DISCOVERY OF 14 RADIO PULSARS IN A SURVEY OF THE MAGELLANIC CLOUDS

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ABSTRACT

A systematic survey of the Large and Small Magellanic Clouds for radio pulsars using the Parkes radio telescope and the 20 cm multibeam receiver has resulted in the discovery of 14 pulsars and the redetection of five of the eight previously known spin-powered pulsars believed to lie in the Magellanic Clouds. Of the 14 new discoveries, 12 are believed to lie within Clouds, three in the Small Cloud and nine in the Large Cloud, bringing the total number of known spin-powered pulsars in the Clouds to 20. Averaged over all positions within the survey area, the survey had a limiting flux density of about 0.12 mJy. Observed dispersion measures suggest that the mean free electron density in the Magellanic Clouds is similar to that in the disk of our Galaxy. The observed radio luminosities have little or no dependence on pulsar period or characteristic age and the differential luminosity function is consistent with a power-law slope of −1, as is observed for Galactic pulsars.

Subject headings: Magellanic Clouds — pulsars: general — surveys

Online material: color figures

1. INTRODUCTION

The Large and Small Magellanic Clouds (LMC and SMC) are our nearest neighbor galaxies and, to date, the only galaxies other than our own that have detectable pulsars. The first systematic survey for radio pulsars in the Magellanic Clouds was by McCulloch et al. (1983), who used a receiver with center frequency 645 MHz and bandwidth 25 MHz on the Parkes 64 m radio telescope to search 7 deg^2 of the LMC. This survey uncovered the first known extragalactic pulsar, PSR B0529−66, which has a period of 0.975 s and a dispersion measure (DM) of 103 cm^{-3} pc, which clearly places it outside the Galactic free-electron layer. This survey was subsequently extended by McConnell et al. (1991) to cover both the LMC and the SMC with higher sensitivity using a receiver with center frequency 610 MHz, a bandwidth 60 MHz in each of two orthogonal polarizations, and 5 ms sampling. With an observation time of 5000 s per pointing, the limiting mean flux density at 610 MHz was 0.5 to 0.8 mJy for pulsars with periods greater than about 500 ms and DMs of 100 cm^{-3} pc or less. Four pulsars were discovered, one in the SMC, two in the LMC, and one foreground pulsar. The SMC pulsar, now known as PSR J0045−7319, was shown by Kaspi et al. (1994) to be in a 51 day orbit round a massive star, optically identified as a 16th magnitude B star. The identification was subsequently confirmed by the detection of orbital Doppler shifts in spectral lines from the B star, showing that the star has a mass of 8–10 $M_\odot$ (Bell et al. 1995).

Many young pulsars emit pulsed emission in the X-ray band, and sometimes detection is easier in this band than at radio wavelengths. Two such pulsars that are clearly located in the LMC are known. The first, PSR B0540−69, was discovered by Seward et al. (1984) using data from the *Einstein X-ray Observatory*. With a pulse period of 50.2 ms and a characteristic age of just 1670 yr, it has properties very similar to those of the Crab pulsar and is located at the center of the supernova remnant (SNR) 0540−693 in the LMC (Manchester et al. 1993b). This pulsar was detected in the radio band by Manchester et al. (1993a) at 640 MHz with a very broad pulse and mean flux density of about 0.4 mJy. Giant radio pulses at 1400 MHz were detected from PSR B0540−69 by Johnston & Romani (2003), and subsequently the 1400 MHz mean pulse emission was observed with a flux density of just 24 μJy by Johnston et al. (2004). Another young Magellanic Cloud pulsar, PSR J0537−6910, was detected by Marshall et al. (1998) using observations with the *Rossi X-ray Timing Explorer*. This pulsar lies within the SNR N 157B in the LMC and has the shortest period, 16.1 ms, of any known young (unrecycled) pulsar. Its characteristic age is 5000 yr, close to the estimated age of N157B. Radio searches for pulsed emission from this pulsar have been unsuccessful, with the best limit on the mean flux density, 10 μJy at 1400 MHz, being set by Crawford et al. (2005).

A decade after the McConnell et al. (1991) search, Crawford et al. (2001) exploited the high survey efficiency of the 13 beam Parkes 20 cm multibeam receiver (Staveley-Smith et al. 1996; Manchester et al. 2001) to undertake a higher sensitivity survey of the SMC. A total area of ∼6.7 deg^2 was covered in 12 pointings of the instrument, with a 0.25 ms sampling interval and 8400 s observation time per pointing giving a 1400 MHz limiting flux density of about 0.08 mJy for pulsars with periods greater than 50 ms and DMs less than 200 cm^{-3} pc. For comparison, the 610 MHz limiting flux density of the McConnell et al. (1991) survey corresponds to a 1400 MHz limiting flux density of about 0.12–0.18 mJy assuming a spectral index of −1.8, typical for most pulsars (Maron et al. 2000). These limiting flux densities apply to a detection at the beam center and do not take into account variations of telescope gain over the surveyed region. The Crawford et al. (2001) survey found two previously unknown pulsars, one of which is believed to be associated with the SMC. In a separate search for pulsed emission from PSR J0537−6910, another pulsar, PSR J0535−6935, was serendipitously discovered.

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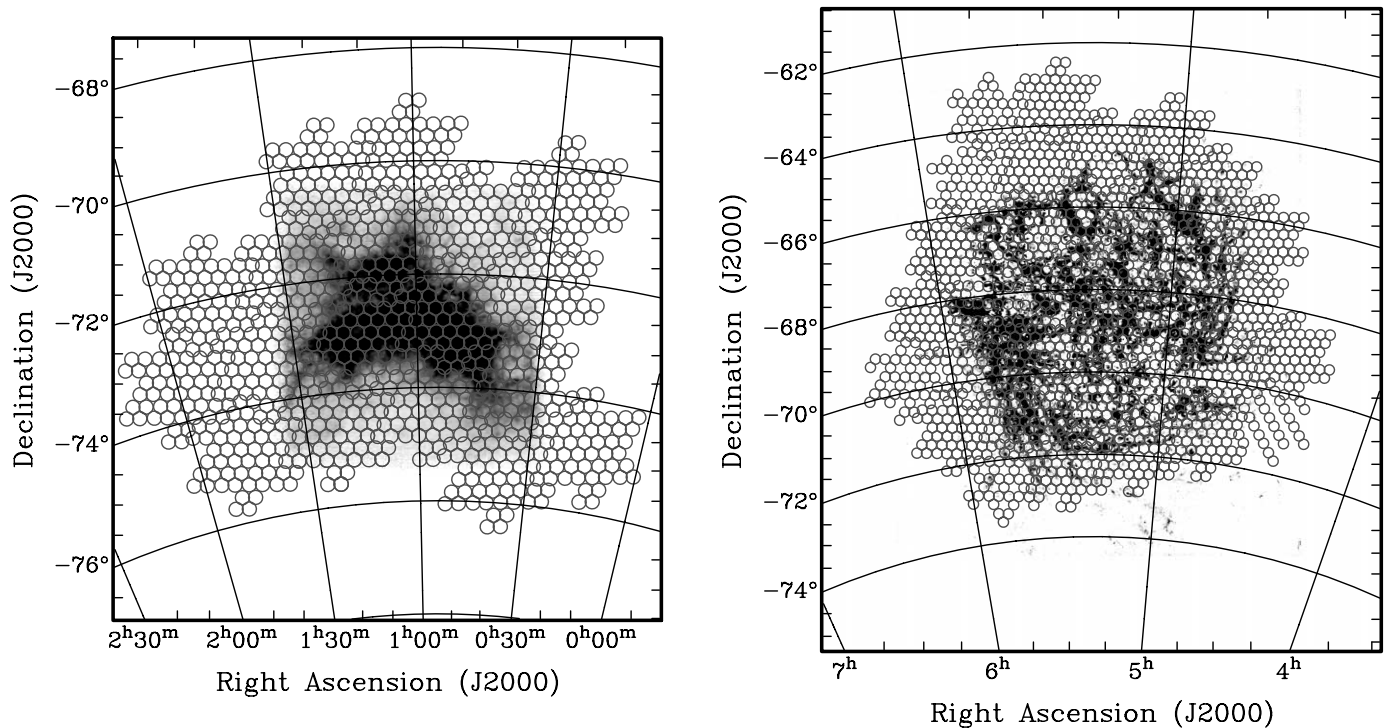[5] Department of Physics, Haverford College, Haverford, PA 19041-1392.

Fig. 1.—Distribution of survey beams across the SMC (*left*) and LMC (*right*) overlaid on a gray scale of the neutral hydrogen distribution from Stanimirović et al. (1999) and Kim et al. (2003) for the SMC and respectively. [*See the electronic edition of the Journal for a color version of this figure.*]

These discoveries brought the total number of known pulsars associated with the Magellanic Clouds to eight, seven of which are radio emitting, two of which are in the SMC, and six of which were discovered in radio surveys. In this paper we report on an extensive radio survey of both the LMC and SMC for pulsars. Like the Crawford et al. (2001) survey of the SMC, this survey used the multibeam receiver on the Parkes 64 m radio telescope. It has a comparable sensitivity to the Crawford et al. (2001) survey, but covers a wider area and is sensitive to higher DMs. The survey was very successful, with 14 pulsars discovered, 12 of which are believed to be in the Magellanic Clouds. In § 2 we describe the survey and timing observations, § 3 gives details of the new discoveries, and the implications of the results are discussed in § 4.

2. OBSERVATIONS AND ANALYSIS PROCEDURES

The survey observations were made using the 13 beam multibeam receiver (Staveley-Smith et al. 1996) on the Parkes 64 m radio telescope in several sessions between 2000 May and 2001 November. The 13 beams lie in a double-hexagon pattern around a central beam, which allows complete sky coverage (with adjacent beams overlapping at the half-power points) with interleaved pointings. A brief description of the observing system follows; for more details see Manchester et al. (2001). Each beam has cryogenic receivers for two orthogonal polarizations centered at 1374 MHz. For each polarization, the received 288 MHz band is split into 96 3 MHz channels. Detected signals from each channel are summed in polarization pairs, high-pass filtered, integrated for 1 ms, one-bit sampled, and written to digital linear tape for subsequent analysis. Each pointing was observed for 8400 s, giving 2^{23} samples per observation. A total of 73 pointings (949 beams) was observed for the SMC and 136 pointings (1768 beams) for the LMC. The distribution of these beams overlaid on images of the neutral hydrogen in the SMC and LMC is shown in Figure 1.

In most respects, offline processing followed the procedures outlined by Crawford et al. (2001) and Manchester et al. (2001), and was carried out on Sun workstations at the Australia Telescope National Facility (ATNF) and at McGill University. Compared to the Crawford et al. (2001) survey of the SMC, a larger DM range was searched in the present survey. A total of 102 DMs up to 277 cm^{-3} pc were searched with 1 ms time resolution, a further 42 DMs were then searched for each of 2 ms, 4 ms, and 8 ms time resolutions, with maximum DMs of approximately 550, 1100, and 2200 cm^{-3} pc, respectively. For most periods and DMs, the sensitivity of this survey was comparable to that of Crawford et al. (2001), with a limiting flux density of about 0.08 mJy for an assumed 5% duty cycle. Because of the 4 times longer sampling interval, the sensitivity for short-period pulsars ($P \lesssim 50$ ms) is reduced compared to the earlier survey. These limiting flux densities apply to a pulsar at the center of the central beam of the multibeam receiver. In general, pulsars will lie some distance from the center of the nearest beam. Furthermore, outer beams have a lower gain than the central beam. Following Manchester et al. (2001), we estimate the limiting mean flux density of the survey averaged over all positions within the tiled region to be approximately 0.12 mJy.

The data analysis resulted in a large number of candidate pulsars, which were graded according to signal-to-noise ratio (S/N) and absence of interference. The better candidates were re-observed using a grid pattern of observations with the center beam of the multibeam system at the nominal position and 9′ north, south, east, and west, typically for 3000 s per pointing. The data from these observations were searched over ranges of period and DM about the nominal values. Detection of a pulsar signal in one or more pointings gave confirmation of the candidate and detection in two or more pointings allowed determination of an improved position for the pulsar.

Following confirmation of a pulsar, a program of timing observations commenced in order to improve the position, period, and DM, and to determine the period derivative. These timing

TABLE 1

PARAMETERS FOR PULSARS DISCOVERED IN THIS SURVEY

PSR	R.A. (J2000)	Decl. (J2000)	DM (cm^{-3} pc)	DM sin $|b|$ (cm^{-3} pc)	S_{1400} (mJy)	W_{50} (ms)
J0045−7042	00 45 25.69(17)	−70 42 07.1(13)	70(3)	50.7	0.11	19
J0111−7131	01 11 28.77(9)	−71 31 46.8(6)	76(3)	54.2	0.06	13
J0131−7310	01 31 28.51(3)	−73 10 09.34(13)	205.2(7)	141.6	0.15	4.8
J0449−7031	04 49 05.67(5)	−70 31 31.7(3)	65.83(7)[a]	38.2	0.14	7.9
J0451−67	04 51 50(70)	−67 18(7)	45(1)	26.6	≲0.05	5.5
J0456−7031	04 56 02.5(3)	−70 31 06.6(12)	100.3(3)[a]	57.5	0.05	8
J0457−6337	04 57 07.79(8)	−63 37 30.4(9)	27.5(10)	16.4	0.18	36
J0511−6508	05 11 56.50(2)	−65 08 36.5(3)	25.66(8)[a]	14.6	0.70	12
J0519−6932	05 19 46.917(12)	−69 32 23.48(7)	119.4(5)	65.5	0.32	4.1
J0522−6847	05 22 23.06(8)	−68 47 02.2(3)	126.45(7)[a]	69.2	0.19	12
J0532−6639	05 32 59.51(6)	−66 39 37.3(5)	69.3(18)	37.2	0.08	9
J0534−6703	05 34 36.17(10)	−67 03 48.8(8)	94.7(12)	50.6	0.08	25
J0543−6851	05 43 52.71(11)	−68 51 25.3(9)	131(4)	67.9	0.22	58
J0555−7056	05 55 01.85(12)	−70 56 45.6(6)	73.4(16)	36.8	0.21	27

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
[a] 70 cm and 20 cm data used for DM determination.

observations used the center beam of the multibeam receiver and the same recording system as was used for the survey. The resulting data were folded at the topocentric period to form mean pulse profiles that were further analyzed using the PSRCHIVE (Hotan et al. 2004) pulsar data analysis package to produce pulse times of arrival (TOAs) for each observation (where there was a detectable pulse). These were analyzed using TEMPO[6] with the DE200 solar-system ephemeris (Standish 1990) and a weighted fit. Typically, the timing observations spanned 400–600 days, with more than 20 observations per pulsar. In most cases, DMs were determined by splitting the observed 20 cm band into four subbands and measuring TOAs separately for each subband. In a few cases the pulsar was also detected using a 70 cm receiver that has a bandwidth of 32 MHz centered at 436 MHz; combination of the 20 cm and 70 cm TOAs resulted in an improved DM for these pulsars. For each pulsar, several observations having high S/N were folded at 2 and 3 times the nominal period in order to uncover detection by the survey analysis software of a harmonic of the true pulse frequency. This procedure

[6] See http://www.atnf.csiro.au/research/pulsar/tempo.

revealed two pulsars that had misidentified periods from the survey analysis.

3. RESULTS

The procedures described above resulted in the detection of 14 previously unknown pulsars, three toward the SMC and 11 toward the LMC. Table 1 lists the J2000.0 right ascension and declination obtained from the timing analysis, the DM and its "z-component," DM sin $|b|$ (where b is the Galactic latitude, which is useful for determining whether the pulsar is within or outside the Galactic electron layer), the mean flux density (averaged over the pulse period) at 1400 MHz, and the pulse width at 50% of the peak amplitude. Table 2 gives other parameters derived from the timing analysis, namely the barycentric pulse period, P, its first time derivative, $\dot{P}$, the epoch of the period in modified Julian days, the time span of the data used in the timing fit, the number of TOAs fitted, and the postfit rms timing residual. Estimated uncertainties given in parentheses after parameter values are twice the TEMPO rms errors and refer to the last quoted digit. Mean flux densities were estimated from the area under grand average profiles formed by summing data from all timing

TABLE 2

PERIOD PARAMETERS FOR PULSARS DISCOVERED IN THIS SURVEY

| PSR	P (s)	$\dot{P}$ (10^{-15})	Epoch (MJD)	Data Span (MJD)	$N_{\rm TOA}$	Residual (ms)
J0045−7042	0.63233580002(6)	2.49(3)	52407.0	52189−52642	17	1.54
J0111−7131	0.68854151164(5)	7.092(4)	52369.0	52041−52695	15	1.14
J0131−7310	0.348124045581(7)	1.7614(7)	52335.0	52038−52631	24	0.40
J0449−7031	0.479163971291(14)	3.371(4)	52465.0	52233−52695	20	0.51
J0451−67[a]	0.24545429(7)	<2	52817.0	52817−52818	5	0.80
J0456−7031	0.80013207321(10)	36.70(3)	52560.0	52316−52804	15	2.25
J0457−6337	2.49701169613(19)	0.21(3)	52465.0	52189−52739	8	0.75
J0511−6508	0.322061827468(8)	0.206(4)	52409.0	52189−52628	27	0.29
J0519−6932	0.263211634568(3)	0.6968(5)	52466.0	52237−52695	26	0.20
J0522−6847	0.67453190906(3)	17.727(14)	52503.0	52311−52695	16	0.29
J0532−6639	0.64274275093(3)	5.354(13)	52462.0	52259−52664	14	0.58
J0534−6703	1.81756503106(17)	425.05(6)	52410.0	52195−52624	16	0.65
J0543−6851	0.70895418575(6)	3.94(3)	52410.0	52195−52624	16	1.32
J0555−7056	0.82783808575(7)	5.96(3)	52408.0	52190−52624	16	0.84

[a] See text.
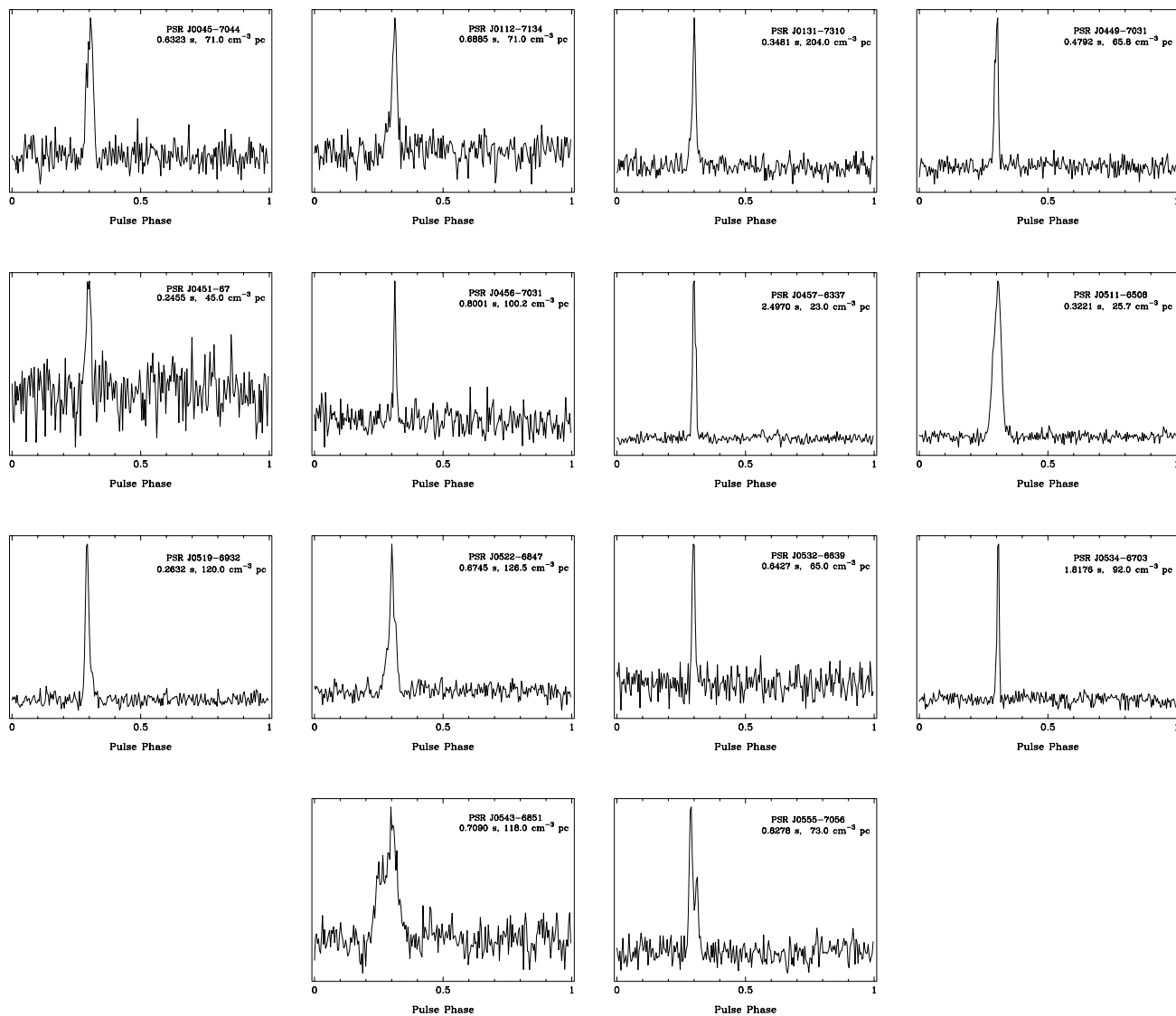
FIG. 2.—Mean total intensity pulse profiles at 1400 MHz for the 14 pulsars discovered in this survey. The pulsar period and dispersion measure are given on each plot below the name.

observations (whether or not the pulsar was detectable) using the derived timing model to phase align the profiles.

PSR J0451−67 was detected just twice in 2 yr of timing observations and a coherent timing solution was not possible. Grid observations were also unsuccessful, so that the quoted position is that of the discovery beam and the uncertainties are the half-power beam radius. The period given in Table 2 was obtained by splitting the best single observation into five parts of equal duration and obtaining TOAs for each part; the quoted error includes a contribution from the position uncertainty. A limit on the period derivative was obtained by differencing the derived period and that from the discovery observation on MJD 51816. The mean flux density was estimated by taking the value for the best detection (on MJD 52817) and dividing by $N^{1/2}$, where N is the total number of timing observations ($\sim$20).

Mean pulse profiles at 1400 MHz for the 14 pulsars are shown in Figure 2; the whole pulse period is shown in each case. These profiles were obtained by summing data from all observations of a given pulsar where there was a detectable pulse and then correcting for the effects of the high-pass filter in the digitization system; see Manchester et al. (2001) for details. Profiles were rotated to place the pulse peak at phase 0.3 for display purposes. It is

notable that, in most cases, the mean pulse profiles are narrow and relatively simple in form. The median duty cycle (W_{50}/P) for these pulsars is just 0.015 (compared to 0.029 for the Galactic population) and the largest (for PSR J0543−6851) is only 0.082. Only two pulsars, PSRs J0543−6851 and J0555−7056, have clear evidence for multiple components in the mean profile.

Five of the seven previously known radio pulsars in the Magellanic Clouds were detected in the survey: PSRs J0045−7319, J0113−7220, J0455−6915, J0502−6617, and J0529−6652. PSR J0540−6919 was well below our detection threshold and PSR J0535−6935 has an estimated 1400 MHz flux density of 0.05 mJy; neither pulsar was detected in the survey. However, in an attempt to obtain a timing solution for PSR J0535−6935, about 50 observations with the beam centered on the nominal position and mostly with a duration of about 3 hr were made between late 1998 and 2004, resulting in about 25 detections. The period and DM giving the highest S/N for the pulse were determined for each observation by searching over a small range in each parameter. The derived periods showed a clear trend over the 6 years. Although a coherent timing solution could not be found, a fit of a straight line to the seven points having S/N greater than 8.0 gave $P = 0.20051133(2)$ s at MJD 52200 and $\dot{P} = 11.5(3) \times 10^{-15}$
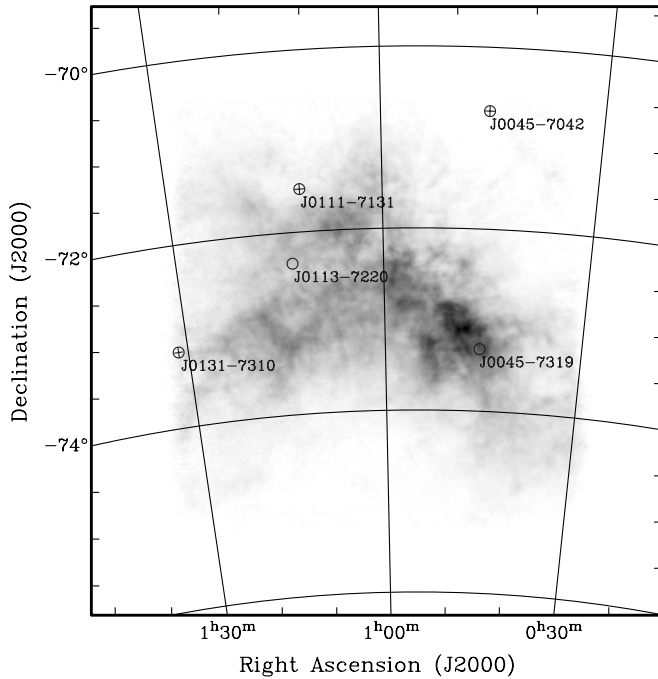
FIG. 3.—Location of pulsars discovered in the SMC survey, marked by a cross, overlaid on an image of the neutral hydrogen in the SMC (Stanimirović et al. 1999). Pulsars believed to be associated with the SMC, including previously known pulsars, are marked by a circle. [*See the electronic edition of the Journal for a color version of this figure.*]
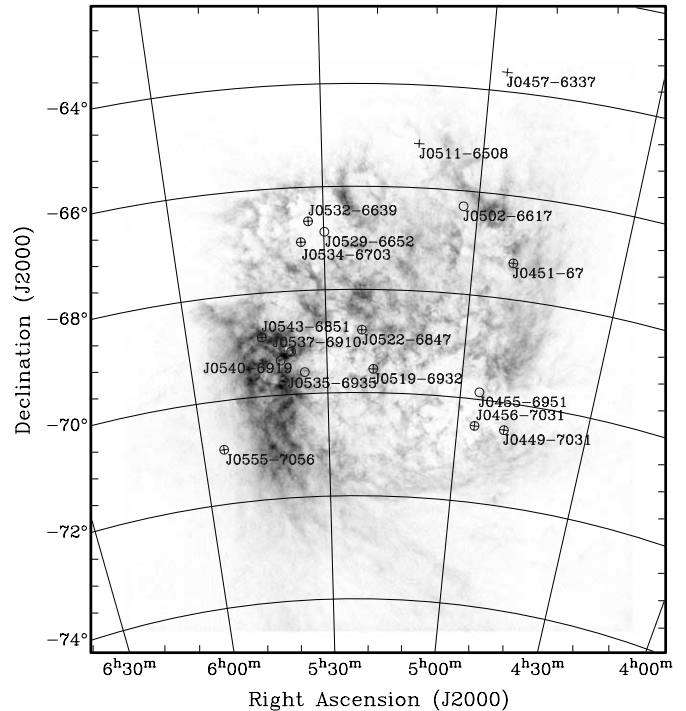

FIG. 4.—Location of pulsars discovered in the LMC survey, marked by a cross, overlaid on an image of the neutral hydrogen in the LMC (Kim et al. 2003). Pulsars believed to be associated with the LMC, including previously known pulsars, are marked by a circle. [*See the electronic edition of the Journal for a color version of this figure.*]

with an assumed position of R.A. $05^h35^m00^s$, decl. $-69°35'00''$. These values are consistent with the period parameters quoted by Crawford et al. (2001) for this pulsar. Averaging the DM values for the seven high-S/N detections gave a mean value of 93.7 ± 0.4 cm^{-3} pc.

4. DISCUSSION

Of the 14 pulsars listed in Table 1, two have values of DM sin $|b|$ significantly less than 25 cm^{-3} pc. As discussed by Crawford et al. (2001), the distribution of DM sin $|b|$ for Galactic pulsars extends to about this value, suggesting that these pulsars, PSRs J0457−6337 and J0511−6508, probably lie within the disk of our Galaxy. A third pulsar, PSR J0451−67, has a DM sin $|b|$ value marginally above this limit, so its association is not clear. However, only nine of the roughly 1500 known Galactic-disk pulsars have DM sin $|b|$ greater than the value for PSR J0451−67.[7] Furthermore, of the eight globular clusters containing known pulsars and with Galactic z-distances greater than 3 kpc, only two have pulsars with DM sin $|b|$ values greater than that for PSR J0451−67. We therefore conclude that it is most probable that PSR J0451−67 lies in the LMC, most likely on the near side. All other pulsars in Table 1 have significantly higher values of DM sin $|b|$ and are almost certainly associated with the Magellanic Clouds.

Figure 3 shows the positions of the three SMC pulsars from Table 1, together with the two previously known SMC pulsars, plotted on a gray-scale image of the H I in the SMC. Two of the newly discovered pulsars are within the H I distribution (at least in projection) but the other, PSR J0045−7042 is outside the main H I region. PSR J0131−7310 lies on the eastern edge of the imaged region but is notable for having the highest DM and DM

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[7] Data obtained from the ATNF Pulsar Catalogue, Version 1.24 (http://www.atnf.csiro.au/research/pulsar/psrcat; Manchester et al. 2005).

sin $|b|$ of any of the Magellanic Cloud pulsars by a considerable margin. Figure 1 shows that a considerable area further to the east of PSR J0131−7310 was searched, but no pulsars were detected there.

Positions of newly discovered pulsars in the direction of the LMC and previously known pulsars believed to be associated with the LMC are shown in Figure 4. All the pulsars believed to be associated with the LMC lie within the H I distribution. The two foreground pulsars lie outside the main H I distribution to the north.

No millisecond pulsars were discovered in the survey. This is not surprising, given the 1 ms sampling interval employed and the generally lower radio luminosity of millisecond pulsars. However, two very long-period pulsars were discovered (Table 2). One of these, PSR J0457−6337, has a small period derivative and hence a very large age, ∼190 Myr. Although we do not believe this pulsar to be associated with the LMC, it has a significant DM sin $|b|$ (Table 1) and must be located in the Galactic halo. Both of the commonly used models for the Galactic electron density (Taylor & Cordes 1993; Cordes & Lazio 2002) place this (and PSR J0511−6508) at or beyond the outer edge of the Galactic electron disk, with z-distances in excess of 1 kpc. The other long-period pulsar discovered in the survey, PSR J0534−6703, is clearly associated with the LMC and is notable for its very large period derivative (Table 2). This pulsar is relatively young ($\tau_c = P/2\dot{P} \sim 68$ kyr) and has a very strong implied surface dipole magnetic field, $B_s = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G $\sim 2.8 \times 10^{13}$ G. Only 10 radio pulsars have a greater surface dipole magnetic field based on their observed period and period derivative.

Table 3 lists the 20 known spin-powered pulsars believed to be associated with the Magellanic Clouds, 12 of which were discovered in the present survey. The table lists the pulse period P, the DM (except for PSR J0537−6910, which has not been

TABLE 3
PROPERTIES OF MAGELLANIC CLOUD PULSARS

J Name	B Name	P (s)	DM (cm^{-3} pc)	log(τ_c)	S_{1400} (mJy)	L_{1400} (mJy kpc^2)	Disc. Ref.	S_{1400} Ref.
J0045−7042.............................	...	0.6323	70.0	6.60	0.11	275	1	1
J0045−7319.............................	...	0.9262	105.4	6.51	0.3	750	2	3
J0111−7131.............................	...	0.6885	76.0	6.18	0.06	150	1	1
J0113−7220.............................	...	0.3258	125.4	6.02	0.4	1000	3	3
J0131−7310.............................	...	0.3481	205.2	6.49	0.15	375	1	1
J0449−7031.............................	...	0.4791	65.8	6.35	0.14	350	1	1
J0451−67.................................	...	0.2454	45	>6.2	≲0.05	≲125	1	1
J0455−6951.............................	B0456−69	0.3204	94.8	5.69	0.25[a]	625	2	2
J0456−7031.............................	...	0.8001	100.3	5.53	0.05	125	1	1
J0502−6617.............................	B0502−66	0.6912	68.9	5.67	0.25[a]	625	2	2
J0519−6932.............................	...	0.2632	119.4	6.77	0.32	800	1	1
J0522−6847.............................	...	0.6745	126.4	5.78	0.19	475	1	1
J0529−6652.............................	B0529−66	0.9757	103.2	6.00	0.3	750	4	3
J0532−6639.............................	...	0.6427	69.3	6.28	0.08	200	1	1
J0534−6703.............................	...	1.8175	94.7	4.83	0.08	200	1	1
J0535−6935.............................	...	0.2005	89.4	5.44	0.05	125	3	3
J0537−6910.............................	...	0.0161	...	3.69	<0.01	<25	5	6
J0540−6919.............................	B0540−69	0.0505	146.5	3.22	0.024	60	7	8
J0543−6851.............................	...	0.7089	131.0	6.45	0.22	550	1	1
J0555−7056.............................	...	0.8278	73.4	6.34	0.21	525	1	1

NOTE.—References: (1) This paper; (2) McConnell et al. 1991; (3) Crawford et al. 2001; (4) McCulloch et al. 1983; (5) Marshall et al. 1998; (6) Crawford et al. 2005; (7) Seward et al. 1984; (8) Johnston et al. 2004.
[a] From S_{610} assuming a spectral index of −1.8.

detected at radio wavelengths), the log of the characteristic age τ_c in years, the mean pulsed flux density at 1400 MHz S_{1400}, the monochromatic radio luminosity at 1400 MHz ($L_{1400} = S_{1400}d^2$, where d is the pulsar distance), the discovery reference, and the reference for the flux density measurement. The distance d is assumed to be 50 kpc in all cases; this is reasonable, since the actual distances are not reliably known. In any case, uncertainties in the luminosities are contributed to, if not dominated by, uncertainties in the mean flux densities.

Based on the observed pulsar positions and DMs, we can estimate the free-electron content of the two Clouds. For the SMC and LMC separately, we first subtract a Galactic contribution, $25/\sin|b|$ cm^{-3} pc from the DM for each pulsar and compute the mean value of the Cloud DMs, obtaining $\langle$DM$\rangle = 80.9$ cm^{-3} pc for the SMC and 49.5 cm^{-3} pc for the LMC. If we assume pulsars are uniformly distributed through a roughly spherical volume for each Cloud, the total integrated electron content across the Cloud is twice the mean value or approximately 160 cm^{-3} pc ($\sim 5 \times 10^{20}$ cm^{-2}) for the SMC and 100 cm^{-3} pc ($\sim 3 \times 10^{20}$ cm^{-2}) for the LMC. We also estimate the mean electron density in each cloud by computing the rms dispersion of the Cloud DMs, 48.2 cm^{-3} pc and 26.8 cm^{-3} pc for the SMC and LMC respectively, and dividing this by the (one-dimensional) rms dispersion of the pulsar spatial coordinates in the right ascension and declination directions (assuming a mean distance of 50 kpc and that the offsets in the two directions are independent), 1025 and 1480 pc, respectively. This procedure gave mean electron densities of 0.047 cm^{-3} for the SMC and 0.018 cm^{-3} for the LMC. We are somewhat limited by small-number statistics in the conclusions that we can draw from these results. For example, the relatively large values for the SMC may simply be a consequence of PSR J0131−7310 lying behind a dense H II region. Nevertheless, the results indicate that the mean free electron density in the Magellanic Clouds is similar to that in the disk of our Galaxy, possibly with a somewhat higher value in the SMC

and a somewhat lower value in the LMC. These results show that the Magellanic Clouds have a much higher proportion of stars contributing to ionization of the interstellar medium compared to the Galaxy, which is consistent with the much higher per unit mass star formation rates in the Clouds (e.g., Grimm et al. 2003).

Despite the lack of an electron density model for the Magellanic Clouds, the relative distance uncertainties are small for the Magellanic Cloud pulsars compared to those in our Galaxy. Therefore Magellanic Cloud pulsars give a more reliable estimation of the luminosity and its dependence on various parameters than can be obtained from Galactic pulsars. Figure 5 shows the 1400 MHz radio luminosity for pulsars in the Galactic disk and the Magellanic Cloud plotted against pulsar period (left) and characteristic age (right). The approximately 1000 Galactic pulsars plotted in these figures exclude apparently recycled pulsars, identified by having $B_s < 3 \times 10^{10}$ G, as well as pulsars in globular clusters. The Magellanic Cloud pulsars are typically of higher radio luminosity than Galactic pulsars. This is simply a result of the limited sensitivity of radio surveys combined with the greater distance of the Magellanic Cloud pulsars.

Although the number of Magellanic Cloud pulsars remains relatively small, they do cover significant ranges of both pulse period and age. The maximum observed period is 1.82 s and more than half the ages are greater than 10^6 yr. Figure 5 shows that there is little or no significant dependence of radio luminosity on either pulsar period or age. This remains true even if PSR J0537−6910 and PSR J0540−6919, neither of which was discovered in radio surveys, are disregarded. Indeed, if anything, there is a weak positive correlation of radio luminosity with characteristic age. This suggests that the emitted radio power is not greatly dependent on pulsar period or age and that other factors dominate the observed luminosity. It is worth noting that, assuming radiation into a circular beam of angular width equal to the observed pulse width, the radio luminosity is a tiny fraction, typically 10^{-4}, of the spin-down luminosity.
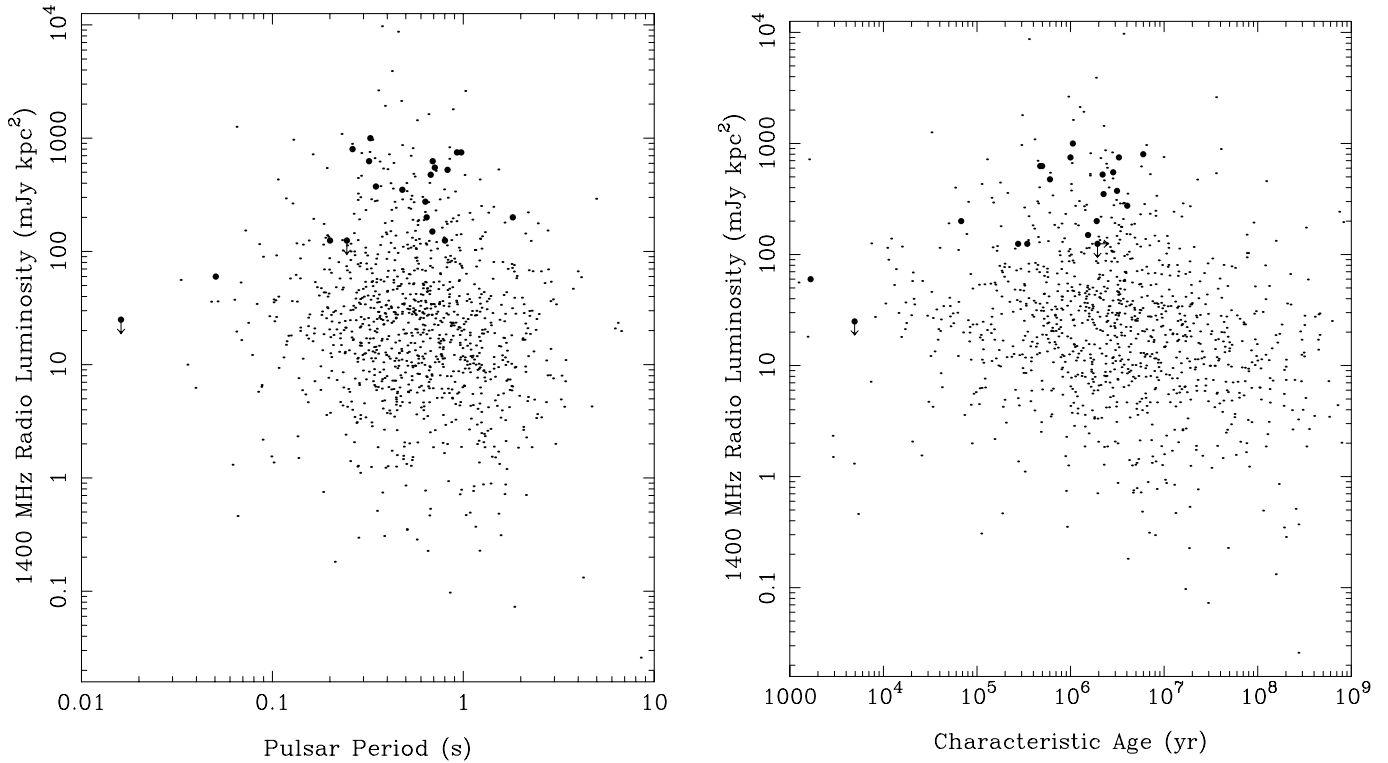
FIG. 5.—Plot of 1400 MHz radio luminosity for non-recycled pulsars in the Galactic disk (*dots*) and Magellanic Clouds (*filled circles*) versus pulsar period (*left*) and characteristic age (*right*). Parameters for Galactic pulsars were obtained from the ATNF Pulsar Catalogue.

The true radio luminosity may be substantially underestimated if only the outer part of the radio beam sweeps across the Earth. Unfortunately, little is known about the pulse polarization of the Magellanic Cloud pulsars, so no estimates of offsets of our viewing angle from the beam center are available. However, experience with Galactic pulsars shows that, even when these data are available, our poor understanding of radio beam shapes precludes making reliable corrections for these offsets (cf. Tauris & Manchester 1998). The narrow and relatively simple pulse profiles observed for most of the pulsars suggests that the observed emission is core dominated, but this remains to be confirmed by polarization and spectral measurements. As mentioned in § 3, the median duty cycle (*w*) for pulsars detected in this survey, 0.015, is considerably less than the median value for the Galactic population, 0.029 (0.028 if millisecond pulsars are excluded). Since the Magellanic Cloud pulsars are all of high radio luminosity, this might suggest a correlation between luminosity and duty cycle, but no such correlation exists in the known Galactic population. It is more likely that the low median duty cycle is a selection effect resulting from the fact that the limiting flux density is proportional to $w^{1/2}$ for small *w*. It is easier to detect pulsars of a given mean flux density if they have a small duty cycle. This effect is significant when a large fraction of the sample is close to the detection threshold.

The two shortest period and youngest known Magellanic Cloud pulsars were both first detected at X-ray wavelengths. Both have low radio luminosities, with only an upper limit for PSR J0537−6910. It is quite possible that the radio beam for both of these pulsars misses or largely misses the Earth, implying that the X-ray beam either covers a wider range of pulsar latitude than the radio beam or is less patchy.

Figure 6 shows the distribution of observed radio luminosities for Galactic and Magellanic Cloud pulsars. This figure clearly illustrates the effect of selection against low flux densities in radio pulsar surveys. For luminosities above about 30 mJy kpc^2 for Galactic pulsars and 300 mJy kpc^2 for Magellanic Cloud pulsars, the effect of selection is less and the distribution approximates the intrinsic luminosity function of pulsars, which in this plot of $d \log N/d \log L$ has a slope of about −1 (Lorimer 2004). Although we are still limited by small-number statistics, there is no evidence that the Magellanic Cloud pulsars have a different luminosity function from their Galactic counterparts.
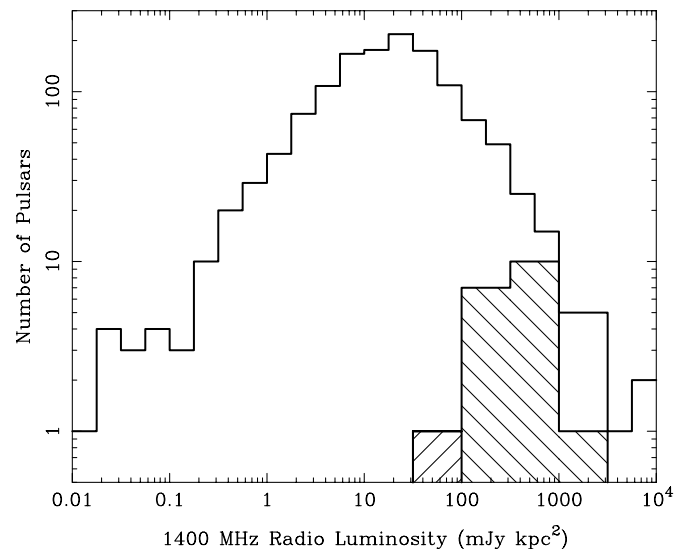

FIG. 6.—Observed distribution of 1400 MHz radio luminosities for the Magellanic Cloud pulsars (*hatched* area) and Galactic disk pulsars. The Magellanic Cloud pulsar with the lowest luminosity is PSR J0540−6919 (shown with different hatching), which was discovered at X-ray wavelengths and subsequently detected at radio wavelengths.

5. CONCLUSION

An extensive survey of the Large and Small Magellanic Clouds for radio pulsars using the Parkes radio telescope at 1400 MHz has resulted in the discovery of 14 pulsars, 12 of which are believed to be associated with the Clouds. The average limiting flux density of the survey was about 0.12 mJy. In general, the associated pulsars appear to be located in the more central regions of each Cloud where there is significant H I emission. Two long-period pulsars were discovered, one of which appears to be a very old pulsar located in the Galactic halo; the other is notable for its very strong implied surface dipole magnetic field.

This survey brings the number of spin-powered pulsars believed to be associated with the Magellanic Clouds to 20. Mean free electron densities averaged over the volume of the Clouds are similar to those in the disk of our Galaxy. Observed luminosities are at the high end of the luminosity function observed for Galactic pulsars but consistent with it. Despite the observed pulse periods and ages covering relatively wide ranges, there is little or no correlation of radio luminosity with either of these parameters.

It will be difficult to significantly improve on this survey with existing instrumentation, as the required observation times are too long to be feasible. Although searches for extragalactic pulsars at relatively low frequencies with large radio telescopes such as Arecibo may have some success, any major increase in the their number will most probably have to wait until the advent of instruments of much larger collecting area, for example, the proposed Square Kilometer Array.

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