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The Parkes Multibeam Pulsar Survey

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Abstract. The Parkes multibeam pulsar survey uses a 13-element receiver operating at a wavelength of 20 cm to survey the inner Galactic plane with remarkable sensitivity. To date we have collected and analyzed data from 45% of the survey region ($|b| < 5°$; $260° < l < 50°$), and have discovered 440 pulsars, in addition to re-detecting 190 previously known ones. Most of the newly discovered pulsars are at great distances, as inferred from a median dispersion measure (DM) of 400 cm^{-3} pc.

1. Introduction

Pulsars are steep-spectrum radio sources, with a "typical" spectral index of -1.6 (Lorimer et al. 1995). For this reason, most large-area pulsar surveys have been done at relatively low frequencies, $\nu \sim 400$ MHz. However, at low frequencies and low Galactic latitudes the contribution from synchrotron radiation (with spectral index ~ -2.7) dominates the system temperature of a radio telescope, greatly reducing the sensitivity to most pulsars.

To search for pulsars along the disk of the Galaxy, one should therefore consider using a relatively high frequency, $\nu \sim 1400$ MHz (λ20 cm). To search for *distant* pulsars along the Galactic plane, one is virtually compelled to use high frequencies, because multi-path propagation of radio pulses through the inhomogeneous interstellar medium results in broadening ("scattering") of intrinsically sharp pulses (see Fig. 4*b*). This effect, greatly reducing the detectability of pulsars, varies with frequency approximately as $\nu^{-4.4}$ (Cordes, Weisberg, & Boriakoff 1985). The obvious drawback of a survey at 1400 MHz is that, in addition to the long individual integration times required to maintain high sensitivity due to the reduced pulsar fluxes, the number of independent telescope pointings needed increases as ν^2.

Despite this hindrance there are very good reasons for wanting to search the Galactic plane: young pulsars will naturally be found close to their places of birth, viz. the Galactic disk. While relatively rare, they are interesting for a variety of reasons, including the study of pulsar–supernova remnant interactions,

Table 1. Three 20 cm pulsar surveys

	Jodrell Bank	Parkes	Parkes
Latitude range, $\|b\|$	$< 1°$	$< 4°$	$< 5°$
Longitude range, l	$-5°\ldots 100°$	$-90°\ldots 20°$	$-100°\ldots 50°$
Center frequency (MHz)	1400	1520	1374
Number of beams	1	1	13
Integration time (min) .	10	2.5	35
Sample interval (ms) ...	2.0	1.2	0.25
Bandwidth (MHz)	$2 \times 8 \times 5$	$2 \times 64 \times 5$	$2 \times 96 \times 3$
$S_{\rm sys}$ (Jy)	60	70	36
$S_{\rm min}$ (mJy).............	1.2	1.0	0.15
Pulsars found/detected.	40/61	46/100	440+/630+
Reference	Clifton et al.	Johnston et al.	this work

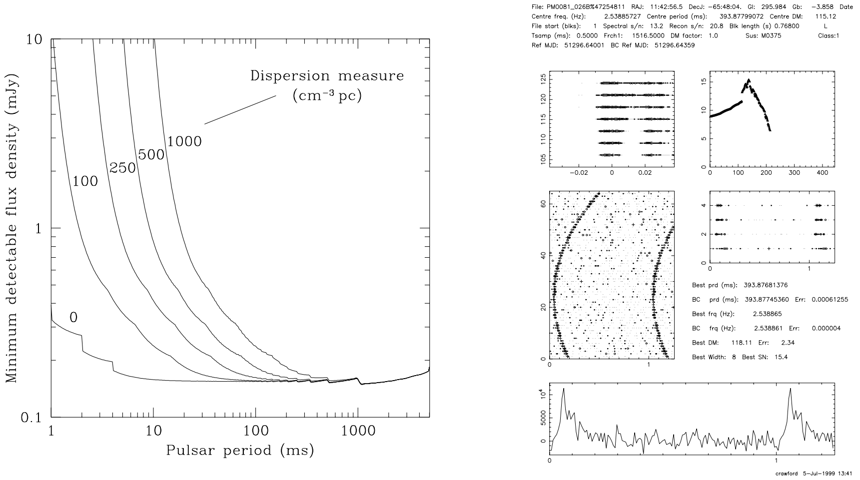
and the preferential display of rotational “glitches”, and increased likelihood of emission at X- and γ-ray energies, which are of interest for studies of the internal dynamics, and cooling and emission mechanisms of magnetized neutron stars, respectively. Also, to obtain an unbiased picture of the intrinsic Galactic distribution of pulsars, rather than just of the local population, one must penetrate deep into the Galaxy, i.e., use high frequencies.

Only two large-area pulsar surveys had been carried out at 20 cm prior to the one described here. The surveys of Clifton et al. (1992) and Johnston et al. (1992) in the 1980s (see Table 1) were very successful at finding many pulsars, preferentially young and relatively distant.

In early 1997 a 13-element receiver package with very good system noise characteristics was installed on the Parkes telescope. Developed for surveying HI in the local universe (Staveley-Smith et al. 1996), it is also ideally suited for pulsar searching.

2. Multibeam Survey

We began collecting data for the survey in August 1997. Receivers for each of 13 beams are sensitive to two orthogonal linear polarizations. Signals from each polarization of each beam are detected in 96 filters, each 3 MHz wide, upon which they are added in polarization pairs, high-pass filtered with a cutoff of 0.2 Hz, integrated for 0.25 ms, and 1-bit sampled before being written to magnetic tape with relevant telescope information, for off-line processing. The sensitivity of the survey to long-period pulsars, about 0.15 mJy, is a factor of seven better than the previous Parkes 20 cm survey (Johnston et al. 1992), and we are even more sensitive to short-period pulsars, owing to the faster sample interval and narrower filters used (see Table 1). Figure 1*a* shows the calculated sensitivity of the survey. Note that the figure does not take into account scattering: according to it a pulsar like the Crab, with period 33 ms, but located across the Galaxy, with DM = 1000 cm^{-3} pc, will be detectable with a minimum flux density of about 0.6 mJy. As Figure 4*b* shows, such a pulsar will most likely not be detectable as a pulsed source almost regardless of strength.



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File start (blks):    1  Spectral s/n:  13.2  Recon s/n:  20.8  Blk length (s) 0.76800       L
Tsamp (ms):  0.5000  Frch1:   1516.5000  DM factor:  1.0          Sus: M0375            Class:1
Ref MJD:  51296.64001  BC Ref MJD:  51296.64359
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BC   prd (ms):  393.87745360  Err:  0.00061255
Best frq (Hz):       2.538865
BC   frq (Hz):       2.538861  Err:     0.000004
Best DM:     118.11  Err:    2.34
Best Width:  8  Best SN:  15.4
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Figure 1. [*a*] Calculated survey sensitivity as a function of period and DM for a pulsar observed at the center of a beam pattern. [*b*] Output of search code for discovery of a binary pulsar in a short-period orbit.

The 13 beam patterns (each subtending a 14′ diameter) are not adjacent on the sky; rather, one central beam (with the best sensitivity) is surrounded by a ring of six beams separated by two beams-widths, surrounded in turn by a second ring separated by a further two beam-widths. We collect data by interleaving pointings on a hexagonal grid, resulting in complete sky coverage with adjacent beams overlapping at half-power points. Each pointing covers an area about $0.6\,\mathrm{deg}^2$, resulting in sky coverage at a rate of $1\,\mathrm{deg}^2/\mathrm{hr}$, and the total survey area requires about 2700 individual pointings.

As of September 1999 we have collected and analyzed about 1200 independent telescope pointings, some $700\,\mathrm{deg}^2$, or 45% of the total. Data reduction takes place in workstations in a manner similar to previous surveys (e.g., Manchester et al. 1996). Figure 1*b* shows the search-code output for the discovery of a binary pulsar. To date we have discovered 440 new pulsars, and have re-detected 190 known pulsars. Because of the long integrations, some binary pulsars (in particular millisecond pulsars) have signal-to-noise ratios reduced, owing to Doppler-induced varying spin periods. We therefore complement our standard search analysis with "acceleration search" reduction, recently begun.

3. Discussion

While we have discovered 10 new pulsars for every 1% of the survey area searched so far, it should not be concluded that we will amass a total of 1000 new pulsars. We began by surveying the regions closest to the Galactic plane, which are richest in pulsars. In Figure 2*a* we see that we have already searched essentially the entire $|b| < 1^\circ$ region, with a new-pulsar density, averaged over the entire longitude range, of slightly over $1/\mathrm{deg}^2$. Clearly the density of pulsars drops dramatically for $|b| \gtrsim 1^\circ$, which comprises much of the region yet to be searched. Conversely in Figure 2*b* we see that, as a function of longitude, the region we

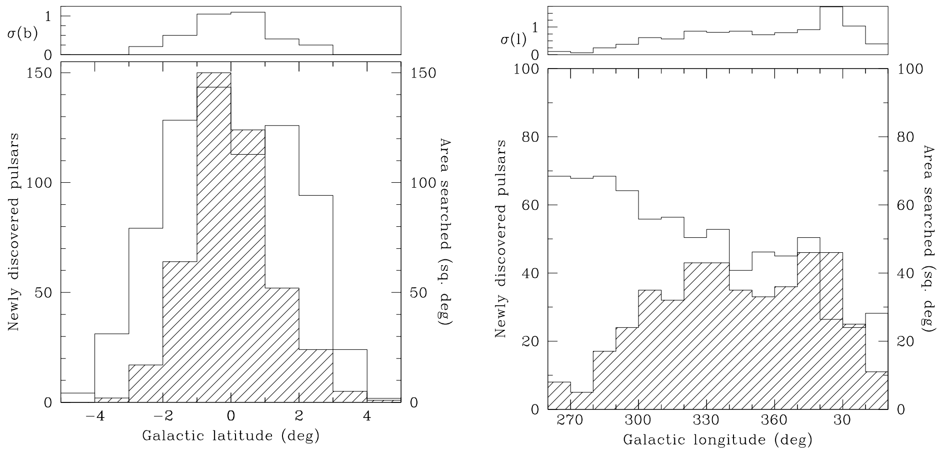

Figure 2. [*a*] Pulsars discovered as a function of Galactic latitude (cross-hatched histogram) and corresponding area searched so far (line histogram). The completed survey corresponds to having the entire area of the figure searched. At top is shown the density of discoveries, in pulsars/square deg. [*b*] As for *a*, as a function of Galactic longitude.

have preferentially searched so far ($260^\circ \lesssim l \lesssim 320^\circ$) has the lowest pulsar density. Accounting for these selection effects in some detail, we predict that the number of new discoveries for the entire survey should be somewhat over 600. Another estimate is derived from the number of pulsars previously known in the overall search area, 255, and the number of (re-)detections: these would suggest an eventual total of $(440/190)255 \simeq 600$ new objects. In fact we expect a total of about 700 pulsars to be discovered, after accounting for some further selection effects (e.g., so far we have not been complete in confirming new pulsar candidates down to the sensitivity level implicit in the calculations underlying Figure 1*a*). We have therefore already detected about 2/3 of all pulsars we will discover. Manchester et al. (this volume) describe in some detail what is already known about many of the new pulsars.

Figure 3*a* shows the distribution of DM for the newly discovered pulsars, and for comparison also shows that for previously known pulsars. Qualitatively the distribution is as expected: we find pulsars predominantly with large DM, since our survey is by far the most sensitive ever to distant pulsars along the Galactic plane; on the other hand we find very few “nearby” (DM $\lesssim 100\,\mathrm{cm}^{-3}$ pc) pulsars, in part because selection effects (e.g., scattering) preventing the detection of such pulsars in past surveys were far less important than for high-DM pulsars. The median DM for the new pulsars is about $400\,\mathrm{cm}^{-3}$ pc, and we also see that there is a marked decrease in the number of objects with DM $\gtrsim 900\,\mathrm{cm}^{-3}$ pc, with a maximum of about $1300\,\mathrm{cm}^{-3}$ pc. Naturally it is more difficult to find such highly dispersed pulsars, both because of the attending level of scattering, and reduced flux density due to large distance. But as we can see from Figure 4*a*, we do not in any case expect large numbers of pulsars in the Galaxy to have DM $\gtrsim 1400\,\mathrm{cm}^{-3}$ pc.

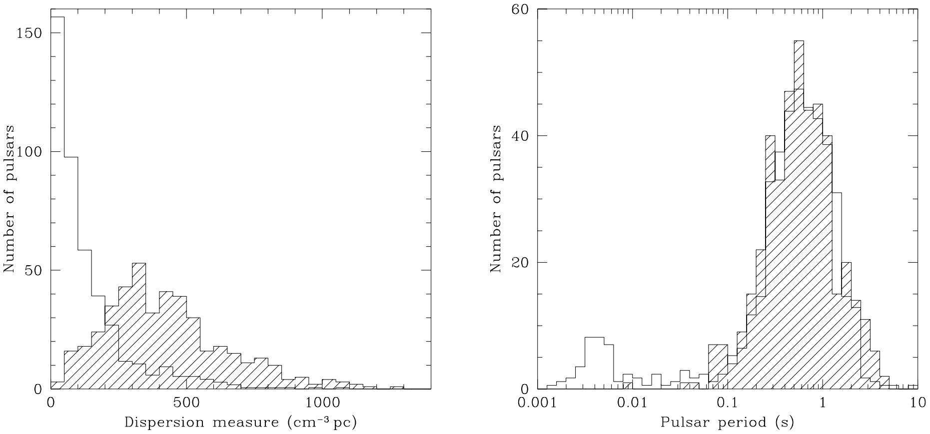

Figure 3. [*a*] Histograms of DM for newly discovered (cross-hatched) and previously known pulsars (line). The area of the latter histogram is scaled to equal that of the former. [*b*] Period histograms, as in *a*.

A comparison of the period distributions for newly discovered and previously known pulsars (Fig. 3*b*) yields some surprises. The most obvious discrepancy is that we have not discovered a significant number of short-period pulsars (only one with $P < 30\,\mathrm{ms}$). The Parkes 70 cm survey (Manchester et al. 1996), with a long-period sensitivity of $\sim 3\,\mathrm{mJy}$ and poorer time- and frequency-resolution than the multibeam survey, yielded 17 millisecond pulsars. Assuming a spectral index of -2, 3 mJy at 70 cm are equivalent to 0.3 mJy at 20 cm — i.e., we should be more sensitive to millisecond pulsars than that survey. One cannot reasonably appeal to hypothetical larger spectral indices: Edwards et al. (this volume) report on the very successful use of the multibeam data-acquisition system for finding millisecond pulsars in a survey at intermediate Galactic latitudes and with short integration times. It is conceivable that strong scattering prevents us from detecting many millisecond pulsars with DM $\gtrsim 70\,\mathrm{cm^{-3}\,pc}$; in any case we are still investigating this dearth of millisecond pulsar discoveries. A second surprise concerns the discovery of relatively many pulsars with long periods, $P \gtrsim 3\,\mathrm{s}$. This may be due to surveys with shorter integration times not collecting data for many such pulse periods, coupled with the prevalence of "nulling" pulsars among those with long periods; and to the effectiveness with which much local radio-frequency interference gets "dispersed away" in our search for high-DM pulsars.

In Figure 4*a* we plot the positions of the pulsars detected in the multibeam survey projected onto the Galactic plane, according to the distance model of Taylor & Cordes (1993). Two things are immediately apparent: the previously known re-detected pulsars are located relatively nearby ($d \lesssim 4\,\mathrm{kpc}$), while many of the newly discovered pulsars are very distant, with many beyond the inner-most spiral arm; and many of the newly discovered pulsars seem to be located along spiral arms, particularly the two inner-most ones. Regarding this last point, we do expect pulsars to be correlated with spiral arm locations, but we

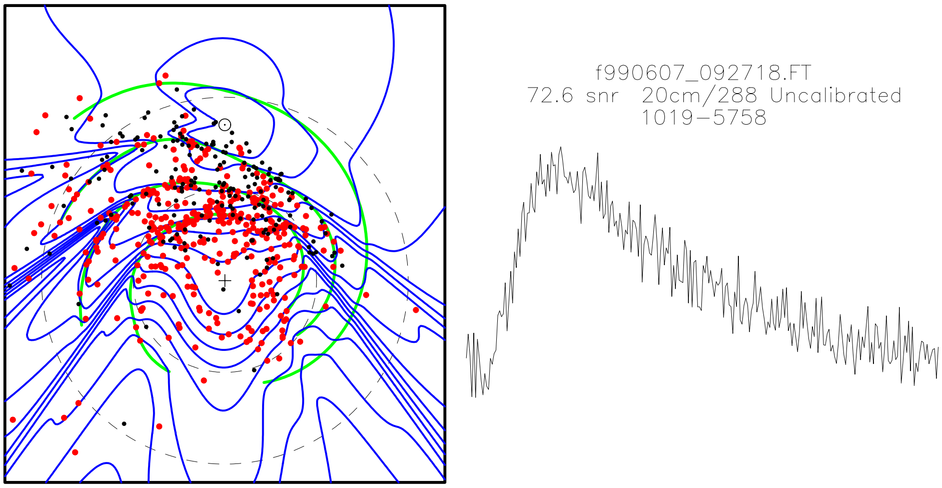

Figure 4. [a] Heliocentric DM contours and pulsars detected. The contours (first one for DM = 50, next ones at 100 cm^{-3} pc and multiples), and pulsar distances, are computed from the Taylor & Cordes (1993) free-electron model. The Sun is located at top (⊙), with the Galactic center (+) 8.5 kpc away. Four spiral arms are represented by grey lines. Newly discovered and previously known, but re-detected, pulsars are represented by grey and smaller black dots, respectively. [b] Pulse profile at 20 cm of a newly discovered pulsar (with period 162 ms and DM = 1035 cm^{-3} pc) shows a significant "scattering tail".

should be careful to consider potential biases in the distance model that will place pulsars preferentially in regions of high electron density.

The multibeam survey is being remarkably successful at uncovering very distant pulsars. The DM-distribution of these pulsars, DM(l, b), together with measured scattering parameters (cf. Fig. 4b), and eventually Faraday-rotation parameters, probing the interstellar magnetic field, should give us a more unbiased picture of the Galactic distribution of pulsars, and add considerably to our knowledge of the interstellar medium.

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