PULSAR BIRTHRATES FROM THE PARKES MULTIBEAM SURVEY

N. VRANESEVIC,[1,2] R. N. MANCHESTER,[2] D. R. LORIMER,[3] G. B. HOBBS,[2] A. G. LYNE,[3] M. KRAMER,[3]
F. CAMILO,[4] I. H. STAIRS,[5] V. M. KASPI,[6] N. D'AMICO,[7] A. POSSENTI,[7] F. CRAWFORD,[8]
A. J. FAULKNER,[3] AND M. A. MCLAUGHLIN[3]

ABSTRACT

We investigate the pulsar birthrate from a sample of 815 nonrecycled pulsars detected by the Parkes multibeam survey, accounting as accurately as possible for all known selection effects. We find that pulsars with magnetic fields greater than 2.5×10^{12} G account for more than half of the total birthrate in spite of comprising only about 5%–10% of the total Galactic population. While we do not find evidence for a significant population of pulsars "injected" into the population with spin periods of ∼0.5 s, we do find that many, perhaps 40%, are born with periods in the range 0.1–0.5 s. The absolute number and birthrate of Galactic pulsars is strongly dependent on the assumed models for pulsar beaming and Galactic electron distribution. Adopting the most recent models, we find the total pulsar birthrate to be between 0.9 and 1.9 pulsars per century for 1400 MHz luminosities greater than 1 mJy kpc², and the total Galactic population of active radio pulsars above this luminosity limit to be between 70,000 and 120,000.

Subject headings: pulsars: general — stars: evolution

1. INTRODUCTION

The birth, life history, and death of radio pulsars have been topics of great interest and debate since the discovery of pulsars 37 years ago (Hewish et al. 1968). In a pioneering statistical study based on a sample of 41 pulsars, Gunn & Ostriker (1970) derived a birthrate of approximately one pulsar every 30 yr in the Galaxy. In a more model-free approach, Vivekanand & Narayan (1981) developed the current pulsar analysis proposed by Phinney & Blandford (1981). Using a sample of 210 pulsars, they derived a Galactic population of ∼6×10^5 active pulsars with a birthrate of one pulsar every 21 yr. Somewhat controversially, they found a significant increase in the current at a period $P \sim 0.5$ s, which led to the conclusion that a large number of pulsars must be injected into the population with initial spin periods $P_0 \gtrsim 0.5$ s.

Subsequent population studies based on larger sample sizes have produced conflicting results. Applying Gunn & Ostriker's approach to a sample of 316 pulsars, Lyne et al. (1985) found the number of active pulsars in the Galaxy to be 2×10^5, with a corresponding birthrate of one pulsar every 30–120 yr. Their analysis was consistent with a simple model in which all pulsars are born spinning rapidly at birth ($P_0 < 0.1$ s). In a later study, Narayan (1987) repeated the current pulsar analysis with 220 pulsars and concluded that injection was significant for pulsars with high magnetic fields ($\gtrsim 10^{12}$ G). He derived the total number of active pulsars in the Galaxy to be ∼1.5×10^5, with one

pulsar born every ∼56 yr. A later application of the pulsar current analysis by Lorimer et al. (1993) using a sample of 412 pulsars found no evidence for injection for the population with 430 MHz luminosities above 10 mJy kpc². They concluded that the birthrate above this luminosity limit is one pulsar in 125–250 yr, with a total Galactic population of ∼7×10^4.

The pulsar samples used in the above studies were almost exclusively derived from surveys conducted at low frequencies, usually near 400 MHz, which were largely insensitive to the distant short-period pulsars in the Galactic plane due to propagation effects. Successful pulsar surveys require a large radio telescope, low-noise receivers, a relatively wide bandwidth, and long observation times. The Parkes multibeam survey (Manchester et al. 2001) met all these requirements and is the most successful pulsar survey so far, with over 700 pulsars discovered. Many of these pulsars are young and relatively distant, including several with strong implied surface dipole magnetic fields (e.g., McLaughlin et al. 2003). Of the 75 radio pulsars currently known with characteristic ages[9] $\tau_c \lesssim 100$ kyr, 43 were discovered in this survey. Therefore we have an excellent basis for investigating the birthrate of pulsars.

While it is obvious that pulsars with large slowdown rates, $\dot{P}$, and hence large implied surface dipole magnetic field strengths contribute disproportionally to the overall birthrate, there has been little quantitative analysis of the dependence of birthrate on magnetic field strength. In this Letter we apply the pulsar current analysis to the Parkes multibeam sample, accounting as accurately as possible for all known selection effects. Following a brief description of the properties of the observed sample used in this study (§ 2), in § 3 we summarize the main computational methods and assumptions used in our analysis. We discuss the main results of this study in § 4.

2. THE OBSERVED SAMPLE

The Parkes multibeam survey was carried out using the 13 beam multibeam receiver on the Parkes 64 m radio telescope. The central radio frequency of the survey is 1374 MHz, and

[1] School of Physics, University of Sydney, Sydney NSW 2006, Australia; natasa.vranesevic@csiro.au.
[2] Australia Telescope National Facility, CSIRO, P.O. Box 76, Epping NSW 1710, Australia.
[3] Jodrell Bank Observatory, University of Manchester, Macclesfield, Cheshire SK11 9DL, UK.
[4] Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027.
[5] Department of Physics and Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada.
[6] McGill University, 3600 University Street, Montreal, QC H3A 2T8, Canada.
[7] Osservatorio Astronomico di Cagliari, locanda Poggio dei Pini, Strada 54, Capoterra I-09012, Italy.
[8] Department of Physics, Haverford College, Haverford, PA 19041.

[9] The characteristic age, τ_c, is defined as $P/(2\dot{P})$, where $\dot{P}$ is the first time derivative of P.

its limiting sensitivity is ∼0.2 mJy. Details of the observing system are given by Manchester et al. (2001). This paper and three other major multibeam survey papers (Morris et al. 2002; Kramer et al. 2003; Hobbs et al. 2004) report the discovery of 600 pulsars and the detection of a further 281 previously known pulsars, giving a total of 881 pulsars. These papers give the pulsar period, period derivative, dispersion measure, pulse width, and mean flux density at 1400 MHz, all of which are required for this study. Of the 881 pulsars, 42 lie outside the nominal survey area ($|b| < 5°$, $l > 260°$, and $l < 50°$) and 13 have no published period derivative, leaving 826 pulsars. Of these, 11 have $P < 100$ ms and $\dot{P} < 10^{-18}$ and are apparently recycled. Although they make a negligible contribution to the pulsar current, they are not relevant to the present study. Removing these leaves a total sample of $N_{psr} = 815$ pulsars with minimum, median, mean, and maximum periods of 36 ms and 0.55, 0.76, and 6.71 s, respectively.

3. COMPUTATIONAL METHODS

3.1. *Scale Factor*

The pulsar current method depends on estimating the number of pulsars in the Galaxy that are similar to each of the pulsars in the sample. We have used the sensitivity threshold of the multibeam survey computed by Crawford (2000; see also Manchester et al. 2001) and compute a weight or scale factor for each pulsar by (1) placing it at a large number of randomly selected locations in the model Galaxy; (2) for each position, calculating the effective dispersion measure and the interstellar scattering and the corresponding survey limiting flux density; and (3) recording the number of detections, i.e., those positions for which the predicted flux density exceeds the survey limit. The scale factor for each pulsar (S_i) is then defined to be the ratio of the total number of pulsars in our model Galaxy (typically 10^5) to the number of model pulsars that would be detected by the survey.

Because of the paucity of observed pulsars toward the Galactic center, the radial distribution of neutron stars is not well understood. Following Narayan (1987), it is often assumed that pulsars have a Gaussian radial distribution about the Galactic center. Johnston (1994) derived an improved model of the radial distribution that has a deficit of pulsars in the inner Galaxy. These two models give very similar results in the present analysis, but since preliminary analysis of the Parkes multibeam sample (Lorimer 2004) gives some support to Johnston's model, we adopt it for this Letter. For the distribution of pulsars with respect to the Galactic plane, we choose a Gaussian distribution in z with scale height of $z_0 = 450$ pc (from Lyne et al. 1998).

We use two models for the Galactic free-electron distribution—the TC93 model (Taylor & Cordes 1993) and the NE2001 model (Cordes & Lazio 2002)—to estimate distances for real pulsars and dispersion and scattering measures for model pulsars. We obtain the sky background temperature from the all-sky survey at 408 MHz of Haslam et al. (1982) and scale to our observing frequency using a -2.8 power-law frequency dependence (Lawson et al. 1987).

3.2. *Current Pulsar Analysis*

The idea of the current pulsar analysis is to compute the flow of pulsars from short to long periods. We assume that the distribution of pulsars in the Galaxy is in a steady state. Hence,

the pulsar current in a period bin P of width ΔP can be written as follows:

$$J(P) = \frac{1}{\Delta P}\left(\sum_{i=1}^{n_{psr}} \frac{S_i \dot{P}_i}{f_i}\right). \quad (1)$$

Here n_{psr} is the number of known pulsars in the period bin and f_i is the beaming fraction of the ith pulsar in that bin. Since (the intrinsic) $\dot{P} > 0$ for all pulsars, $J(P)$ is equal to the total birthrate of pulsars in the period range 0 to P, minus the death rate in the same range (Vivekanand & Narayan 1981). Therefore, $J(P)$ is less than or equal to the total birthrate.

In a few cases, as noted previously by Lorimer et al. (1993), the computed pulsar current is dominated by a single pulsar and hence has large statistical uncertainty, resulting in a possible overestimation of the actual birthrate. Lorimer et al. removed such pulsars by placing a luminosity cutoff. We minimize the effects of such pulsars by a simple outlier removal method. If the computed current for a pulsar lies more than 2 σ outside of the mean, we removed it from the sample.

Given a sample of N_{psr} pulsars, the number of potentially observable pulsars in the Galaxy is the sum of all their scale factors, with a statistical error

$$\sigma_N = \left(\sum_{i=1}^{N_{psr}} S_i^2\right)^{1/2}. \quad (2)$$

Note that these number and birthrate estimates do not account for the population of pulsars with radio luminosities below the minimum value of the observed sample. For this reason, when quoting our results in § 4, we always list the corresponding luminosity limit for the sample under consideration. This and the removal of pulsars with anomalously high currents both reinforce the interpretation of birth rates and Galactic populations as lower limits on the true values.

3.3. *Beaming Fraction*

Since the radio emission from pulsars is beamed, some fraction of the "active" pulsars are unobservable because their emission is not directed toward the Earth. The fraction f of the sky in which the emission is beamed is generally believed to be a function of period. In this work, we take the beaming model of Tauris & Manchester (1998), who find a beaming fraction/pulse period relation of the form

$$f(P) = 0.09[\log (P/s) - 1]^2 + 0.03. \quad (3)$$

Since there is much debate as to the exact shape and evolution of the beam and the distribution of beam parameters, we quote results with and without the application of a beaming correction. This is advantageous since the uncorrected results (i.e., $f_i = 1$) represent the potentially observable pulsar population.

4. RESULTS AND DISCUSSION

In addition to applying the current pulsar analysis to the entire pulsar sample, we also quote results for three roughly equal size subsets ranked according to the inferred surface dipole magnetic field strength $B_s = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G. That allows us to explore how the population and birthrate differ as a function of B_s. The low-field set contains 275 pulsars with minimum, maximum, and mean in $\log (B_s/G)$ of 10.14, 11.96, and 11.57, respectively, and mean $\langle \log (\tau_c/yr)\rangle = 7.27$. The
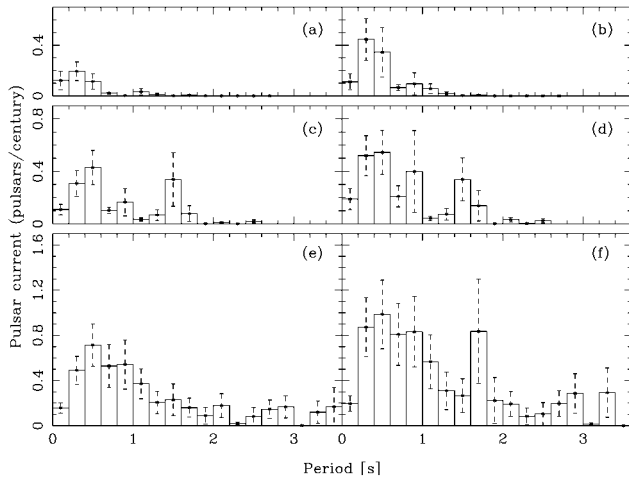
Fig. 1.—Pulsar current distributions using the Taylor & Cordes (1993) electron density model (*left*) and the Cordes & Lazio (2002) model (*right*). (*a*, *b*) Distribution for low-field pulsars; (*c*, *d*) distribution for middle-field pulsars; and (*e*, *f*) distribution for high-field pulsars.

middle-field set contains 292 pulsars with $\log (B_s/G)_{\min} =$ 11.97, $\log (B_s/G)_{\max} = 12.40$, and $\langle \log (B_s/G)\rangle = 12.19$ and mean $\langle \log (\tau_c/\mathrm{yr})\rangle = 6.30$. Finally, the high-field set contains 248 pulsars with $\log (B_s/G)_{\min} =$ 12.41, $\log (B_s/G)_{\max} =$ 13.97, $\langle \log (B_s/G)\rangle = 12.70$, and $\langle \log (\tau_c/\mathrm{yr})\rangle = 5.58$.

The results are summarized in Figure 1 and Table 1. The figure shows the derived pulsar currents for the two electron density models and for the different ranges of magnetic field strength. The table gives estimates of the birthrate (maximum current) for the total sample and each range of magnetic field strength with a 1400 MHz luminosity cutoff of 0.35 and 0.19 mJy kpc^2 for the TC93 and NE2001 models, respectively, and cutoffs of 1 and 10 mJy kpc^2 for the total sample (cf. Lorimer et al. 1993) separately for the two electron density models. The numbers in parentheses are the sample size after omitting the anomalous current pulsars as described above.

Regardless of which electron density model is used, it is clear that the high-field pulsars account for more than 50% of the overall current and hence the overall birthrate. This is in spite of the fact that these pulsars comprise less than 30% of the observed sample and, as can be inferred from Table 1, less than 10% of the total Galactic population.

For the mid- and high-magnetic field ranges, the current in the first period bin ($0\ \mathrm{s} < P < 0.2\ \mathrm{s}$) is systematically lower than that in the second bin ($0.2\ \mathrm{s} < P < 0.4\ \mathrm{s}$), indicating that many pulsars are born spinning with periods in the 0.2–0.4 s range. This result is similar to that discussed by Narayan (1987), but our improved statistics show that the period range with the highest net birthrate of high-B_s pulsars is below rather than above 0.5 s. It remains true that there is good evidence against high-field pulsars being born with periods $\lesssim 100$ ms.

At longer periods, the current distributions for the low magnetic field range are consistent with a plateau (suggesting that no further pulsars are being born at higher periods) or a steady decline (suggesting that pulsars are beginning to die). For the high-B_s pulsars, the current remains high to periods in excess of 1 s. This implies either that high-B_s pulsars do not die until their periods are greater than 1 s, or, if some of these pulsars die when their period is $\gtrsim 0.4$ s, that this death rate is matched by further births in the period range 0.4–1 s.

Birthrates for a sample cutoff $L_{1400} > 1$ mJy kpc^2 are approximately 3 times those for $L_{1400} > 10$ mJy kpc^2. Lorimer et al. (1993) suggested that few pulsars are born with $L_{1400} < 4$ mJy kpc^2, but recent detections of low-luminosity young pulsars (e.g., Camilo et al. 2002) suggest that this may not be correct. Our results support the idea that many pulsars are born with low luminosities.

Table 1 also gives the estimated total number of potentially observable and active pulsars in the Galaxy for each electron density model. Since many pulsars are less distant in the NE2001 model, the implied scale factors and hence total Galactic population are greater than for the TC93 model. For the NE2001 model and a luminosity cutoff $L_{1400} > 1$ mJy kpc^2, there are ~16,000 potentially detectable pulsars and ~110,000 active pulsars in the Galaxy.

According to Table 1, the total birthrates for $L_{1400} > 1$ mJy kpc^2 correspond to birth intervals of 76–109 and 52–80 yr for the TC93 and NE2001 models, respectively. These results are in

TABLE 1
Pulsar Birthrates and Galactic Populations

Subsample	TC93		NE2001	
	Birthrate[a]	Number in Galaxy	Birthrate[a]	Number in Galaxy
	$L > 0.35$ mJy kpc^2		$L > 0.19$ mJy kpc^2	
Total:	(782 pulsars)		(777 pulsars)	
$f = 1$	0.24 ± 0.04	21900 ± 5200	0.39 ± 0.08	50800 ± 13500
$f = f(P)$	1.13 ± 0.21	139000 ± 33300	1.86 ± 0.37	316400 ± 83100
High B_s:	(224 pulsars)		(224 pulsars)	
$f = 1$	0.13 ± 0.03	1300 ± 200	0.19 ± 0.06	2200 ± 400
$f = f(P)$	0.60 ± 0.16	11600 ± 1600	0.93 ± 0.28	21100 ± 5100
Middle B_s:	(285 pulsars)		(283 pulsars)	
$f = 1$	0.08 ± 0.02	4200 ± 800	0.11 ± 0.03	6300 ± 1300
$f = f(P)$	0.37 ± 0.12	34100 ± 7700	0.53 ± 0.16	49500 ± 11700
Low B_s:	(273 pulsars)		(270 pulsars)	
$f = 1$	0.03 ± 0.01	16400 ± 5100	0.09 ± 0.04	42300 ± 13500
$f = f(P)$	0.15 ± 0.07	93300 ± 32300	0.40 ± 0.18	245800 ± 82100
$L > 1$ mJy kpc^2:	(777 pulsars)		(765 pulsars)	
$f = 1$	0.23 ± 0.04	11900 ± 1400	0.33 ± 0.07	15700 ± 1600
$f = f(P)$	1.12 ± 0.20	79100 ± 9800	1.58 ± 0.33	106600 ± 11700
$L > 10$ mJy kpc^2:	(610 pulsars)		(539 pulsars)	
$f = 1$	0.09 ± 0.02	1800 ± 100	0.08 ± 0.02	1800 ± 100
$f = f(P)$	0.38 ± 0.08	11700 ± 700	0.37 ± 0.08	11700 ± 700

[a] In units of pulsars per century.

good agreement with recent estimates of the supernova rate in our Galaxy of one in 63–119 yr (Cappellaro et al. 1999).

REFERENCES

Camilo, F., Manchester, R. N., Gaensler, B. M., Lorimer, D. L., & Sarkissian, J. 2002, ApJ, 567, L71
Cappellaro, E., Evans, R., & Turatto, M. 1999, A&A, 351, 459
Cordes, J. M., & Lazio, T. J. W. 2002, preprint (astro-ph/0207156)
Crawford, F. 2000, Ph.D. thesis, MIT
Gunn, J. E., & Ostriker, J. P. 1970, ApJ, 160, 979
Haslam, C. G. T., Stoffel, H., Salter, C. J., & Wilson, W. E. 1982, A&AS, 47, 1
Hewish, A., Bell, S. J., Pilkington, J. D. H., Scott, P. F., & Collins, R. A. 1968, Nature, 217, 709
Hobbs, G., et al. 2004, MNRAS, 352, 1439
Johnston, S. 1994, MNRAS, 268, 595
Kramer, M., et al. 2003, MNRAS, 342, 1299
Lawson, K. D., Mayer, C. J., Osborne, J. L., & Parkinson, M. L. 1987, MNRAS, 225, 307

Lorimer, D. R. 2004, in IAU Symp. 218, Young Neutron Stars and Their Environments, ed F. Camilo & B. M. Gaensler (San Francisco: ASP), 105
Lorimer, D. R., Bailes, M., Dewey, R. J., & Harrison, P. A. 1993, MNRAS, 263, 403
Lyne, A. G., Manchester, R. N., & Taylor, J. H. 1985, MNRAS, 213, 613
Lyne, A. G., et al. 1998, MNRAS, 295, 743
Manchester, R. N., et al. 2001, MNRAS, 328, 17
McLaughlin, M. A., et al. 2003, ApJ, 591, L135
Morris, D. J., et al. 2002, MNRAS, 335, 275
Narayan, R. 1987, ApJ, 319, 162
Phinney, E. S., & Blandford, R. D. 1981, MNRAS, 194, 137
Tauris, T. M., & Manchester, R. N. 1998, MNRAS, 298, 625
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Vivekanand, M., & Narayan, R. 1981, J. Astrophys. Astron., 2, 315