Ia. ROTATION-POWERED PULSARS

The Population

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PULSAR SURVEYS

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ABSTRACT. The current situation regarding pulsar surveys is briefly reviewed. Most of the known pulsars have been found by major radio surveys that were unbiased in the sense of more-or-less uniformly covering a given area of sky. The results from two recent such surveys, the Green Bank 390 MHz survey of Stokes et al. (1985) and the Jodrell Bank 1400 MHz survey of Clifton and Lyne (1986) are compared. Conclusions are drawn regarding the effect of observing frequency on the results of pulsar surveys and the galactic distribution of pulsars and interstellar electrons.

1. PULSAR STATISTICS

At last count there were 437 pulsars known. (In this paper the term "pulsar" refers to rotationally powered pulsars and not to accretion-powered systems, which are generally detected at X-ray frequencies.) All but two of the known pulsars were discovered at radio frequencies. These two, PSR 1509-58 and PSR 0540-69, were discovered using the Einstein X-ray observatory (Seward and Harnden, 1982; Seward et al., 1984). Only four pulsars have been detected at frequencies above the radio band. These are the two pulsars mentioned above and the Crab and Vela pulsars, PSR 0531+21 and PSR 0833-45 respectively. All four of these pulsars are young and all are associated with known supernova remnants. They are in fact the only pulsars for which the association with a supernova remnant is reasonably definite. Only the Crab and Vela pulsars have been detected at gamma-ray frequencies and PSR 0540-69 has been detected in the optical band. Despite several intensive searches, this pulsar has not yet been detected in the radio band; the limiting mean flux density at a frequency of 1 GHz is <1 mJy. The situation regarding detection of pulsars in different frequency bands is summarized in Table I.

All but two of the known pulsars are located within our galaxy. Both of the exceptions are within the Large Magellanic Cloud; they are PSR 0540-69, discussed above, and PSR 0529-66, discovered in a radio search at Parkes (McCulloch et al., 1983). The distribution of pulsars in galactic coordinates is illustrated in Figure 1. The well-known concentrations toward the galactic equator and toward the galactic centre can be seen in this figure. These clearly show that pulsars are a galactic disk population and that, at least near the Sun, their spatial density increases with decreasing galactocentric radius. Lyne et al. (1985) have discussed

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TABLE I - Detection of pulsars in different frequency bands*

PSR	Radio	Optical	X-ray	γ-ray
Crab	D	x	x	x
Vela	D	x		x
1509-58	x		D	
0540-69		x	D	

*D indicates the discovery frequency band.

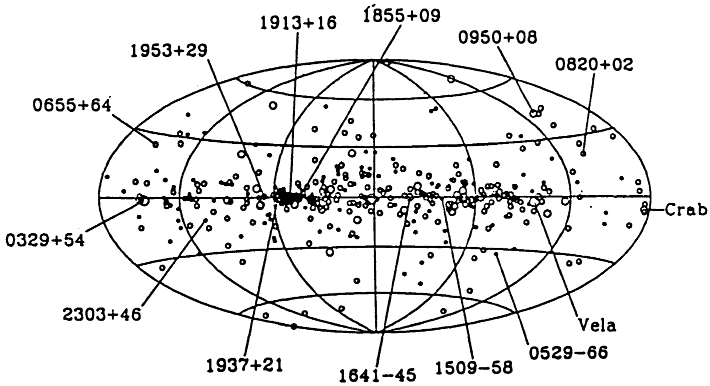

Figure 1. Distribution of 398 pulsars in galactic coordinates. The galactic centre is at the centre of the diagram and the size of the circles indicates the 400 MHz mean flux density. Locations of selected pulsars are marked. (From Taylor and Stinebring, 1986.)

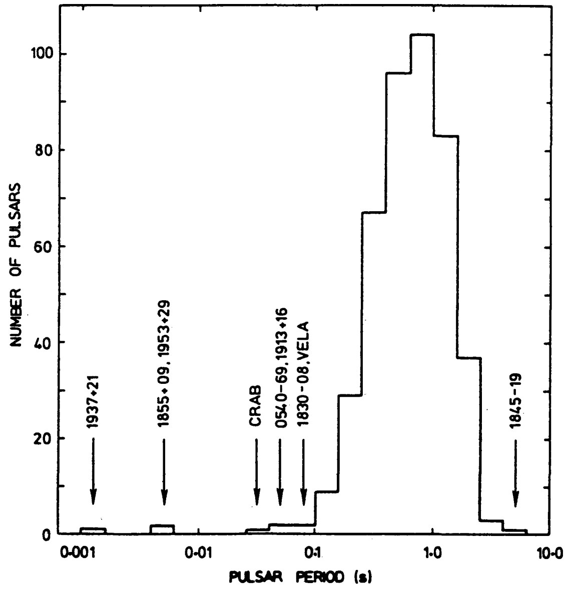

Figure 2. The observed period distribution of 437 pulsars.

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the galactic distributions of pulsars that are implied by these results.

Figure 2 illustrates the period distribution of the observed sample of pulsars. The extreme range of pulsar periods is 0.0015 to 4.30 s but the vast majority of pulsars have periods in the range 0.2 to 2.0 s. The observed range was greatly extended by Backer et al.'s (1982) discovery of the millisecond pulsar PSR 1937+21. Despite a number of intensive searches since this initial discovery, only two more millisecond pulsars have been discovered, PSR 1953+29 (Boriakoff et al., 1983) and PSR 1855+09 (Segelstein et al., 1986). These have periods of 6.1 and 5.4 ms respectively.

For binary pulsars the picture is a little more encouraging. Since the discovery of PSR 1913+16 by Hulse and Taylor (1974) a further six binary pulsars have been found. The main parameters of the binary pulsars are summarized in Table II. They appear to fall into two distinct groups, those with high eccentricity and relatively large mass functions and those with almost circular orbits and low mass functions. For systems in the first group the companion is almost certainly a neutron star, whereas for those in the second group it is probably a white dwarf (van den Heuvel, 1984; Segelstein et al., 1986; Kulkarni, 1986). It is worth noting that two of the three known millisecond pulsars are members of binary systems.

TABLE II - Parameters of binary pulsars

PSR	P (ms)	Log $\dot{P}$	Log B (G)	P_b (days)	e	Probable m_2 ($M_\odot$)
1913+16	59.0	-17.1	10.3	0.32	0.6171	1.4
0655+64	195.6	-18.2	10.0	1.03	<0.00005	0.7-1.3
1831-00	520.9	<-17.0	<10.9	1.81	<0.005	0.06-0.13
1855+09	5.4	-18.8	9.0	12.33	0.00002	0.2-0.4
2303+46	1066.4	-15.4	11.8	12.34	0.6584	1.2-2.5
1953+29	6.1	-19.5	8.6	117.35	0.0003	0.2-0.4
0820+02	864.9	-16.0	11.5	1232.40	0.0119	0.2-0.4

2. MAJOR PULSAR SURVEYS

Of the 430 or so known pulsars over 390 were discovered in one or more of 11 major pulsar surveys. These surveys, the main parameters of which are summarized in Table III, all covered a given area of sky in a relatively unbiased way. Most of the pulsars were discovered in the 1970s and early 1980s in large-scale computer-based searches. These searches covered the whole of the celestial sphere to a reasonably uniform limiting mean flux density; the Arecibo searches are exceptional in that they were about an order of magnitude more sensitive owing to the large collecting area of this instrument. Most of these surveys had sampling intervals of 16 or 20 ms and so were insensitive to pulsars with periods of $\lesssim$100 ms. (In Table III the quoted minimum period is twice the data sampling interval and the limiting mean flux density quoted refers to pulsar periods greater than about five times this value.)

Following the discovery of the millisecond pulsar, searches have used faster sampling and hence have been sensitive to pulsars of shorter period. The Princeton-Green Bank (Stokes et al., 1985) and Jodrell Bank (Clifton and Lyne, 1986) surveys are discussed extensively below. The

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TABLE III - Major pulsar surveys

	Group	Antenna	Freq. (MHz)	Sky cover (sr)	P_{min} (ms)	S_{min} (mJy)	No. of PSRs discovered
1	Cambridge	Sq. array	81.5	~6	~100	~100	6
2	Sydney	Mills arm	408	7	>5	>20	31
3	Jodrell Bank	MkIA	408	1.0	160	15	39
4	U. Mass.	Arecibo	430	0.05	33	1.5	40
5	CSIRO/Syd.	Mills arm	408	8.4	40	15	155
6	U. Mass.	GB 92-m	400	4	33	15	23
7	Princeton	GB 92-m	390	1.8	33	2	34
8	Princeton	GB 92-m	390	1.1	4.0	2	20
9	Jodrell Bank	MkIA	1400	0.06	4.0	~1	40
10	Princeton	Arecibo	430	0.10	0.6	3	5
11	CSIRO/Pal./Pri./Syd.	MOST	843	0.06	1.0	8	≥1

References: 1, Hewish et al. (1968); 2, Large and Vaughan (1971); 3, Davies et al. (1972, 1973); 4, Hulse and Taylor (1974, 1975); 5, Manchester et al. (1978); 6, Damashek et al. (1978, 1982); 7, Dewey et al. (1985); 8, Stokes et al. (1985); 9, Clifton and Lyne (1986); 10, Stokes et al. (1986); 11, D'Amico et al. (1986).

Princeton-Arecibo survey, described by Stokes et al. (1986), surveyed a small region near the galactic plane at a frequency of 430 MHz with good sensitivity for short-period pulsars and found a total of five pulsars, including the binary millisecond pulsar PSR 1855+09. A survey of a 2°-wide strip along the southern galactic plane has been carried out at Molonglo by D'Amico et al. (1986). The Molonglo instrument works at a frequency of 843 MHz and the survey had reasonable sensitivity down to periods of a few milliseconds. Analysis is not yet complete and so far one pulsar has been confirmed, PSR 0906-49, which has a period of 106 ms, a characteristic age of $\sim 1.2 \times 10^5$ years and a relatively strong interpulse.

Excepting the original Cambridge survey, most surveys have been at frequencies near 400 MHz. This frequency is a good compromise between interstellar effects, which tend to degrade the sensitivity at low frequencies, and the reduced sensitivity at high frequencies due to the steep intrinsic spectrum of pulsar radio emission. In addition, at these frequencies the antenna beam is relatively large and hence it is practicable to survey a large area of sky. However, the discovery at a higher radio frequency of several high-dispersion pulsars which are undetectable at frequencies around 400 MHz because of the effects of interstellar scattering (Manchester et al., 1985) showed that low-frequency surveys were missing a substantial portion of the galactic population of pulsars. These effects are most severe in directions along the galactic plane and especially towards the galactic centre and for short-period pulsars. To illustrate this it is instructive to compare two recent surveys for pulsars, one carried out at a frequency of 390 MHz and the other at 1400 MHz.

3. COMPARISON OF THE STOKES ET AL. (1985) AND CLIFTON AND LYNE (1986) PULSAR SURVEYS

Comparison of the Stokes et al. (S85) and Clifton and Lyne (CL86) surveys is of interest since these two surveys have a number of parameters in common but differ in observing frequency. The S85 survey at Green Bank was at a frequency of 390 MHz, whereas the Jodrell Bank survey of CL86 was made at 1400 MHz. Both surveys covered an area of sky along the galactic plane north of the galactic centre and both used a sampling interval of 2 ms. The basic parameters of the two surveys are summarized in Table IV. The limiting flux density is for directions away from the

TABLE IV - Basic parameters for the Stokes et al. (1985) and Clifton and Lyne (1986) surveys

	Stokes et al.	Clifton and Lyne
Antenna	Green Bank 92-m	Jodrell Bank 76-m
Frequency	390 MHz	1400 MHz
Sampling interval	2 ms	2 ms
Filter bandwidths	2x32x0.25 MHz	2x8x5 MHz
Limiting flux density	$\gtrsim$3 mJy	$\gtrsim$1 mJy
Area surveyed	3725 sq. deg	200 sq. deg
Pulsars detected	87	62
Pulsars discovered	20	40

galactic plane and for pulsar periods greater than ~10 times the sampling interval. Although at the observing frequency the CL86 survey has a lower limiting flux density than the S85 survey, when one compensates for the average spectral index of pulsars the S85 survey actually has about twice the sensitivity of the CL86 survey. It detected more pulsars than the CL86 survey, although to do this it had to cover nearly 20 times as much area of sky. Another notable difference between the two surveys is that for the S85 survey less than one-quarter of the pulsars detected were new discoveries, whereas for the CL86 survey nearly two-thirds of the pulsars detected were new.

Figure 3 illustrates the period distributions of the pulsars

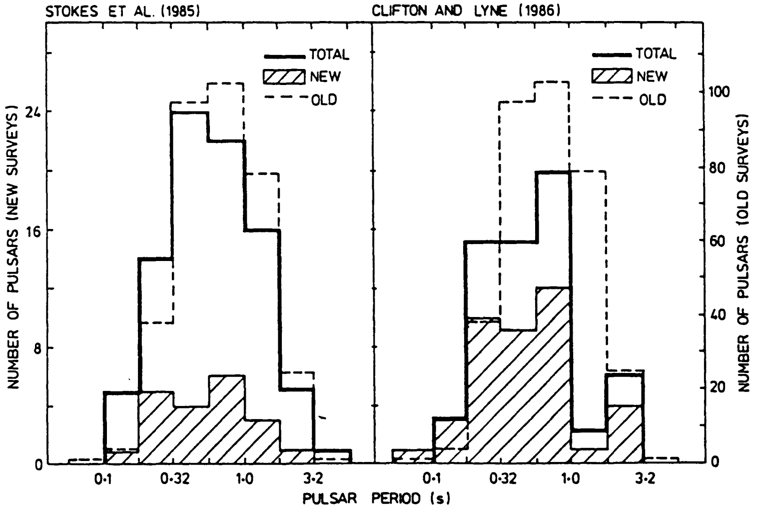

Figure 3. Period distributions for the pulsars detected (solid line), and pulsars discovered (hatched region) for the Stokes et al. (1985) and Clifton and Lyne (1986) surveys and for pulsars detected in previous major surveys (dashed line).

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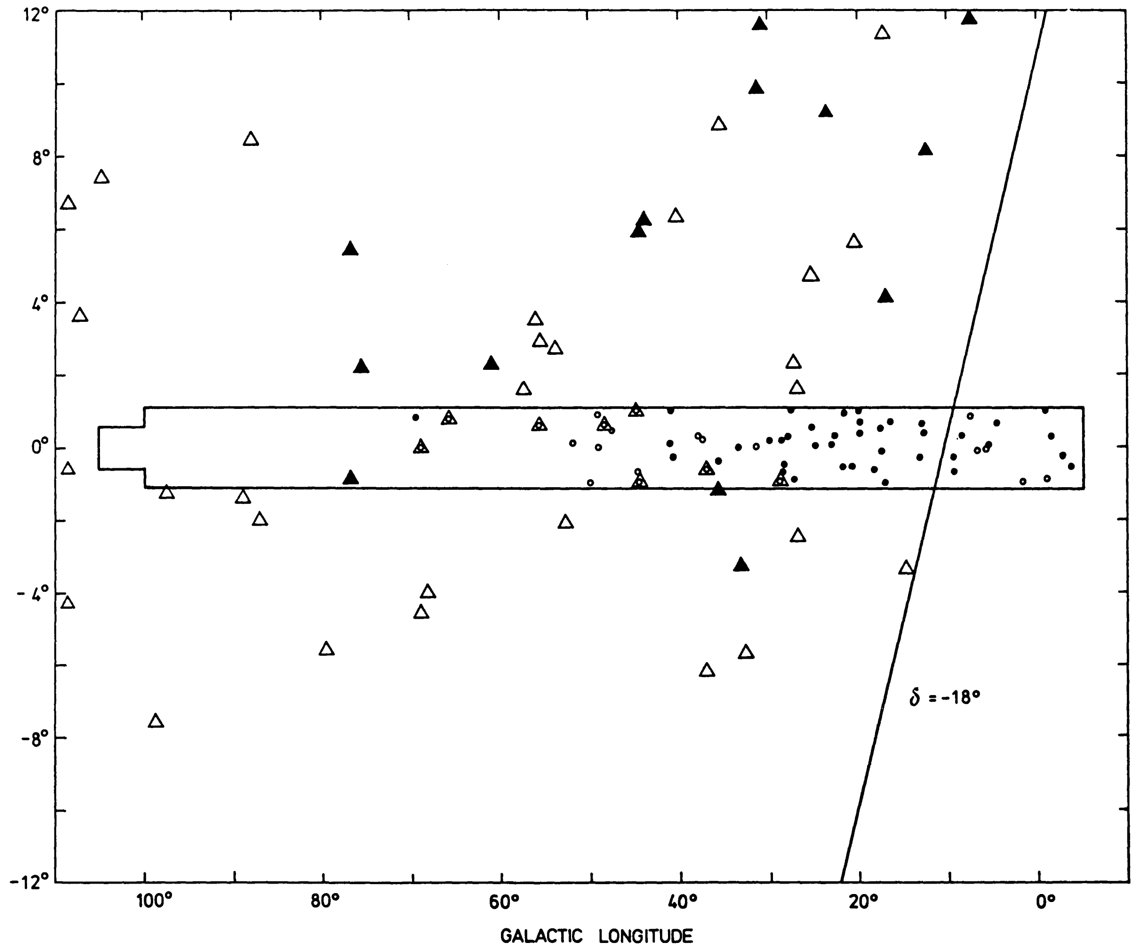

Figure 4. Galactic distribution of pulsars detected in the Stokes et al. (S85) and Clifton and Lyne (CL86) surveys. The inner box indicates the region covered by CL86. All of the area shown north of declination -18° was covered by S85. For CL86 filled circles indicate new pulsars and open circles previously known ones; for S85 filled triangles indicate new pulsars and open triangles previously known ones.

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detected and discovered in the two surveys and for reference also gives the period distribution of pulsars detected in previous major surveys. The first point is that neither survey detected any millisecond pulsars despite having some, albeit reduced, sensitivity down to periods of 4 ms. In fact, only one pulsar with period <100 ms was detected, namely PSR 1830-08, which has a period of 85 ms, detected by CL86. Both surveys detected a higher proportion of short-period pulsars compared to earlier surveys, but the bias towards short periods is significantly greater for the CL86 survey. The median periods for the S85 pulsars, the CL86 pulsars and the previously known pulsars are respectively 0.60, 0.51 and 0.67 s.

As indicated above, the area density of detected pulsars is much higher for the CL86 survey compared to the S85 survey. In Figure 4 the distribution in galactic coordinates of pulsars detected in the two surveys is compared. A total of eight of the previously known pulsars were detected by both surveys, but none of the new pulsars are in common. For the S85 pulsars the distribution is essentially independent of longitude over the range shown in the figure whereas for the CL86 pulsars the distribution is quite different. No pulsars were detected at longitudes $>70°$ and all but five are at longitudes $<50°$. There is a marginal drop-off in density near the galactic centre, where the survey sensitivity is most affected by high galactic background temperatures and interstellar scattering. For the limited latitude range covered by the CL86 survey there is no significant latitude dependence of the observed distribution.

Associated with the very different sky distribution for the two surveys there is a very different distribution of dispersion measures (DM), as illustrated in Figure 5. The S85 pulsars have a distribution

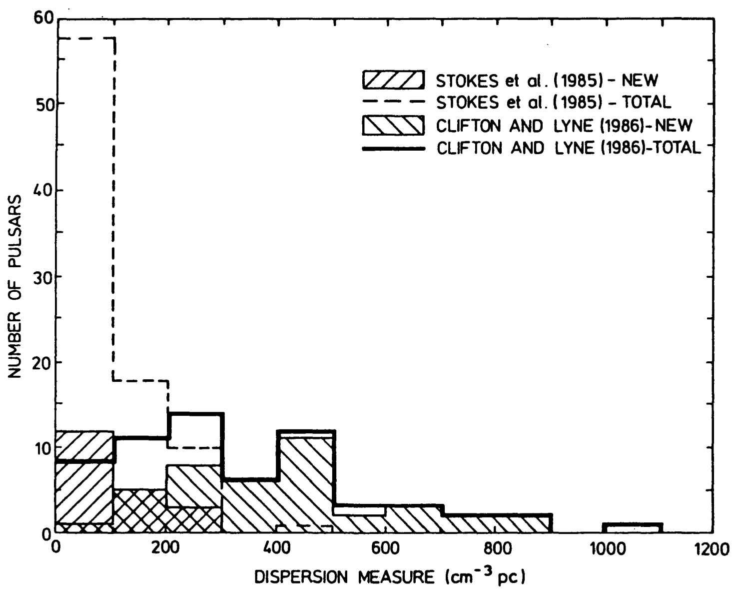

Figure 5. Distribution of dispersion measures for the new and previously discovered pulsars in the Stokes et al. (1985) survey and the Clifton and Lyne (1986) survey.

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peaking at low dispersions very similar to that of previously known pulsars. The highest DM detected (for PSR 1859+03) was 403 cm^{-3} pc and the highest value for a new pulsar was ~250 cm^{-3} pc. In contrast, the CL86 pulsars have dispersions extending to over 1000 cm^{-3} pc (for PSR 1758-23), with a broad peak in the distribution at around 400 cm^{-3} pc.

The different sky and DM distributions of pulsars from the CL86 survey show that, on average, these pulsars are much more distant than both those from the S85 survey and those previously known. (It is however true that the distances derived for these pulsars from most models of the interstellar electron density distribution - for example, that derived by Lyne et al. (1985) - must in most cases be too large.) The CL86 survey in fact detected a different population of pulsars from that detected by previous surveys. Most of them are located in the inner part of the Galaxy, although it is not clear yet whether the true distribution peaks at the galactic centre or is annular in form. Despite the relatively high observing frequency, most of the CL86 pulsars with DM greater than about 500 cm^{-3} pc are significantly affected by interstellar scattering. These pulsars would be quite undetectable at frequencies around 400 MHz. Even at 1400 MHz it is likely that some short-period pulsars have not been detected because of the combined effects of interstellar scintillation and high galactic background temperature. Consequently, even higher frequency searches may be required to determine the true galactic and period distributions of pulsars.

To summarize the conclusions derived from the results of these two surveys:

(i) There are few detectable pulsars in the Galaxy with periods between 10 and 100 ms. If pulsars evolve in period with constant luminosity (at least at these short periods), then only one or two pulsars would be expected in this period range from these surveys, so the statistical significance of this result may not be high.

(ii) High background temperatures and strong interstellar scattering, at least in the inner part of the Galaxy, are limiting factors for pulsar surveys at frequencies <1 GHz.

(iii) Determination of the true galactic and period distributions of pulsars will require extensive surveys at frequencies $\gtrsim 1$ GHz.

(iv) At galactocentric radii $\lesssim 5$ kpc, the interstellar electron density has a mean value at least a factor of three higher than the local value and fluctuations that cause strong scattering of radio signals.

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DISCUSSION

S. Krishnamohan: How can one explain the nondetection of the Jodrell pulsars discovered by Clifton and Lyne in the Green Bank Survey by Stokes et al.? Is interstellar scattering a sufficient reason or does one have to invoke a flatter spectrum for these pulsars?

R. Manchester: I believe that the combination of high background temperature and interstellar scattering is sufficient to account for the non-detection of Clifton and Lyne pulsars by Stokes et al. The background temperature is more important for low DM pulsars and the scattering for high DM pulsars.

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A. Lyne: I think that without exception all the new pulsars having dispersion measures in excess of 600 pc cm^{-3} suffer from the effects of multipath scattering. Thus, even this survey has reduced sensitivity to such objects and may be missing many. We may not therefore be seeing even as far as the galactic center and the electron density enhancement in the inner regions of the Galaxy may be even greater than you suggest. A still higher frequency is needed to determine this.

R. Manchester: I agree.

A. Blaauw: In comparing the period distributions of the two surveys, is there evidence for a larger percentage of longer periods in the Stokes et al. survey (which includes higher latitudes)?

R. Manchester: No in fact, the Clifton and Lyne survey found four pulsars with periods between 1.8 and 3.2 seconds whereas the Stokes et al. survey found only one, but the difference is not statistically significant.

G. Bignami: What fraction of the high-latitude sky has been searched in reasonably sensitive recent pulsar surveys?

R. Manchester: With the exception of some observations toward selected objects, surveys sensitive to pulsars with periods less than about 100 ms have been almost totally confined to within 15 degrees of the galactic plane. The 390 MHz survey of Dewey et al. (1985) covered 1.8 steradian of sky, mostly at high latitudes, but was only sensitive to pulsars with period greater than about 100 ms.

J. Dolan: Given the volume of phase space which has been investigated so far (S_{min}, ν, Period, Ω), and the number of pulsars discovered so far (390), can you estimate the total number of pulsars observable from the Earth with currently available instrumentation?

R. Manchester: On the assumption of a planar pulsar distribution, the total number of pulsars detected in a flux density-limited survey is proportional to the inverse of the limiting flux density. For relatively low-frequency surveys (~ 400 MHz say) the effective limiting flux density is dominated by high background temperature and interstellar scattering near the galactic plane. On the other hand, these surveys can cover a large area of sky more easily. The number of pulsars to be detected in the future will be largely limited by telescope time assignment committees and the stamina of the observers. I would guess that the number of pulsars discoverable in the future with currently available instrumentation will be about equal to the number currently known.