

A 1400-MHz pilot search for young pulsars

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Abstract. We have used the Effelsberg 100-m radio telescope to conduct a 1400-MHz (λ 21-cm) search for young and rapidly rotating radio pulsars along a 2 deg^2 strip of the northern Galactic plane defined by $28^\circ \leq l \leq 30^\circ$ and $|b| \leq 0.5^\circ$. This region lies close to the Scutum spiral arm which is already known to contain a number of radio and X-ray pulsars. The search was nominally sensitive to pulsars with 1400-MHz flux densities above 0.3 mJy; this represents a threefold improvement in sensitivity over all previous searches of this region of the Galaxy. Four new long-period pulsars were discovered as a result of this survey. All three previously known pulsars in this region were also detected. The four new pulsars are relatively young ($< 0.5 \text{ Myr}$), weak ($< 1 \text{ mJy}$) sources with dispersion measures in the range $170\text{--}910 \text{ cm}^{-3} \text{ pc}$. None of the newly-discovered pulsars are associated with catalogued supernova remnants.

Key words: telescopes – techniques: miscellaneous – stars: pulsars: individual: PSR J1841–0345, PSR J1842–0415, PSR J1844–0310, PSR J1845–0316

1. Introduction

Although the majority of pulsar radio flux density spectra peak at frequencies around 400 MHz, during the 1980s it was realised that the sensitivity of pulsar surveys conducted at such frequencies becomes seriously compromised when searching along the Galactic plane. The reasons for this are twofold: (1) The system temperature becomes dominated by the sky background radiation. Typical 400-MHz sky background temperatures are $\sim 900 \text{ K}$ in the direction of the Galactic centre, and $\sim 300 \text{ K}$ along the Galactic plane (Haslam et al. 1982). (2) The observed pulse width can become much larger than the intrinsic width due to multi-path scattering and/or dispersion by free electrons in the interstellar medium. Both these effects lead to a net reduction in signal-to-noise ratio. In extreme cases of scattering and dispersion, the observed pulse width becomes comparable to

the pulse period and the pulsar is no longer visible as a periodic radio source.

Fortunately, all these effects diminish strongly at a higher observing frequency: The brightness temperature of the radio continuum emission T_ν at a given observing frequency ν has a power law dependence $T_\nu \propto \nu^\beta$ with a spectral index $\beta \sim -3$ (Lawson et al. 1987; Reich & Reich 1988). This means that the 408-MHz sky background temperatures quoted above are reduced by more than an order of magnitude for high frequency ($\gtrsim 1\text{-GHz}$) surveys. Furthermore, pulse dispersion and scattering scale as $\Delta\nu/\nu^3$ and ν^{-4} respectively (e.g. Manchester & Taylor 1977), for an observing frequency ν and bandwidth $\Delta\nu$.

Clifton & Lyne (1986) (see also Clifton et al. 1992) were the first to really demonstrate the worth of surveying at high frequencies. In a 1400-MHz survey of a thin strip of 200 deg^2 along the Galactic plane, Clifton et al. found 40 new pulsars. All of these sources were missed by a previous 390-MHz survey (Stokes et al. 1985) which overlapped the same region. This was in spite of the fact that, after scaling the sensitivity limits for typical pulsar spectral indices, the Stokes et al. survey had twice the nominal sensitivity of the Clifton et al. survey. Johnston et al. (1992a) carried out a complementary survey of the southern Galactic plane using the Parkes radio telescope at 1520 MHz, finding 46 pulsars missed by previous lower frequency searches covering this region (Manchester et al. 1978).

The pulsars discovered in these two high frequency surveys are primarily young neutron stars that have not had time to move far from their birth places close to the Galactic plane. A large sample of such objects is desirable for studies of the birth and evolution of neutron stars and of the size of the neutron star population in the inner Galaxy (Johnston 1994). In addition, these surveys discovered several interesting binary pulsars including PSR B1259–63 – a 48-ms pulsar in a 3.4-yr orbit around a $10 M_\odot$ Be star (Johnston et al. 1992b).

Significant improvements in sensitivity have led to renewed interest in Galactic plane searches. In particular Camilo et al. (2000a) report the discovery of over 400 pulsars in the first half of a new survey of the southern Galactic plane using the recently commissioned Parkes λ 21-cm multibeam system. Their survey is some seven times more sensitive than the Clifton et al. and Johnston et al. surveys, and the new discoveries already

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include several binary pulsars (e.g. Lyne et al. 1999), as well as a large number of very distant, high dispersion measure, sources.

A preliminary account of the exciting results from the Parkes multibeam survey (Camilo et al. 1997) prompted us to utilise the large collecting area of the 100-m Effelsberg radio telescope to perform a new search along the northern Galactic plane. In this paper we report on a small survey carried out during 1998 to test the feasibility of future observations with a wide-bandwidth search system currently under development. This pilot search proved successful, discovering four new pulsars – the first ever found with this telescope. In Sect. 2 we describe in some detail the survey observations and data reduction techniques. In Sect. 3 we estimate the sensitivity of the survey. The results are presented in Sect. 4. These results, along with follow-up timing observations, are discussed in Sect. 5. Finally, in Sect. 6, we summarise the main conclusions from this work and their implications for future pulsar search experiments at Effelsberg.

2. Survey observations and data reduction

All observations reported in this paper were carried out at a centre frequency of 1402 MHz on a number of separate sessions between 1998 June and 1999 April using the 100-m Effelsberg radio telescope operated by the Max-Planck-Institut für Radioastronomie. Although 1400-MHz timing observations at Effelsberg are routinely made with typical bandwidths of 40 MHz or more (see e.g. Kramer et al. 1998), the search hardware available to us has a maximum bandwidth of 16 MHz in each of the two orthogonal, circular polarisation channels. Nonetheless, the large forward gain of the telescope at 1400 MHz (1.5 K Jy^{-1}), the relatively low system temperature of the receiver (35 K) and long integration times employed in the survey (35 min per pointing) means that the system achieves a sensitivity which represents a threefold improvement over that achieved by Clifton et al. (1992) during their survey.

The main aim of the observations reported here was to test the feasibility of a larger search with a 100-MHz bandwidth system which is presently being commissioned. Given the limited amount of telescope time available for this pilot project, we chose to restrict our search area to a 2 deg^2 patch of the Galactic plane defined by $28^\circ < l < 30^\circ$ and $|b| < 0.5^\circ$. The rationale for this choice is simple – this line-of-sight is close to the Scutum spiral arm and as a result passes through one of the most pulsar-rich parts of the northern Galactic plane. In addition, since this part of the sky is not visible from Arecibo, Effelsberg is presently the largest radio telescope in the world capable of surveying it. The survey region was divided up into a grid of 126 positions consisting of 9 strips of 14 positions along lines of constant galactic latitude ($b = 0.0^\circ, \pm 0.12^\circ, \pm 0.24^\circ, \pm 0.36^\circ, \pm 0.48^\circ$). This choice of spacing ensured some overlap between the 3-dB width of the telescope beam ($9'$). The $b = 0.0^\circ$ strip was centred on $l = 29^\circ$. Beam centres on adjacent strips were alternately offset by half a beam width to ensure the most efficient coverage on the sky.

At the start of each observing run, we carried out a 5-min observation of PSR B2011+38. This relatively luminous 230-ms

pulsar has a dispersion measure of $239 \text{ cm}^{-3} \text{ pc}$ and is known not to be prone to significant intensity variations due to interstellar scintillation (Lorimer et al. 1995). The fact that the search code detected this pulsar with consistently high signal-to-noise ratios (consistent with its 1400-MHz flux density – $6.4 \pm 0.5 \text{ mJy}$; Lorimer et al. 1995) gave us confidence that the individual filterbank channels were functioning normally, and that the nominal system sensitivity was being achieved.

The search field is visible from Effelsberg for about 8.5 hr per day. Since each grid position in the field was observed for 35 min, we typically observed up to 14 separate positions on the sky during a given transit. In search mode, the incoming signals of each polarisation are fed into a pair of 4×4 -MHz filterbanks. The outputs from the filterbanks are subsequently detected and digitised every $500 \mu\text{s}$ using 2-MHz voltage-to-frequency converters, resulting in an effective 10-bit quantisation of the signals. This is the fastest sustainable data rate using this system. Signals from the orthogonal polarisations were combined to form a total power time series for each 4-MHz frequency channel over the band. These four frequency channels are then passed to the standard Effelsberg Pulsar Observing System (see Kramer 1995) which stored contiguous blocks of data to disk every 1024 samples (0.512 s).

The four-channel search system used for this survey results in refreshingly low data rates compared to most other searches where the backends routinely sample 256 channels or more (see e.g. Manchester et al. 1996). The main advantage of such a simple system is that, as soon as each 35-min integration was complete, a preliminary analysis of the data could be carried out well within the time that the telescope was observing the next grid position. This quasi on-the-fly processing scheme allowed rapid re-observation of any pulsar candidates found during the search.

The data analysis procedure was optimised to search Fourier spectra of each 35-min time series for dispersed periodic signals. The software for this purpose was developed largely from scratch, taking advantage of ideas used to process our ongoing search of the Galactic centre from Effelsberg (Kramer et al. 1996; Kramer et al. 2000), as well as previous experience gained by one of us (DRL) during the Parkes $\lambda 70$ -cm Southern Sky Survey (Manchester et al. 1996; Lyne et al. 1998). We also made use of several “standard” pulsar search techniques described in detail by a number of authors (Hankins & Rickett 1975; Lyne 1988; Nice 1992). In what follows we give a brief overview of our analysis procedure.

We adopted a two-stage data analysis procedure whereby the data were quickly analysed after the observation at Effelsberg and then stored on magnetic tape for more detailed off-line analyses at Bonn. The three differences in the analyses are the range of dispersion measures searched, the signal-to-noise thresholds, and the method used to excise radio frequency interference (see below).

Both analyses begin by computing the Fast Fourier Transform of the 2^{22} point time series in each of the four frequency channels. Since the dispersion measure (DM) of any pulsar is a priori unknown we need to de-disperse the data for a num-

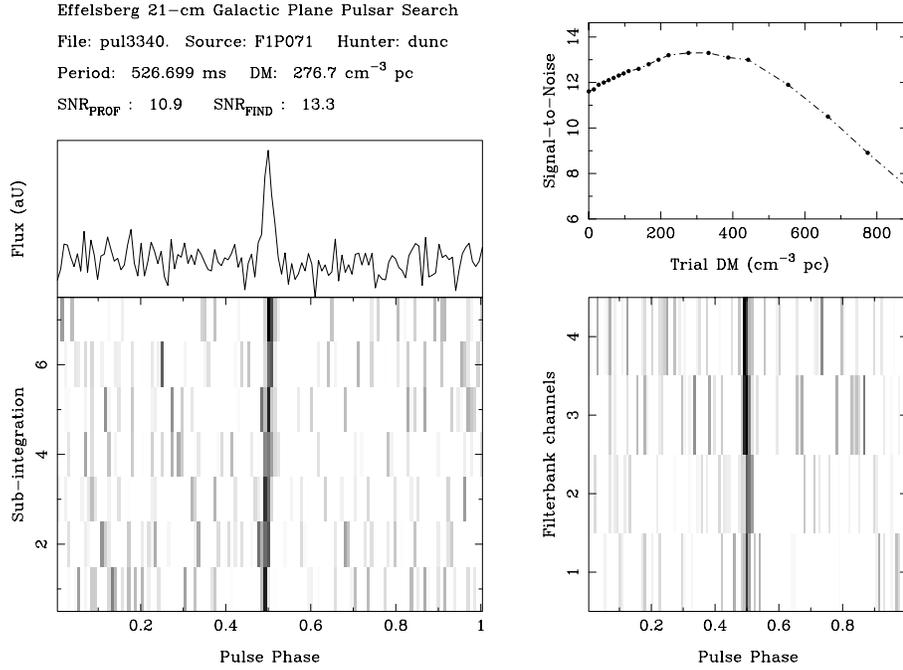


Fig. 1. Sample search code output showing the discovery observation of PSR J1842–0415—the first of the four pulsars found during the survey. This plot shows how a typical pulsar appears to the search code and summarises the various diagnostics we used to identify the best pulsar candidates from the survey (see text).

ber of trial DM values before the periodicity search begins. For our purposes this is most readily achieved by applying the shift theorem (see e.g. Bracewell 1965) to the Fourier components of each channel before summing appropriately to produce a number of de-dispersed amplitude spectra. Our on-line analysis in Effelsberg produced 18 amplitude spectra for each beam corresponding to a DM range between zero and $1,500 \text{ cm}^{-3} \text{ pc}$. Subsequent analyses in Bonn produced, in addition to this, a further 18 spectra per beam which increased the range of DMs out to $10,000 \text{ cm}^{-3} \text{ pc}$. Each amplitude spectrum was then searched for harmonically related spikes in the Fourier domain – the characteristic signature of any periodic signal. Since pulsar signals have generally short duty cycles, and therefore many harmonics, we summed the spectra over 2, 4, 8, and 16 harmonics using an algorithm described by Lyne (1988) and repeated the search for significant spectral features.

Having completed the search of all the amplitude spectra for a given beam, we then compiled a list of all non-harmonically-related spectral features with a signal-to-noise ratio greater than 8 in the Effelsberg analyses and 7 in the Bonn analyses. Typically, depending on the amount of interference present in the data, there are of order five to ten such “pulsar candidates” in each beam. For each candidate, the analysis described so far resulted in a period P and dispersion measure DM; the latter quantity is based upon the maximum spectral signal-to-noise ratio found as a function of all the DM trials. Working now in the time domain, we fold the filterbank channels at the nominal period of each candidate to produce one pulse profile per channel. These profiles are then de-dispersed at the nominal DM to produce an integrated profile over the 16-MHz band.

The results of this analysis are summarised in the plot of the form shown in Fig. 1 which is the output from the discovery observation of PSR J1842–0415. This plot serves as a good ex-

ample showing the characteristics of a strong pulsar candidate. The high signal-to-noise integrated profile (top left panel) can be seen as a function of time and radio frequency in the grey scales (lower left and right panels). In addition, the dispersed nature of the signal is immediately evident in the upper right hand panel which shows the signal-to-noise ratio as a function of trial DM. This combination of diagnostics proved extremely useful in differentiating between a good pulsar candidate and spurious interference.

The most significant difference between our two data reduction strategies concerns the methods employed to eliminate radio frequency interference. Since the radio frequency environment in Effelsberg is pervaded by a number of man-made signals with fluctuation frequencies predominantly between 10–2000-Hz, both modes of data reduction required some means of excising these unwanted signals. The “on-line” data reduction mode in Effelsberg achieved this by simply clipping all spectral features above 10-Hz whose amplitudes exceeded five times the spectral rms! Whilst this simple-minded approach was sufficient to detect and confirm all the pulsars finally discovered in the survey, we were aware that it significantly compromised our sensitivity to pulsars with periods below 0.1 s.

To address this important issue, our data analysis procedure in Bonn made use of the fact that the vast majority of man-made interfering signals are not dispersed and occur predominantly at a constant fluctuation frequency at any given epoch. These signals are immediately apparent in a compilation of a large number of zero-DM amplitude spectra for different beam positions. Based on the statistics of over 60 individual spectra, we constructed a “spectral mask” which contains the frequencies of those spectral features which occur more than 5 times above a signal-to-noise threshold of 7. We found 611 such frequencies between 30 and 2000-Hz – 0.06% of the total number

of spectral bins. Most of these are in fact related to the 50-Hz mains power line. By masking (i.e. ignoring) just these frequencies in our analysis, it was then possible to detect short-period pulsars with fundamental frequencies outside the masked frequency bins in our data. We verified the validity of this approach by analysing a number of test observations on millisecond and short-period pulsars which were essentially undetectable without the use of the spectral mask, simply because of the dominating effect of the interfering signals. Thus, although we did not detect any short-period pulsars in this survey, we are confident that no potentially detectable pulsars with fundamental frequencies outside the masked frequency bins were missed because of radio frequency interference.

3. Search sensitivity

To estimate the sensitivity of this survey, we make use of the following expression which is similar to that derived by Dewey et al. (1984) to find the minimum detectable flux density a pulsar has to have in order to be detectable:

$$S_{\min} = \frac{\eta T_{\text{sys}}}{G\sqrt{2\Delta\nu\tau}} \left(\frac{W}{P-W} \right)^{1/2}. \quad (1)$$

Here the constant factor η takes into account losses in the hardware and the threshold signal-to-noise ratio above which a detection is considered significant ($\eta \approx 10$ in our case), T_{sys} is the system temperature (see below), G is the gain of the telescope (1.5 K Jy^{-1} for Effelsberg operating at 21-cm), $\Delta\nu$ is the observing bandwidth (16-MHz for this survey), the factor of $\sqrt{2}$ indicates that two polarisation channels were summed, τ is the integration time per telescope pointing (35 min), P is the period of the pulsar and W is the observed width of the pulse.

The system temperature T_{sys} is essentially the sum of the noise temperature of the receiver T_{rec} , the spillover noise into the beam side-lobes from the ground T_{spill} and the excess background temperature T_{sky} caused largely by synchrotron radiating electrons in the Galactic plane itself. From regular calibration measurements we found T_{rec} to be 35 K. The spillover contribution T_{spill} was estimated to be 5 K for typical telescope elevations during survey observations. We estimate T_{sky} by scaling the 408-MHz all-sky survey of Haslam et al. (1982) to 1400 MHz assuming a spectral index of -2.7 (Lawson et al. 1987), finding a typical value in the direction $l = 29$ and $b = 0.0$ to be 15 K. With these values in Eq. (1), we find the minimum flux density for detecting a 0.5 s pulsar with a duty cycle of 4% to be about 0.3 mJy.

We caution that this sensitivity estimate should be viewed as a “best case scenario”, valid for relatively long-period pulsars with low dispersion measures and narrow pulses observed at the beam centre. The effects of sampling and dispersion and pulse scattering significantly degrade the search sensitivity at short periods. Specifically, the observed pulse width W in Eq. (1) is often likely to be greater than the intrinsic width W_{int} emitted at the pulsar because of the scattering and dispersion of pulses by free electrons in the interstellar medium, and by the post-detection integration performed in the receiver. The sampled

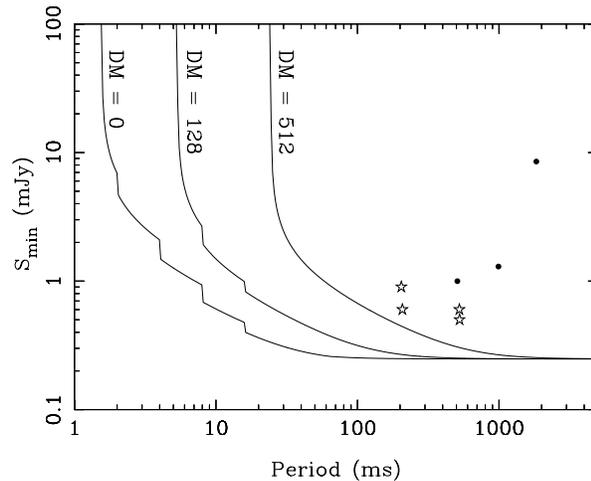


Fig. 2. The limiting sensitivity of the survey as a function of pulse period. The scattering times used in these calculations were estimated from the Taylor & Cordes (1993) electron density model for each DM for the Galactic coordinates ($l = 29^\circ$; $b = 0^\circ$). Solid points denote the three previously known pulsars. Stars show the four newly-discovered pulsars.

pulse profile is the convolution of the intrinsic pulse width and broadening functions due to dispersion, scattering and integration and is estimated from the following quadrature sum:

$$W^2 = W_{\text{int}}^2 + t_{\text{samp}}^2 + t_{\text{DM}}^2 + t_{\text{scatt}}^2, \quad (2)$$

where t_{samp} is the data sampling interval, t_{DM} is the dispersion broadening across one filterbank channel and t_{scatt} is the interstellar scatter broadening.

To highlight the effects of pulse broadening on sensitivity, in Fig. 2 we present the effective sensitivity as a function of period for a hypothetical pulsar with an intrinsic duty cycle of 5% for assumed DMs of 0, 128 and 512 $\text{cm}^{-3} \text{ pc}$. The scallops in the curves at short periods reflect the reduction in sensitivity due to the loss of higher-order harmonics in the Fourier spectrum (see e.g. Nice 1992). The severe degradation in sensitivity at short periods and high dispersion measures is clearly seen in this diagram. In particular, we note that due to the dispersion across individual filterbank channels, the present observing system is essentially insensitive to pulsars with periods less than 30 ms and DMs larger than 500 $\text{cm}^{-3} \text{ pc}$.

In the discussion hitherto we have implicitly assumed that the apparent pulse period remains constant during the observation. Given the necessarily long integration times employed to achieve good sensitivity, this assumption is only valid for solitary pulsars, or those in binary systems where the orbital periods are longer than about a day. For shorter-period binary systems, as noted by a number of authors (see e.g. Johnston & Kulkarni 1992), the Doppler shifting of the pulse period results in a spreading of the total signal power over a number of frequency bins in the Fourier domain. Thus, a narrow harmonic becomes smeared over several spectral bins.

As an example of this effect, as seen in the time domain, Fig. 3 shows a 35-min search mode observation of PSR B1744–

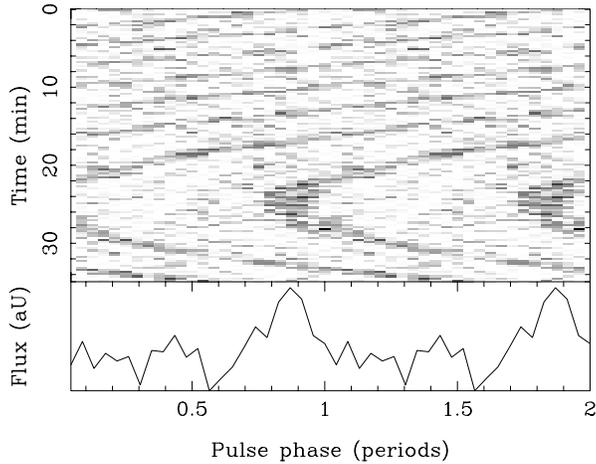


Fig. 3. A search-mode observation of the eclipsing binary pulsar B1744–24A in Terzan 5. Top panel: Data folded modulo the constant period reported by the search code (11.56 ms). The changing pulse period is clearly seen as a drift in phase from one sub-integration to the next. Lower panel: the integrated pulse profile whose signal-to-noise ratio is significantly degraded by the orbital motion during the integration.

24A; the 11.56 ms eclipsing binary pulsar in the globular cluster Terzan 5 (Lyne et al. 1990). Given the short orbital period of this system (1.8 hr), the observation covers about one third of the orbit! Although the search code nominally detects the pulsar with a signal-to-noise ratio of 9.5 for this observation, the Doppler shifting of the pulse period seen in the individual sub-integrations clearly results in a significant reduction in sensitivity.

The analysis reported in this paper makes no attempt to recover the loss in sensitivity due to this effect. To date, the only pulsar searches where this issue is tackled has been in searches for binary pulsars in globular clusters (e.g. Anderson et al. 1990; Camilo et al. 2000b). These searches applied a technique whereby the time series is compensated for first-order Doppler accelerations. Although these searches have been very successful they add significantly to the computational effort required to reduce the data, and have therefore only been applied to globular clusters where the DM is known a-priori from observations of solitary pulsars. For our data, where the DM is a-priori unknown, we are presently developing computationally-efficient algorithms which will permit us to greatly improve the sensitivity to binary pulsars by re-analysing these data in future. We note that the present analysis results in significantly reduced sensitivity to binary pulsars with orbital periods less than one day.

We conclude this discussion with some remarks on the search sensitivity to very long-period ($P > 5$ s) pulsars. The existence of radio pulsars with such periods are of great relevance to theories of pulsar emission, many of which predict that the emission ceases when the period crosses a critical value (see e.g. Chen & Ruderman 1993). Young et al. (1999) have recently demonstrated that the period of PSR J2144–3933, originally discovered in the Parkes Southern Sky Survey, is 8.5 s – three

times that previously thought. This is presently the longest period for a radio pulsar. Young et al. make the valid point that such pulsars could be very numerous in the Galaxy since they have very narrow emission beams and therefore radiate to only a small fraction of the celestial sphere. An additional factor here is that the number of pulses emitted by e.g. a 10-s pulsar during typical pulsar survey integration times is $\lesssim 30$. If the pulsar undergoes significant periods in the null state, as might be expected (Ritchings 1976), it will be harder to detect in an FFT-based search (Nice 1999).

One way to tackle this problem is to employ longer integration times, such as we do here. The FFT-based periodicity search we use is, however, not an ideal means to find long period signals since the sensitivity is degraded by a strong “red noise” component in the amplitude spectrum. The noise itself is a result of DC-level fluctuations (e.g. in the receiver) during an observation. In the above analysis of the survey data, we minimised the effects of this red noise component by subtracting a baseline off the spectrum before normalising it. However, because of the rapid increase of the red noise below about 0.1-Hz, we chose to ignore all spectral signals with frequencies below this value. Whilst this is common practice in pulsar search codes, it obviously reduces our sensitivity to $P > 10$ s pulsars! In recognition of this selection effect, we are currently re-analysing our data using a so-called “fast folding” algorithm (e.g. Staelin 1969) to search for periodic signals in the period range 3–20 s. The results of this analysis, and a detailed discussion of the algorithm, will be presented elsewhere (Müller et al. in preparation).

4. Survey results

A total of seven pulsars were detected during the course of the survey, four of which were previously unknown. Follow-up observations carried out to confirm the existence of each of the new pulsars were used to check that the true period had been correctly identified by the search code. The basic properties and detection statistics of all seven pulsars are summarised in Table 1. Flux values for the previously known pulsars are taken from Lorimer et al. (1995). Flux values for the newly discovered pulsars are averages of a number of independent measurements based on the timing measurements described in Sect. 5 and have fractional uncertainties of about 30% in each case. The relative positions of all these pulsars are shown on our sensitivity curve in Fig. 2.

The astute reader will, by now, have noticed a striking similarity between the periods of PSRs J1842–0415 and J1844–0310 and, to a lesser extent, PSRs J1845–0316 and J1841–0345. This unexpected result initially gave us some cause for concern as to whether the signals we had detected were indeed pulsars! However, having thoroughly investigated each new pulsar, we are now confident that this is nothing more than a bizarre coincidence. A number of independent facts confirm this. Firstly, all the new pulsars are separated by a significant number of telescope pointings on the sky. Secondly, the periods are detected *only* at the nominal position of each pulsar, and therefore cannot be put down to terrestrial interference. Furthermore, all

Table 1. Basic parameters and search signal-to-noise ratios (S/N) for the seven pulsars detected. Multiple S/N entries correspond to detections in neighbouring grid positions.

PSR	P (ms)	DM (cm^{-3} pc)	S_{1400} (mJy)	S/N
Previously known pulsars				
B1842–02	507.7	429	1.0	21,7.0
B1839–04	1840	196	8.5	34,41,85
B1841–04	991.0	124	1.3	34
Newly discovered pulsars				
J1841–0345	204.1	170	0.9	21,32
J1842–0415	526.7	167	0.5	13
J1844–0310	525.1	908	0.6	7.5,10
J1845–0316	207.7	500	0.6	8.0

the dispersion measures are significantly different. Finally, our timing measurements show that each pulsar has a distinct set of spin-down parameters.

We note in passing that this survey places an upper limit to the pulsed radio emission from the 6.97-s anomalous X-ray pulsar J1845.0–0300 discovered by Torii et al. (1998) that lies in the search region. No radio pulsations were seen at the grid position closest to this pulsar, setting a 1400-MHz pulsed flux limit of $\sim 0.3(\delta/4)^{1/2}$ mJy, where δ is the pulse duty cycle in percent. This limit assumes (possibly incorrectly) that the effects of interstellar scattering are negligible along this line of sight at this observing frequency. Deeper radio searches for this object, and also for the 11.8-s pulsar in Kes 73 (Vasisht & Gotthelf 1997), should be carried out in future at different observing frequencies.

5. Follow-up observations

In order to obtain more detailed spin and astrometric parameters of the newly-discovered pulsars, following confirmation, each was included in our monthly λ 21-cm timing observations of millisecond pulsars using the Effelsberg-Berkeley-Pulsar-Processor. Full details of the observing procedures are described by Kramer et al. (1999). In brief, during each observing session, a pulse time-of-arrival (TOA) measurement is obtained for each pulsar by cross-correlating the observed pulse profile with a high signal-to-noise “template” profile constructed from the addition of many observations. The template profiles obtained in this way are presented in Fig. 4.

For each pulsar, the TOAs obtained from all the sessions were referred to the equivalent time at the solar system barycentre and fitted in a bootstrap fashion to a simple spin-down model using the TEMPO software package¹. In Fig. 5, we present the resulting model-observed TOA residuals from this analysis.

The phase-coherent timing solutions we obtain for each pulsar indicate that they are all solitary objects. The fitted parameters are summarised in Table 2. A sub-arcsecond position has

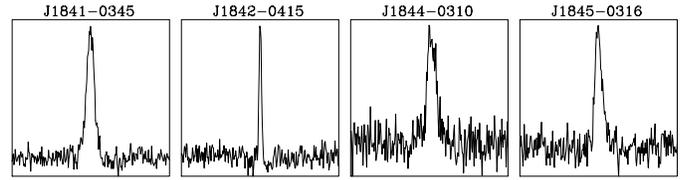


Fig. 4. Integrated 1400-MHz pulse profiles for the four newly discovered pulsars. The ordinate axis shows intensity, whilst the abscissa shows rotational phase. Each profile displays 360 degrees of rotational phase. These profiles are freely available in digital form at the European Pulsar Network data archive (<http://www.mpifr-bonn.mpg.de/div/pulsar/data>).

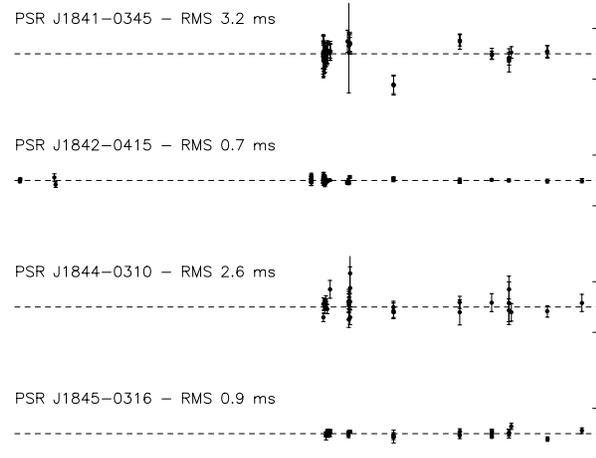


Fig. 5. Timing model residuals for the four newly discovered pulsars. The timing baseline (dotted line) spans 440 days (MJD 51025–51465) in all cases to accommodate early points gathered for PSR J1842–0415. Vertical bars at the end of each plot denote ± 10 ms.

been determined for PSR J1842–0415, where the baseline of timing observations already spans over a year. The remaining pulsars have timing baselines spanning just over 6 months. This is however, sufficient to decouple the covariant effects of position error and spin down and, as a result, we have determined accurate period derivatives for each pulsar. Table 2 also lists the characteristic ages (τ_c) and surface magnetic field strengths (B) inferred from these measured period and period derivatives (see e.g. Manchester & Taylor 1977 for definitions of these parameters). In addition, we also list the distance (D) to each pulsar inferred from its DM, Galactic coordinates and the Taylor & Cordes (1993) electron density model, as well as the 1400-MHz luminosities inferred from these distances and the observed flux densities as $S_{1400}D^2$.

It is significant that five of the seven pulsars detected in this survey (including all the newly-discovered pulsars) have characteristic ages below 0.5 Myr – over an order of magnitude younger than the median age of the normal pulsars detected by the Parkes 70-cm Southern Sky survey (Manchester et al. 1996; Lyne et al. 1998). This result should not be surprising when it is realised that we have preferentially selected a sample of objects located close to their birth sites along the Galactic plane (Clifton et al. 1992; Johnston et al. 1992a).

¹ Available from <http://pulsar.princeton.edu/tempo>

Table 2. Parameters for the four newly discovered pulsars. Values in parentheses are uncertainties in the least significant digit.

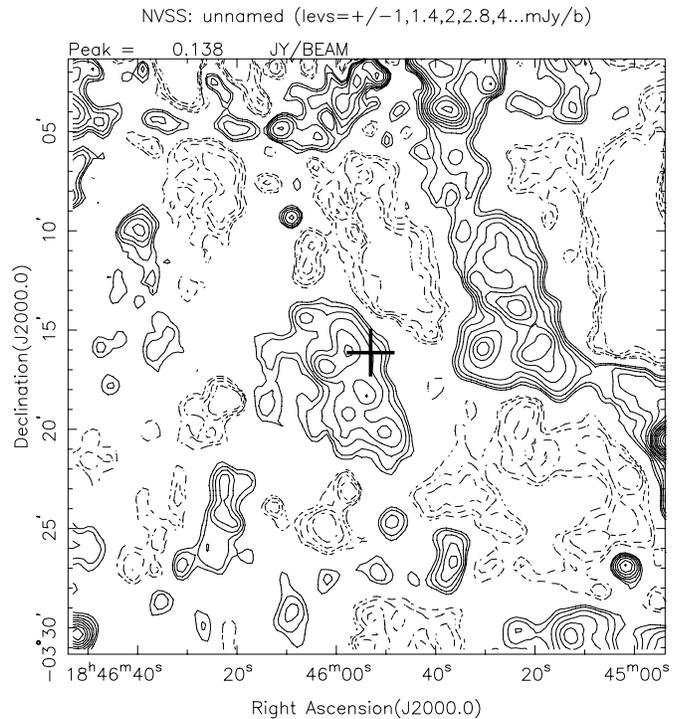
PSR	J1841–0345	J1842–0415	J1844–0310	J1845–0316
R. A. (J2000)	18 ^h 41 ^m 37.2(2) ^s	18 ^h 42 ^m 11.31(2) ^s	18 ^h 44 ^m 45.7(2) ^s	18 ^h 45 ^m 52.9(1) ^s
Decl. (J2000)	−03°45′01(50)″	−04°15′38.2(5)″	−03°10′53(32)″	−03°16′05(12)″
<i>l</i> (deg)	28.5	28.1	29.3	29.4
<i>b</i> (deg)	+0.47	+0.11	+0.03	−0.26
Period (s)	0.2040665324(4)	0.52668125777(7)	0.5250489275(4)	0.2076357201(1)
Epoch (MJD)	51330	51070	51350	51350
\dot{P} (10 ^{−15} s/s)	58.9(3)	21.94(1)	10.1(4)	8.86(6)
DM (cm ^{−3} pc)	170(5)	167(1)	910(30)	500(5)
Data Span (MJD)	51257–51451	51028–51451	51257–51451	51259–51451
Number of TOAs	45	42	29	24
RMS residual (ms)	3.2	0.7	2.6	0.9
τ_c (kyr)	55	380	380	371
<i>B</i> (10 ¹² G)	3.5	3.4	2.3	1.4
<i>D</i> (kpc)	3.7	3.6	9.4	6.5
<i>L</i> ₁₄₀₀ (mJy kpc ²)	12.5	6.0	56.6	24.4

By far the youngest of the new discoveries is PSR J1841–0345, which has a characteristic age of only 55 kyr. Since this is within the mean lifetime of supernova remnants (60 kyr – Frail et al. 1994), we checked the position of this and the other newly discovered pulsars with the most recent catalogue of supernova remnants (Green 1998) for spatial coincidences. No supernova remnants in the catalogue lie within 0.3 degrees of J1841–0345, or indeed any of the other new pulsars.

In their study of pulsar-supernova remnant associations Frail et al. (1994) undertook a programme of deep radio imaging to search for previously undetected supernova remnants around several of the young pulsars from the Johnston et al. (1992a) survey. Using the accurate positions we obtained from the timing analysis, we examined the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) images of the fields surrounding each pulsar for evidence of diffuse λ 20-cm emission which could be attributed to uncatalogued supernova remnants. The only pulsar for which any diffuse emission is evident in the NVSS survey (down to the 1-mJy sensitivity limit) is J1845–0316, shown in Fig. 6. It is presently not at all obvious whether this emission is attributable to the supernova remnant associated with this pulsar simply because there is such a high density of similar radio sources in this region of the sky. As a result, the by-chance probability of finding unrelated diffuse radio emission, particularly in deeper images of this region, will be rather high, making it difficult to unambiguously identify any associated supernova remnants without additional information (e.g. independent distance estimates to the pulsar and the candidate remnant).

6. Conclusions

The discovery of four sub-mJy pulsars in the limited pilot search observations reported here clearly demonstrate the potential for future pulsar surveys with the Effelsberg radio telescope. As mentioned earlier, the main aim of this survey was to test the feasibility of finding pulsars with a new wide-band search system currently under development. This new system employs nar-

**Fig. 6.** NVSS image of the field surrounding PSR J1845–0316. The pulsar position is marked by the + sign at the rim of an extended radio source.

rower channel bandwidths and has much faster sampling rates than presently available; it will therefore have significantly improved sensitivity to short-period, highly dispersed pulsars.

Now that the Parkes multibeam survey is extending its coverage out to $l = 50^\circ$ (Lyne et al. 2000) there is little to be gained in using the new system at Effelsberg to initiate a large-scale λ 21-cm search of the Galactic plane. A targeted λ 21-cm search of globular clusters, however, is a worthy scientific goal since deep (several hour) integrations would achieve a substantially

improved sensitivity over previous searches (see e.g. Biggs & Lyne 1996). Such a search would be particularly timely given the flurry of binary pulsar discoveries in a recent λ 21-cm search of 47 Tucanae (Camilo et al. 2000b).

Another excellent use of the new system would be an λ 11-cm search for heavily scattered pulsars close to the plane. Such a search would open up an entirely new area of parameter space in Galactic plane searches since it is known that many pulsars discovered at λ 21-cm are still strongly affected by interstellar scattering. The strong inverse dependence of scattering on observing frequency means that the effects of scattering on an λ 11-cm search would be an order of magnitude smaller than at λ 21 cm. In the vicinity of the Galactic centre, where scattering is expected to be greatest (Cordes & Lazio 1997), the best prospects for finding pulsars still seem to be in searches carried out at 5 GHz (λ 6-cm), or even higher frequencies (see e.g. Kramer et al. 1996; Kramer et al. 2000).

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