings).

3. $\gamma$-ray (EGRET) sources: a subset of these are expected to be powered by young pulsars. However the positional uncertainty of the sources is usually very large, making blind searches of the error boxes a difficult task (see, e.g., Nice & Sayer 1997; Roberts et al., these proceedings). The process is simplified if there is a good X-ray candidate within the error box that can be followed with maximal effort to search for pulsations (see §5.1).

4. "Unusual" (X-ray) sources:

   - *ROSAT* soft sources (see §6; Kaplan 2004).
   - Central Compact Objects (CCOs; see §7; Pavlov et al., these proceedings).
   - AXPs and SGRs (see Kaspi, these proceedings). None have been detected at radio wavelengths (e.g., Crawford et al. 2002).
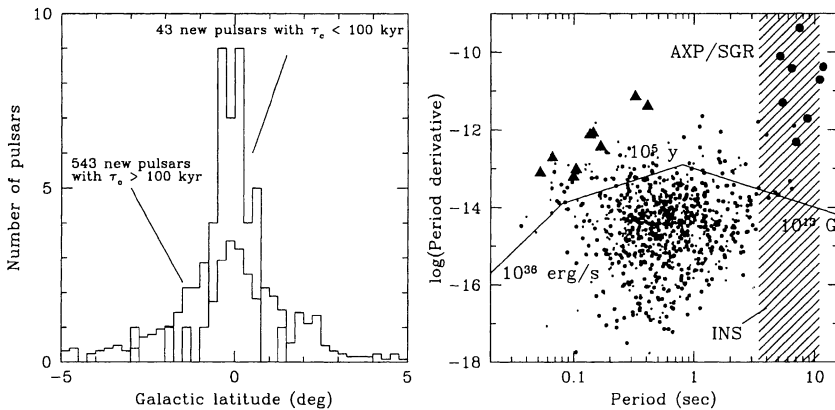
Figure 1. *Left:* Distribution in latitude for the pulsars discovered in the Parkes multibeam survey that have a known characteristic age: young pulsars have a much smaller scale-height than older ones (both histograms have equal areas). *Right:* The $P$–$\dot{P}$ diagram with three lines, above which lie the energetic, young, or high-$B$ pulsars; the period range of the INSs is indicated, and AXPs/SGRs are shown at top right. Multibeam pulsars are represented by medium-size dots. Nine young pulsars mentioned in §4.1 and Table 1 are indicated at top left.

5. Radio steep spectrum/polarized sources: the young pulsar B1951+32 in SNR CTB 80 was found in this manner (Strom 1987; Kulkarni et al. 1988). This method has not produced results of late (e.g., Crawford et al. 2000; Kaplan et al. 2000; Kouwenhoven 2000).

## 4.  The Parkes Multibeam Survey of the Galactic Plane

This search along the inner Galactic plane ($|b| < 5°$; $260° < l < 50°$) has discovered $\sim 725$ new pulsars in an area where 330 were previously known (e.g., Kramer et al. 2003). Here we emphasize aspects related to young pulsars. The survey had a sensitivity comparable to those of the directed SNR searches of the 1990s (Gorham et al. 1996; Kaspi et al. 1996; Lorimer et al. 1998).

The survey has found 43 pulsars with $\tau_c < 10^5$ yr, compared to 24 previously known. Of these, 14 are "Vela-like" in that they are energetic, with $\dot{E} > 10^{36}$ ergs s$^{-1}$, doubling the number of such pulsars known — the kind that primarily power X-ray-bright PWNe. On average the new pulsars are more distant than those previously known; some are being observed with *Chandra* and *XMM* and it remains to be seen what they may add to PWN phenomenology.

An unexpected haul from the survey has been the number of pulsars with $B > 10^{13}$ G, 25 compared to nine previously known. Some have spin parameters indistinguishable from those of some AXPs (e.g., McLaughlin et al. 2003, and these proceedings). However, their emission characteristics are apparently entirely radio-pulsar-like, with no particularly plentiful X-rays.

### 4.1.    Youngest multibeam pulsars; a serendipitous X-ray discovery

*J1119–6127:*    Unusual in being very young ($\tau_c = 1600\,\mathrm{yr}$) while having a large $P = 0.4\,\mathrm{s}$. The latter is a consequence of its large $B = 4 \times 10^{13}$ G. It is also one of only six pulsars with a known braking index ($n = 2.9$; Camilo et al. 2000). The newly identified (Crawford et al. 2001) X-ray-bright (Pivovaroff et al. 2001) shell SNR G292.2–0.5 was subsequently found to be associated with the pulsar, and a faint X-ray PWN has also been identified (Gonzalez & Safi-Harb 2003).

*J1357–6429:*    Less exotic than J1119–6127, but still one of the 10 youngest Galactic pulsars known, with $P = 166\,\mathrm{ms}$ and $\tau_c = 7300\,\mathrm{yr}$. It is positionally coincident with the SNR candidate G309.8–2.6 (Camilo et al., in preparation). Further radio and X-ray work are required in order to characterize this system.

*J1846–0258:*    Discovered serendipitously by *RXTE* within the composite SNR Kes 75, with parameters comparable to those of J1119–6127: $P = 0.3\,\mathrm{s}$, $\tau_c = 720\,\mathrm{yr}$ (Gotthelf et al. 2000). Has an unusually "efficient" PWN ($L_X \approx 0.25\dot{E}$; Helfand et al. 2003) and no radio pulse detection (Camilo et al., in preparation).

### 4.2.    Possible SNR associations with multibeam pulsars

The most curious candidates are PSR J1726–3530/G352.2–0.1 and PSR J1632–4818/G336.1–0.2 (Manchester et al. 2002). The putative SNRs are apparently coincident shells identified in MOST survey maps and require further investigation. Interestingly, both pulsars have $\tau_c < 20\,\mathrm{kyr}$ and $P \approx 1\,\mathrm{s}$ — two more examples of large-$B$, long-$P$, youthful multibeam pulsars: 16 out of 43 with $\tau_c < 10^5$ yr have $P > 0.4$ sec, compared to five out of 33 previously known!

### 4.3.    Possible EGRET associations with multibeam pulsars

Two energetic multibeam pulsars that are coincident in projection with two unidentified EGRET sources can plausibly power them (D'Amico et al. 2001). A few other pairings are possibly real (e.g., Torres et al. 2001; Kramer et al. 2003). However, none of these cases are ironclad. The difficulty in assessing such identifications is illustrated by one small patch of sky containing three energetic multibeam pulsars, two EGRET sources, one PWN, one SNR, with substantial overlap — and with no clear understanding of the relationships, if any, between these objects (Roberts et al. 1999, 2001; Doherty et al. 2003).

### 5.    Directed Searches

### 5.1.    EGRET error boxes

The "method" used in §4.3 for evaluating the potential association of serendipitously discovered energetic pulsars with positionally coincident EGRET error boxes suffers from one fatal flaw: there is no guarantee that the $\gamma$-ray source (which must produce substantial X-ray flux) is not some as-yet-unidentified X-ray source within the error box, corresponding to an as-yet-undetected pulsar.

    The only way to be certain of an EGRET source–neutron star correspondence (short of detection of $\gamma$-ray pulsations), is to survey the entire EGRET box, methodically identifying all X-ray sources, until only one remains otherwise unidentified that has characteristics typical of neutron stars. This method was

Table 1.    Young pulsars discovered in directed searches.

| PSR | $P$ (ms) | $\tau_c$ (kyr) | $\dot{E}$ (ergs s$^{-1}$) | Association | Refs |
|---|---|---|---|---|---|
| J2229+6114 | 51 | 10 | $2 \times 10^{37}$ | 3EG J2229+6122 | (1) |
| J2021+3651 | 104 | 17 | $3 \times 10^{36}$ | 3EG J2021+3716 | (2) |
| J0205+6449 | 65 | 5.4 | $3 \times 10^{37}$ | SNR 3C 58 | (3) |
| J1124−5916 | 135 | 2.9 | $1 \times 10^{37}$ | SNR G292.0+1.8 | (4) |
| J1930+1852 | 136 | 2.9 | $1 \times 10^{37}$ | SNR G54.1+0.3 | (5) |
| J1747−2958 | 98 | 25 | $2 \times 10^{36}$ | "Mouse" PWN | (6) |

Refs: (1) Halpern et al. 2001; (2) Roberts et al. 2002; Hessels et al. 2004; (3) Murray et al. 2002; Camilo et al. 2002b; (4) Hughes et al. 2001; Camilo et al. 2002a; Hughes et al. 2003; (5) Lu et al. 2002; Camilo et al. 2002c; (6) Camilo et al. 2002d; Gaensler et al. 2004.

used by Halpern et al. (2002) to identify the magnetospherically active neutron star RX J1836.2+5925 with 3EG J1835+5918 — even if, despite considerable efforts, no pulsations were detected. The same method pursued by Halpern et al. (2001) led to the detection of PSR J2229+6114, the first object listed in Table 1. With some differences, a broadly comparable method was used by Roberts et al. (2002) to survey five EGRET GeV sources, leading to the detection of PSR J2021+3651. In these cases, after extensive preliminary work, pulsations were first detected in deep radio searches, and then also in X-rays. A further recent search along these lines was performed by Becker et al. (2004) of a candidate neutron star within 3EG J2020+4017 coincident with the $\gamma$-Cygni SNR. The source turned out not to be a neutron star, and deep radio searches for pulsations from the EGRET source were also negative. However, in this case only part of the EGRET box was surveyed with sensitive X-ray observations, and it is possible that an as-yet-undetected X-ray source/neutron star lurks within.

## 5.2.    Pulsar Wind Nebulae

Pulsations were detected from the third-through-fifth sources in Table 1 after they had been identified as clear PWNe with central point sources via high-resolution X-ray observations. Sensitive pulsation searches were then successful, in X-rays in the case of PSR J0205+6449 and at radio wavelengths for the other two pulsars. Following the initial detections, all three now have pulsations detected in both wavebands. Another example of such a search is that for the pulsar in the SNR CTA 1 (coincident with 3EG J0010+7309). In this case, *Chandra* imaging observations reveal the pulsar, but even extremely constraining radio searches have failed to uncover pulsations (Halpern et al. 2004). The last source in the Table was thought to be a PWN shaped by a bow shock caused by the supersonic motion of an unseen pulsar through the interstellar medium. A deep radio observation confirmed this by detecting the pulsar J1747−2958.

In these examples the pulsars have very low radio luminosities ($L_{1400} \equiv S_{1400}d^2 \sim 1\,\text{mJy kpc}^2$, with $S_{1400}$ the 1400 MHz flux density), suggesting that such limits must be attained in other searches before alternative explanations for non-detection of pulsations (e.g., beaming, radio-quietness) need be entertained.

Table 2.    INSs and their periods.

| Name (RX) | $P$ (s) | Notes/References |
|---|---|---|
| J0420.0–5022 | 3.4 | $B \lesssim 8 \times 10^{13}$ G; Haberl et al. 1999, 2004 |
| J0720.4–3125 | 8.4 | $B \lesssim 10^{13}$ G; Zane et al. 2002; Kaplan et al. 2002 |
| J0806.4–4132 | 11.4 | $B \lesssim 3 \times 10^{14}$ G; Haberl & Zavlin 2002 |
| J1308.6+2127 | 10.3 | Hambaryan et al. 2002; Haberl et al. 2003 |
| J1605.3+3249 | ? | van Kerkwijk et al. 2004 |
| J1856.5–3754 | ? | Ransom et al. 2002 |
| J2143.0+0654 | ? | Zampieri et al. 2001 |

## 6.    ROSAT Isolated Neutron Stars (INSs)

These are bright (nearby) soft X-ray sources, with optical counterparts, no SNR associations, and with no radio emission detected (e.g., Kaplan et al. 2003; Johnston 2003). Table 2 lists these sources and shows that many now have a periodicity determined. In a search for other neutron stars in a *ROSAT* survey, Rutledge et al. (2003) estimate that there are $\lesssim 67$ possible candidates.

## 7.    Central Compact Objects

These are bright X-ray sources at the center of SNRs, thought to be neutron stars. They have broadly similar spectral, but different temporal properties. No radio emission has been detected from any of them (e.g., Gaensler et al. 2000). No pulsations have been detected from the CCOs in Cas A, G266.2–1.2, RCW 103, or Pup A. Candidate CCOs have been recently identified in G347.3–0.5 (Lazendic et al. 2003) and Kes 79 (Seward et al. 2003), and no radio pulsations have been detected from them either (Camilo et al., in preparation).

The one exception to the non-detection of pulsations from CCOs is of the neutron star in the SNR PKS 1209–51/52, with $P = 424$ ms (Zavlin et al. 2000). However, the spin behavior of this source is puzzling (e.g., Zavlin et al. 2004), and the last word on it has not yet been written (see Pavlov et al. and De Luca et al., these proceedings).

## 8.    Conclusions

Six of the nine youngest Galactic pulsars known (with $\tau_c < 10$ kyr) were discovered in the past five years at both radio and X-ray wavelengths. Three more energetic pulsars were discovered in directed searches of PWNe, with several more detected in the multibeam survey. These advances point to the complementarity of undirected and directed, as well as of radio and X-ray searches.

The median luminosity for the multibeam pulsars with $\tau_c < 10^5$ yr is $L_{1400} \approx 27$ mJy kpc$^2$, compared to $L_{1400} \approx 60$ mJy kpc$^2$ for those previously known. However, an analysis of deep radio searches of 23 PWNe (Camilo et al., in preparation) shows that the bottom of the luminosity function for young pulsars is at least one-to-two orders of magnitude below this value.

We now also recognize that some very young pulsars, like PSR J1119–6127 (§4.1; see also §4.2), do not betray their presence via previously detected PWNe.

They may lurk within otherwise seemingly empty shell SNRs or where no SNR has yet been identified. The birth rate of these systems is not known.

The impact of these realizations toward pursuing a thorough understanding of the population of young rotation-powered neutron stars is sobering: a *lot* more work remains to be done! Much deeper undirected searches should be done, and the very deepest possible searches of promising targets must be accomplished. New instrumentation (e.g., ALFA at Arecibo; the GBT) will be useful in this regard, and so will the future *GLAST* mission. This work should be done, as much as possible, while *Chandra* and *XMM* are still happily collecting photons.

Taken as a whole, the many advances of the past five years in the areas of AXPs, SGRs, CCOs, INSs, and "standard" pulsars help paint a fascinating if still rather incomplete picture of the demographics and environments of young neutron stars. The search for pulsations remains a key aspect of this discipline.

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