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A DEEP SAMPLE OF NEW PULSARS AND THEIR SPATIAL EXTENT IN THE GALAXY

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ABSTRACT

We present parameters for 40 pulsars discovered in a survey conducted at the Arecibo Observatory, and list the 10 previously known pulsars which were also detected. Of this total of 50 pulsars, 47 lie in the main search region $42° \lesssim l \lesssim 60°$, $|b| \lesssim 4°$. The survey reached a limiting average flux density of ~1 mJy, and appears to have detected a limit to the spatial distribution of pulsars in this direction, at a distance corresponding to DM = 260 cm^{-3} pc. This limit is consistent with a markedly reduced density of pulsars at distances beyond 8–10 kpc from the galactic center.

Subject headings: Galaxy, The — pulsars

I. INTRODUCTION

The region of the galactic plane within the limits $42° \lesssim l \lesssim 60°$, $|b| \lesssim 4°$, as well as a few smaller regions, has been searched for pulsars to a limiting average flux density of approximately 1 mJy. Observations were made at a frequency of 430 MHz using the 1000-foot (305-m) telescope of the Arecibo Observatory and an automated data collection and processing system designed to maintain uniform sensitivity over a wide range of possible pulsar parameters (Taylor 1974; Hulse and Taylor 1974). Fifty pulsars have now been detected in this work, of which 40 were not previously known.

This paper presents the measured parameters for the 40 newly discovered pulsars, and lists the 10 already known objects. Twelve of the 40 new pulsars have already been announced (Hulse and Taylor 1974, 1975), but are included here for completeness and also to report improved parameters for some of them. Forty-seven of the 50 pulsars detected lie in the main search region at $|b| < 4°$. An interesting result is that all but two of these pulsars have dispersion measures less than or equal to 260 cm^{-3} pc. It will be shown that this is a real effect related to the spatial distribution of pulsars in the Galaxy.

II. SURVEY COVERAGE

Because of the limited declination range of the Arecibo telescope, only two sectors of the galactic plane are observable: one toward the galactic anticenter ($170° \lesssim l \lesssim 210°$), and the other toward longitudes $35° \lesssim l \lesssim 75°$. Twenty-four square degrees of sky were searched in the first of these regions, but no pulsars were detected there (Hulse and Taylor 1974). Our main effort was spent in coverage of about 140 square degrees in the second longitude range. As shown in Figure 1, nearly uniform coverage was achieved in the region defined by $42° \lesssim l \lesssim 60°$, $|b| \lesssim 4°$. Filled circles in the figure represent the 47 pulsars (38 new and 9 old) detected there. Small gaps in the coverage due to interference have been omitted from Figure 1 for clarity. Gaps also effectively exist in the immediate vicinity of strong continuum sources (the area near W51 is shown as omitted) and close to the stronger pulsars. With 38

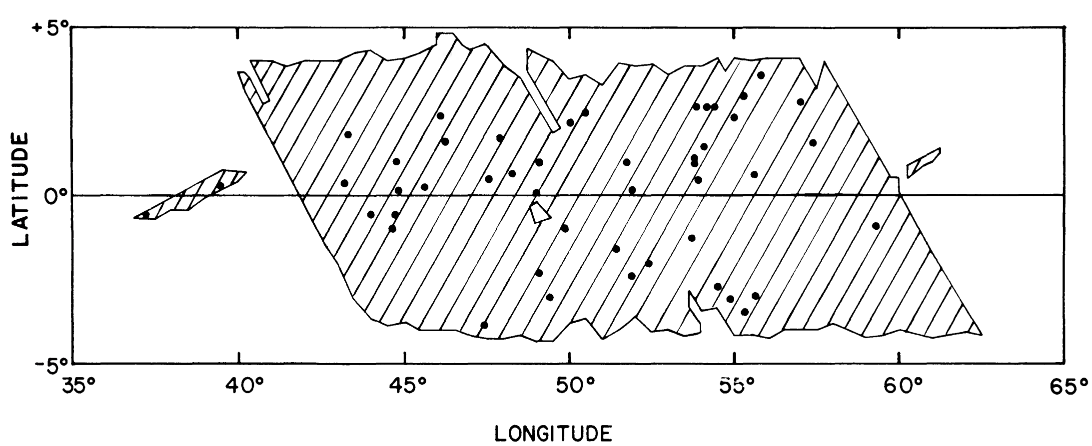

Fig. 1.—The shaded area indicates the region where the primary search effort was made, with small gaps in coverage omitted for clarity. The positions of the 47 pulsars (38 new and 9 old) detected by the survey are shown as filled circles.

new pulsars in this region of roughly 140 square degrees, and a search rate of 0.5 square degrees per hour, a new pulsar was detected every 7.4 hours of observation on the average.

III. THE PULSARS DETECTED

The 40 new pulsars detected in the course of this search are presented in Table 1, along with their parameters. PSR 1913+16 is unique in being the only known example of a pulsar in a binary system; data on this pulsar have been presented separately (Hulse and Taylor 1975; Taylor 1975), and a more accurate analysis of the timing data will soon be published. All of the pulsars have been reobserved several times after initial discovery, both to confirm their existence and to obtain improved measurements of their periods, pulse shapes, and flux densities.

The positions given in Table 1 are accurate to approximately half a beamwidth, or $\pm 5'$ in declination and $\pm 20^s$ in right ascension. The PSR designations have been assigned by the usual truncation of these coordinates, with duplicate names avoided in two cases

TABLE 1

PARAMETERS OF THE 40 NEW PULSARS

PSR	Right Ascension (1950.0)	Declination (1950.0)	l	b	Period ($s \pm \mu s$)	Pulse Width (ms)	Dispersion Measure ($cm^{-3}pc$)	Average Flux (mJy)	Notes
1900+05.........	$19^h00^m15^s$	05°52′	39°.5	0°.2	0.746569±2	30	170	12.6	1
1901+10.........	19 01 40	10 00	43.3	1.8	1.856568±20	35;35	140	0.8	2
1904+12.........	19 04 57	12 40	46.1	2.3	0.827096±2	30	260	1.0	
1906+09.........	19 06 40	09 10	43.2	0.3	0.830271±4	45	250	2.4	
1908+12.........	19 08 06	12 28	46.2	1.6	1.441735±6	40	260	2.5	
1910+10.........	19 10 30	10 30	44.8	0.1	0.409338±2	25	140	1.2	
1911+13.........	19 11 10	13 54	47.9	1.6	0.521472±1	25	145	3.1	1
1911+09.........	19 11 30	09 30	44.0	−0.6	1.241964±15	45	155	1.4	
1911+11.........	19 11 57	11 15	45.6	0.2	0.600997±2	20	80	2.6	
1913+10.........	19 13 05	10 05	44.7	−0.6	0.404531±2	40	240	14.4	
1913+167........	19 13 10	16 40	50.5	2.4	1.616237±8	45	55	2.8	
1913+16.........	19 13 13	16 00	50.0	2.1	0.059030±1	10	167	6.0	3
1914+09.........	19 14 10	09 47	44.6	−1.0	0.270253±1	20	60	22.8	1, 4
1914+13.........	19 14 40	13 06	47.6	0.4	0.2818399±0.5	20	230	12.2	1
1916+14.........	19 16 00	14 40	49.1	0.9	1.180883±3	25	30	3.2	1
1919+14.........	19 19 10	14 12	49.0	0.0	0.618180±2	30	95	8.5	1
1919+20.........	19 19 40	20 00	54.2	2.6	0.760682±2	20;25	70	0.7	5
1920+20.........	19 20 08	20 10	54.4	2.6	1.172761±7	35;35	215	3.1	6
1921+17.........	19 21 06	17.00	51.7	0.9	0.547209±2	25	135	0.9	
1922+20.........	19 22 30	20 30	55.0	2.3	0.237790±1	20	215	2.0	
1924+19.........	19 24 16	19 20	54.1	1.4	1.346010±8	55	420	0.9	
1924+16.........	19 24 30	16 42	51.9	0.1	0.579811±2	25	170	4.8	1
1924+14.........	19 24 35	14.30	49.9	−1.0	1.324921±3	30;40	205	4.4	1, 7
1925+18.........	19 25 00	18 50	53.8	1.0	0.482765±2	35	250	1.4	
1925+22.........	19 25 08	22 30	57.0	2.7	1.431066±13	60	180	3.0	
1925+188........	19 25 27	18 50	53.8	0.9	0.298312±2	30	90	1.3	
1927+18.........	19 27 18	18 40	53.9	0.4	1.220466±5	30	110	1.4	
1927+13.........	19 27 35	13 10	49.1	−2.3	0.760031±1	25	200	2.7	
1929+15.........	19 29 30	15 30	51.4	−1.6	0.314351±2	30	120	1.5	1
1930+20.........	19 30 09	20 15	55.6	0.6	0.268210±3	20	200	3.6	1, 8
1930+22.........	19 30 30	22 15	57.4	1.5	0.1444265±0.2	8	219	5.6	9
1930+13.........	19 30 58	13 00	49.4	−3.1	0.928325±4	35	165	0.9	
1933+17.........	19 33 15	17 40	53.7	−1.3	0.654408±3	35	210	1.4	
1933+15.........	19 33 40	15 30	51.9	−2.4	0.967339±4	30	165	0.8	1
1939+17.........	19 39 47	17 40	54.5	−2.7	0.696261±8	65	175	1.4	
1942+17.........	19 42 15	17 50	54.9	−3.1	1.996898±5	40;30	160	0.5	10
1943+18.........	19 43 18	18 30	55.6	−3.0	1.068707±4	35	240	1.6	
1944+22.........	19 44 16	22 40	59.3	−1.0	1.334451±4	30	140	1.5	
2024+21.........	20 24 55	21 40	63.6	−9.5	0.3981726±1.5	20	90	1.3	
2028+22.........	20 28 24	22 20	64.6	−9.8	0.630512±1	25	60	4.4	

NOTES.—(1) Discovery previously announced (Hulse and Taylor 1974). (2) Double pulse, separation 135 ms. (3) Member of a binary system (Hulse and Taylor 1975). (4) Improved position (originally published as 1915+09). (5) Double pulse, separation 30 ms. (6) Double pulse, separation 35 ms. (7) Double pulse, separation 130 ms. (8) Improved position. (9) $dP/dT = 63 \pm 20 \times 10^{-15}$ s s^{-1}, epoch JD 2,442,433 (10) Double pulse, separation 180 ms.

by appending a digit corresponding to rounded tenths of a degree in declination for the more recently discovered pulsar. Note that the positions given for PSR 1914+09 (originally published as 1915+09) and PSR 1930+20 have been changed slightly. The latter change does not affect the possible identification of PSR 1930+20 with the supernova remnant G55.6+0.7 (Crovisier 1974).

Accurate periods were obtained to facilitate detection of these pulsars at observatories which do not have the large collecting area available at Arecibo. These periods were determined by measuring pulse arrival times over intervals of about an hour, and hence integrations of similar duration should be possible with the periods given. The period derivative listed for PSR 1930+22 was obtained by comparing independent determinations of the period separated by 138 days. A formal age $\frac{1}{2}P/\dot{P} \approx 36{,}000$ yr makes this object one of the youngest pulsars known.

Due to the coarse time resolution used, the pulse widths listed should be regarded as guides only, or perhaps as upper limits to the true pulse widths. Any multiple pulse structure that was clearly resolved is mentioned in the Notes to Table 1.

The uncertainty associated with the listed dispersion measures is on the order of the dispersion resolution of the search, or ± 20 cm^{-3} pc. Dispersion measures for PSR 1913+16 and PSR 1930+22 were determined independently of the search apparatus and have uncertainties of ± 5 cm^{-3} pc.

The flux densities shown correspond to the received flux averaged over many pulsar periods. They were determined by measuring the signal-to-noise ratio of the pulses and using the known system noise as a calibrator. A separate estimate was made of the system temperature for each pulsar observation, including contributions from receiver noise, sky background, and spillover, and the consistency obtained between separate determinations for the same pulsar show the method to be reasonably reliable. Nevertheless, errors as large as a factor of 2 are probably to be expected in these numbers.

Table 2 lists the 10 pulsars detected in the survey whose existence was previously known. No known pulsar in the search region escaped detection in the present survey, and all of the new pulsars are weaker than the weakest of the already known objects. These facts lend some confidence in the thoroughness and reliability of the searching techniques now being used.

TABLE 2

THE 10 PREVIOUSLY KNOWN PULSARS DETECTED IN THE SURVEY

1859+03
1907+10
1915+13
1919+19
1919+21
1920+21
1929+10
1933+16
1944+17
2020+28

A prime objective of this project has been to obtain a statistically significant sample of pulsars influenced by a minimum of instrumental selection effects. For the most part this goal was realized, with good sensitivity achieved over the ranges $0 \leq \mathrm{DM} \leq 1240$ cm^{-3} pc, $0^{\mathrm{s}}033 \leq P \leq 3^{\mathrm{s}}9$, and $0.016 \leq W/P \leq 0.125$ (Hulse and Taylor 1974). However, the exact sensitivity reached is still somewhat a function of these parameters, as well as of the celestial coordinates. Hence uncorrected distributions of the parameters of these pulsars should not be interpreted too closely. Detailed statistical conclusions will be presented in a future paper, upon quantification of these effects.

IV. SPATIAL DISTRIBUTION OF THE SAMPLE PULSARS

One conclusion which can be safely drawn is that the pulsars in this sample show a remarkably limited range in dispersion measure: with the exception of two pulsars (PSR 1859+03 and PSR 1924+19) with DM $\approx$ 400, all of the sources detected have DM $\leq$ 260. That this is not the result of any instrumental bias is assured by the de-dispersion processing used in this survey. In the following discussion we will use the sample of 47 pulsars detected in the low-latitude region shown in Figure 1. Parameters used are from Table 1 for the new pulsars, and from the compilation of Taylor and Manchester (1975) for the others.

The detectability of high-dispersion pulsars can be reduced as a result of scintillation broadening of the pulses as they propagate through the interstellar medium (see, for example, Sutton 1971 and references therein). Komesaroff *et al.* (1973) showed this effect to be important in a pulsar survey that covered galactic longitudes $-60° < l < 10°$. However, the present survey does not appear to have been affected by this problem, as the measured pulse widths show no tendency to increase with dispersion measure. Though some scintillation broadening is no doubt present for these pulsars, it is not of a detection-limiting magnitude at least up to DM $\sim$ 260, and presumably does not become discontinuously worse beyond this value. It would appear that the distribution of thermal electrons in the direction $l \approx 50°$ is more uniform than that in the directions surveyed by Komesaroff *et al.*, so that scintillation effects are considerably weaker in our survey. This conclusion is in accord with the general lack of galactic H II regions in the direction $l \approx 50°$ (see, for example, Reifenstein *et al.* 1970).

A second possible observational barrier to the detection of pulsars with DM > 260 is our minimum detectable flux density. At least on a statistical basis, pulsar dispersion measures have been shown to be reasonable indicators of distance (Gómez-González and Guélin 1974). Thus, pulsars with higher dispersions are in general fainter and more difficult to detect. However, the range of intrinsic pulsar luminosities is large, and many of the pulsars that we detected at DM $\approx$ 200 would have been easily detectable at much greater distances.

In Figure 2 we have plotted the average flux densi-

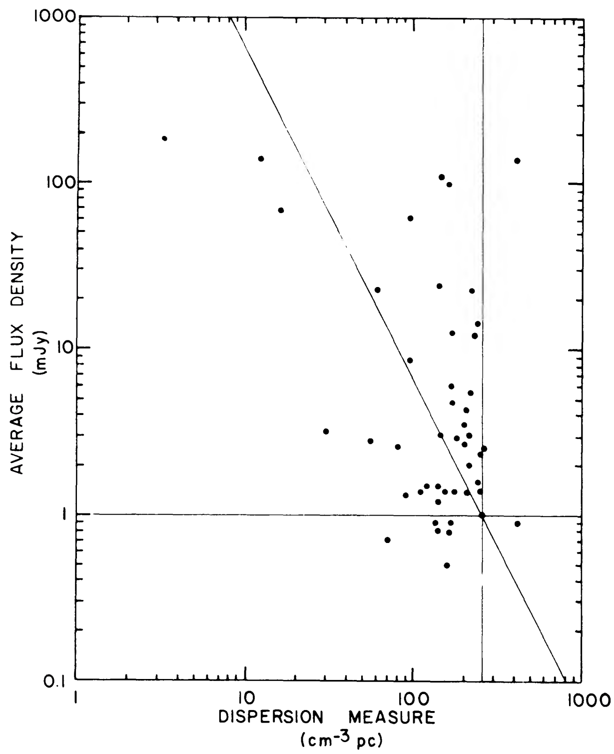

FIG. 2.—Average flux densities of the 47 pulsars plotted as a function of dispersion measure. The horizontal line at 1 mJy shows the approximate detection threshold, and the vertical line is drawn at DM = 260 cm^{-3} pc. The diagonal line (slope = −2) corresponds to pulsars whose intrinsic luminosity would produce an observed flux density of 1 mJy at DM = 260 cm^{-3} pc, assuming a linear dependence of dispersion measure on distance. Pulsars located above this line are sufficiently luminous to have been detected by this survey out to dispersion measures beyond 260 cm^{-3} pc, which demonstrates that the observed cutoff at this value does not arise from limited sensitivity. The 38 new pulsars in this sample are those with flux densities below 23 mJy.

ties of the 47 pulsars as a function of dispersion measure. Our detection threshold of ~1 mJy is indicated by the horizontal line, and the vertical line emphasizes the cutoff observed at DM ≈ 260. If dispersion measure is a linear function of distance, then lines in Figure 2 with slope −2 are lines of constant luminosity. One such line has been drawn, corresponding to the luminosity which would give an observed flux of 1 mJy at DM = 260. Any pulsars less luminous than this value (below the diagonal line) were unlikely to have been detected by this survey at DM > 260. But more than half of the pulsars observed have luminosities greater than this value, and 12 of these would have been detectable out to dispersions of over 400. The lack of high-dispersion pulsars becomes even more significant when we note that the volume of space corresponding to 260 < DM < 400 is greater than the entire volume surveyed at DM < 260 and should, *a priori*, contain *more* pulsars.

The cutoff at DM ≈ 260 occurs uniformly over the galactic latitudes we observed, which indicates that the scale height of pulsars in distance z from the galactic plane is less than the corresponding scale height of the dispersing electrons. This conclusion is in good agreement with the work of Bridle and Venugopal (1969) and Falgarone and Lequeux (1973), who conclude that the scale height of thermal electrons in the Galaxy is 500–1000 pc. The two pulsars with DM ≈ 400 are unlikely to be a manifestation of enhanced $\langle n_e \rangle$ at low z, as they are too few to be significant; one would expect a continuum of lower-latitude, higher-dispersion pulsars, not just two separated from the rest by a gap of ~140 in dispersion measure.

V. CONCLUSIONS

We thus appear to have detected a real limit to the depth of the pulsar distribution in the region $42° \lesssim l \lesssim 60°$, occurring at some distance corresponding to DM = 260 cm^{-3} pc. In a previous paper (Hulse and Taylor 1974) we interpreted our null result searching in the direction $l \approx 180°$ as evidence for a markedly reduced density of pulsars beyond 10 kpc from the galactic center, and we compared this with the similar distribution of supernova remnants in the Galaxy (Ilovaisky and Lequeux 1972). We interpret the limited spatial extent of pulsars in the direction $l \approx 50°$ in the same way. The abruptness of the cutoff and its distance from the galactic center are difficult to determine, because the effect has been detected over only a small range of longitudes; also, at large distances we are detecting only the most luminous pulsars, rather than the much more numerous low-luminosity objects. A mean electron density of $\langle n_e \rangle = 0.03$ cm^{-3} would place the cutoff at ~9 kpc from the Sun, or ~8 kpc from the galactic center, which is only slightly smaller than the result inferred for the solar direction. However, a sharp cutoff at 8 kpc from the galactic center would result in a strong dependence of number of pulsars on galactic longitude within our survey, and, in addition, the more highly dispersed pulsars would be expected at lower longitudes. Only a weak effect of this sort is observed. Increasing the distance assigned to the cutoff tends to remove this problem, which suggests that the correct value of $\langle n_e \rangle$ is somewhat less than 0.03 cm^{-3} in this direction. The value $\langle n_e \rangle = 0.02$ cm^{-3} implies a cutoff at about 13 kpc from the Sun, or 10 kpc from the galactic center, and these distances may be more reasonable values. Measurements of neutral hydrogen absorption for a number of pulsars in our survey would be of great help in calibrating this distance scale.

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