F. Camilo

Pulsar Searches in the Northern Hemisphere

Abstract

We summarize the main parameters of all searches for radio pulsars known to us carried out in the northern hemisphere since about 1990, including searches of supernova remnants (SNRs), OB runaway stars, γ- and X-ray error boxes, and compact radio sources, in addition to undirected "all-sky" surveys. We also tabulate some parameters of the 47 binary and recycled pulsars known in the disk of the Galaxy.

I Introduction

One of two general approaches may be adopted in deciding where to search for pulsars: if we believe we know where pulsars are located (e.g., in SNRs, near their birthplaces), we may carry out *directed searches* of the appropriate targets; alternatively we may search "blindly" over large areas of sky, carrying out *undirected searches*. Both approaches have yielded exciting discoveries, such as that of PSR B1937+21, the first millisecond pulsar (Backer et al. 1982), and that of PSR B1913+16, the first binary pulsar (Hulse & Taylor 1975), respectively.

In the tables that follow we include the radio frequency used in each search, the sampling interval used (the minimum detectable pulse period is at least $2\,T_{\rm samp}$), the time spent pointing in each direction, and the minimum flux density detectable in the search. This quantity, $S_{\rm min}$, is usually appropriate only for long period pulsars observed at the telescope beam center and in directions where the sky temperature is as low as it can be within the search area. For a fuller discussion of sensitivity issues see, e.g., Camilo, Nice & Taylor (1996).

II Directed Searches

The *supernova remnant* searches summarized in Table 1 have not discovered many associated pulsars, but it is not easy to infer how many SNRs actually have associated pulsars: many remnants are large and have not been fully surveyed, the high remnant

Table 1: Directed Searches

Telescope	Number of Targets	Frequency (MHz)	$T_{\rm samp}$ (ms)	$T_{\rm int}$ (min)	$S_{\rm min}$ (mJy)	Pulsars Found
		Supernova Remnants				
Arecibo	18[a]	430/1420	0.5–1.0	30–90	0.2–1.0	0
Arecibo	10	1400	0.5	5	> 0.2	1[b]
Jodrell Bank[c]	33	606	1.0	$\simeq 35$	> 2	2
		OB Runaway Stars				
VLA	44	1400[d]	2.6	12	0.2	0
NRAO 140′	40	575/770	1.0	72	1	1[e]
		EGRET (γ-ray) Error Boxes				
Arecibo	7	430	0.2	3	0.2	1[f]
NRAO 140′	27[g]	370/770/1390	0.5–2.0	36–143	0.4–3.6	0
		Einstein (X-ray) IPC Sources				
Arecibo	1300[h]	430	0.2	3.1	> 0.2	3[i]
		Steep Spectrum Compact Radio Sources				
WSRT	1[j]	325/410	$\simeq 0.2$	$\simeq 30$	$\simeq 1$	1[k]

[a] Many only partially surveyed (Gorham et al. 1996).

[b] PSR B1853+01 in W44 (Wolszczan, Cordes & Dewey 1991).

[c] See contribution by Lorimer et al. in these proceedings.

[d] Also used maps made at 5 GHz (Philp et al. 1996).

[e] Pulsar unrelated to OB star (Sayer, Nice & Kaspi 1996).

[f] Millisecond pulsar J0751+1807 unrelated to EGRET source (Lundgren, Zepka & Cordes 1995).

[g] 19 sources are in the second EGRET catalog (Nice & Sayer 1997).

[h] Total area surveyed $\simeq 27$ deg^2 (Zepka et al. 1996).

[i] One young pulsar, J0631+1036, possibly related to X-ray source.

[j] Linear polarization of $\sim 40\%$, spectral index of ~ -3 (WENS survey continuing; Kouwenhoven et al., in prep.).

[k] Pulsations from the millisecond pulsar J0218+4232 detected at Jodrell Bank (Navarro et al. 1995).

temperatures are non-uniform resulting in highly variable $S_{\rm min}$, pulsars with high velocity can escape the remnant boundaries, and many SNR properties (such as distance and age) are poorly constrained. For a survey of southern SNRs with the Parkes telescope see Kaspi et al. (1996), and see Kaspi (1996) for a discussion of pulsar/SNR associations.

OB runaway stars are thought to acquire their high velocities when their binary companions explode in SNe. If some of the newly-formed neutron stars remain bound, and the radio emission is not quenched in the winds of the OB stars, one may detect pulsars in these systems. None have been found to date, placing constraints on the binary survival fraction (see references from Tab. 1).

All identified Galactic γ-ray point sources are pulsars. There are some 40 unidentified unresolved sources detected by the *EGRET* instrument. Searches of some of these have proven unfruitful to date (Tab. 1), somewhat constraining models of the γ-ray source population (see references).

Some young radio pulsars emit substantial amounts of X-rays, making *unidentified X-ray sources* intriguing targets for the search of this distinctive class of pulsars. A recent search used a new algorithm for identifying X-ray sources, and surveyed 2/3 of those visible from Arecibo (Tab. 1).

Pulsars are virtually the only *steep spectrum compact radio sources* with high degrees of linear polarization. Follow-up work on one such source resulted in the discovery of PSR J0218+4232 (see Tab. 1), mimicking in several aspects the discovery of PSR B1937+21. Curiously these two are among the most luminous and have the largest period derivatives, $\dot{P}$, of any millisecond pulsars.

Other projects have included the search for radio pulsations from the γ-ray pulsar Geminga (Arecibo); the search of several Be/X-ray transients (Jodrell Bank); follow-up of compact, polarized candidates from the 21 cm Northern VLA Sky Survey (Green Bank); and a search of $\sim$ 150 low-mass white dwarfs that must have evolved in binary systems (Jodrell Bank & Parkes). No positive results have been reported, with some projects continuing.

III Undirected Searches

While most large-area pulsar surveys have been conducted at low radio frequencies, surveying the Galactic plane can be done to great advantage at high frequencies, reducing the deleterious effects of dispersion and scattering. Two very successful surveys at 1400 MHz were carried out in the late 1980s at Jodrell Bank and Parkes (Clifton et al. 1992; Johnston et al. 1992a). The *Effelsberg* high-frequency survey of the Galactic center region aims to detect pulsars that are severely scatter-broadened even at 1400 MHz. Such surveys, and those using a large telescope like *Arecibo* at high frequencies, have very small rates of sky coverage (see Table 2).

The "piggyback" survey searched most of the sky visible from *Arecibo* several times by using the 430 MHz feed slaved to the 1400 MHz feed being used to track sources in other programs (Tab. 2).

Table 2: Undirected Searches

Telescope	Search Area	Frequency (MHz)	$T_{\rm samp}$ (ms)	$T_{\rm int}$ (sec)	$S_{\rm min}$ (mJy)	Pulsars Found
		Assorted Searches				
Effelsberg	$\|b\| < 0.5°, \|l\| < 0.5°$	4850	0.5	540	0.2	0[a]
Arecibo	1 deg^2 at $b = 0°$	1400	0.25	300	0.2	1[b]
Arecibo	$-1° < \delta < +39°$	430	0.3	10	> 1	...[c]
		All-Sky Surveys for Millisecond Pulsars				
Jodrell Bank	$\delta > +35°$	408	0.3	314	3	1[d]
Green Bank	$\delta > +0°$	370	0.256	134	8	8[e]
Cambridge[f]	$\delta > -20°$	81.5	0.768	100–400	> 200	0
Bologna	$\delta > +0°$	408	0.064	67	9	0[g]

[a] About 25% of search area covered to date (Kramer et al., in preparation).

[b] $l \simeq 50°$, DM $= 400$ cm^{-3} pc (Wolszczan).

[c] Piggyback survey: 8 known pulsars detected; about 400 candidates to reobserve (Cordes & Backer, in preparation).

[d] 4,000 deg^2 searched so far (Nicastro et al. 1995).

[e] Relativistic binary PSR J1518+4904 discovered (see Nice, these proceedings). $15,900 + 1,500$ deg^2 searched and 76 known pulsars detected (Sayer, Nice & Taylor 1997).

[f] 30,300 deg^2 searched. $S_{\rm min}$ varies *greatly* as a function of δ. 20 known pulsars detected (Shrauner 1996).

[g] 1,100 deg^2 searched so far (D'Amico).

By far the most successful pulsar searches in the 1990s have been the large-area surveys for millisecond pulsars. Those summarized in Tab. 2 aim to cover about 2π sr in a relatively short period of time, sometimes with unusual parameters like very low radio frequency or very fast sampling rate.

The Arecibo surveys (Table 3) have discovered nearly half of all disk millisecond pulsars known. They are complementary to the very successful survey of the southern sky at the Parkes telescope that discovered 17 millisecond pulsars (Manchester et al. 1996; Lyne et al. 1997; see also Manchester, these proceedings): they are more sensitive (the numbers of pulsars found in the two surveys are comparable, while the area covered so far at Arecibo is 1/4 that at Parkes), but proceed more slowly. Several groups carry out the surveys at Arecibo; at present each of five groups is assigned eight disjoint 1°-wide declination strips with central declinations given in Tab. 3. After a long hiatus caused by a telescope upgrade, the searches will soon resume, with a four-fold improvement in frequency- and time-resolution that will increase sensitivity to the shortest-period pulsars. (For a more complete review of millisecond pulsar surveys see Camilo 1996.)

Table 3: Arecibo Millisecond Pulsar Surveys*

Group	Search Area	New Pulsars (MSP/Total)
Princeton	$\|b\| < 8°$ (260 deg^2)	2/24[a†]
	$21^h < \alpha < 02^h$ (680)	4/12[b]
	$\delta = (0.5 + 5n)°$ (1428)	2/21[c]
Penn State/NRL[d]	$13^h < \alpha < 18^h$(828)	4/17 †
	$\delta = (3.5 + 5n)°$ (527)	1/2
Caltech[e]	$08^h < \alpha < 13^h$ (360)	0/2
	$\delta = (2.5 + 5n)°$ (600)	1/12
CIT/PSU/UCB[f†]	$01^h < \alpha < 09^h$ (448)	0/0
STScI/Arecibo	$\delta = (1.5 + 5n)°$ (500)	1[g]/9
Arecibo Total	5,630 deg^2	15/99[h]

*Frequency = 430 MHz, $T_{\rm samp} = 250\ \mu$s, $T_{\rm int} = 33$ s, $S_{\rm min} > 0.5$ mJy; $2 \times 32 \times 250$ kHz filterbank used.

†Higher-frequency-resolution correlator used for at least a portion of the survey.

[a] Nice, Fruchter & Taylor 1995.

[b] Camilo, Nice & Taylor 1996.

[c] Camilo et al. 1996.

[d] 230 deg^2 searched with high-time-resolution PSPM (Foster et al. 1995).

[e] Ray et al. 1996.

[f] $8 < T_{\rm int} < 67$ s (Ray et al. 1995).

[g] PSR J0418+16 ($P = 25.7$ ms; Fruchter et al., in preparation).

[h] About 5,000 deg^2 of Arecibo sky uniquely searched. The 15 "MSP" include PSRs B1534+12 and J2235+1506.

Table 4 lists some parameters for all binary and recycled pulsars known in the disk of the Galaxy. Here we regard isolated pulsars as recycled if they have periods $P < 60$ ms and low surface magnetic field strengths, as inferred from their $\dot{P}$. We list observed $\dot{P}$s, although these differ significantly from the intrinsic ones for many millisecond pulsars (Camilo, Thorsett & Kulkarni 1994). The companion masses, m_2, are derived from the pulsar mass function for an assumed pulsar mass of 1.4 $M_\odot$ and "median" inclination angle of $i = 60°$, with the exception of PSRs B1855+09, B1534+12, and B1913+16, for which they are measured with the help of relativistic orbital effects, and PSR J0045−7319, from optical measurements (Bell et al. 1995b). Distances are obtained from the dispersion measure and the Taylor & Cordes (1993) model. Thirty-four of the 47 pulsars listed were discovered in the last 6 years in the surveys summarized in this paper and in the Parkes southern sky survey. For these pulsars we provide the discovery reference and the most up-to-date source of parameters, if different.

Table 4: Parameters of binary and recycled pulsars known in the disk of the Galaxy.

PSR	P (ms)	$\dot{P}$ (10^{-18})	P_b (d)	$a_1 \sin i/c$ (s)	e	m_2 ($M_\odot$)	d (kpc)	$\lvert z \rvert$ (kpc)	Refs.*
Circular Orbit Pulsars ($e \lesssim 0.01$)									
J0034−0534	1.88	0.0051	1.589	1.438	<0.00002	0.17	1.0	0.9	[3,8]
J0218+4232	2.32	0.08	2.029	1.984	<0.00002	0.20	>5.8	>1.8	[22]
J0437−4715	5.76	0.057	5.741	3.367	0.000019	0.17	0.1	0.1	[14,6]
J0613−0200	3.06	0.0096	1.199	1.091	<0.00002	0.15	2.2	0.4	[19,5]
J0621+1002	28.85	0.04	8.319	12.032	0.0025	0.54	1.9	0.1	[9,†]
J0751+1807	3.48	0.008	0.263	0.397	<0.0001	0.15	2.0	0.8	[20]
J1012+5307	5.26	0.015	0.605	0.582	<0.00002	0.13	0.5	0.4	[23,17]
J1022+1001	16.45	0.04	7.805	16.765	0.000098	0.87	0.6	0.5	[9]
J1045−4509	7.47	0.017	4.084	3.015	0.000024	0.19	3.3	0.7	[3,5]
J1455−3330	7.99	0.024	76.175	32.362	0.00017	0.30	0.7	0.3	[19,8]
J1603−7202	14.84	0.014	6.309	6.881	<0.00002	0.33	1.6	0.4	[18]
J1640+2224	3.16	<0.003	175.461	55.330	0.00080	0.30	1.1	0.7	[12]
J1643−1224	4.62	0.018	147.017	25.073	0.00051	0.14	>4.9	>1.8	[19,5]
J1709+23	4.63						1.9	1.0	[12]
J1713+0747	4.57	0.0085	67.825	32.342	0.000075	0.33	0.9	0.4	[13,7]
J1804−2717	9.34	0.042	11.129	7.281	0.000035	0.24	1.2	0.1	[18]
B1855+09	5.36	0.018	12.327	9.231	0.000022	0.26	1.0	0.1	[16]
J1911−1114	3.63	0.013	2.717	1.763	<0.00001	0.14	1.6	0.3	[18]
B1953+29	6.13	0.030	117.349	31.413	0.00033	0.21	5.4	0.0	[29]
B1957+20	1.61	0.017	0.382	0.0892	<0.00004	0.03	1.5	0.1	[2]
J2019+2425	3.93	0.0070	76.512	38.768	0.00011	0.37	0.9	0.1	[26,25]
J2033+1734	5.95	0.011	56.308	20.163	0.00013	0.22	1.4	0.3	[27,‡]
J2051−0827	4.51	0.013	0.099	0.045	<0.0003	0.03	1.3	0.6	[28]
J2129−5721	3.73	0.020	6.625	3.501	<0.00002	0.16	>2.6	>1.8	[18]
J2145−0750	16.05	0.030	6.839	10.164	0.000019	0.51	0.5	0.3	[3,8]
J2229+2643	2.98	0.0019	93.016	18.913	0.00025	0.15	1.4	0.6	[11]
J2317+1439	3.45	0.0024	2.459	2.314	0.000001	0.21	1.9	1.3	[10,11]
B0655+64	195.67	0.69	1.029	4.126	<0.00003	0.81	0.5	0.2	[1]
B0820+02	864.87	104.3	1232.395	162.145	0.012	0.23	1.4	0.5	[1]
J1803−2712	334.42	17.3	406.781	58.940	0.00051	0.17	3.6	0.2	[29]
B1831−00	520.95	10.7	1.811	0.723	<0.004	0.08	2.6	0.2	[1]
Other Binary Pulsars ($e \gtrsim 0.25$)									
J0045−7319	926.28	4486.	51.169	174.254	0.808	8.8	57.		[15]
B1259−63	47.76	2280.	1236.81	1296.00	0.870	4.19	4.6	0.1	[21]
J1518+4904	40.93	0.027	8.634	20.044	0.249	1.01	0.7	0.6	[24]
B1534+12	37.90	2.43	0.421	3.729	0.274	1.34	0.7	0.5	[30,1]
B1820−11	279.83	1376.	357.762	200.673	0.795	0.80	6.3	0.1	[1]
B1913+16	59.03	8.63	0.323	2.342	0.617	1.39	7.1	0.3	[29]
B2303+46	1066.37	569.1	12.340	32.688	0.658	1.46	4.2	0.9	[1]

Table 4: *(cont.)*

PSR	P (ms)	$\dot{P}$ (10^{-18})	P_b (d)	$a_1 \sin i/c$ (s)	e	m_2 ($M_\odot$)	d (kpc)	$\|z\|$ (kpc)	Refs.*
				Other Recycled Pulsars					
J0711−6830	5.49	0.015	Isolated				1.0	0.4	[4]
J1024−0719	5.16	0.018	Isolated				0.3	0.2	[4]
B1257+12	6.22	0.11	Planets				0.6	0.6	[32,31]
J1730−2304	8.12	0.020	Isolated				0.5	0.1	[19,8]
J1744−1134	4.07	0.0086	Isolated				0.2	0.0	[4]
B1937+21	1.56	0.11	Isolated				3.6	0.0	[16]
J2124−3358	4.93	0.021	Isolated				0.2	0.2	[4]
J2235+1506	59.77	0.16	Isolated				1.2	0.7	[10,11]
J2322+2057	4.81	0.0097	Isolated				0.8	0.5	[26,25]

* Reference keys are decoded in the **References** section.
† $\dot{P}$ unpublished (author).
‡ Updated parameters obtained from Nice & Thorsett (private communication).

Of the 35 millisecond pulsars in Tab. 4 (5% of all known pulsars), 22 (3/5) are in nearly circular orbits with companions of mass $0.15 \lesssim m_2 \lesssim 0.45$ $M_\odot$, presumably helium white dwarfs. Seven (1/5) are isolated objects. Three have intermediate-mass companions ($m_2 \geq 0.45$ $M_\odot$), probably carbon-oxygen white dwarfs, 2 are in eclipsing systems with companions of very low mass ($m_2 \lesssim 0.05$ $M_\odot$), and one has at least three planetary-mass companions. It is not clear how the evolutionary histories of all these systems relate to each other.

Acknowledgements

I thank Ed van den Heuvel and the organizers of the Colloquium for a wonderful meeting, and David Nice and Joe Taylor for all the shared fun of the last few years searching for pulsars.

References

Arzoumanian, Z. 1995, Ph.D. Thesis, Princeton Univ. [1]
Arzoumanian, Z., Fruchter, A.S. & Taylor, J.H. 1994, ApJ, 426, L85 [2]
Backer, D.C. et al. 1982, Nature, 300, 615
Bailes, M. et al. 1994, ApJ, 425, L41 [3]
Bailes, M. et al. 1997, ApJ, 481, 386 [4]
Bell, J.F. et al. 1997, MNRAS, 286, 463 [5]
Bell, J.F. et al. 1995a, ApJ, 440, L81 [6]
Bell, J.F. et al. 1995b, ApJ, 447, L117

Camilo, F. 1996, in High Sensitivity Radio Astronomy, ed. N. Jackson & R.J. Davis (Cambridge: Cambridge Univ. Press), 14
Camilo, F., Foster, R.S. & Wolszczan, A. 1994, ApJ, 437, L39 [7]
Camilo, F. et al. 1997, ApJ, in preparation [8]
Camilo, F. et al. 1996, ApJ, 469, 819 [9]
Camilo, F., Nice, D.J. & Taylor, J.H. 1993, ApJ, 412, L37 [10]
Camilo, F., Nice, D.J. & Taylor, J.H. 1996, ApJ, 461, 812 [11]
Camilo, F., Thorsett, S.E. & Kulkarni, S.R. 1994, ApJ, 421, L15
Clifton, T.R. et al. 1992, MNRAS, 254, 177
Foster, R.S. et al. 1995, ApJ, 454, 826 [12]
Foster, R.S., Wolszczan, A. & Camilo, F. 1993, ApJ, 410, L91 [13]
Gorham, P.W. et al. 1996, ApJ, 458, 257
Hulse, R.A. & Taylor, J.H. 1975, ApJ, 195, L51
Johnston, S. et al. 1993, Nature, 361, 613 [14]
Johnston, S. et al. 1992, MNRAS, 255, 401
Kaspi, V.M. 1996, in Pulsars: Problems and Progress, IAU Colloqium 160, ed. S. Johnston, M.A. Walker & M. Bailes (San Francisco: ASP), 375
Kaspi, V.M. et al. 1994, ApJ, 423, L43 [15]
Kaspi, V.M. et al. 1996, Astron. J., 111, 2028
Kaspi, V.M., Taylor, J.H. & Ryba, M. 1994, ApJ, 428, 713 [16]
Lorimer, D.R. et al. 1995a, Nature, 376, 393 [17]
Lorimer, D.R. et al. 1996, MNRAS, 283, 1383 [18]
Lorimer, D.R. et al. 1995b, ApJ, 439, 933 [19]
Lundgren, S.C., Zepka, A.F. & Cordes, J.M. 1995, ApJ, 453, 419 [20]
Lyne, A.G. et al. 1997, MNRAS, 295, 743
Manchester R.N., et al. 1995, ApJ, 445, L137 [21]
Manchester R.N. et al. 1996, MNRAS, 279, 1235
Navarro, J. et al. 1995, ApJ, 455, L55 [22]
Nicastro, L. et al. 1995, MNRAS, 273, L68 [23]
Nice, D.J., Fruchter, A.S. & Taylor, J.H. 1995, ApJ, 449, 156
Nice, D.J. & Sayer, R.W. 1997, ApJ, 476, 261
Nice, D.J., Sayer, R.W. & Taylor, J.H. 1996, ApJ, 466, L87 [24]
Nice, D.J. & Taylor, J.H. 1995, ApJ, 441, 429 [25]
Nice, D.J., Taylor, J.H. & Fruchter, A.S. 1993, ApJ, 402, L49 [26]
Philp, C.J. et al. 1996, Astron. J., 111, 1220
Ray, P.S. et al. 1995, ApJ, 443, 265
Ray, P.S. et al. 1996, ApJ, 470, 1103 [27]
Sayer, R.W., Nice, D.J. & Kaspi, V.M. 1996, ApJ, 461, 357
Sayer, R.W., Nice, D.J. & Taylor, J.H. 1997, ApJ, 474, 426
Shrauner, J.A. 1996, Ph.D.. Thesis, Princeton Univ.
Stappers, B.W. et al. 1996, ApJ, 465, L119 [28]
Taylor, J.H. & Cordes, J.M. 1993, ApJ, 411, 674
Taylor, J.H., Manchester, R.N. & Lyne, A.G. 1993, ApJS, 88, 529 [29]
Wolszczan, A. 1991, Nature, 350, 688 [30]

Wolszczan, A. 1994, Science, 264, 538 [31]
Wolszczan, A., Cordes, J.M. & Dewey, R.J. 1991, ApJ, 372, L99
Wolszczan, A. & Frail, D.A. 1992, Nature, 355, 145 [32]
Zepka, A. et al. 1996, ApJ, 456, 305

Authors' Address

The University of Manchester, NRAL, Jodrell Bank, Macclesfield, Cheshire SK11 9DL, UK; fernando@jb.man.ac.uk