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RADIO PULSARS IN THE MAGELLANIC CLOUDS

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ABSTRACT

We report the results of a survey of the Small Magellanic Cloud (SMC) for radio pulsars conducted with the 20 cm multibeam receiver of the Parkes 64 m telescope. This survey targeted a more complete region of the SMC than a previous pulsar search and had an improvement in sensitivity by a factor of about 2 for most pulsar periods. This survey is much more sensitive to fast young pulsars (with $P \lesssim 100$ ms) and is the first survey of the SMC with any sensitivity to millisecond pulsars. Two new pulsars were discovered in the survey, one of which is located within the SMC. The number of pulsars found in the survey is consistent with the expected number derived using several methods. We also report the serendipitous discovery of a new pulsar in the 30 Doradus region of the Large Magellanic Cloud (LMC). These discoveries bring the total number of rotation-powered pulsars currently known in the Magellanic Clouds to eight. We have also made refined timing measurements for the new discoveries as well as for three previously known LMC pulsars. The age distribution of luminous Magellanic Cloud pulsars supports the conjecture that pulsars younger than about 5 Myr are more luminous on average than older pulsars.

Subject headings: Magellanic Clouds — pulsars: individual (PSR J0057−7201, PSR J0113−7220, PSR J0535−6935) — stars: neutron — surveys

On-line material: color figure

1. INTRODUCTION

The Magellanic Clouds contain the most distant population of radio pulsars observable with current technology. Since the distances to the Magellanic Clouds are large, only the most luminous pulsars are detectable. However, despite the small number of pulsars currently known, these pulsars are among the most interesting in the pulsar population. Of the six pulsars discovered previously, one is in an unusual binary system and two are younger than 10 kyr. For comparison, of over 700 Galactic pulsars cataloged prior to the commencement of the Parkes Multibeam Pulsar Survey (see below), only one is in a similar binary system, and only five Galactic pulsars are younger than 10 kyr.

Surveying the Magellanic Clouds for radio pulsars is difficult because of the large surface area to be covered and their large distances. Long integrations using a telescope with a large collecting area are needed. With its southern latitude, the Parkes 64 m radio telescope in New South Wales, Australia, is the most appropriate telescope for conducting such searches.

The difficulty of obtaining sufficient sensitivity has been somewhat alleviated by the installation of the 20 cm multibeam receiver at Parkes (Staveley-Smith et al. 1996). This receiver is simultaneously sensitive to 13 distinct locations on the sky which can be interleaved in separate pointings to give complete and efficient spatial coverage of large regions. The Parkes Multibeam Pulsar Survey is currently using this receiver to search for pulsars in the Galactic plane, and that survey has discovered 580 pulsars to date (Camilo et al. 2000a; Manchester et al. 2000; Lyne et al. 2000). This demonstrates that the multibeam system is capable of finding faint pulsars and is an appropriate instrument to search for pulsars in the Magellanic Clouds.

Only one full-scale pulsar survey of the Magellanic Clouds has been conducted previously. McConnell et al. (1991) searched for pulsars using Parkes at a wavelength of 50 cm. This survey effort was split into three phases with different observing parameters used for each phase of the survey. Although the region surveyed in each phase was not described, the third phase of the survey was used for 5 of the 7 years of the effort, and we use this phase for a sensitivity comparison with our survey. In this phase, they used a center frequency of 610 MHz with a total bandwidth of 60 MHz split into 24 2.5 MHz contiguous frequency channels. Two orthogonal polarizations were used with a sampling time of 5 ms and a 5000 s dwell time for each pointing. The second phase of their survey had a comparable sensitivity to the third phase, but the first phase had significantly reduced sensitivity to fast pulsars as a result of the much larger sampling time of 40 ms used.

In their data reduction procedure, McConnell et al. (1991) assumed a dispersion measure (DM) of 100 pc cm^{-3} in an initial subband dedispersion in their analysis. Magellanic Cloud pulsars found to date have DMs which are roughly centered on this value, but the observed DM range is from about 70 to 150 pc cm^{-3}. Thus, their sensitivity to pulsars with DMs far from 100 pc cm^{-3} was significantly reduced. McConnell et al. (1991) also targeted the optical bar and the southern and western parts of the Small Magel-

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lanic Cloud (SMC) (see their Fig. 1). Our survey had more complete coverage in the northern and eastern regions of the SMC. McConnell et al. (1991) reported the discovery of four pulsars, three in the Large Magellanic Cloud (LMC) and one in the SMC.

We report the results of a more sensitive and complete survey for pulsars in the SMC in which we have discovered one new SMC pulsar and one foreground pulsar. Below we describe the observations and data reduction procedure for our survey and the subsequent timing observations. We also report on the serendipitous discovery of a pulsar in the 30 Doradus region of the LMC, as well as on timing observations of three previously known LMC pulsars. We discuss our results and summarize the currently known Magellanic Cloud pulsar population. The two new Magellanic Cloud pulsars found in our survey, combined with the four pulsars found by McConnell et al. (1991) and the two known X-ray pulsars in the LMC, bring the total number of known rotation-powered pulsars in the Magellanic Clouds to eight.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *Survey Observations and Data Reduction*

The multibeam receiver is capable of simultaneously observing 13 separate regions on the sky and has been designed to interleave pointings in such a way that clusters can be formed from each set of four pointings, thereby offering efficient and complete sky coverage. System and observing details can be found elsewhere in descriptions of the Parkes Multibeam Pulsar Survey (Lyne et al. 2000; Camilo et al. 2000b; R. N. Manchester et al. 2001, in preparation). The receiver for each beam is a dual-channel cryogenically cooled system sensitive to orthogonal linear polarizations. A 288 MHz bandwidth is centered on a frequency of 1374 MHz. Each beam has a full-width half-power diameter of $\sim 14'$ with an average system noise temperature of 21 K (33 Jy) on cold sky. A filterbank system covering the 288 MHz bandwidth which has 96 separate 3 MHz channels for each polarization for each beam was used.

During observing, detected signals from each channel were square-law detected and added in polarization pairs before undergoing high-pass filtering. The signals were then one-bit digitized every 0.25 ms and recorded on magnetic tape for processing and analysis. We observed each of a total of 12 pointings (156 separate beams) for 8400 s, providing a limiting flux density sensitivity of ~ 0.08 mJy for most of the pulsar period range. The total area surveyed was ~ 6.7 deg^2, corresponding to an area of ~ 6.6 kpc^2 for an assumed distance to the SMC of 57 kpc (Cole 1998). Figure 1 illustrates the distribution of beams in our survey overlaid on an IRAS 60 μm image[9] of the emission in the region in gray scale.

Off-line processing was conducted on Sun workstations. Each beam was dedispersed for 191 trial values of DM varying from 0 to 442 pc cm^{-3}, a much greater range than that of the DMs of the known Magellanic Cloud pulsars. The dedispersed data for each DM trial were high-pass filtered before an amplitude spectrum was formed using a 2^{25} point fast Fourier transform (FFT). Portions of the spectrum (typically a few percent) were masked for each DM trial according to whether radio-frequency interference appeared significantly in the zero-DM spectrum. Higher sensitivity to narrow pulses was achieved through incoherent addition of up to 16 harmonics (including the fundamental).

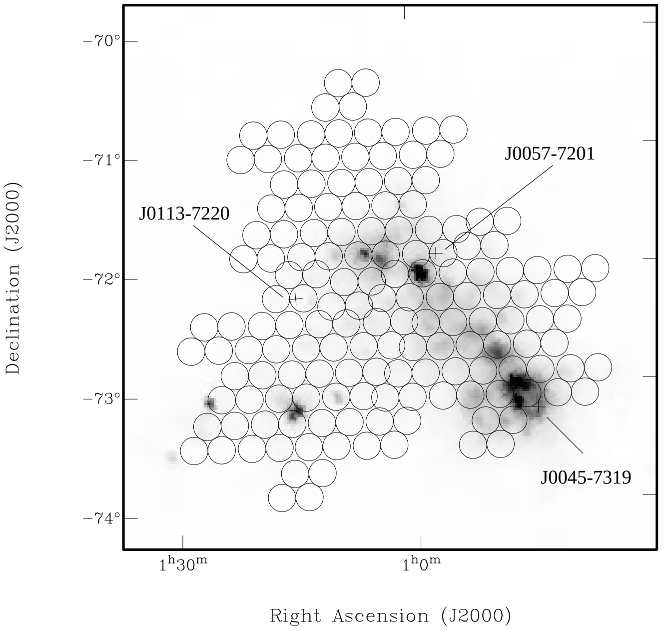

FIG. 1.—Multibeam survey coverage of the SMC. Each circle represents the half-power beamwidth of a single beam of the receiver. A total of 12 pointings (156 beams) were interleaved for tiled coverage. IRAS 60 μm emission is indicated in gray scale and roughly defines our survey region. The locations of the three pulsars discovered in the direction of the SMC to date are indicated by crosses. PSR J0057−7201 is a foreground pulsar while the other two lie in the SMC.

The strongest candidates in each DM trial were recorded if they had a signal-to-noise ratio greater than 7 and appeared in at least six of the DM trials (in order to avoid an excess of spurious candidates). The original data were then reprocessed by dedispersing and folding the data over a small range of DMs and periods centered on the candidate values. Follow-up confirmation observations were undertaken in the half-dozen cases where the resulting folded data showed a pulsar-like signature (i.e., in cases where a signal was well localized in period/DM phase space).

The relatively high frequency of the multibeam receiver compared to the lower frequency used in the McConnell et al. (1991) survey is an advantage since dispersive smearing and interstellar scattering are greatly reduced at this frequency, thereby allowing the detection of fast, distant, and highly scattered pulsars which may have been previously missed.

Since our survey was conducted at a different frequency than the McConnell et al. (1991) survey, we must scale the sensitivity of each survey in order to compare them. We have scaled each survey to a 400 MHz luminosity (L_{400}), assuming a distance to the SMC of 57 kpc (Cole 1998) and a typical pulsar spectral index $\alpha = -1.6$ in each case (Lorimer et al. 1995), where α is defined according to $S \sim \nu^{\alpha}$. Figure 2 shows a comparison of the sensitivity of the two surveys for a variety of pulsar periods and DMs. Our survey is significantly more sensitive to fast young pulsars (with $P \lesssim 100$ ms) and is the first survey of the SMC which has any sensitivity to millisecond pulsars.

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[9] http://www.ipac.caltech.edu.

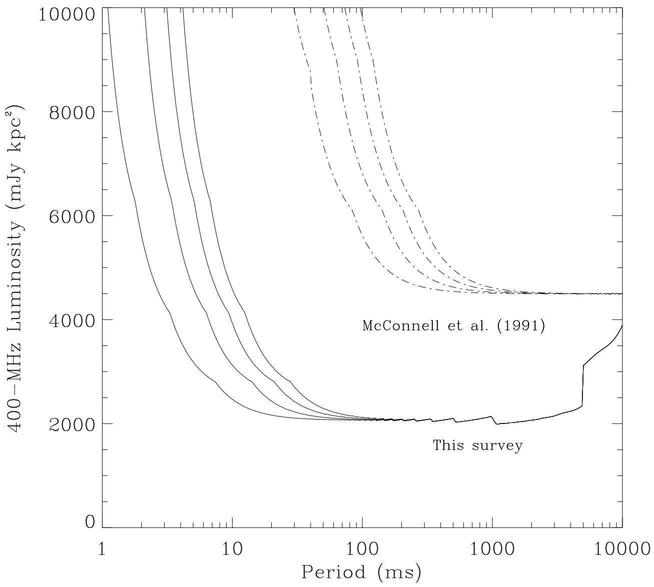

FIG. 2.—Limiting luminosity of pulsars in the SMC as a function of pulsar period for our survey (*solid lines*) and for the third phase of the McConnell et al. (1991) survey (*dash-dotted lines*). A 5% pulsed duty cycle is assumed in each case. The two surveys were conducted at different radio frequencies, so the sensitivity has been scaled to a minimum detectable 400 MHz luminosity assuming a standard pulsar spectral index ($\alpha = -1.6$) and an SMC distance of 57 kpc. Curves for DM values of 50, 100, 150, and 200 pc cm^{-3} are shown (from left to right). The detailed sensitivity calculation used here follows that found in Crawford (2000) for the Parkes Multibeam Pulsar Survey.

2.2. *Timing Observations and Data Reduction*

New pulsars discovered in our survey were timed regularly for about a year following their discovery. The observing system used for timing these pulsars at Parkes is identical to that used in the survey with the exception that the data were only recorded from the center beam of the multibeam receiver. Several additional timing observations were made at 70 cm. The start time of each observation was recorded and was synchronized with an observatory time standard, and data were usually recorded on magnetic tape. After dedispersion, the resulting time series was then folded at the topocentric rotation period of the pulsar, generating a single pulse profile for each observation. A topocentric pulse time of arrival (TOA) was obtained for each timing observation by cross-correlating the pulse profile with a high signal-to-noise template profile. Spin and astrometric parameters were then determined using the TEMPO software package[10] and the JPL DE200 planetary ephemeris (Standish 1990). The TEMPO package converts each TOA to the solar system barycenter and refines the estimated spin and astrometric parameters by minimizing the residual differences between measured and model TOAs over the span of observations. Timing data for three known pulsars in the LMC were previously obtained at several observing frequencies at Parkes with an observing system described elsewhere (Kaspi 1994; Johnston et al. 1995). These data were reprocessed to obtain refined timing parameters.

3. RESULTS

We have discovered two new pulsars in our survey of the SMC. One pulsar, PSR J0057−7201, has a significantly smaller DM than the population of known Magellanic Cloud pulsars, and therefore we believe it is a foreground Galactic object. The other new pulsar, PSR J0113−7220, has a DM of 125 pc cm^{-3}, a value which is somewhat larger than the only previously discovered SMC pulsar, PSR J0045−7319, indicating that it is located within the SMC.

As part of an ongoing campaign to search for radio pulsations from X-ray targets in the LMC, while pointing at the X-ray pulsar PSR J0537−6910 (Marshall et al. 1998; Crawford et al. 1998), we have serendipitously discovered one new pulsar, PSR J0535−6935, in one of the outlying beams of the multibeam receiver. With a DM of 89 pc cm^{-3}, this pulsar almost certainly lies in the LMC, making it the sixth LMC rotation-powered pulsar known.

The measured parameters for the three newly discovered pulsars are given in Table 1 and integrated 20 cm profiles are given in Figure 3. Flux densities at 1374 MHz were estimated for these pulsars from the detection strengths in

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[10] http://pulsar.princeton.edu/tempo.

TABLE 1

ASTROMETRIC AND SPIN PARAMETERS FOR NEWLY DISCOVERED PULSARS

Name	J0057−7201	J0113−7220	J0535−6935
Right ascension, α (J2000)	00 57 44.0(4)	01 13 11.09(3)	05 35(2)
Declination, δ (J2000)	−72 01 19(2)	−72 20 32.20(15)	−69 35(7)
Period, P (ms)	738.0624426(2)	325.88301613(1)	200.51011(2)
Period derivative, $\dot{P}$ ($\times 10^{-15}$)	0.10(8)	4.8590(15)	11.4(8)[a]
Dispersion measure, DM (pc cm^{-3})	27(5)	125.49(3)	89.4(8)
Epoch of period (MJD)	51213.0	51212.0	51006.8
rms residual (ms)	1.2	0.3	...
Number of TOAs (20 cm/50 cm/70 cm)	16/0/0	35/0/3	...
Timing span (Days)	300	430	...
Characteristic age, τ_c (Myr)[b]	~ 100	1.1	0.28
Surface magnetic field B ($\times 10^{12}$ G)[c]	~ 0.3	1.3	1.5
Spin-down luminosity, $\dot{E}$ (ergs s^{-1})[d]	$\sim 10^{31}$	5.5×10^{33}	5.6×10^{34}
Notes	Foreground	In SMC	In LMC, no timing info.

NOTE.—Values in parentheses represent 1 σ uncertainties in the least-significant digit quoted. Right ascension measured in hours, minutes, and seconds. Declination measured in degrees, arcminutes, and arcseconds.

[a] Estimated by comparing the barycentric period in observations taken 1 year apart.

[b] $\tau_c \equiv P/2\dot{P}$.

[c] $B \equiv 3.2 \times 10^{19} (P\dot{P})^{1/2}$ G.

[d] $\dot{E} \equiv 4\pi^2 I\dot{P}/P^3$.

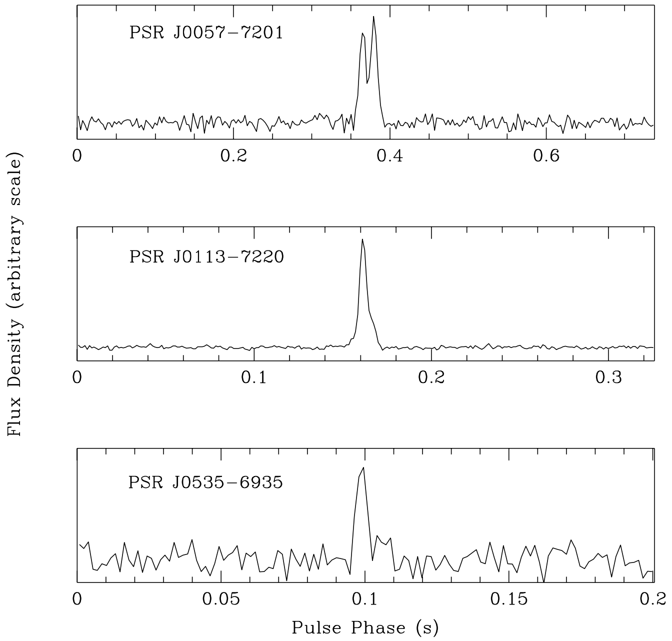

FIG. 3.—20 cm integrated total intensity profiles for PSRs J0057−7201, J0113−7220, and J0535−6935, the three newly discovered radio pulsars reported here.

the discovery observations. The results of timing measurements of the previously known pulsars are given in Table 2. Table 3 summarizes the general characteristics of the eight pulsars now known in the Magellanic Clouds, and we briefly describe each of these in turn below, as well as the new Galactic pulsar PSR J0057−7201.

3.1. *PSR J0045−7319*

PSR J0045−7319 was discovered in the SMC in the previous survey of the region by McConnell et al. (1991). Timing observations subsequently showed it to be in a 51 day binary orbit around a B1 class V star with a mass of 9 $M_\odot$ (Kaspi et al. 1994). Of over 700 pulsars cataloged by Taylor, Manchester, & Lyne (1993)[11] prior to the start of the Parkes Multibeam Pulsar Survey, only one other pulsar, PSR B1259−63, has been shown to be in a similar system (Johnston et al. 1992). The large DM sin |*b*| of PSR J0045−7319 (Fig. 4) suggests that it is in the SMC. Its location in the SMC was confirmed by its association with the B star companion, which was known to be in the SMC.

We detected PSR J0045−7319 in several diagnostic observations in the survey. We notice an unusual broadband ($\gtrsim$300 MHz) effect at 20 cm in which large amplitude fluctuations occur on timescales of tens of minutes. In some timing observations, the pulsar is not detectable at all at 20 cm. It is possible that this behavior is an unusual form of refractive scintillation, perhaps related to the binary nature of the pulsar, but a detailed study of this behavior is beyond the scope of this paper.

3.2. *PSR J0057−7201*

PSR J0057−7201 is a 738 ms pulsar that was discovered in our survey. From its DM of 27 pc cm^{-3}, which is signifi-

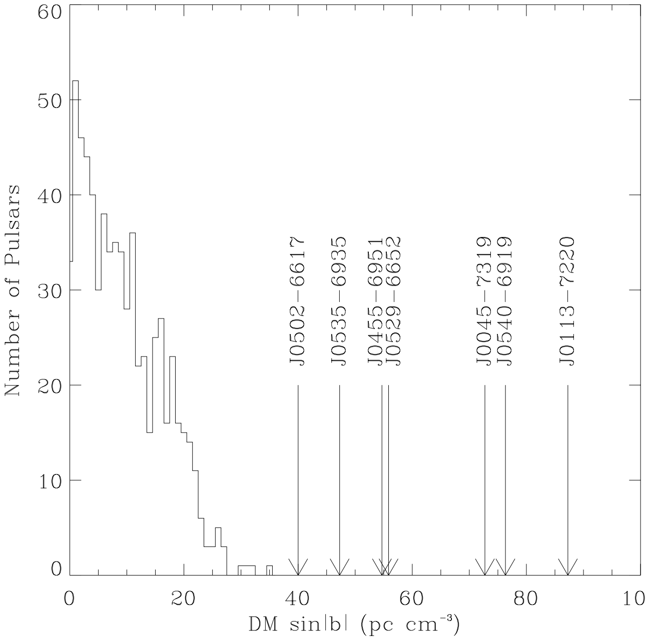

FIG. 4.—Histogram of DM sin |*b*| for 681 Galactic pulsars. Values of DM sin |*b*| for the seven Magellanic Cloud pulsars for which the DM has been measured are indicated by arrows.

TABLE 2

REFINED ASTROMETRIC AND SPIN PARAMETERS FOR THREE PREVIOUSLY KNOWN PULSARS

Name	J0455−6951	J0502−6617	J0529−6652
Right ascension, α (J2000)	04 55 47.55(8)	05 02 50.53(10)	05 29 50.92(13)
Declination, δ (J2000)	−69 51 34.3(6)	−66 17 58.8(9)	−66 52 38.2(9)
Period, P (ms)	320.422711526(12)	691.25141818(4)	975.72496638(6)
Period derivative, $\dot{P}$ (× 10^{-15})	10.2119(15)	23.090(6)	15.509(6)
Dispersion measure, DM (pc cm^{-3})	94.89(14)	68.9(3)	103.2(3)
Epoch of period (MJD)	48757.0	48771.0	48739.0
rms residual (ms)	1.6	2.2	3.1
Number of TOAs (20 cm/50 cm/70 cm)	1/7/28	2/0/27	4/1/28
Timing span (days)	850	850	900
Characteristic age, τ_c (Myr)	0.50	0.48	1.0
Surface magnetic field, B (× 10^{12} G)	1.8	4.0	3.9
Spin-down luminosity, $\dot{E}$ (ergs s^{-1})	1.2 × 10^{34}	2.8 × 10^{33}	6.6 × 10^{32}
Notes	In LMC	In LMC	In LMC

NOTE.—Parameters as in Table 2. Right ascension measured in hours, minutes, and seconds. Declination measured in degrees, arcminutes, and arcseconds.

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[11] The Public Pulsar Catalogue containing entries for 772 pulsars can be found at http://www.atnf.csiro.au/research/pulsar/psr.

TABLE 3

Currently Known Magellanic Cloud Pulsars

Name	P (ms)	DM (pc cm^{-3})	Radio/X-Ray?	Timing References	S_{1374} (mJy)	S_{1374} Flux References	S_{610} (mJy)	S_{610} Flux References	L_{400}[a] (mJy kpc^2)
SMC J0045−7319[b]	926	105	Y/N	1	0.3 ± 0.1	2	1.0 ± 0.2	3	7000 ± 2500
SMC J0113−7220	326	125	Y/N	2	0.4 ± 0.1	2	…	…	9500 ± 2500
LMC J0535−6935[c]	201	89	Y/N	2	~ 0.05	2	…	…	~ 1000
LMC J0537−6910[c,d]	16	…	N/Y	4	<0.06	5	<0.2[f]	5	<1200
LMC J0540−6919[c,e]	50	146	Y/Y	6	…	…	~ 0.4[g]	6	~ 2000
LMC J0455−6951	320	95	Y/N	2	…	…	1.0 ± 0.5	3	4900 ± 2500
LMC J0502−6617	691	69	Y/N	2	…	…	0.7 ± 0.4	3	3500 ± 2000
LMC J0529−6652	976	103	Y/N	2	0.3 ± 0.1	2	1.8 ± 0.8	3	6000 ± 1500

[a] Distances to the LMC and SMC are assumed to be 50 kpc and 57 kpc, respectively (Cole 1998).
[b] Binary with B star companion.
[c] Located in the 30 Doradus region of the LMC.
[d] Fastest known nonrecycled pulsar, has associated plerion.
[e] Crab twin, has associated plerion.
[f] 660 MHz flux density estimate.
[g] 640 MHz flux density estimate.
References.—(1) Kaspi et al. 1994; (2) this work; (3) McConnell et al. 1991; (4) Marshall et al. 1998; (5) Crawford et al. 1998; (6) Manchester et al. 1993.

cantly smaller than the lowest known DM for a suspected Magellanic Cloud pulsar (69 pc cm^{-3} for PSR J0502−6617), we conclude that it is a foreground object. The Taylor & Cordes (1993) DM-distance model indicates that the distance to PSR J0057−7201 is greater than 2.5 kpc, which is the limit of the Galactic plasma in the direction of this pulsar. However, the value of DM sin $|b|$ for PSR J0057−7201 is 19 pc cm^{-3}, still well within the distribution of Galactic pulsars (Fig. 4). Thus we cannot conclude that it is located within the SMC. The pulsar exhibits significant scintillation on timescales comparable to the length of the timing observations ($\sim$1 hr) and was only detectable in about half of the 20 cm timing observations and in none of the 70 cm observations.

3.3. *PSR J0113−7220*

PSR J0113−7220 was first discovered in our SMC survey and has a 326 ms period. The pulsar shows no noticeable scintillation, consistent with the known population of luminous LMC pulsars. Its DM of 125 pc cm^{-3} is larger than that of PSR J0045−7319, the only other known SMC pulsar, and implies that it is also located within the SMC. Radio timing results for PSR J0113−7220 (Table 1) reveal a characteristic age of $\sim$1 Myr. PSR J0113−7220 is also very luminous with a narrow profile peak. It is the most luminous pulsar currently known in either of the Magellanic Clouds.

3.4. *PSR J0535−6935*

PSR J0535−6935 was discovered serendipitously in the 30 Doradus region of the LMC in one of the outlying beams of the multibeam receiver during a deep search for radio pulsations from PSR J0537−6910 with the center beam (Crawford et al. 1998). Figure 5 shows an 843 MHz radio image of the 30 Doradus region from the Sydney University Molonglo Sky Survey,[12] with the locations of the three known pulsars in that region indicated. PSR J0535−6935 proved too faint for regular timing, so an estimate of $\dot{P}$ was made by comparing the barycentric period in observations obtained 1 year apart. Table 1 lists the result. The positional uncertainty remains large ($\sim$7′, the radius of the detection beam). The pulsar was detected in observations of length 21,600 s and 17,200 s and would have been too faint to detect in our standard 8400 s integrations in the SMC survey.

3.5. *PSR J0537−6910*

PSR J0537−6910 is a 16 ms X-ray pulsar in the 30 Doradus region of the LMC (Fig. 5). This Crab-like pulsar was first detected in X-rays (Marshall et al. 1998) and is associated with the plerionic supernova remnant (SNR) 0538−69.1 (N157B) in the LMC. The pulsar has a characteristic age of $\sim$5 kyr, making it the fastest young rotation-

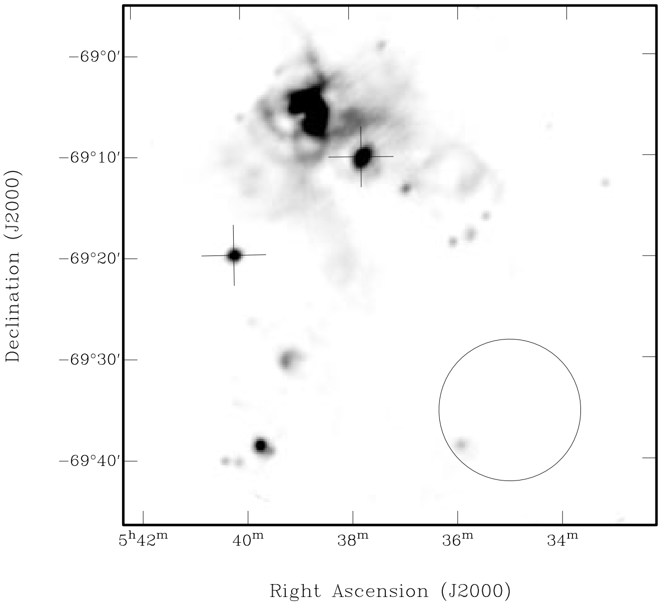

Fig. 5.—Molonglo Observatory Synthesis Telescope 843 MHz image of the 30 Doradus region of the LMC. The two crosses indicate the positions of two young pulsars, PSR J0537−6910 (*upper right*) and PSR J0540−6919 (*lower left*), which are associated with SNR 0538−69.1 (N157B) and SNR 0540−69.3, respectively. The discovery of PSR J0535−6935 in an outlying beam of the multibeam receiver during a search for radio pulsations from PSR J0537−6910 with the center beam is reported here; the error circle for this pulsar's location is shown. The faint source within the circle is too bright to be the pulsar.

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[12] http://www.astrop.physics.usyd.edu.au/SUMSS.

powered pulsar currently known and one of the few pulsars with a confirmed SNR association. Efforts to find a radio counterpart to this X-ray pulsar have so far been unsuccessful at both 50 and 20 cm (Crawford et al. 1998), but constraints on the radio luminosity are poor as a result of the large distance.

3.6. *PSR J0540−6919 (B0540−69)*

PSR J0540−6919 (B0540−69) is a 50 ms Crab-like pulsar in the 30 Doradus region of the LMC (Fig. 5) which was first discovered in X-rays (Seward, Harnden, & Helfand 1984) and subsequently detected at radio wavelengths (Manchester et al. 1993). The pulsar is associated with the composite SNR 0540−69.3 in the LMC and is very young, with a characteristic age of 1.7 kyr, making this system a twin of the Crab system. The measured DM of 146 pc cm^{-3} for PSR J0540−6919 is the largest yet measured for any pulsar in the Magellanic Clouds. An electron density of $n_e \sim 2$ cm^{-3} has been estimated for the 30 Doradus region in the direction of SNR 0538−69.1 (N157B) (Lazendic et al. 2000). The excess DM of ∼50 pc cm^{-3} for PSR J0540−6919 relative to other known LMC pulsars would suggest a characteristic size of ∼25 pc for a region with a similarly enhanced plasma density. This is significantly larger than the ∼1 pc size of SNR 0540−69.3 (∼0.′1 at 50 kpc) and suggests that the larger DM of PSR J0540−6919 could be accounted for by a region of enhanced plasma density extending well beyond SNR 0540−69.3 itself.

3.7. *PSR J0455−6951, PSR J0502−6617, and PSR J0529−6652*

These three pulsars were first discovered in the 50 cm survey of the Magellanic Clouds by McConnell et al. (1991) but were not subsequently timed by them. Timing results were first obtained by Kaspi (1994) but not published elsewhere. In Table 2 we present updated and refined timing results for these pulsars which we obtained by reprocessing the timing data.

4. DISCUSSION

4.1. *Dispersion Measures*

The Taylor & Cordes (1993) model of the electron distribution in the Galaxy incorporates layers of electrons in which the density decreases with increasing z-distance from the Galactic plane. This clearly limits the Galactic contribution to the DM as a function of Galactic latitude. One reason that pulsars are believed to be in the Magellanic Clouds is their large DMs, which exceed those expected for Galactic pulsars at that Galactic latitude. The quantity DM sin $|b|$ is a measure of the z-contribution to the DM and can be used to distinguish Galactic from extragalactic pulsars. Figure 4 shows a histogram of the measured DM sin $|b|$ values for 681 Galactic pulsars. There is a clear dropoff close to zero at about 27 pc cm^{-3} with several pulsars between 30 and 35 pc cm^{-3}. The DM sin $|b|$ values of Magellanic Cloud pulsars range from 40 to about 90 pc cm^{-3}, a much larger range than the Galactic population itself. One reason for this is that the projected z-contribution of electrons from the Magellanic Clouds is not a flat disk (like our Galaxy), but rather is extended in the line of sight.

One interesting question to ask is whether the spread in DM seen in the known pulsar population can reveal anything about the Magellanic Clouds themselves. The observed range for the two SMC pulsars is 105–125 pc cm^{-3}. The observed range in the LMC (where there are more known pulsars) is about 80 pc cm^{-3}, from the smallest value of about 70 pc cm^{-3} to the largest value of about 150 pc cm^{-3}. Assuming an electron density of 0.03 cm^{-3} for the Magellanic Clouds which is comparable to estimated mean Galactic values (Manchester & Taylor 1977; Spitzer 1978; Taylor & Cordes 1993), the DM spread corresponds to a distance range of 0.7 and 2.7 kpc for the SMC and LMC, respectively.

From distance measurements of 161 Cepheids in the SMC, Mathewson (1985) has estimated that the depth of the SMC is between 20 and 30 kpc, much larger than the projected size of the SMC on the sky of ∼4 kpc (∼4°). The observed DM spread for pulsars in both Magellanic Clouds indicates line-of-sight depths that are much smaller than this, as indicated above. In fact, for an SMC depth of 20–30 kpc, the implied mean electron density from the pulsar DM distribution (assuming that the pulsars are separated by a significant fraction of the SMC size) would be $n_e \lesssim 0.001$ cm^{-3}, much smaller than Galactic values. Our survey is sensitive to high-DM pulsars and our data processing includes DM $\lesssim$ 450 pc cm^{-3}, but we did not detect any pulsars with DM greater than 125 pc cm^{-3}. Our results are more consistent with the suggestion of Zaritsky et al. (2000) that the inner part of the SMC is roughly spherical in morphology, though a comparison of the older population of Cepheids with the younger population of pulsars may not account for systematic differences in their distributions as a result of their ages. Should a significant number of additional SMC pulsars be found in the future in this same DM range, this will be at odds with an elongated line-of-sight morphology for the SMC.

4.2. *Expected Number of Detectable Pulsars in the Magellanic Clouds*

Establishing formation rates of neutron stars and determining the beaming fraction and luminosity characteristics of pulsars is important for understanding the birth and emission characteristics of the pulsar population. Although the Galactic pulsar population currently provides a much larger sample of pulsars with which to model these parameters, it suffers from selection effects and distance uncertainties. The Magellanic Clouds suffer much less from these effects. Here we compare the observed number of pulsars in the SMC with the number predicted from several methods using different model assumptions.

We follow the method of McConnell et al. (1991) to estimate the number of SMC pulsars expected to be detectable in our survey. The number of potentially observable pulsars in the SMC, $N_{\rm SMC}$, can be estimated using the number of potentially observable pulsars in our solar neighborhood which is defined as a cylinder with a base area of 1 kpc^2 in the Galactic disk. We scale this number by a factor which includes the mass ratio of the SMC and the solar neighborhood and their relative star formation rates,

$$N_{\rm SMC} = R\,\frac{N_{\rm SN}\,M_{\rm SMC}}{M_{\rm SN}}\,. \qquad (1)$$

Here R is the star formation rate in the SMC relative to the solar neighborhood, $N_{\rm SN}$ is the number of potentially observable pulsars in the solar neighborhood, and $M_{\rm SMC}$

and $M_{\rm SN}$ are the masses of the SMC and solar neighborhood, respectively.

Lequeux (1984) indicates that the star formation rate per unit total mass in the SMC is greater than the solar neighborhood, yielding $R = 1.6$. The total masses of the solar neighborhood and SMC are estimated to be $9 \times 10^7\ M_\odot$ and $1.8 \times 10^9\ M_\odot$, respectively (Vangioni-Flam et al. 1980). The number of potentially observable pulsars with $L_{400} > 1$ mJy kpc^2 in the solar neighborhood has been estimated by Lyne et al. (1998). They derive a local space density of 30 ± 6 kpc^{-2} and 28 ± 12 kpc^{-2} for nonrecycled and millisecond pulsars, respectively, above this luminosity limit. These estimates include beaming effects and, hence, are a fraction of the true underlying pulsar population. Putting these numbers in equation (1) gives 1000 ± 200 and 900 ± 400 for the number of potentially observable nonrecycled and millisecond pulsars respectively in the SMC with $L_{400} > 1$ mJy kpc^2.

We can convert this result into an estimate of the number of pulsars detectable in our survey, which is sensitive to pulsars with $L_{400} > 1950$ mJy kpc^2 for most periods. We assume that the Galactic and SMC luminosity distributions are similar. Lorimer et al. (1993) show that for the Galactic population, the number of pulsars above a luminosity threshold L_0 scales as the inverse of L_0. Thus, the expected number of pulsars above our detection limits in the SMC is 0.5 ± 0.1 nonrecycled pulsars and 0.5 ± 0.2 ms pulsars. The number of detectable millisecond pulsars is an upper limit since this number may be overestimated for two reasons. First, our survey sensitivity begins to significantly decrease at millisecond periods (see Fig. 2), and second, the younger age of the oldest star clusters in the SMC relative to the Galaxy (Olszewski, Suntzeff, & Mateo 1996) may indicate that the SMC presently contains fewer old recycled pulsars. In any case, with two known SMC pulsars, both of which are nonrecycled, and assuming Poisson statistics, the prediction is consistent with our results.

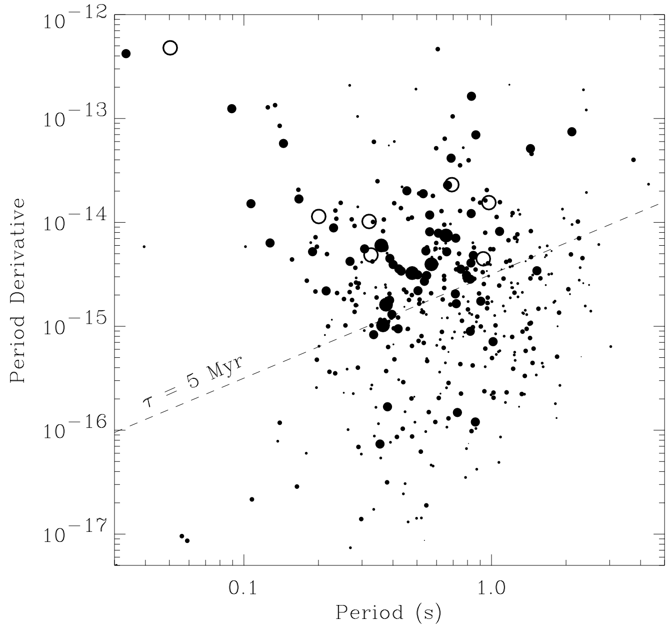

FIG. 6.—*P*-*Ṗ* diagram for a subset of Galactic pulsars with cataloged radio luminosities (*filled circles*). The symbol size scales logarithmically with increasing radio luminosity. Also shown are the seven Magellanic Cloud pulsars for which a radio luminosity has been estimated (*open circles*). The dashed line is the 5 Myr isochrone. [*See the electronic edition of the Journal for a color version of this figure.*]

We can also estimate the number of pulsars detectable in our survey using the supernova rate for irregular galaxies, of which the SMC is one. Turatto (2000) estimates that the Type II supernova rate for irregular galaxies is 0.65 ± 0.39 SNu, where SNu is a unit defined as

$$\mathrm{SNu} = \frac{1}{100\ \mathrm{yr}} \frac{1}{10^{10}\ L_\odot^B}\ , \qquad (2)$$

where $L_\odot^B$ is the bolometric luminosity of the galaxy in solar units and where $H_0 = 75$ km s^{-1} Mpc^{-1} is assumed.

Vangioni-Flam et al. (1980) estimate the SMC bolometric luminosity to be $7.8 \times 10^8\ L_\odot$, implying a Type II supernova rate of $(5 \pm 3) \times 10^{-4}$ per year. We assume that all compact objects formed in these supernovae are NSs, and that all NSs formed are active pulsars with $L_{400} > 1$ mJy kpc^2 with a mean lifetime of 10 Myr. This yields 5100 ± 3600 active pulsars in the SMC. We apply the Biggs (1990) beaming fraction of 0.3 for nonrecycled pulsars in the range $0.1\ \mathrm{s} < P < 1$ s to get 1520 ± 1070 potentially observable pulsars in the SMC. Scaling this to the number expected to be detectable in our survey using the luminosity law of Lorimer et al. (1993) gives 0.8 ± 0.5 for the predicted number of detectable nonrecycled pulsars in our survey. Our observed sample of two is consistent with this prediction.

4.3. *The Magellanic Cloud Pulsar Luminosity Distribution on the P-Ṗ Diagram*

Distances to pulsars in our Galaxy are generally determined by the DM-distance model of Taylor & Cordes (1993), which has large uncertainties. This unfortunately introduces large uncertainties in pulsar luminosity estimates. The Magellanic Clouds have more accurately determined distances than Galactic pulsars, and therefore their pulsars have better known luminosities. Since only the upper end of the luminosity function is detectable in the Magellanic Clouds, we can use luminosity estimates of their pulsars to compare the high end of the Magellanic Cloud pulsar luminosity function with that of the Galaxy.

Table lists radio luminosities for the seven known radio pulsars in the Magellanic Clouds using flux density estimates from several sources. Taylor et al. (1993) have shown that Galactic pulsars older than ~5 Myr have significantly lower luminosities than younger pulsars. Figure 6 shows a *P*-*Ṗ* diagram for the seven Magellanic Cloud radio pulsars and Galactic pulsars with cataloged radio luminosities. The distribution of the Magellanic Cloud pulsars is consistent with the Galactic distribution of luminous pulsars and supports the suggestion of Taylor et al. (1993).

5. CONCLUSIONS

We have conducted a survey of the SMC for radio pulsars and have discovered two new pulsars, one of which is located within the SMC. We present timing results for both of these pulsars as well as refined values for three previously known LMC pulsars. We have also discovered serendipitously a new pulsar in the LMC, bringing the total number of known rotation-powered pulsars in the Magellanic Clouds to eight. The results of our survey are consistent with the expected number of detectable SMC pulsars estimated using several methods. However, the small number of pulsars currently known in the SMC prevents significant constraints on the parameter assumptions made in these estimates. The luminosity distribution of the Magellanic Cloud pulsar population on the P-$\dot{P}$ diagram is consistent with the Galactic distribution of luminous pulsars and supports the conclusion of Taylor et al. (1993) that pulsars younger than ~ 5 Myr are more luminous on average than older pulsars. The DM distribution of the newly discovered pulsars is consistent with the known pulsar population in the Magellanic Clouds. Both of the known SMC pulsars are in a narrow DM range, and if additional SMC pulsars are found in the future which are also confined to this narrow range, this will be at odds with the SMC depth estimated from Cepheid observations. Significantly increasing the sensitivity of searches for pulsars in the Magellanic Clouds is not practical with current technology given constraints on telescope time, etc. However, next-generation instruments such as a square-kilometer array should greatly increase the number of known pulsars in the Magellanic Clouds and will enhance and refine the conclusions drawn in this paper.

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