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The Parkes Multibeam Pulsar Survey – V. Finding binary and millisecond pulsars

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ABSTRACT

The Parkes Multibeam Pulsar Survey is the most successful survey of the Galactic plane ever performed, finding over 600 pulsars in the initial processing. We report on a reprocessing of all 40 000 beams with a number of algorithms, including conventional frequency-domain searches and an acceleration search for fast binary pulsars. The very large volume of results coupled with the need to distinguish new candidates from known pulsars and their many harmonics, often with multiple detections from different search algorithms, necessitated the development of a new graphical selection tool tightly linked to a web-based results data base. We discuss and demonstrate the benefits of these software systems, which are specifically designed for large survey projects. The results of this processing have been encouraging. We have discovered 128 new pulsars, including 11 binary and 15 millisecond pulsars; in addition to those previously found in the survey, we have thus far discovered 737 pulsars. In this paper, we discuss the discoveries of PSR J1744−3922 (a 172-ms mildly recycled pulsar in a 4.6-h orbit that exhibits nulling behaviour, not previously observed in recycled or binary objects), PSR J1802−2124 (an intermediate mass binary pulsar) and PSR J1801−1417 (a solitary millisecond pulsar).

Key words: surveys – pulsars: general – pulsars: individual: PSR J1744−3922 – pulsars: individual: PSR J1801−1417 – pulsars: individual: PSR J1802−2124.

1 INTRODUCTION

Binary pulsars provide the only environment for precise measurements to test general relativity in strong-field conditions (Taylor 1993). The orbital decay of double neutron star systems is currently the only observational demonstration of the existence of gravitational waves (Taylor & Weisberg 1989). For the effects of general relativity to be seen, the pulsar usually has to have a massive companion (>1 $M_{\odot}$) and an orbital period of only a few hours. The discovery of a black hole–pulsar binary would be very important for even more stringent tests of general relativity (Damour & Esposito-Farèse 1998). The pulsar itself must be timed to high precision, implying that ideally it will be a strong millisecond pulsar with a narrow pulse profile.

Millisecond pulsars with spin periods less than 2 ms probe the equation of state for the degenerate matter which makes up neutron stars. PSR B1937+21 has the shortest known period of 1.55 ms (Backer et al. 1982). Finding a new pulsar with a shorter spin period would clearly be very significant. Conversely, not finding such a system in a major survey reinforces the so-called stiff theories of the equation of state (e.g. Friedman 1995) or other spin-period limitations, such as gravitational radiation (Andersson, Kokkotas & Schutz 1999).

Finding binary pulsars with orbital periods of a few hours or less is very difficult; the received signal from pulsars in binary systems has a period variation dependent upon the orbital motion, making conventional spectral analysis considerably less sensitive. To recover

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sensitivity to binary pulsars, particularly in relatively long observations, requires the use of computationally expensive 'acceleration' searches (e.g. Camilo et al. 2000a).

We report here on the successful use of an efficient acceleration search algorithm and optimized interference filters applied to the large number of observations taken as part of the Parkes Multibeam Pulsar Survey (PMPS), described in Manchester et al. (2001, hereafter Paper I). In Section 2 we briefly summarize the PMPS, with a review of all employed search algorithms in Section 3. In Section 4 we detail the data reduction processing and in Section 5 we describe a graphical approach to reviewing the results and ensuring that known pulsars are correctly identified. In Section 6 we demonstrate that the system performed as expected. Also, we report on the discovery of a significant number of millisecond pulsars using conventional processing techniques. These discoveries are discussed in Section 7 and future activities are considered in Section 8.

2 PARKES MULTIBEAM PULSAR SURVEY SYSTEM

The PMPS covers the Galactic plane in the region $|b| < 5^\circ$ and $260^\circ < l < 50^\circ$. It has been very successful, with reported discoveries of more than 600 new pulsars so far, discussed in Paper I, Morris et al. (2002), Kramer et al. (2003) and Hobbs et al. (2004). However, there were only four millisecond (which we define as having a period <30 ms) and 12 binary pulsars reported. In 2002 a new Beowulf computer cluster at Jodrell Bank Observatory, COBRA, started to be used to process all the data from the PMPS, including some data that had never been processed before, employing newly developed algorithms (hereafter 'COBRA processing').

The details of the receiving system and its performance can be found in Paper I. It is the most sensitive survey of the Galactic plane ever undertaken, consisting of 35-min integrations performed with a sensitive, wide bandwidth receiver. Most of the observations took place between 1997 and 2002. The data now represent a unique archive, which may not easily be reproduced due to steadily increasing radio-frequency interference. By processing the data in a consistent fashion, all pulsars above the limiting flux density thresholds within the survey area can readily be compared. The raw (as recorded at the telescope) data, the processing results and plots are archived using on-line disc storage. These data are expected to provide a basis for further analyses (e.g. detailed population studies of Galactic pulsars).

There are ∼14 per cent more observations than the 2670 pointings of 13 beams originally planned. Additional observations were taken for a number of reasons including aborted observations due to high winds, difficulty in reading some tapes thus losing some data, or administrative errors. The additional observations can be useful duplicates of the main observations; for example, they can be used for initial validation of a candidate or a discovery of a pulsar that has an intermittent received signal, possibly because of nulling (see Backer 1970) or scintillation (see Lyne & Rickett 1968). All these data, including truncated observations (17.5–35 min), have now been processed.

3 SEARCH ALGORITHMS

The standard frequency-domain search using a fast Fourier transform (FFT) is extremely good at detecting stable periodicities from solitary pulsars. The standard FFT approach was applied to all the data of the PMPS as described in Paper I. Harmonic summing (Taylor & Huguenin 1969) was used to compensate for the relatively low duty cycle of a pulsar to maximize sensitivity. However, there are some classes of pulsars where the FFT-based search is less sensitive, including pulsars in binary systems, 'long-period' pulsars, which we define as having periods >3 s, and pulsars in which we can observe only intermittent individual pulses. Throughout this paper we use the term 'detection' for any signals identified by a search algorithm, including known pulsars or possible new pulsars and their harmonics and interference. The term 'candidate' is a detection that has been reviewed and considered to be a possible new pulsar.

3.1 Acceleration searches

Searching for pulsars in binary systems is made difficult because their changing line-of-sight velocity causes a varying received pulsar period. The effect on a search is to spread the signal detection over a frequency range. An FFT divides the received signal into discrete frequencies, so-called 'spectral bins'; hence, a varying received frequency will spread a detection over a number of bins, thus reducing significantly the signal-to-noise (S/N) ratio of a detection. This effect becomes more severe with shorter orbital and pulsar periods, and with longer observations. Consequently, some of the most interesting systems, namely millisecond pulsars in tight binary orbits, are very difficult to detect.

It is possible to modify the time series such that the pulse period variations caused by binary motion are removed; an FFT-based search can then be used to find periodicities with no loss of sensitivity. This is a 'coherent' search, meaning that all the available information (time, amplitude and phase) from an observation is preserved and operated on as a whole. However, this method is extremely computationally expensive in a blind search, with three parameters (binary period, orbital amplitude and phase) to search for circular orbits, with an additional two (orbital eccentricity and longitude of periastron) for significantly elliptical orbits. This is impractical using today's technology (e.g. Dhurandhar & Vecchio 2001).

The task is simplified by only searching over one parameter, average acceleration, which approximates the period changes over time to a straight line, referred to as a 'linear acceleration' search. This works well for orbital periods which are much longer than the observation length, particularly if the observations happen to be made at an orbital phase where the pulsar's acceleration varies least from being constant (Johnston & Kulkarni 1991). Linear acceleration searches can be performed either in the time or frequency domain. In the time domain, the time series is adjusted by resampling to compensate for the quadratic change in pulse phase over the observation time, and then an FFT-based search is performed. This needs to be repeated for all the different accelerations tested as discussed in Camilo et al. (2000a).

Alternatively, in the frequency domain, an FFT of the zero acceleration time series is performed, and then a series of matched filters is applied to correct the frequency spectrum to look for accelerated periodicities (e.g. Ransom, Eikenberry & Middleditch 2002). While the frequency-domain approach is computationally more efficient for a blind search, both techniques still require considerable processing at each dispersion measure (DM) to be searched. Consequently, a coherent linear acceleration search is generally only feasible if the DM is already known, as in the case of globular cluster searches when there is already a confirmed pulsar. It is currently impractical to apply a coherent acceleration search using 200 trials (see Camilo et al. 2000b) to the PMPS data, because the total processing time would increase by ∼100 times.

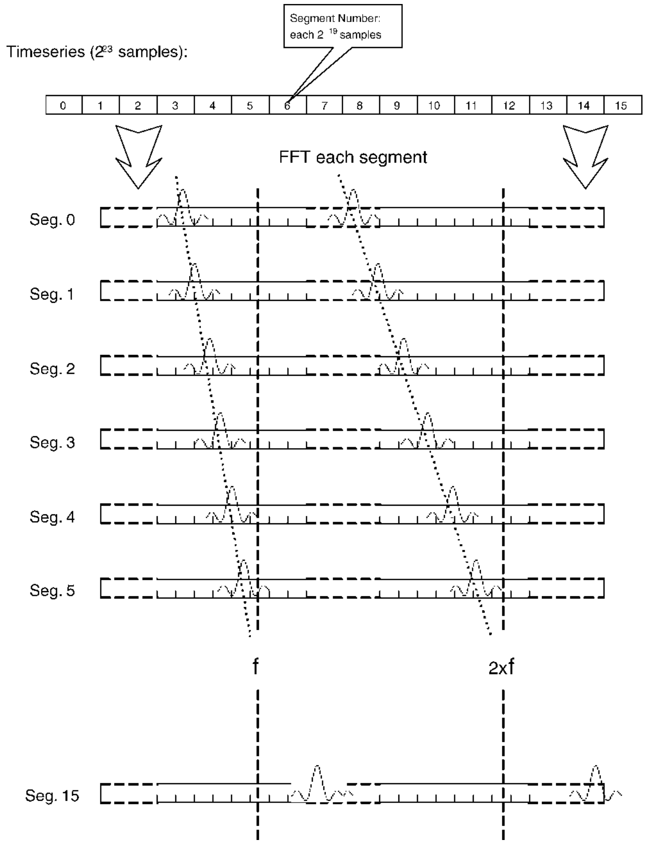

Figure 1. An illustration of the stack search approach to acceleration searching. The received time series is first broken into a number of segments (in this case 16), which are individually fast Fourier transformed and the amplitude spectrum formed, using interpolation to recover signals lying midway between bins. These spectra are then summed at different rates of change of frequency to produce a final spectrum. Note that higher harmonics of signals need to have a rate of change of frequency proportional to the harmonic number.

By operating on the data in sections, known as an 'incoherent' search, some information is lost, in this case phase. However, by sacrificing some sensitivity, an incoherent acceleration search, or 'stack search' as discussed by Wood et al. (1991) can be used to save substantial computing resources. The stack search is illustrated in Fig. 1. It involves splitting the received time series into a number of segments (16 in the case of the PMPS), performing an FFT on each of these individually and producing an amplitude spectrum. Use of very short segment observations, over time $T_{\rm seg}$, considerably improves the relative sensitivity to varying periods. In a short observation the period does not change much and each spectral bin covers a much larger frequency range ($\Delta f = 1/T_{\rm seg}$). By summing each of the bins of the same frequency from all the segments, a spectrum of the full observation can be made. Some overall sensitivity will be lost due to the incoherent summing. However, the pulse duty cycle, hence the summing of harmonics, makes it hard to predict the precise effect on spectral S/N. In the case of the PMPS, there are five trials, the fundamental only and then progressively adding up to the second, fourth, eighth and sixteenth harmonics. By comparing the spectral S/N for the standard search with spectral S/N for the stack search for a variety of solitary pulsars, we found there to be a S/N loss of between 15–35 per cent over a coherent search. Linear accelerations, a, can then be applied to the whole sequence by adding up the bins at a slope proportional to the change in frequency over the observation. The frequency change, $\Delta\nu$, from segment to segment for an observation of length T with number of segments $N_{\rm seg}$ and speed of light c is

$$\Delta\nu = \nu_0 a T/(N_{\rm seg} c)\ \mathrm{Hz}. \qquad (1)$$

Because the number of bins shifted must be an integer, the frequency change needs to be rounded to the nearest bin. Prior to harmonic summing, the nth harmonic must be corrected for acceleration using a slope n times the fundamental slope. The FFTs for all of the segments take a similar or less time to produce than a single full-length FFT. Spectra for each of the trial accelerations are produced by addition, making the stack search fast and efficient. This is the technique that has been applied to processing of the PMPS. Without the stack search, the double neutron star PSR J1756−22[1] (Faulkner et al., in preparation) would not have been detected.

Highly accelerated systems which have more than 1.5 orbits over the length of the observation can be found using a 'phase modulation' search (Jouteux et al. 2002; Ransom, Cordes & Eikenberry 2003). In the case of the PMPS this would apply to orbital periods less than 20 min. The algorithm finds the orbital periodicity by identifying sidebands in the power spectrum of the time series. Any sidebands present are summed by stepping through the power spectrum taking short FFTs. This is a fast process and should reveal the pulsar period and orbital period. It has been incorporated into the search algorithms and any results will be reported in a separate paper.

3.2 Other search algorithms incorporated

Frequency-domain searches using FFTs are effective for most of the range of pulse periods, from the Nyquist limit up to approximately 3 s in the case of the PMPS. However, when dealing with periods that are greater than 3 s, which lie in the first few thousand spectral bins, the period resolution becomes very coarse. In addition, the presence of low-frequency noise in the Fourier spectrum of the radio-astronomical time series can be very difficult to remove. By using a time-domain search the period resolution is much finer and resolves the true spin period more accurately. A time-domain search works effectively on arbitrary pulse profiles, and therefore is more effective on the very narrow pulses typical of long-period pulsars. Because the search is for long periods, greater than 3 s, the sampling time can be considerably increased with no significant loss of sensitivity, thus reducing the processing required. An efficient algorithm (Staelin 1969) has been included in the COBRA processing; details of this implementation will be described in a separate paper. This algorithm has been successful at finding a new pulsar with a 7.7-s period, which will be published in a future paper.

It has been shown (McLaughlin & Cordes 2003) that some pulsars can only be detected by observing their individual giant pulses. It is possible to detect these individual pulses if they are large enough. A 'single-pulse search' for dispersed irregular pulses has been incorporated into the search routines. Over 30 per cent of all pulsars (new and known) detected in the PMPS were also detected in the single-pulse search. In addition, the single-pulse search has detected four pulsars which were not detectable in the standard periodic processing. The results from this search will be presented in a future paper.

[1] Names quoted with just two digits of declination are interim.

4 PROCESSING

Details of the observing and search analysis systems are mostly as reported in Paper I. Modifications and enhancements are discussed below.

All the data were gathered at Parkes and stored on 160 DLT tapes. The tapes have been collected at Jodrell Bank Observatory for processing. With the ongoing reduction in disc storage costs, all the raw data have been transferred to 5 TB of on-line RAID disc systems. Thus, alternative processing approaches can easily be tried in the future.

The data flow from observation data through processing to produce detection lists and plot files is shown in Fig. 2. The processing task is divided into two principal areas: separating the data into individual beams and searching for major interference signals, followed by detailed searches of individual beams.

The first parts of the processing, stages one and two described in Paper I, take the raw data files, split them into 13 individual beams, and perform interference search and excision. The resulting data files, header files and accounting files are passed to the search stage.

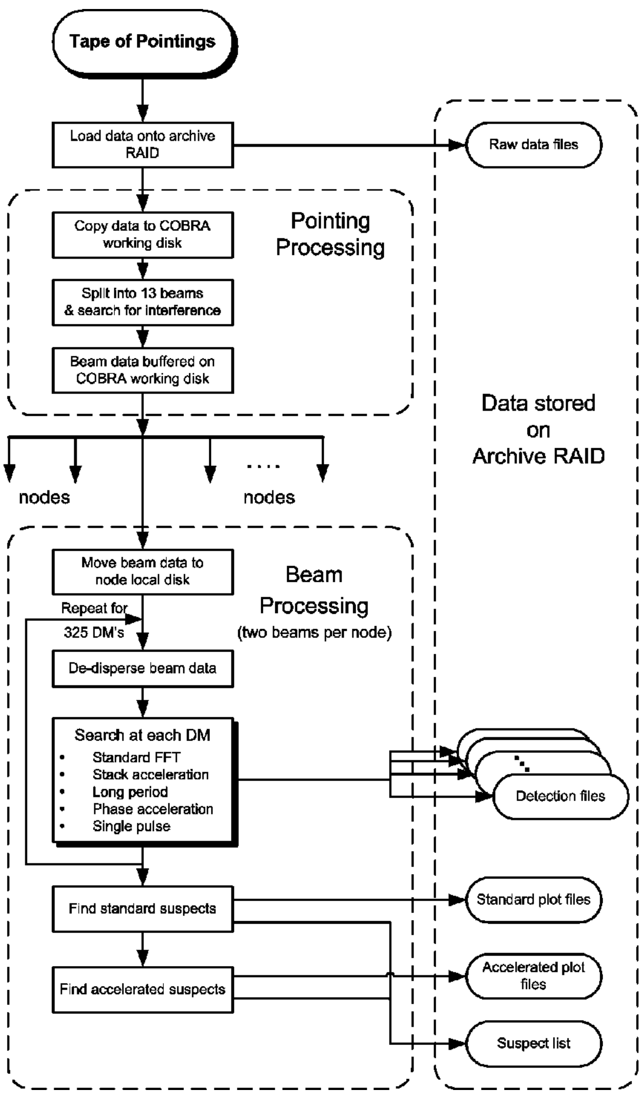

Figure 2. Processing on COBRA. There are three phases: first, data from the tape are loaded on to archive RAID, and the data are then copied to COBRA's local working disc and split into beams followed by a search for interference specific to a tape; the beam data, headers and accounting files are put into a buffer; the beam processing searches an individual beam on one processor, followed by candidate identification.

Table 1. Frequency filters for removing identified interference, probably related to mains 50 Hz plus harmonics and local and instrumental sources. ν is the central frequency of the individual filter, *i* and *j* are integers and $\nu_{\rm nyq}$ is the Nyquist frequency of the PMPS. In all cases, ν wraps around the Nyquist frequency and returns to lower frequencies. Frequency definitions are: $\nu_1 =$ 134.99776 Hz; $\nu_2 = 99.99592$ Hz; $\nu_{\rm nyq} = 2000$ Hz; $\nu_{\rm nyq2} = 4000$ Hz; $\nu_{\rm nyq4} = 8000$ Hz.

Central frequency ν (Hz)	Width (Hz)	Ranges (i, j)	Limit (Hz)
$\frac{2^{(i-1)}}{8.192} \times (1 + 2^{j-1})$	0.001	$\{^{i:1\to15}_{j:1\to10}$	$\nu < \nu_{\rm nyq}$
$\nu_2 \times i$	0.1	$0 \to 120$	$\nu > 2$
$\vert\nu_1 \times i + \nu_2 \times j\vert$	0.004	$\{^{i:1\to50}_{j:-20\to20}$	$\nu > 1.00$
$\nu_1 \times i$	0.04	$51 \to 160$	
$\nu_1 \times i$	0.4	$1 \to \nu_{\rm nyq4}/\nu_1$	
$\nu_1 \times i + 3.9$	0.3	$1 \to \nu_{\rm nyq2}/\nu_1$	
$\nu_1 \times i - 3.9$	0.3	$1 \to \nu_{\rm nyq2}/\nu_1$	
$50 \times i$	0.2	$1 \to \nu_{\rm nyq}$	
$200 + i$	0.26	$-20 \to 20$	
$0.14704 \times i$	0.0024	$1 \to 100$	
1349	12		
$508.65 \times i$	$0.400 \times i$	$1 \to 2$	
2.045	0.002		
$1.2032 \times i$	$0.001 \times i$	$1 \to 40$	
$1.0000 \times i$	$0.001 \times i$	$1 \to 30$	
$0.6433 \times i$	$0.001 \times i$	$1 \to 50$	

During the period of PMPS observations and ongoing processing, progressively more frequency filters were added to combat interference. However, they also restricted the amount of spectrum left for searching, particularly at millisecond pulsar frequencies. Significant rationalization of these 'interference' frequency bands was made prior to this COBRA processing, which substantially increased the amount of spectrum available to find new pulsars. There is now <10 per cent of the spectrum removed, as opposed to ~40 per cent in previous analyses (Hobbs 2002). This is a significant contributor to the success at finding a high proportion of new millisecond pulsars. A summary of the filters is shown in Table 1; a full discussion of the purpose and changes made to each of the filters is given by Hobbs (2002).

Terrestrial interference is normally not dispersed, so an FFT is taken of the time series not adjusted for dispersion, the 'zero-DM' spectrum, and the result is stored. These data can be used for a future analysis of interference signals at Parkes.

4.1 Beam processing

The searching of each of the 40 000 beams (stage 3 of Paper I) can be performed on a beam-by-beam basis, essentially unaffected by any other data or process. This is the perfect environment for a Beowulf cluster, which in its simplest form is a collection of interconnected PCs. Hence, each beam is assigned to a separate processor; each node consisting of two processors is able to search two beams simultaneously. An individual beam was typically processed in about 6–7 h on a single processor. Excellent total throughput of processing is achieved by assigning many processors, typically about 100. A tape of ~300 beams was processed in a day.

The various tasks (see Fig. 2) that make up a search of a beam are controlled by a script running on each processor.

The data are de-dispersed as described in Paper I. The search routines then process the time series for each of the 325 different DMs. The spectra from each DM for both accelerated and standard FFT searches are searched for the top 100 detections (increased from 50 in Paper I), which ensures that all detections above the noise floor are stored. The resulting detection lists are stored. To qualify the detections, they are analysed for the highest S/N signals (reconstructed by inverse transformation to the time domain for standard searches and spectral S/N for the segmented search) and the DM of the strongest detection is found for each identified period. Detections with harmonic relationships are identified and eliminated except the period corresponding to the strongest signal and the detection with twice this period. Any detections over a S/N of 6 are then further analysed in the time domain largely as described in Paper I. The standard FFT detections are searched over DM and a narrow period range, using 64 subintegrations (increased from 16 subintegrations in Paper I) each of ∼30 s, to find an optimized S/N, and the results recorded, known as a 'candidate plot'. The S/N is calculated by convolving the profile with a box-car function, trialed with widths from 1 bin to half the length of the profile. Similarly, the best detections from the accelerated search are searched in period and frequency derivative by repeated adjustment of the time series, and the results also recorded. Examples of both types of candidate plot are shown in Fig. 3.

For the long-period search, six results from each beam, which are the best S/N detections from any DM searched, are recorded. These are post-processed into candidate plots and stored for later inspection. The single-pulse search stores S/N, time index in the observation, width and DM for all single pulses with a S/N in excess of 4. The period, orbital period and DM information from the phase modulation search are recorded for off-line analysis.

5 FINDING CANDIDATES

The processing produced a large quantity of output to be analysed, with each tape of 26 pointings producing around 50 000 qualified

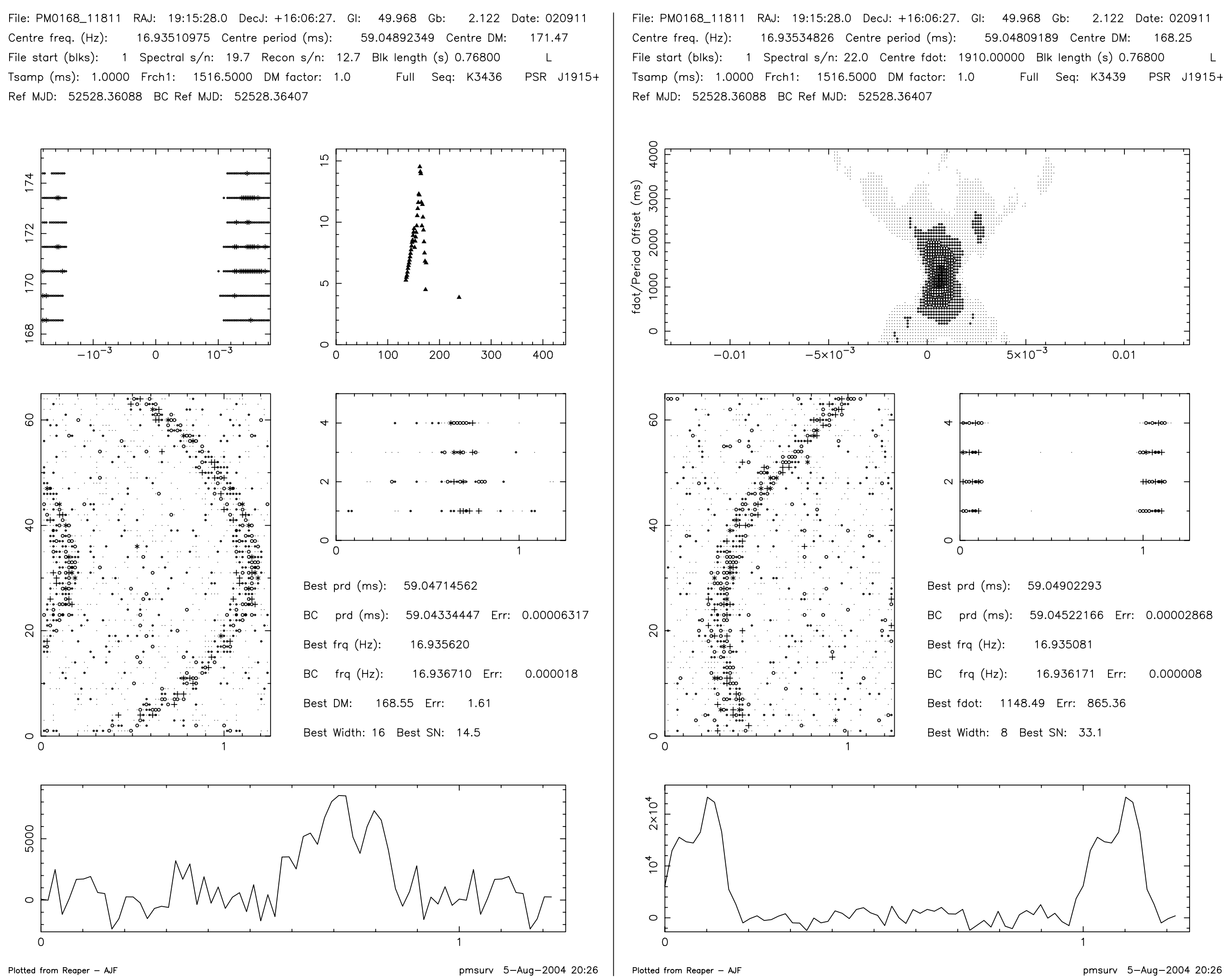

Figure 3. Example candidate plots comparing standard (left) and acceleration (right) searches, these show the re-detection of PSR B1913+16, the first binary pulsar. It can be seen that the acceleration search considerably improves the final S/N and pulse profile. The acceleration information presented shows beam and detection information at the top; the top plot shows the S/N variation with small changes in the frequency due to acceleration (fdot) and period; centre left is a signal strength plot over pulse period (*x*-axis) and time through the observation (*y*-axis) of 64 subintegrations; centre right shows four frequency bands plotted against pulse phase; finally, the corrected pulse profile is along the bottom. The standard search information is similar to the accelerated plot except the top-left plot shows S/N variation with period changes and DM, and the top-right plot shows S/N variation with widely changing DM.

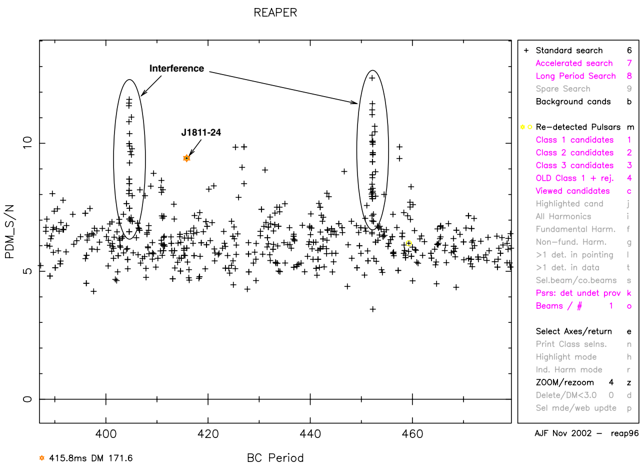

Figure 4. Annotated REAPER screen-shot of the discovery of PSR J1811−24 showing that the S/N is only slightly above the noise floor and surrounded by interference, but still easily discernible. Other isolated candidates were seen to be interference from their candidate plots.

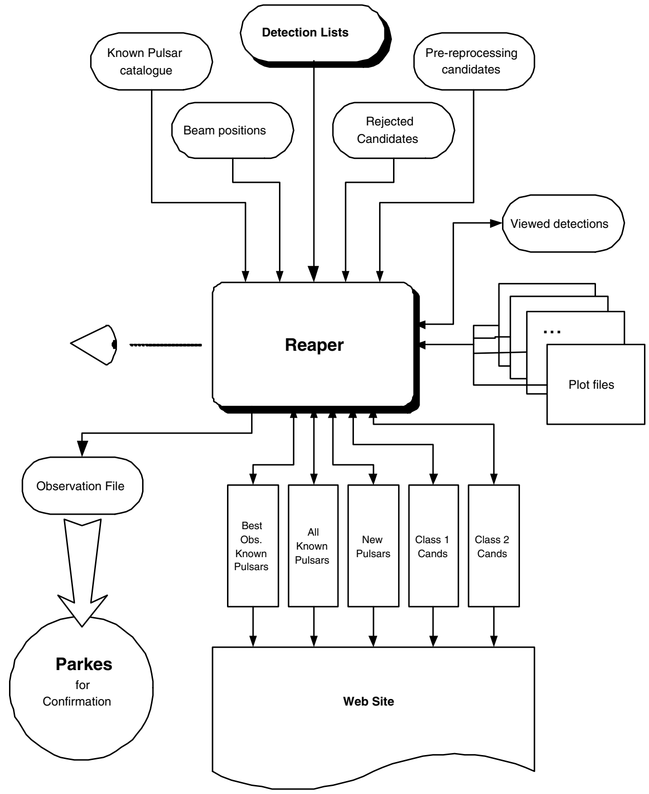

Figure 5. Data flow after processing, through REAPER, to create new candidates for observation at Parkes and placing on a website. See text for ‘Best Obs.’ description.

detections. These detections are a mixture of interference signals, known pulsars with their integer, non-integer harmonics and sub-harmonics and, occasionally, candidates but also their harmonically related detections. Many of these results will be duplicated in more than one of the standard, stack or long-period search algorithms.

5.1 Benefits of a graphical interface

With tens of thousands of signals to choose from, it is clearly not feasible to manually inspect all the output plots from the search algorithms. Two different philosophies to select a more reasonable number of candidates for inspection are: (i) to use an algorithm that selects mainly on S/N; (ii) to give the observer enough information in a comprehensible form to enable a selection to be made. The algorithmic approach was used originally on the PMPS as discussed in Paper I. Using a graphical plot to visually select suitable candidates means that interference is more easily avoided and fewer plots need to be inspected. Candidates that would not be identified by a simple algorithm can be seen graphically. For example, if the detection does not have a high S/N, but is clear of interference and the noise floor, which can relatively easily be seen on a graphical display, then it would be selected for inspection, as with the discovery of PSR J1811−24 shown in Fig. 4. These candidates may be the most interesting discoveries. Other benefits of a graphical approach are the relative ease of investigations of possible candidates/known pulsars, e.g. detections in adjacent beams, harmonic relationships, positions of known pulsars relative to beam centres, etc. The graphical approach has been used successfully for the Swinburne intermediate-latitude pulsar survey (see Edwards et al. 2001).

5.2 REAPER

A suite of programs, known as REAPER, for graphically investigating the results of the PMPS has been developed. All the results from one tape of observations are loaded at a time. Fig. 5 shows the flow of data from lists of detections and their candidate plots, existing pulsars, previous candidates and previously viewed candidates through to observation lists at Parkes and information on a web site. An illustration screen is shown in Fig. 6. Its user interface consists of an

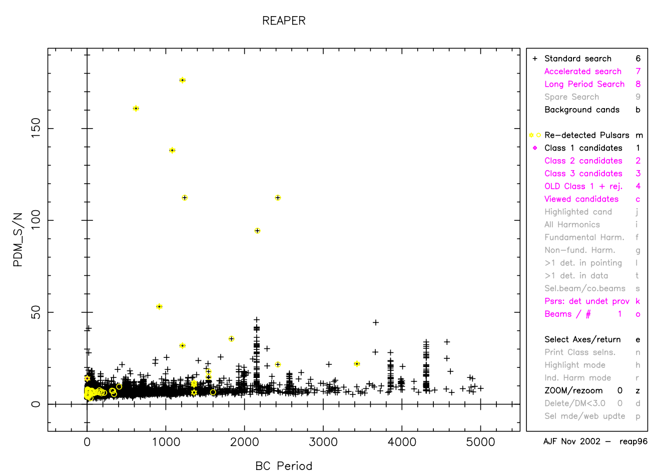

Figure 6. A typical search screen for REAPER, showing detections, candidates and known pulsars for a particular tape of observations. The clickable menu of commands on the right highlights chosen selections; the details are not relevant here.

X–Y plot of a pair of chosen parameters, typically period and S/N, with a menu of selectable commands on the right. The parameters that may be plotted are:

(i) spin period;
(ii) spectral S/N;
(iii) reconstructed S/N (if available);
(iv) candidate plot S/N;
(v) dispersion measure;

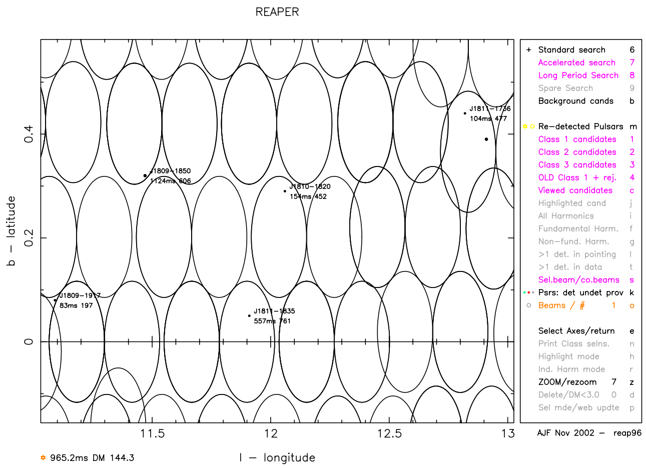

Figure 7. REAPER displaying a Galactic plot indicating the FWHM of the observation beams and highlighting known pulsars.

(vi) pulse width;
(vii) number of harmonics summed;
(viii) spin frequency;
(ix) spin frequency derivative (if available);
(x) Galactic latitude and longitude.

Other information can be superimposed with the detections, including known pulsars and their harmonics, previously selected candidates and previously viewed detections. This is done using a variety of colours and symbols.

The *X*–*Y* plot can be navigated with zoom and movement commands. Any detection can have its candidate plot viewed by selecting its symbol. The Galactic position (see Fig. 7) of a possible candidate can be displayed. Also on the plot, the exact position, period and DM of known pulsars can be shown, primarily to confirm that there is no potential link between the detection and a known object. Visual guides for the beamwidth and beam identifications can be overlaid, hence showing the beams which may have other detections.

If necessary, all the detections for a beam can be viewed, for example, to investigate an apparent non-detection of a known pulsar or to see a search's response to a very large interference signal or powerful nearby pulsar. All the detections from the standard and accelerated searches are available. In this case the top 100 detections at each DM and harmonic sum are recorded with S/N and, if appropriate, the acceleration in terms of frequency derivative. This amounts to more than 300 000 detections per beam. Graphically, these can be viewed and zoomed into for particular periods over the various DMs seen.

The graphical access to the results data base for the entire PMPS is a valuable tool for investigating known pulsars, interference signals and potential single-pulse candidates.

5.3 Selecting and confirming candidates

The selection of candidates is a matter of experience; in general, candidate plots are viewed if they have $S/N > 8$, are not identified as the fundamental or harmonic of a known pulsar and are clear of detections in multiple beams, which would probably be interference. Solitary candidates normally are present in both the standard and acceleration searches. If the plot shows a reasonably good profile at a DM which is greater than 3 pc cm^{-3} (to avoid terrestrial interference) and does not become changed substantially from the spectral search through time-domain refinement (see Section 4.1) then it may be a candidate. It is important to verify that it is not related to a known pulsar, so a check is made of the immediate area of sky $\pm 1^\circ$ using REAPER's Galactic plot. A final check is made by restricting a S/N–period plot to just the detection beam and ensuring that there are no large interference signals in the beam which could cause spurious detections.

After carefully considering a detection to ensure that it is unlikely to be interference or a known pulsar, it may be assigned to one of three classes as a candidate. Class 1 candidates will be prepared for confirmation observations at Parkes at the next opportunity, class 2 candidates are kept for further consideration, and class 3 candidates are effectively discarded but kept for future reference. An individual detection can be promoted or demoted by reselecting their class within REAPER.

At any time, candidates selected are in various stages of the confirmation process – waiting for confirmation, observations made but not seen, gridded (e.g. Morris et al. 2002), confirmed as a new pulsar or rejected. To keep all the information readily available, REAPER writes out candidates to a web site; other information is also collected from the central archive files and displayed. The candidate plot is an essential feature, so confirmation plots are also displayed for ease of reviewing at the participating institutions.

REAPER has been used to view all the processing results from the PMPS, typically only taking about one hour per tape. Both the processing system and REAPER are modular and can be ported to other major surveys. For example, both systems have been ported to the related survey, the Parkes High Latitude Pulsars Survey (PH Survey). It was in the PH Survey that REAPER first detected the millisecond pulsar PSR J0737−3039A of the double-pulsar system (Burgay 2004).

6 SYSTEM PERFORMANCE

With a complex system such as the PMPS, including the subsequent processing, it is important to know that it performs as predicted. To verify if the sensitivity, sky coverage and detection algorithms are working correctly, we consider the re-detections of known pulsars, pulsars in the search area which were not detected and any detections that showed any anomalies.

There are more than 1000 pulsars in the survey area found from many surveys including all the PMPS processing. As has been reported in Hobbs et al. (2004), of the 264 pulsars in the survey area discovered by other surveys, all but 11 have been re-detected with no unaccountable non-detections.

Pulsars were detected over the whole area of the survey at spin periods from 1.85 ms to 7.7 s and at DMs from 3 to 1200 pc cm^{-3}. Reviewing flux density measurements from Hobbs et al. (2004) of the weakest detected pulsars shows that the system meets the sensitivity calculated in Paper I.

6.1 Non-standard detections

The detection of PSR B1635−45 (Johnston et al. 1992) was at a fundamental period of 529.1 ms instead of the catalogue period of 264.55 ms. Further checking showed that the catalogue period was incorrect and it has now been updated.

As noted in Section 4, filters are used to eliminate some known interference signals. These filters can also remove pulsars which happen to be at the same period. In the case of PSR B1240−64, which has a spin frequency of 2.574 Hz, its detection was discarded, with the first 12 harmonics, by a filter which removed frequencies from 0.6423 to 0.6443 Hz together with the next 50 harmonics. Because PSR B1240−64 is very strong, having a S/N of 1466, it was seen at its thirteenth and other higher harmonics and strongly at a period of 3/4 of the fundamental; however, a weaker pulsar might have been lost.

Very strong pulsars are seen in multiple beams. One of the tests for interference signals is that they are not localized to a small section of sky, but seen in many of the beams on a tape. These signals are excised from all the beams on a particular tape, assuming them to be interference. This did not prove to be a problem for the PMPS, because in all these cases the pulsar was seen in adjacent beams on a different tape. However, at the periphery of a search the very strongest pulsars could be lost.

6.2 Multiple detections

Reasonably strong pulsars or those near the edge of beams are likely to have detections in adjacent beams. All these detections are recorded for analysis and the strongest S/N listed as the 'best observation' as shown in Fig. 5. REAPER can relate beam position to pulsar position and any anomalous behaviour can then be identified; for example, these detections were used to improve the position of PSR J1744−2335 which is close to the ecliptic plane, where timing alone does not give good resolution in ecliptic latitude. In this case, scintillation was not a problem. Also, nulling pulsars can be identified, either by seeing nulling within an observation or by finding that a pulsar is not detected in the beam(s) in which a detection is expected.

A particular use of multiple detections is to extend the timing baseline of newly discovered pulsars. After a year of timing observations it is possible that a phase-connected solution may be found which will be coherent with the original detection observation. Including a much earlier pulse arrival time will add significant constraints to the ephemeris of the new pulsar. Ideally, there will be multiple detections in the survey, which can be identified using REAPER to further improve the timing solution. We note that major surveys using multiple beam receivers use interlaced observations to have complete coverage of an area. For future timing of new discoveries using the survey observations, the scheduling of adjacent beams to be evenly spread over the survey period is worth considering.

7 DISCOVERIES

There have been 128 new pulsars discovered in the COBRA processing. These are being regularly observed to obtain a coherent timing solution and they will all be published in future papers. A list of provisional parameters for the 11 binary and 15 millisecond (spin period <30 ms) pulsar discoveries are shown in Table 2. All but two of the binary discoveries are also millisecond pulsars. Listed for comparison are the spectral S/N for both the standard and stack acceleration searches and the S/N from the candidate plot. For solitary and long orbital period binaries, the S/N for the stack search is lower than in the standard search, as expected. However, for the short spin period, tight orbit pulsars, the S/N with the stack search has been substantially improved; as has been stated, for PSR J1756−22 there was no detection at all in the standard search. It is worth noting that for very short spin periods (<10 ms), the spectral S/N is typically higher than the candidate plot S/N which was derived in the time domain. This is due to the small number of time samples over the period of the pulsar, making the time-domain S/N hard to determine accurately. REAPER was used to investigate spectral S/N against period from <1 to 20 ms, specifically to look for short-period candidates.

Table 2. Provisional names and parameters for all the binary and millisecond pulsars found using COBRA processing, showing spin period, orbital period and DM. Interim pulsar names have two digits of declination. The orbit for PSR J1723-28 has yet to be determined (tbd). The spectral S/N for the standard search (Std) and the stack acceleration (Acc.) search are shown to highlight the differences in search algorithm. The 'Plot' S/N is the refined S/N from the candidate plot; the values in italics are where the acceleration plot S/N has been used.

PSR J	Period (ms)	Orbit (d)	DM (pc cm^{-3})	S/N Std.	S/N Acc.	S/N Plot
1125−60	2.630	8.75	53.1	11.5	–	9.8
1215−64	3.540	4.08	47.7	19.5	16.1	16.6
1439−54	28.639	2.12	14.5	7.1	10.1	*17.5*
1551−49	6.284	–	114.6	12.2	–	10.2
1723−28	1.856	tbd	19.9	16.7	40.3	*20.8*
1726−29	27.081	–	60.9	8.9	7.3	12.2
1744−3922	172.449	0.19	145.7	15.3	13.8	*26.5*
1756−22	28.456	0.32	121.6	–	10.6	*18.4*
1801−1417	3.625	–	57.2	31.5	17.5	23.7
1802−2124	12.643	0.70	145.7	8.3	15.0	*16.1*
1813−26	4.430	–	122.5	14.7	9.4	11.1
1822−08	834.856	290.2	165.0	28.7	17.0	28.7
1841+01	29.773	10.48	125.9	11.1	7.1	11.2
1843−14	5.471	–	114.6	12.5	6.2	11.6
1853+13	4.092	115.7	30.6	20.5	10.7	15.9
1911+13	4.626	–	31.1	29.0	17.7	38.2
1910+12	4.984	58.32	38.1	20.8	14.6	18.0

In Fig. 8 we plot spin period, orbital period and DM of these new discoveries with the other known millisecond and binary pulsars previously found in the search area. It can clearly be seen that the COBRA processing, with improved interference filters and acceleration searches, has been substantially more successful at finding pulsars in binary systems with tight orbits and shorter pulsar periods than the earlier PMPS processing. These objects are being timed and will be discussed in future papers. Paper I discusses the reduced sensitivity of the PMPS to pulsars with very short spin periods at increasing DM just due to dispersion smearing. For example, the sampling time is increased to 1.0 ms above a DM of 140 pc cm^{-3}, to match the dispersion smearing and thus save processing time. It can be seen in Fig. 8(b) that there are no PMPS millisecond pulsars above a DM of 150 pc cm^{-3}.

In the following subsections we discuss three newly discovered pulsars, two in binary systems and a solitary millisecond object. Both binary systems have very low eccentricity; for such systems, the longitude of periastron is not well defined. To avoid large covariance between the usually quoted longitude and epoch of periastron, we have adopted the ELL1 timing model, which uses the Laplace–Lagrange parameters, $\eta = \epsilon \sin\omega$ and $\kappa = \epsilon \cos\omega$, where ϵ is the orbital eccentricity and ω is the angle of periastron, plus the time of ascending node $T_{\rm ASC}$. A detailed description of this binary model can be found in Lange et al. (2001). The parameters for the named pulsars are in Table 3, including the derived parameters: characteristic age, $\tau_{\rm c} = P/(2\dot{P})$; surface dipole magnetic field strength, $B_{\rm s} = 3.2 \times 10^{19}(P\dot{P})^{1/2}$ G. The pulsar mass was assumed to be 1.35 $M_{\odot}$. Distance, d, is computed from the DM with both the TC93 model (Taylor & Cordes 1993), for consistency with earlier publications, and NE2001 (Cordes & Lazio 2002) for comparison. The pulse profiles are shown in Fig. 9. All of the pulsars reported

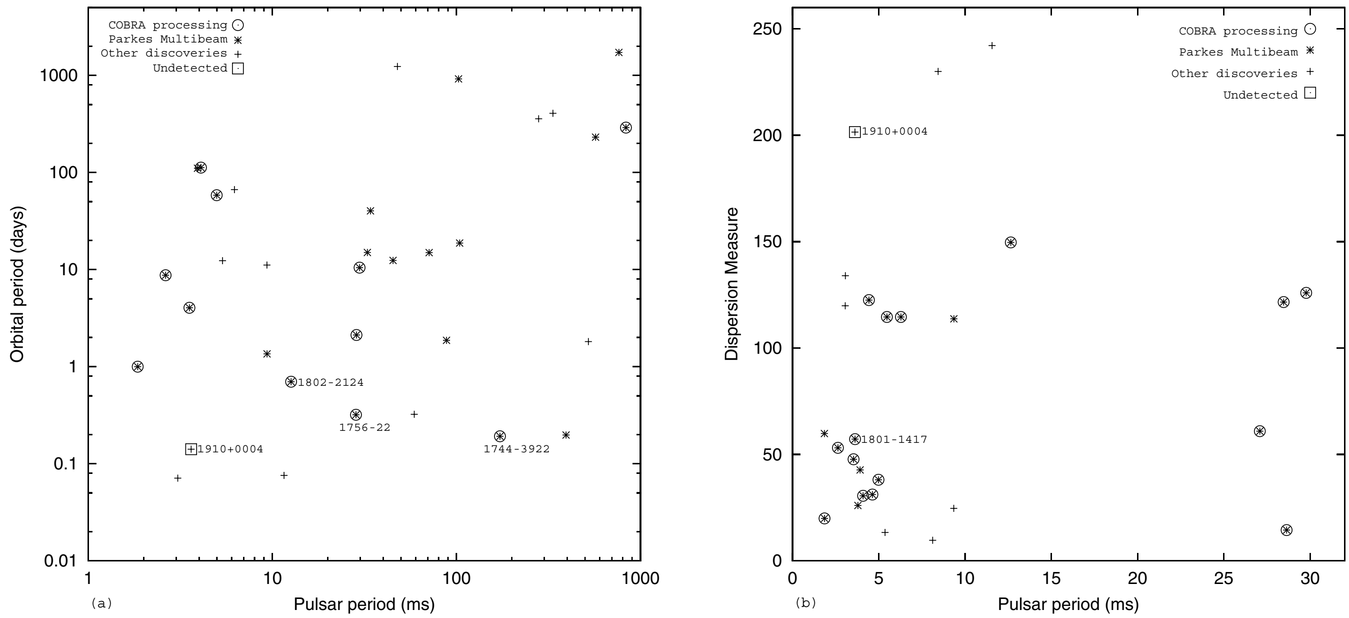

Figure 8. All binary and millisecond pulsars within the PMPS search area. The systems discovered by the PMPS are shown with the new discoveries enclosed in a circle. (a) shows the relationship between spin and orbital periods of the binary pulsars. (b) shows the spin period and DM for the millisecond pulsars. Named pulsars are discussed in the text.

Table 3. Positions, flux densities, measured and derived parameters for the newly discovered pulsars with complete timing solutions. Values in parenthesis are twice the nominal TEMPO uncertainties in the least significant digits quoted, obtained after scaling time-of-arrival (TOA) uncertainties to ensure $\chi^2_\nu = 1$. The pulsar has an assumed mass of 1.35 $M_\odot$.

Parameter	PSR J1744−3922	PSR J1801−1417	PSR J1802−2124
Right ascension (J2000) (h:m:s)	17:44:02.675(10)	18:01:51.0771(3)	18:02:05.3352(3)
Declination (J2000) (°:′:″)	−39:22:21.1(4)	−14:17:34.547(3)	−21:24:03.6(3)
Galactic longitude (°)	350.91	14.55	8.38
Galactic latitude (°)	−5.15	+4.16	+0.61
Period P (ms)	172.444360995(2)	3.6250966597450(15)	12.647593582763(5)
Period derivative $\dot{P}(\times 10^{-18})$	1.55(12)	0.00528(5)	0.072(1)
Epoch (MJD)	52530.0000	52340.0000	52855.0000
Dispersion measure (pc cm^{-3})	148.1(7)	57.2(1)	149.6(1)
Orbital period P_b (d)	0.19140624(7)	–	0.6988892434(8)
$a \sin i$ (lt-s)	0.2120(2)	–	3.718866(7)
Laplace–Lagrange parameters			
η	$0.8(20)\times10^{-3}$	–	$0.3(8)\times10^{-5}$
κ	$0.1(2)\times10^{-2}$	–	$0.1(6)\times10^{-5}$
T_{ASC} (MJD)	52927.16723(3)	–	52595.7950781(4)
Eccentricity e	<0.006	–	<0.00001
N_{toa}	36	64	32
Timing data span (MJD)	51 953–53 107	51 561–53 119	52 605–53 105
RMS timing residual (μs)	197	26.0	7.0
Flux density at 1400 MHz (mJy)	0.20(3)	0.87(10)	0.77(9)
Luminosity, log Sd^2 (mJy kpc^2)	0.62	0.45	0.92
W_{50} (ms)	3.4	0.35	0.37
W_{10} (ms)	–	–	0.74
Characteristic age τ_c (Gyr)	1.8	10.8	2.8
Magnetic field B_s (10^8 G)	166	1.4	9.7
Minimum companion mass ($M_\odot$)	0.083	–	0.81
Distance d (kpc) – TC93	4.6	1.8	3.3
Distance d (kpc) – NE2001	3.1	1.5	2.9
$\lvert z \rvert$ (kpc)	0.41	0.13	0.04
Detection beam number	4	9	4
Radial distance (beam radii, ∼7 arcmin)	1.3	0.8	0.9
Detection S/N ratio	26.5	23.7	16.1

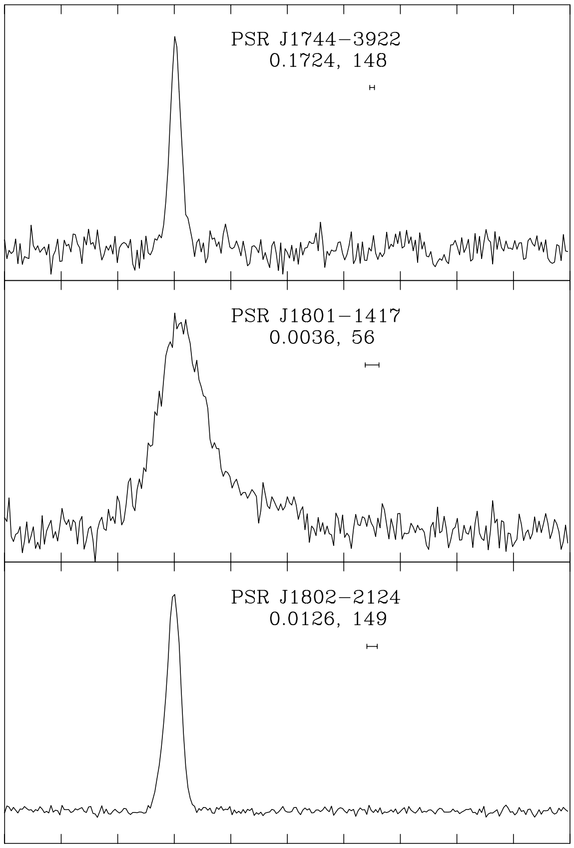

Figure 9. Pulse profiles for the three pulsars discussed. The highest point in the profile is placed at phase 0.3. The pulsar name, period (in s) and DM (in pc cm^{-3}) are given. The small horizontal bar under the DM indicates the effective resolution of the profile, including the effects of interstellar dispersion. Integration times used were 313, 147 and 599 min for PSRs J1744−3922, J1801−1414 and J1802−2124, respectively.

here have had regular timing observations covering more than one year, either at Parkes or at Jodrell Bank Observatory or both. Timing analysis was carried out using the TEMPO program[2] as described in Paper I.

7.1 PSR J1744−3922

PSR J1744−3922 was discovered in 2003 February; it completes more than 12 per cent of its orbit during a 35-min search observation. Consequently, the acceleration correction improved the optimized S/N by nearly 50 per cent from 17.8 to 26.5. There have been regular observations at Parkes since the discovery. Subsequently, pulse times of arrival from survey observations with detections of PSR J1744−3922, taken in 2001 February and June have been used to improve the timing solution substantially. The companion appears to be light, with a minimum mass of 0.083 solar masses. This pulsar has an unusual combination of characteristics: (i) it is in a compact circular orbit of only 4.6 h with a projected semimajor axis of 0.21 lt-s; (ii) it has an unusually long spin period of 172 ms; (iii) it experiences a lack of detectable emission for some of the time. The spin period would suggest a young pulsar; however, the characteristic age of 1.8 Gyr and a low eccentricity orbit indicate a mildly recycled object.

The evolution of this type of system is the source of considerable discussion in the literature; however, a typical scenario for a low-mass binary pulsar with $P_{\rm b} < 1$ d is given by Phinney & Kulkarni (1994). In summary, the larger, primary star with mass greater than the critical mass for a supernova explosion (∼8 $M_\odot$) evolves and expands, causing the secondary to spiral in. The He core of the primary eventually explodes, forming a neutron star. During the evolution of the secondary, mass transfer to the neutron star takes place, thus spinning up the pulsar. The second mass transfer phase circularizes the orbit and probably causes a second spiral-in phase; hence the very tight orbit.

The position of PSR J1744−3922 is well within the 95 per cent error box of the Energetic Gamma-Ray Experiment Telescope (EGRET) source 3EG J1744−3934 (Hartman et al. 1999). Indeed, this pulsar was independently detected in a targeted search of EGRET sources (Hessels et al. 2004). However, because the source is highly variable (variability index, V, of 5.12; McLaughlin 2001) and sources due to pulsars typically have $V < 1$, the association is unlikely. Kramer et al. (2003) reviewed possible PMPS discovery associations with EGRET γ-ray sources. We follow the same assessment approach using the pulsar's spin-down energy given by $\dot{E} = 4\pi^2 I \dot{P} P^{-3}$ in erg s^{-1}, where a neutron star moment of inertia $I = 10^{45}$ g cm^{-2} is assumed. For PSR J1744−3922, $\dot{E} = 19.68 \times 10^{30}$ erg s^{-1} at a distance, d, of 3.1 kpc (using NE2001; Cordes & Lazio 2002) such that $\log[\dot{E}/d^2$ (ergs^{-1} kpc^{-2})] = 30.35. 3EG J1744−3934 has a γ-ray flux, $\bar{F}$, of $1.27 \pm 0.26 \times 10^{-10}$ erg s^{-1} cm^{-2} implying a γ-ray luminosity which is 550 times the spin-down luminosity. Clearly, the EGRET source cannot be identified with the spin-powered pulsar PSR J1744−3922.

The occasional lack of radio emission could be intrinsic or extrinsic to the pulsar. Possible extrinsic phenomena are scintillation (e.g. Lyne & Rickett 1968) or the companion star obscuring the pulsar. There is no evidence of systematic changes in the radiation characteristics at different phases of the orbit, so it is unlikely to be due to eclipsing by the companion. With a DM of 148 pc cm^{-3} and an observing frequency of 1.4 GHz, we expect strong diffractive scintillation to produce scintles with a typical width of a few MHz (Cordes, Weisberg & Boriakoff 1985). The bandwidth of the receiving system is 288 MHz (see Paper I); consequently, any strong scintillation effects are averaged out and would not be seen. It is likely that the cause of the radiation fluctuations is intrinsic and probably due to nulling, first reported by Backer (1970) for normal pulsars.

The nulling of PSR J1744-3922 occurs in short time-scales. The pulse can be visible from less than a minute to a few minutes with off-times up to a few tens of minutes. Some 35-min observations do not have any detections. Overall, there is no detectable radiation at 20 cm for ∼75 per cent of the time. To our knowledge, this is the first time that nulling has been observed in a binary or a (mildly) recycled pulsar.

There have been attempts to find correlations between pulsar nulling and other pulsar characteristics (e.g. Rankin 1986; Biggs 1992); for instance, Biggs found a marginally significant correlation between pulsar characteristic age and null fraction. For recycled pulsars, many parameters are considerably different, e.g. they have much larger characteristic ages and their periods are typically shorter. Until this discovery, recycled pulsars were not observed to null. Physically, it is possible that the potential drop, $\Delta\Psi$, between the magnetic pole and polar cap may have an influence on a pulsar's emission mechanism. We have investigated the magnitude of

[2] See http://www.atnf.csiro.au/research/pulsar/tempo/.

Table 4. The potential drop $\Delta\Psi$ for groups of pulsars. All the published data are taken from the ATNF Catalogue (Manchester et al. 2004). The groups used are: 1, all pulsars; 2, pulsars known to null taken from Rankin (1986) and Biggs (1992), and PMPS pulsars observed to null; 3, all recycled pulsars (magnetic field $<10^{11}$ G and characteristic age $>10^8$ yr); 4, short-period recycled pulsars ($P <$ 100 ms); 5, long-period recycled pulsars ($P \geqslant 100$ ms). Included is PSR J1744−3922 for comparison.

Type of pulsar	Number	log[$\Delta\Psi$(V)] Median
(1) All pulsars	1381	$13.8^{+0.7}_{-0.7}$
(2) Known nullers	29	$13.2^{+0.4}_{-0.1}$
(3) All recycled	121	$14.1^{+0.6}_{-1.0}$
(4) 'Short' recycled	79	$14.3^{+0.6}_{-0.4}$
(5) 'Long' recycled	42	$13.0^{+0.3}_{-0.3}$
PSR J1744−3922	1	13.0

this potential for different types of pulsars to look for evidence of a correlation. In terms of observable parameters, the potential drop is

$$\Delta\Psi \simeq 2 \times 10^{13} \left(\frac{P}{s}\right)^{-3/2} \left(\frac{\dot{P}}{10^{-15}}\right)^{1/2} \mathrm{V}, \tag{2}$$

where P is spin period and $\dot{P}$ is the period derivative (Goldreich & Julian 1969). We considered the median potential drops for the groups of pulsars and compared the results with PSR J1744−3922. The results are shown in Table 4. It can be seen that nulling pulsars may have a lower potential drop than the median of all pulsars or all recycled pulsars, which we have somewhat arbitrarily defined as having a characteristic age $>10^7$ yr and surface magnetic field $<10^{11}$ G. There is a difference between recycled pulsars with $P <$ 100 ms and those with $P >$ 100 ms, which we show separately in Table 4. The lowest potential drop is for recycled pulsars with $P \geqslant$ 100 ms, which is the category for PSR J1744−3922. With some exceptions, there could be a trend among normal pulsars between nulling and $\Delta\Psi$; the same relationship between PSR J1744−3922 and other similar objects is not clear.

7.2 PSR J1802−2124

This system has a heavy companion with a minimum mass >0.8 $M_\odot$ which could be another neutron star. However, the circular orbit of the pulsar implies that it is unlikely that a second supernova explosion occurred in the system; hence, the companion is probably a heavy white dwarf (e.g. Phinney & Kulkarni 1994). The evolution is likely to be similar to that of PSR J1744−3922, except that the progenitor secondary star was considerably more massive in this system. This would result in the neutron star being engulfed during the red giant phase of the companion, accreting material and consequently being spun up. This process would also cause the two stars to spiral in towards each other and to eject the giant's envelope, leaving a pulsar in a tight, circular orbit with a large white dwarf companion. The system is categorized as being an intermediate mass binary pulsar (IMBP) as introduced by Camilo et al. (1996) and further discussed in Camilo et al. (2001), defined as having intermediate-mass donor stars. They identified binary systems with the pulsar spin period $10 < P < 200$ ms, $e < 0.001$, companion mass >0.4 $M_\odot$ and $0.5 < P_b < 15$ d as likely IMBPs. PSR J1802−2124 meets all these criteria and is clearly a member of this class of system; it has added to the subclass of relatively short spin periods with a 12.6 ms rotation, similar to PSRs J1435−6100/J1757−5322. which contrast with PSR B0655+54 at 195 ms noted by Camilo et al.

PSR J1802−2124 brings the number of IMBPs known to 15 (for a list of the other 14, see Hobbs et al. 2004), with eight either found or detected by the PMPS. This concentration near to the Galactic plane is discussed in Camilo et al. (2001), with a possible reason being that the birth velocity is restricted because of the high system mass. PSR J1802−2124 with $|z|$ of only 0.04 kpc supports this view, although there may be selection effects due to the high sensitivity survey coverage of the PMPS along the Galactic plane.

PSR J1802−2124 has a narrow pulse profile of <0.4 ms (<3 per cent of the period), which may be even narrower if the effects of dispersion smearing are removed. This probably accounts for the flux density being apparently less than the nominal PMPS flux limit, which is calculated at a 5 per cent duty cycle.

7.3 PSR J1801−1417

PSR J1801−1417 is a solitary 3.62-ms pulsar, first discovered in 2002 November. It has a characteristic age of 10.8 Gyr. The ephemeris of this pulsar has been considerably improved by including three detections from the PMPS back to 2000 January.

Following an earlier suggestion by Bailes et al. (1997), Kramer et al. (1998) put forward evidence that solitary millisecond pulsars are less luminous than when they are in binary systems. By calculating the flux density times the square of the distance, Sd^2, we can make luminosity comparisons; the values of $\log Sd^2$ (mJy kpc^2) for our sources are shown in Table 3. As can be seen, the luminosity of PSR J1801−1417 is significantly lower than that of PSR J1802−2124, although both are more luminous than the ranges identified by Kramer et al. (mean value, $\log Sd^2$ of -0.5 ± 0.3 and 0.2 ± 0.1 for solitary and binary millisecond pulsars, respectively). We note that it is unlikely that either of these pulsars would have been discovered if their luminosity was as low as Kramer et al.'s ranges; both pulsars exceed the 1.5 kpc previously used, with PSR J1802−2124 at 3.3 kpc.

We have updated the luminosity statistics for recycled pulsars, as defined by Kramer et al. (1998) for the current known population using a distance limit of 2.0 kpc, increased from 1.5 kpc. The population has increased from 7 to 10 solitary pulsars and from 11 to 19 in binary systems. With a distance limit of 2.0 kpc, the luminosity mean values are $\log Sd^2$ of -0.4 ± 0.2 and 0.1 ± 0.1 for solitary and binary objects, respectively. These results, which were also checked at a limit of 1.5 kpc, are consistent with Kramer et al. and provide further evidence that solitary millisecond pulsars are less luminous radio sources than their binary counterparts. The cause of this effect is still not known. There will be future analysis of all the new millisecond discoveries of the PMPS.

8 FUTURE WORK

The PMPS has been the most successful search for pulsars ever undertaken. However, there is still further work to do. The processing performed so far is still insensitive to fast millisecond pulsars in binary orbits of a few hours or less; for example, the binary pulsar PSR J0737−3039 (Burgay et al. 2003) would only be detected at the times in its 2.4-h orbit where the apparent spin period changes are most constant. This system was found using essentially the same software system as used in this processing, but the observation time was only 4 min, which radically reduces pulse smearing. Short observations also reduce potential sensitivity, so there is considerable scope for further reanalysis of the data with more sophisticated software or as partial observations.

We are processing the observations in four quarters, using the standard and stack search algorithms. With a shorter observation time there will be less pulse smearing of highly accelerated pulsars, as discussed in Section 3.1. This may find objects in fast orbits, but at a price of reduced base sensitivity by a factor of 2. Evolutionary population studies suggest that black hole–pulsar binaries exist in the Galactic field (Sigurdsson 2003). Such systems may be in very tight orbits. One or more could be in the PMPS data set and a better acceleration search algorithm may find them.

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REFERENCES

Andersson N., Kokkotas K., Schutz B. F., 1999, ApJ, 510, 846
Backer D. C., 1970, Nat, 228, 42
Backer D. C., Kulkarni S. R., Heiles C., Davis M. M., Goss W. M., 1982, Nat, 300, 615
Bailes M. et al., 1997, ApJ, 481, 386
Biggs J. D., 1992, in Hankins T. H., Rankin J. M., Gil J. A., eds, The Magnetospheric Structure and Emission Mechanisms of Radio Pulsars, IAU Colloquium 128. Pedagogical University Press, Zielona Góra, Poland, p. 22
Burgay M., 2004, PhD thesis, University of Bologna
Burgay M. et al., 2003, Nat, 426, 531
Camilo F., Nice D. J., Shrauner J. A., Taylor J. H., 1996, ApJ, 469, 819
Camilo F., Lorimer D., Freire P., Lyne A. G., Manchester R. N., 2000a, ApJ, 535, 975
Camilo F. et al., 2000b, in Kramer M., Wex N., Wielebinski R., eds, Pulsar Astronomy - 2000 and Beyond, IAU Colloquium 177. Astronomical Society of the Pacific, San Francisco, p. 3 (astro-ph/9911185)
Camilo F. et al., 2001, ApJ, 548, L187
Cordes J. M., Lazio T. J. W., 2002, preprint (astro-ph/0207156)
Cordes J. M., Weisberg J. M., Boriakoff V., 1985, ApJ, 288, 221
Damour T., Esposito-Farèse G., 1998, Phys. Rev. D, 58, 1
Dhurandhar S. V., Vecchio A., 2001, Phys. Rev. D, 63, 122001
Edwards R. T., Bailes M., van Straten W., Britton M. C., 2001, MNRAS, 326, 358
Friedman J. L., 1995, in Fruchter A. S., Tavani M., Backer D. C., eds, Millisecond Pulsars: A Decade of Surprise. Astronomical Society of the Pacific Conference Series, p. 177
Goldreich P., Julian W. H., 1969, ApJ, 157, 869
Hartman R. C. et al., 1999, ApJS, 123, 79
Hessels J. W. T., Ransom S. M., Stairs I. H., Kaspi V. M., Freire P. C. C., Backer D. C., Lorimer D. R., 2004, in Camilo F., Gaensler B. M., eds, Young Neutron Stars and Their Environments, IAU Symp. 218. Astron. Soc. Pac., San Francisco, p. 131
Hobbs G., 2002, PhD thesis, University of Manchester
Hobbs G. et al., 2004, MNRAS, 352, 1439
Johnston H. M., Kulkarni S. R., 1991, ApJ, 368, 504
Johnston S., Lyne A. G., Manchester R. N., Kniffen D. A., D'Amico N., Lim J., Ashworth M., 1992, MNRAS, 255, 401
Jouteux S., Ramachandran R., Stappers B. W., Jonker P. G., van der Klis M., 2002, A&A, 384, 532
Kramer M., Xilouris K. M., Lorimer D., Doroshenko O., Jessner A., Wielebinski R., Wolszczan A., Camilo F., 1998, ApJ, 501, 270
Kramer M. et al., 2003, MNRAS, 342, 1299
Lange C., Camilo F., Wex N., Kramer M., Backer D., Lyne A., Doroshenko O., 2001, MNRAS, 326, 274
Lyne A. G., Rickett B. J., 1968, Nat, 218, 326
McLaughlin M., 2001, PhD thesis, Cornell University
McLaughlin M. A., Cordes J. M., 2003, ApJ, 596, 982
Manchester R. N. et al., 2001, MNRAS, 328, 17 (Paper I)
Manchester R., Hobbs G., Teoh A., Hobbs M. 2004, ApJ, submitted
Morris D. J. et al., 2002, MNRAS, 335, 275
Phinney E. S., Kulkarni S. R., 1994, ARA&A, 32, 591
Rankin J. M., 1986, ApJ, 301, 901
Ransom S. M., Eikenberry S. S., Middleditch J., 2002, AJ, 124, 1788
Ransom S. M., Cordes J. M., Eikenberry S. S., 2003, ApJ, 589, 911
Sigurdsson S., 2003, in Bailes M., Nice D. J., Thorsett S., eds, ASP Conf. Ser. 302: Radio Pulsars. p. 391
Staelin D. H., 1969, Proc. IEEE, 57, 724
Taylor J. H., 1993, in Fontaine G., Vân J. T. T., eds, Particle Astrophysics, IVth Rencontres de Blois. Editions Frontieres, Gif-sur-Yvette, France, p. 367
Taylor J. H., Cordes J. M., 1993, ApJ, 411, 674
Taylor J. H., Huguenin G. R., 1969, Nat, 221, 816
Taylor J. H., Weisberg J. M., 1989, ApJ, 345, 434
Wood K. S. et al., 1991, ApJ, 379, 295

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