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New limits on the population of normal and millisecond pulsars in the Large and Small Magellanic Clouds

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ABSTRACT

We model the potentially observable populations of normal and millisecond radio pulsars in the Large and Small Magellanic Clouds (LMC and SMC) where the known population currently stands at 19 normal radio pulsars. Taking into account the detection thresholds of previous surveys, and assuming optimal period and luminosity distributions based on studies of Galactic pulsars, we estimate there are $(1.79 \pm 0.20) \times 10^4$ and $(1.09 \pm 0.16) \times 10^4$ normal pulsars in the LMC and SMC respectively. When we attempt to correct for beaming effects, and the fraction of high-velocity pulsars which escape the clouds, we estimate birth rates in both the LMC and SMC to be comparable and in the range 0.5–1 pulsar per century. Although higher than estimates for the rate of core-collapse supernovae in the clouds, these pulsar birth rates are consistent with historical supernova observations in the past 300 yr. A substantial population of active radio pulsars (of order a few hundred thousand) have escaped the LMC and SMC and populate the local intergalactic medium. For the millisecond pulsar (MSP) population, the lack of any detections from current surveys leads to respective upper limits (at the 95% confidence level) of 15,000 for the LMC and 23,000 for the SMC. Several MSPs could be detected by a currently ongoing survey of the SMC with improved time and frequency resolution using the Parkes multibeam system. Giant-pulse emitting neutron stars could also be seen by this survey.

Key words: pulsars:general

1 INTRODUCTION

Our closest neighbouring galaxies, the Large and Small Magellanic Clouds (henceforth LMC and SMC), contain 19 known radio pulsars (Manchester et al. 2006). Since both the LMC and SMC represent a different star formation environment compared to our Galaxy and its globular cluster system, it is interesting to use these results to constrain the pulsar content in the clouds. So far, no millisecond pulsars (MSPs) have been found, though this is in part a result of the relatively low sampling rates and frequency resolutions of previous surveys (see Table 1). The aim of this paper is to use Monte Carlo simulations to reproduce the results from previous LMC and SMC surveys, determine the most likely size of the normal pulsar population, place upper limits on the MSP population, and make predictions for future surveys of the clouds.

In Section 2, we compare some of the past surveys of the Magellanic Clouds. Section 3 contains a detailed description of our simulations and how we are able to reproduce results from the past surveys. From this model, we are able to in-

fer the population of normal pulsars in the LMC and SMC. New limits from our MSP simulations are presented in Section 4. We discuss our results and present predictions for future Magellanic Cloud surveys in Section 5, and finally, in Section 6, we draw our conclusions.

2 PREVIOUS SURVEYS OF THE MAGELLANIC CLOUDS

Multiple radio surveys have been completed of both the Large and Small Magellanic clouds. We discuss the various features and results of each survey in this section. The survey data acquisition parameters are summarized in Table 1.

The original pulsar survey of the clouds was by McConnell et al. (1991) which detected three pulsars in the LMC and one in the SMC. With the advent of the Parkes Multibeam Pulsar Survey (Manchester et al. 2001), searches of the clouds with greatly increased sensitivity were performed. Crawford et al. (2001) surveyed the SMC, finding two more associated pulsars, one in each cloud.

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Table 1. Survey parameters for the previous surveys considered in this paper, as well as the parameters for a currently ongoing survey using the BPSR pulsar backend at the Parkes Radio Telescope.

Parameter	McConnell et al. (1991)	Crawford et al. (2001)	Manchester et al. (2006)	BPSR Survey (2009)
t_{obs} (s)	5000	8400	8400	8400
t_{samp} (ms)	5.000	0.250	1.000	0.064
T_{sys} (K)	60	21	21	20
f (MHz)	610	1374	1374	1374
Δf (MHz)	120	288	288	288
Δf_{chan} (MHz)	2.5	3.0	3.0	0.1

Manchester et al. (2006) extended this effort, surveying both the SMC and LMC. For the SMC, this survey discovered 3 new pulsars, while the LMC survey discovered 9 more normal pulsars. Currently, there are a total of 19 known spin-powered radio pulsars in the LMC and SMC.

3 MODELING THE NORMAL PULSAR POPULATION

Our goal is to create a working model of normal pulsars distributed throughout the Magellanic Clouds that can accurately reproduce the results found in each of the three surveys carried out so far. To do this, we perform Monte Carlo simulations of the pulsar population using an adapted version of the freely available `PSRPOP` software package¹ (Lorimer et al. 2006).

The simulation begins by seeding each pulsar in the Magellanic Clouds. To do this for the SMC, we consider a sphere with a radius of 2.0 kpc centred at a Right Ascension of 0h 51m and a Declination of $-73^\circ 07'$. We populate this sphere with pulsars using an exponential distribution (in the x, y, and z directions) having a scale length of 1.25 kpc (Gonidakis et al. 2009). Similarly, the LMC simulations create a sphere with a radius of 4.5 kpc centred at 05h 17m and $-69^\circ 02'$ (Kim et al. 1998), and use an exponential distribution with a scale length of 1.50 kpc (van der Marel 2001).

The dispersion measure (DM) is randomly selected in the range 70–210 cm^{-3} pc. This is based on the DMs of other pulsars found in the Magellanic Clouds listed in Table 2. For the distance to each pulsar, we use a value of 51 kpc for the LMC (Koerwer 2009) and 60 kpc for the SMC (Harries et al. 2003).

The period of each pulsar is then randomly generated from a log-normal distribution derived from a study of Galactic pulsars (Lorimer et al. 2006). For a period in ms, the mean of this distribution is 2.7 and the standard deviation is 0.34. Similarly, the radio luminosity is drawn from the log-normal function found by Faucher-Giguère & Kaspi (2006).

To determine the number of pulsars to generate, we use one set of survey parameters and attempt to replicate their results. For our trials, we choose the Manchester et al. (2006) survey because of its larger sample of detected pulsars. We create a sample distribution for both the LMC and the SMC. We run `PSRPOP` and generate enough SMC pulsars so that the Manchester survey would detect 5 of them, and

Table 3. Survey results for the three surveys considered in our paper. We compare what was actually detected to what our sample pulsar distributions predict to be detected. The first number is the actual number of pulsars detected, while the second number is the expected number of detections.

SURVEY	SMC	LMC
McConnell	1/1	2/3
Crawford	2/2	NA
Manchester	5/5	12/12

enough LMC pulsars so that it would detect 12. We then use these two distributions to analyse the McConnell and Crawford surveys.

Table 3 shows how the results of all three surveys compared with what we expect to detect. As can be seen, these results provide a self-consistent model of the Magellanic Cloud pulsars. This allows us to now model any future survey using this distribution of pulsars and predict what results should be obtained.

To determine the number of normal pulsars in the LMC and SMC, we generate enough pulsars to detect the corresponding number of pulsars found in each cloud by the Manchester et al. survey. Repeating this process 1000 times allows us to get a mean value for each cloud. The LMC has a mean value of $(1.79 \pm 0.20) \times 10^4$ pulsars, while the SMC has a mean of $(1.09 \pm 0.16) \times 10^4$. Fig. 1 shows the distributions of normal pulsars produced by these simulations.

4 MODELING THE MILLISECOND PULSAR POPULATION

Since no MSPs have been detected in the Magellanic Clouds, we can only find an upper limit on the number of MSPs that could lie in the clouds. As before, we use the Manchester et al. survey as a reference, and we follow a procedure similar to that described in the previous section. We keep all pulsar parameters the same, with the exception of the period distribution. Here we use a distribution of MSP periods used in a recent study (Smits et al. 2009). For each of the LMC and SMC, we again run `PSRPOP` until the Manchester et al. survey detects one of the MSPs. The number of pulsars generated to get that one detection will be the upper limit of the number of MSPs in the cloud.

To limit statistical noise and fluctuations, we run 1000 simulations, create a histogram of the number of pulsars generated, and determine the mean. To further limit these

¹ <http://psrpop.sourceforge.net>

Table 2. List of all spin-powered radio pulsars in the LMC and SMC. We note that the Crawford et al. survey did not observe the entire LMC, so we do not consider their LMC results in our simulations. Also, PSR B0540-69 is the only currently known LMC pulsar that was not detected in any of these surveys.

PSR Name	Location	DM (pc cm ⁻³)	McConnell et al. (1991)	Crawford et al. (2001)	Manchester et al. (2006)
J0045-7319	SMC	105.4	X	X	X
J0455-6951	LMC	94.9	X		X
J0502-6617	LMC	68.9	X		X
J0529-6652	LMC	103.2	X		X
J0113-7220	SMC	125.5		X	X
J0535-6935	LMC	93.7		X	
B0540-69	LMC	146.5			
J0045-7042	SMC	70.0			X
J0111-7131	SMC	76.0			X
J0131-7310	SMC	205.2			X
J0449-7031	LMC	65.8			X
J0451-67	LMC	45.0			X
J0456-7031	LMC	100.3			X
J0519-6932	LMC	119.4			X
J0522-6847	LMC	126.5			X
J0532-6639	LMC	69.3			X
J0534-6703	LMC	94.7			X
J0543-6851	LMC	131.0			X
J0555-7056	LMC	73.4			X
TOTALS	SMC		1	2	5
	LMC		3	NA	12

Figure 1. Distributions of the number of pulsars generated to model the LMC normal pulsars (solid), alongside the SMC pulsars (dashed).

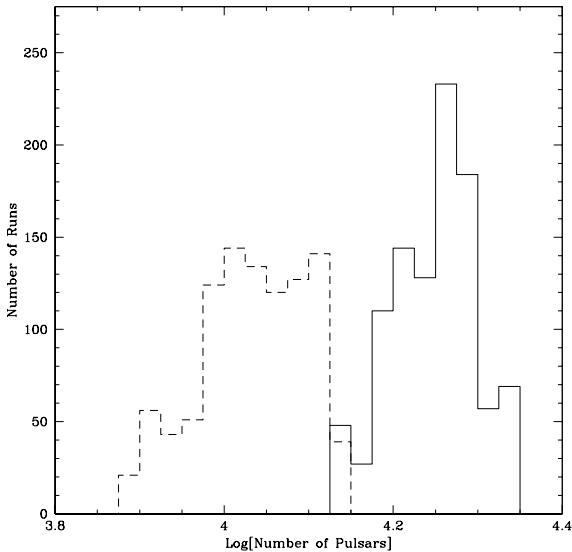
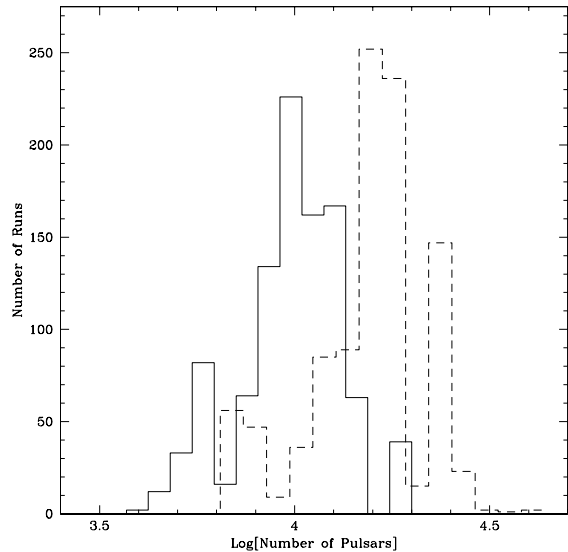


Figure 2. Similar to normal pulsar histograms, we show the distribution of pulsars generated for the MSP simulations of the LMC (solid) and SMC (dashed).



variances, we run our simulation to detect 10 MSPs, and then divide our final number of pulsars generated by 10. Fig. 2 shows our simulation results.

To determine upper limits from these distributions, we consider a point below which 95% of our simulations are contained. For the LMC MSP population, we find, with 95% confidence, an upper limit of 15,000 pulsars. The equivalent simulations of the SMC yield somewhat higher numbers, presumably due to the fact that they are located at a farther

distance from the Earth. The corresponding 95% confidence upper limit is 23,000.

5 DISCUSSION

We have produced a self-consistent model of the normal pulsar population in the LMC and SMC. We now make some straightforward inferences from our results and comment on the yields of future Magellanic Cloud surveys.

5.1 Birthrates of normal pulsars

To estimate the birthrate of normal pulsars in the Magellanic Clouds, we use the results Faucher-Giguère & Kaspi (2006) to obtain an average lifetime for Galactic pulsars. When their estimated number of pulsars of $(1.2 \pm 0.3) \times 10^6$ is divided by their Galactic pulsar birthrate of 2.8 ± 0.1 pulsars per century, we get an average radio lifetime of $(4.3 \pm 0.1) \times 10^7$ years. To calculate the birthrates in the LMC and SMC, we divide the respective number of pulsars we find by this average lifetime, and then multiply by a factor to correct for those pulsars whose beams we do not see due to beaming effects. This factor is approximately 10 when averaged over the normal pulsar population (Tauris & Manchester 1998). These calculations lead to birthrates of 0.42 ± 0.03 and 0.25 ± 0.03 pulsars per century for the LMC and SMC respectively.

These birth rates, however, are likely to be underestimates of the true value due to the fact that both the LMC and SMC have relatively small escape velocities. Using values for the mass and radius of the SMC from Bekki & Stanimirović (2009), we calculate an escape velocity $v_{\text{esc}} = \sqrt{2GM/R}$, of roughly 120 km s^{-1} . Similarly, we find an escape velocity for the LMC of 157 km s^{-1} . Given the high birth velocities known for Galactic pulsars (Hobbs et al. 2005; Faucher-Giguère & Kaspi 2006, e.g.), potentially a large number of pulsars that are born in the clouds will eventually lie outside of the surveyed area within the age in which they are expected to be radio loud.

To quantify the impact of this effect on the birthrates, we ran a simple simulation in which the velocity of each pulsar was chosen from a Maxwellian distribution with a 1-D dispersion of 265 km s^{-1} (Hobbs et al. 2005). After randomly selecting the age of the pulsar to be between 0 and 4.3×10^7 years, we calculate the distance the pulsar has traveled by multiplying the age and the velocity. Assuming that the pulsar starts at the centre of either cloud, we compute the final position to determine if the pulsar has remained within the surveyed area of the cloud (radii of 5.6° and 2.2° for the LMC and SMC) for the duration of its lifetime. We find that nearly half of all pulsars born in the LMC (45.9%) escape the cloud, while 67.2% of all pulsars born in the SMC escape. The population of ejected radio pulsars that are active from both Magellanic Clouds is therefore substantial, of order 3.5×10^5 objects.

The above calculations lead us to modified birthrates of 0.8 pulsars per century for both the LMC and SMC. Given the uncertainties involved in making these corrections, the best conclusion we can reach from the data at hand is that radio pulsar birth rates are comparable and likely to be somewhere in the range of 0.5–1 pulsar per century in both the LMC and SMC.

Tammann, Löffler & Schröder (1994) carried out an extensive study of the Galactic and extragalactic supernova rate. They find a combined rate of type Ib and II supernovae of 0.45 and 0.11 per century in the LMC and SMC respectively. While the rate for the LMC is consistent with our estimate above, the pulsar birthrate in the SMC appears to be significantly higher than these supernova rates. In spite of this discrepancy, a simple exercise using Poissonian statistics shows that both pulsar and supernovae populations are consistent with the observation of one supernova in the LMC and zero supernovae in the SMC during the past 300 years of observations.

5.2 Predictions for future surveys

Previous surveys were limited in their ability to detect millisecond and rapidly rotating pulsars by the low data sampling rates and frequency resolution. A current survey of the Magellanic Clouds is making use of a new data acquisition system, BPSR, developed for the Parkes High Time Resolution Universe Legacy Survey² which is currently undertaking a large-scale search for pulsars along the Galactic plane. The parameters of this new system high-resolution pulsar data acquisition system for our search of the Magellanic Clouds are summarized in Table 1. As can be seen, the time resolution is improved by factors of 4 and 16 over the Crawford et al. and Manchester et al. surveys, while the frequency resolution is improved by a factor of 30.

With the MSP upper limits as references, we now create a sample distribution of the LMC and SMC MSP populations, and attempt to detect the pulsars using the new survey parameters. Using 8400 s integrations, these simulations predict that we will find at most 3 MSPs in each of the two Magellanic Clouds. With a full survey of the LMC and SMC, the absence of MSP detections would lower the upper limits on the number of MSPs to 5,500 and 8,000, respectively.

A pilot survey of the SMC began in May 2009 using this new system. The goal of this new survey is to detect or place stringent limits on the population of MSPs and giant-pulse emitting neutron stars in the Magellanic Clouds. Following the survey pointings from Crawford et al. (2001), giant pulses from PSR B0540–69 have been observed, and three previously known pulsars have been redetected. Processing of all data from this survey should be completed by August of 2010.

We also briefly look at future predictions using the Square Kilometre Array (SKA). Following the ‘‘A’’ implementation (Smits et al. 2009) of the SKA, we choose survey parameters that allow us to search the LMC and SMC for both normal and millisecond pulsars. With a sky coverage per pointing of nearly 250 deg^2 , the LMC can be covered in only 4 pointings, while the SMC can be completely searched with only 3. Using 10 minute integration times would keep the total survey time for either region under 1 hour, and results in 2,500 and 1,400 normal pulsar detections in the LMC and SMC respectively. Additionally, this SKA survey could potentially detect 850 and 800 MSPs in the LMC and

² <http://astronomy.swin.edu.au/pulsar/?topic=hlsurvey>

SMC, which is a considerable improvement over previous and current surveys of the Magellanic Clouds.

6 CONCLUSIONS

We successfully reproduce the results from three past Magellanic Cloud surveys, giving us an accurate normal pulsar population for both the LMC and SMC. These populations provide estimates of the number of normal pulsars located in the LMC and SMC of $(1.79 \pm 0.20) \times 10^4$ and $(1.09 \pm 0.16) \times 10^4$ pulsars respectively. Taking into account pulsars whose beams do not intersect our line of sight, and the significant fraction of pulsars which escape both the LMC and SMC, we find that the mean radio pulsar birth rate is most likely to be in the range 0.5–1 pulsars per century in either cloud. This is consistent with historical observations of supernovae in the Magellanic Clouds. We find that a substantial population of radio pulsars will be ejected from the clouds and populate the local intergalactic medium.

Extending our analysis to the MSP population yields upper limits of 15,000 for the LMC and 23,000 for the SMC. If the current SMC survey at Parkes produces no MSP detections, that upper limit will be reduced to 8,000. Consequently, we can realistically expect no more than 3 MSPs to be detected in that survey. Also, if the current SMC survey extends to the LMC, a maximum of 3 MSPs would be detected, but a lack of MSP detections would reduce the MSP upper limit to 5,500.

Our results here, along with the future results of the ongoing BPSR survey will continue to constrain the number of pulsars, both normal and millisecond, found in the Magellanic Clouds. With improved simulation techniques and more sensitive surveys, we will be able to model the true pulsar population with increased accuracy to allow for further research in this area. A logical extension of our work would be a full dynamical model of the pulsar content in the Magellanic Clouds as has been recently carried out for radio pulsars in our Galaxy (Faucher-Giguère & Kaspi 2006; Ridley & Lorimer 2010).

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