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Discovery of four binary millisecond pulsars

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ABSTRACT

We present detailed parameters for four binary millisecond pulsars discovered during a survey of the southern sky with the Parkes radio telescope. Subsequent observations using the Parkes and Jodrell Bank radio telescopes have determined that the pulsars, PSRs J1603−7202, J1804−2717, J1911−1114 and J2129−5721, have spin periods ranging between 3.6 and 14.8 ms and are in circular orbits of periods between 2.7 and 11.1 d with low-mass (~ 0.1–$0.3\ M_{\odot}$) companions. The Parkes survey is now complete and has discovered a total of 17 millisecond pulsars; combining these results with large-area surveys at Arecibo and Jodrell Bank, the total number of millisecond pulsars known in the Galactic disc (i.e. not inside globular clusters) is 35. Based on this sample, we use a self-consistent Monte Carlo approach to derive the corrected pulsar spin period distribution which, over the range of presently known spin periods, should match the true spin period distribution more closely than the observed one. For periods $\gtrsim 3$ ms, the distribution is well constrained by this method. At shorter periods, however, the distribution is highly uncertain because of small-number statistics.

Key words: methods: statistical – pulsars: individual: J1603−7202 – pulsars: individual: J1804−2717 – pulsars: individual: J1911−1114 – pulsars: individual: J2129−5721 – Galaxy: stellar content.

1 INTRODUCTION

Millisecond pulsars are distinguished from normal pulsars primarily by their short spin periods ($P \lesssim 30$ ms, compared with ~ 1 s) and weak magnetic fields ($B \sim 5 \times 10^8$ G, compared with $\sim 10^{12}$ G). Often, they have the additional distinction of having a low-mass ($\lesssim 0.3\ M_{\odot}$) binary companion star. The standard model for producing binary millisecond pulsars involves the spin-up of an old neutron star by the accretion of matter from its evolved binary companion during a low-mass X-ray binary phase (Alpar et al. 1982). This process ceases when the companion star loses its outer layers to leave a millisecond pulsar–white dwarf binary system (Bhattacharya & van den Heuvel 1991). The recent flurry of optical identifications of millisecond pulsar companions (Bell, Bailes & Bessel 1993; Lorimer et al. 1995a; Bell et al. 1995; Lundgren et al. 1996; van Kerkwijk, Bergeron & Kulkarni 1996) confirms that they are low-mass white dwarfs. However, the connection with low-mass X-ray binaries remains somewhat problematic as a result of the well-documented discrepancy between the birth rates of millisecond pulsars and low-mass X-ray binaries (Kulkarni & Narayan 1988; see also Tavani 1991; Johnston & Bailes 1991; Lorimer 1995).

The number of known millisecond pulsars in the Galactic disc has increased dramatically in the last few years as a result of a number of large-area surveys at various observatories conducted at radio frequencies around 400 MHz (see for example Camilo, Nice & Taylor 1993; Manchester et al. 1996; Foster et al. 1995). The search of the entire southern sky with the 64-m Parkes radio telescope (Manchester et al. 1996) has been particularly successful. This survey is now complete and full results for the second half of the survey will be published soon (Lyne et al., in preparation). In this paper we report the discovery of, and give detailed parameters for, four binary millisecond pulsars found in the survey. Together with the eight millisecond pulsars discussed by Manchester et al. (1996), and five other pulsars (Stappers et al. 1996, Bailes et al. 1996), the completed Parkes survey has thus yielded 17 millisecond pulsars, about half of the presently known Galactic sample. This

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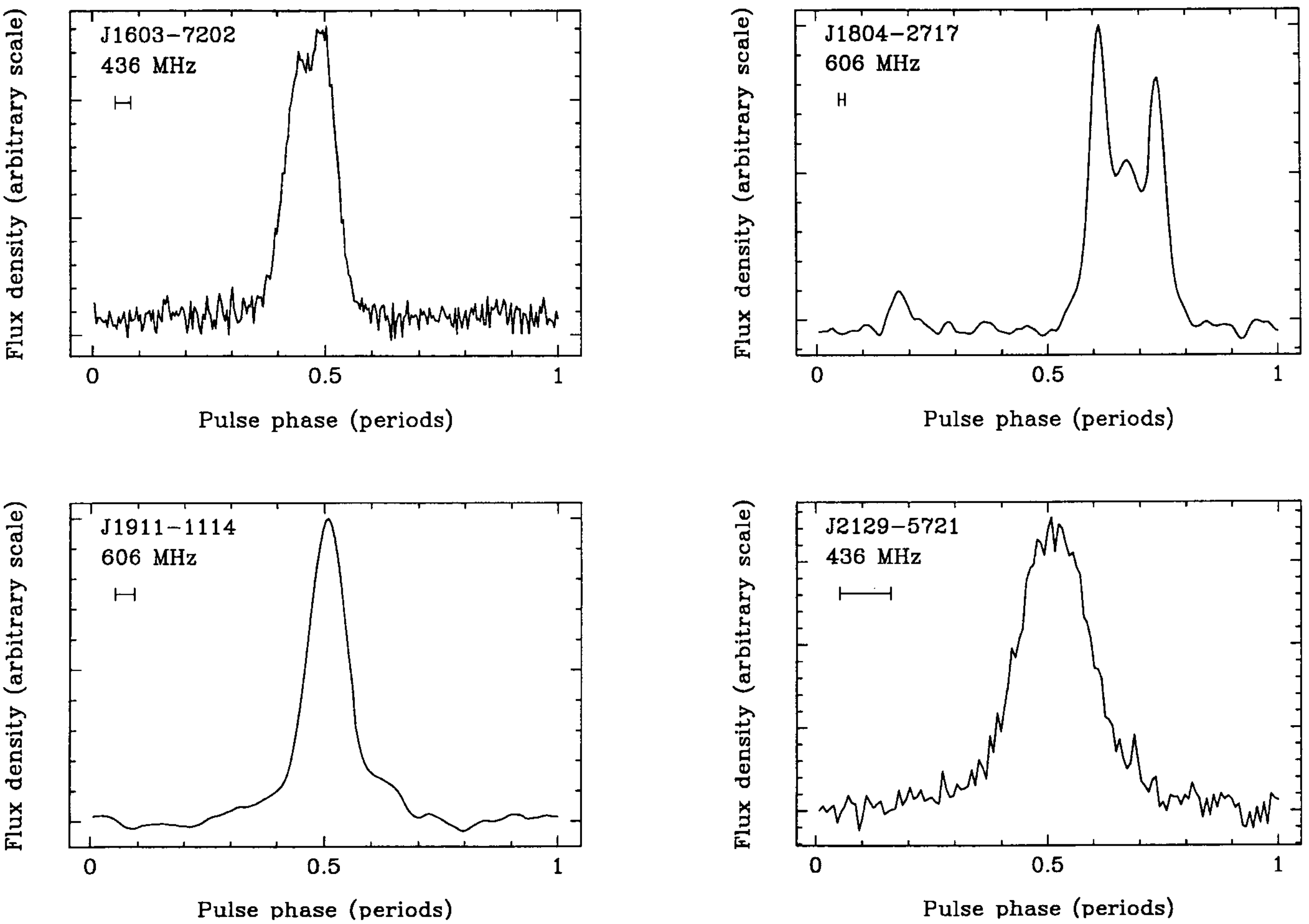

Figure 1. Total-intensity pulse profiles of the four millisecond pulsars. The 436-MHz observations for PSRs J1603−7202 and J2129−5721 were made at Parkes, and the 606-MHz observations of PSRs J1804−2717 and J1911−1114 were made at Jodrell Bank (see text). For each profile, the horizontal bar shows the limiting time resolution resulting from dispersion smearing across individual filterbank channels.

increase in sample size should provide a better base for statistical studies of the Galactic population of millisecond pulsars than has been available in the past. As well as providing detailed parameters for the four newly discovered binary millisecond pulsars, we investigate their distribution in spin period. Details of the data analysis and observing system for this survey are described elsewhere (Manchester et al. 1996).

2 FOUR BINARY MILLISECOND PULSARS

The spin periods of the new pulsars range between 3.6 ms for PSR J1911−1114 and 14.8 ms for PSR J1603−7202. All the pulsars are observed at Parkes typically once or twice a month as part of a systematic timing programme. In addition, PSRs J1804−2717 and J1911−1114 are observed in a complementary timing programme at Jodrell Bank using the 76-m Lovell radio telescope. The timing observations at both observatories take place at a variety of frequencies centred between 400 and 1500 MHz (see Manchester et al. 1996). Total-intensity, mean pulse profiles from these observations are presented in Fig. 1 for each pulsar. At 606 MHz, PSR J1804−2717 shows an interpulse at about 10 per cent of the peak amplitude of the main pulse, approximately 180° in rotational phase away from the centre of the complex main pulse, which shows at least three distinct peaks of emission.

Topocentric pulse arrival times for each observation were obtained by cross-correlating the observed pulse profiles with a standard template profile that is representative of the pulse shape at a given observing frequency. These data were then analysed using the TEMPO timing analysis package (Taylor & Weisberg 1989), the times being reduced to equivalent times of arrival at the Solar system barycentre using the JPL DE200 ephemeris (Standish 1982). For all of the millisecond pulsars, we found that the arrival times were well described by a timing model including astrometric, spin and Keplerian binary parameters. Table 1 summarizes the observed and derived parameters obtained from these solutions. Based on the present data, PSR J1911−1114 has the greatest potential for future high-precision timing measurements because of its relatively narrow pulse and reasonably large flux density.

Significant period derivatives have been measured for all four pulsars, from which we infer characteristic ages of 17, 3.5, 4.3 and 3.0 Gyr and surface magnetic field strengths of 4.6, 6.3, 2.2 and 2.8×10^8 G, respectively, similar to many other Galactic millisecond pulsars. For PSR J1603−7202, we note that the anomalously great age compared with that of the Galaxy (~ 10 Gyr) is likely to be even greater when the apparent period derivative is corrected for the effect of the transverse speed of the pulsar (Shklovskii 1970; Camilo, Thorsett & Kulkarni 1994). Assuming that the true age of the pulsar is less than 10 Gyr then it is

Table 1. Observed and derived parameters for the four binary millisecond pulsars. Errors quoted in parentheses represent twice the formal errors in the last quoted digit, obtained from a least-squares fit. Because of the low orbital eccentricity, the epoch and longitude of periastron are highly covariant for PSR J1804−2717; more precise values of these quantities are quoted for observers to allow accurate predictions of the pulse period.

Pulsar	PSR J1603−7202	PSR J1804−2717	PSR J1911−1114	PSR J2129−5721
RA (J2000)	$16^h\,03^m\,35^s.687(2)$	$18^h\,04^m\,21^s.1304(5)$	$19^h\,11^m\,49^s.2947(5)$	$21^h\,29^m\,22^s.755(3)$
Dec (J2000)	$-72°\,02'\,32''.65(1)$	$-27°\,17'\,31''.1(2)$	$-11°\,14'\,22''.33(3)$	$-57°\,21'\,14''.08(2)$
Galactic longitude	316.6	3.5	25.1	338.1
Galactic latitude	−14.5	−2.7	−9.6	−43.6
Period (ms)	14.84195201430(6)	9.34303068115(1)	3.625745570656(9)	3.72634841714(2)
Period derivative (10^{-20})	1.4(2)	4.2(1)	1.34(9)	2.0(1)
Epoch (MJD)	49524.0	49750.0	49840.0	49528.3
Dispersion measure (cm^{-3} pc)	38.05(2)	24.673(2)	30.957(4)	31.852(2)
Orbital period (days)	6.3086296(1)	11.1287115(1)	2.71655761(4)	6.6254930(2)
$a_p \sin i$ (light-s)	6.88067(2)	7.28145(1)	1.762871(9)	3.50057(2)
Eccentricity	$< 2 \times 10^{-5}$	$3.5(3) \times 10^{-5}$	$< 1.3 \times 10^{-5}$	$< 1.7 \times 10^{-5}$
Epoch of periastron (MJD)	49524.15287(6)	49615.11366(10000)	49838.953093(2)	49528.32498(2)
Longitude of periastron (deg)	0.0 (assumed)	159.7629(40000)	0.0 (assumed)	0.0 (assumed)
Timing data span (MJD)	49529–50117	49455–50086	49604–50075	49535–50242
RMS timing residual (μs)	50	33	20	31
Flux density at 400 MHz (mJy)	15(5)	20(3)	31(9)	5(2)
Flux density at 600 MHz (mJy)	-	3(1)	8(2)	-
Flux density at 1400 MHz (mJy)	3.0(5)	0.4(2)	0.5(2)	1.4(2)
Characteristic age (Gyr)	17	3.5	4.3	3.0
Magnetic field (10^8 Gauss)	4.6	6.3	2.2	2.8
Spectral Index	−1.3	−3.0	−3.3	−1.1
Minimum companion mass ($M_\odot$)	0.29	0.21	0.12	0.14
Distance (kpc)	1.6	1.2	1.6	> 2.6
$\|z\|$ (pc)	410	60	265	> 1800
Luminosity at 400 MHz (mJy kpc^2)	38	29	79	> 34

straightforward to show (Camilo et al. 1994) that the initial spin period of this pulsar was at least 9.5 ms. We can also use the measured period derivative to place an upper limit on the transverse speed for PSR J1603−7202 of about 120 km s^{-1}. The combination of a low period derivative and a relatively long spin period makes this pulsar a very good candidate for placing limits on the time derivative of Newton's gravitational constant G (Will 1981; Camilo, Nice & Taylor 1996a). The limit of $|\dot{G}/G| < 5 \times 10^{-11}\ \mathrm{yr}^{-1}$, based on the period and period derivative of J1603−7202, is only slightly weaker than the best limit of $< 3 \times 10^{-11}\ \mathrm{yr}^{-1}$ set by other millisecond pulsar timing results (see Camilo et al. 1996a and references therein). The limit set by PSR J1603−7202 will improve if the contribution of the pulsar's proper motion to $\dot{P}$ can be determined.

To estimate the masses of the companions we use the Keplerian mass function which relates the projected semimajor axis $a_p \sin i$ and the orbital period P_{orb} with the pulsar and companion masses in the following way:

$$f(m_p, m_c) = \frac{4\pi^2}{G}\frac{(a_p \sin i)^3}{P_{\mathrm{orb}}^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2}. \qquad (1)$$

Assuming a pulsar mass m_p of 1.4 $M_\odot$, the mass of the orbiting companion m_c can be estimated as a function of the unknown orbital inclination i. The minimum companion mass occurs when the orbit is assumed to be viewed edge-on ($i = 90°$), and is about 0.29 $M_\odot$ for PSR J1603−7202, 0.21 $M_\odot$ for PSR J1804−2717, 0.12 $M_\odot$ for PSR J1911−1114 and 0.14 $M_\odot$ for PSR J2129−5721. With the exception of PSR J1603−7202, these companion masses are, within the uncertainties arising from the unknown orbital inclinations, consistent with the orbital period–companion mass relationship (Joss, Rappaport & Lewis 1987; Rappaport et al. 1995; see, however, the discussion in Tauris 1996). The orbital eccentricity for PSR J1804−2717 and the present upper limits for PSRs J1603−7202, J1911−1114 and J2129−5721 agree well with the theoretical relationship between orbital period and eccentricity derived by Phinney's (1992) convective fluctuation–dissipation theory.

The somewhat larger mass of the companion to PSR J1603−7202, together with the relatively long spin period of the pulsar, suggests that this system may belong to the class of 'intermediate-mass' binary pulsars (van den Heuvel 1994; Camilo 1995). The white dwarf companions to these systems are expected to be carbon–oxygen rich rather than helium rich, thought to be the case for the lower mass binary pulsars. Optical identification and spectroscopy of the companion star to PSR J1603−7202 would therefore be of great interest.

An inspection of the Digital Sky Survey Archive has not revealed any candidate objects in the fields surrounding any of the four pulsars, down to the limiting visual magnitude of the survey of between 20 and 22 in these regions. This is not surprising given the distances to the binary systems, which range between 1.2 kpc (J1804−2717) and greater than 2.6 kpc (J2129−5721), as estimated from their dispersion measures and the Taylor & Cordes (1993) electron density model. These distances and the characteristic ages of the millisecond pulsars lead us to expect visual magnitudes of about 25 if the companions are low-mass white dwarfs. Thus, for future optical observations, using a sensitive instrument such as the *Hubble Space Telescope* would be more appropriate. We note in passing that PSR J1804−2717 lies only about 5° on the sky from the

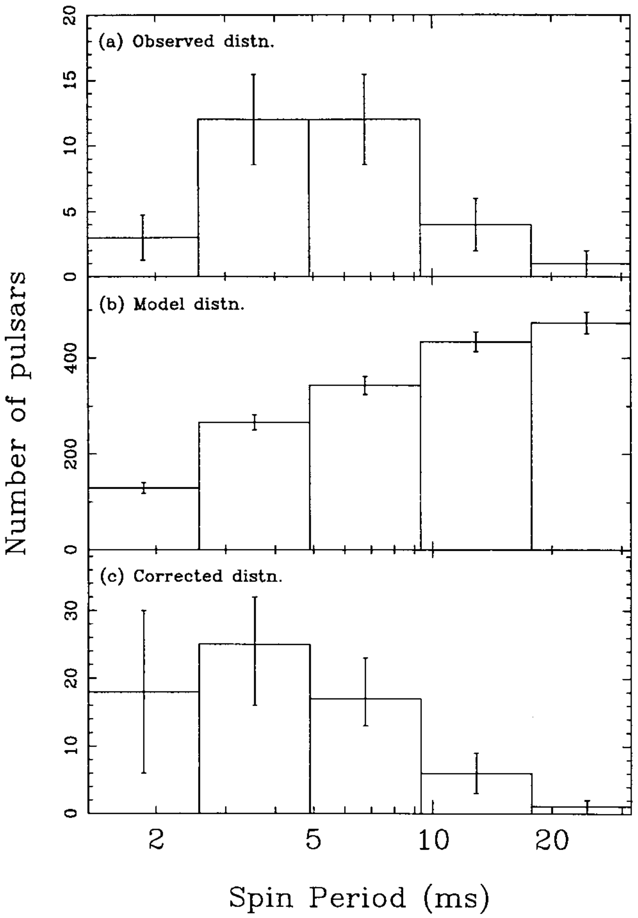

Figure 2. The observed distribution of millisecond pulsar spin periods (a) is in stark contrast to the expected observed distribution of rotation periods for ~1500 model pulsars (b) with an assumed pulse duty cycle of 10 per cent, drawn from a parent population with a flat distribution in log P. The dearth of observable millisecond pulsars with short periods highlights the serious degradation of the period sensitivity below about 3 ms for the present surveys. The corrected distribution (c) is obtained by summing the scalefactors of all pulsars contained within each period bin (see text).

direction of the Galactic Centre. Because of the high stellar density and optical extinction in this region, obtaining a convincing optical detection will be difficult.

3 THE GALACTIC MILLISECOND PULSAR POPULATION

The number of millisecond pulsars found by Galactic disc searches has risen to 35, and the observed population is now large enough to investigate some interesting statistical properties of the Galactic population. An important, and as yet largely unknown, property of the population is the *underlying*, as opposed to the observed, distribution of rotation periods. The underlying period distribution will almost certainly differ from the observed distribution shown in Fig. 2(a) because of the significant degradation in search sensitivity at short periods ($P \lesssim 10$ ms). In this regime, the amount of pulse broadening can become comparable to, or greater than, the pulse period resulting from a combination of pulse dispersion and multipath scattering, finite sampling and the effects of aliasing in the frequency domain (Lyne 1988; Camilo et al. 1996a).

These effects can be reasonably well quantified for a given set of survey parameters (see for example Manchester et al. 1996), so that it is possible to calculate for each pulsar a scalefactor which represents the number of pulsars in the Galaxy with similar spin periods. The distribution of all the scalefactors as a function of pulse period should then give a better indication of the true distribution of rotation periods in the Galaxy. The millisecond pulsars in the present sample result from a number of surveys with different sensitivities covering different parts of the sky. This, coupled with the fact that the sky background temperature and interstellar medium effects on the search sensitivities are distinctly non-uniform, makes any analytical approach to deriving the scalefactor impractical. Following previous work (Lorimer et al. 1993, 1995b), we use a Monte Carlo simulation of the Galactic population of pulsars to derive the scalefactors. This approach has the great advantage over analytical methods of being able to account much more rigorously for the known selection effects which bias the observed sample.

To simulate the Galactic distribution of millisecond pulsars we use a Gaussian radial dependence and an exponential distribution above the Galactic plane with a scaleheight of 600 pc (Lorimer 1995). The precise form of the radial distribution turns out to be unimportant, since most of the millisecond pulsars found are relatively local ($d \lesssim 3$ kpc) objects. We then draw their radio luminosity from a power-law distribution with a slope of $\mathrm{d}\log N/\mathrm{d}\log L \sim -1$ as is the case for normal pulsars (Lyne, Manchester & Taylor 1985). The minimum luminosity is taken to be 2.5 mJy kpc^2 (Lorimer et al. 1995b). In addition to the surveys considered by Lorimer et al. (1995b), we include the more recent Arecibo searches (Ray et al. 1995; Camilo et al. 1996a,b) as well as the Jodrell Bank millisecond pulsar survey (Nicastro et al. 1995). More recent phases of the Penn State–Naval Research Laboratory Arecibo survey (Foster et al. 1995) are not included in our analysis, since the published sky coverage information is not sufficient to permit a reliable model.

To clarify the distinction between the model and real pulsar samples, we are concerned with the following:

(i) the *underlying sample* of model pulsars, the properties of which are well understood (see above);

(ii) the *model observed sample*, i.e. all model pulsars that are theoretically detectable;

(iii) the *real observed sample*, i.e. the 32 millisecond pulsars discovered in the surveys that we simulate.

As we believe that the latter two samples are subject to the same selection criteria, it is then appropriate to compare their properties statistically. Since all the model pulsars are subject to Poissonian statistics, we take care to ensure that the model-observed samples contain a large number of pulsars (typically ~ 1500) to minimize the effect of statistical noise.

To demonstrate the extent to which the real observed sample suffers from period selection effects, we initially assume that the underlying period distribution in log P is *uniform*, and then form the model-observed distribution. The result of this process is shown in Fig. 2(b), where the dearth of short-period pulsars demonstrates the strength of the above effect in selecting against such pulsars. Another important point to notice from Fig. 2(b) is that it shows convincingly that the period distribution of millisecond pulsars above about 10 ms is inconsistent with a flat distribution in log P. On the other hand, we have no a priori expectation that it should be flat, as it depends upon the detailed evolutionary history of the pulsars in our sample, which may arise from several types of progenitor systems.

To correct for this selection effect, we calculate the period scalefactor for each millisecond pulsar in the real observed sample as the number of detections predicted by our model for a pulsar with all the attributes of the millisecond pulsar, but with a long period (500 ms). By definition, then, this number is the total number of millisecond pulsars with similar periods that we would expect to see if the surveys were not affected by period selection effects. We can compare the period distribution (in $\log P$) of the real observed sample shown in Fig. 2(a) and the corrected distribution formed by summing the scalefactors of the observed millisecond pulsars, shown in Fig. 2(c). As expected, the most striking difference between the observed and corrected distributions is for periods $\lesssim 3$ ms, which are seriously under-represented in the real observed sample. Because of the large statistical errors in the corrected distribution at short periods, we cannot currently discriminate between a flat distribution and a cut-off in this region.

The existence of a cut-off would be of great interest, as it may indicate that the minimum neutron star spin period is not much less than that of the shortest period pulsar in our sample, PSR B1937+21, with a period of 1.5 ms. This would argue against the softer neutron star equations of state which predict much shorter limiting spin periods (Brown 1988). However, care should be taken in drawing any firm conclusions on the minimum period, since the present sample is subject to small-number statistics. To test this hypothesis further, it will be necessary to reduce the error bars in Fig. 2(c) significantly by surveying larger volumes of the Galaxy with increased short-period sensitivity. Currently several groups are improving the period sensitivity of low-frequency surveys at a number of observatories, to this end. However, these surveys will necessarily survey only the local Galactic neighbourhood; another obvious strategy would be to survey regions close to the Galactic plane region at a higher frequency (~ 1.4 GHz) with rapid sampling. Such an approach proved most successful for probing the Galactic plane for normal pulsars (Clifton et al. 1992; Johnston et al. 1992). Such surveys are currently planned at Jodrell Bank, Parkes and Nançay, and should also be superb probes of the large-scale, as opposed to the local, distribution of millisecond pulsars.

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