2012

Discovery Of Five New Pulsars In Archival Data

M. B. Mickaliger

D. R. Lorimer

J. Boyles

M. A. McLaughlin

A. Collins

See next page for additional authors

Authors
M. B. Mickaliger, D. R. Lorimer, J. Boyles, M. A. McLaughlin, A. Collins, L. Hough, N. Tehrani, C. Tenney, A. Liska, and J. Swiggum

The Astrophysical Journal, 759:127 (5pp), 2012 November 10 doi:10.1088/0004-637X/759/2/127

DISCOVERY OF FIVE NEW PULSARS IN ARCHIVAL DATA

M. B. Mickaliger, D. R. Lorimer[1], J. Boyles[2], M. A. McLaughlin[1], A. Collins,
L. Hough, N. Tehrani, C. Tenney, A. Liska, and J. Swiggum
Department of Physics, West Virginia University, Morgantown, WV 26506, USA
Received 2012 June 13; accepted 2012 September 25; published 2012 October 29

ABSTRACT

Reprocessing of the Parkes Multibeam Pulsar Survey has resulted in the discovery of five previously unknown pulsars and several as-yet-unconfirmed candidates. PSR J0922−52 has a period of 9.68 ms and a dispersion measure (DM) of 122.4 pc cm^{-3}. PSR J1147−66 has a period of 3.72 ms and a DM of 133.8 pc cm^{-3}. PSR J1227−6208 has a period of 34.53 ms, a DM of 362.6 pc cm^{-3}, is in a 6.7 day binary orbit, and was independently detected in an ongoing high-resolution Parkes survey by Thornton et al. and also in independent processing by Einstein@Home volunteers. PSR J1546−59 has a period of 7.80 ms and a DM of 168.3 pc cm^{-3}. PSR J1725−3853 is an isolated 4.79 ms pulsar with a DM of 158.2 pc cm^{-3}. These pulsars were likely missed in earlier processing efforts due to the fact that they have both high DMs and short periods, and also due to the large number of candidates that needed to be looked through. These discoveries suggest that further pulsars are awaiting discovery in the multibeam survey data.

Key word: pulsars: individual (PSR J0922−52, PSR J1147−66, PSR J1227−6208, PSR J1546−59, PSR J1725−3853)

1. INTRODUCTION

While targeted searches have been useful in finding unique pulsars, most pulsars known today have been found in large-scale, blind pulsar surveys. One such survey, the Parkes Multibeam Pulsar Survey (PMPS; Manchester et al. 2001), surveyed a strip along the Galactic plane using the 13 beam receiver on the Parkes 64 m telescope. Initial processing of the data resulted in the discovery of 742 pulsars (Manchester et al. 2001; Morris et al. 2002; Kramer et al. 2003; Hobbs et al. 2004; Faulkner et al. 2004; Lorimer et al. 2006). Another 44 pulsars and 30 RRATs were found in further reprocessings (Eatough et al. 2009, 2010, 2011; Keith et al. 2009; McLaughlin et al. 2006; Keane et al. 2010, 2011), and an additional 21 pulsars have been found so far by Einstein@Home[3] (B. Knispel et al., in preparation). The 44 additional pulsars were found due to the implementation of new techniques for removing terrestrial interference and new techniques for sorting pulsar candidates.

In this paper, we present the discovery of a further five pulsars in the PMPS data. The motivation for our re-analysis of the PMPS data was a single-pulse study, which will be presented elsewhere. Single-pulse studies involve the search for and characterization of transient, non-periodic bursts. We performed periodicity searches as well as single-pulse searches since the additional processing time was negligible. In Section 2, we describe the data reduction and analysis. Section 3 details the five pulsars that we discovered, and conclusions are given in Section 4.

2. DATA REDUCTION

The PMPS data were searched for periodic signals using freely available analysis software.[4] First, the frequency channels in the data were shifted to correct for the dispersion due to free electrons in the interstellar medium. This dedispersion is done at many dispersion measures (DMs; which is the integrated column density of electrons along the line of sight) and results in a time series for each DM. The total number of DMs searched was 203 and was optimally chosen by the `dedisperse_all`[5] program, which we used for dedispersion due to its speed and efficiency. The time series were processed by `seek`, a program that searches for periodic signals from an object. We searched for both periodic signals and single pulses out to a DM of 5000 pc cm^{-3}. This upper limit was chosen in order to be sensitive to highly dispersed bursts. Results from the single-pulse search will be presented in another paper. The periodicity-search analysis method implemented in `seek` is the standard Fourier-based approach (see, e.g., Lorimer & Kramer 2005) where the amplitude spectrum is subject to multiple harmonic folds, summing 2, 4, 8, and 16 harmonics. This process increases sensitivity to narrow pulses in a close-to-optimal fashion (Ransom et al. 2002). All candidate signals, with spectral signal-to-noise ratios (S/Ns) greater than six, are sought and saved during this process. After all DM trials have been searched, statistically significant candidates with S/N greater than nine are subject to further analysis. For these candidates, the raw multi-channel data are then folded at the period of each candidate using `prepfold`, part of the PRESTO package.[6] The `prepfold` program carries out a search to optimize the period from `seek` and produces a set of diagnostic plots for each candidate. Figure 1, which is the discovery plot for PSR J1725−3853, is one example of these diagnostic plots. These plots consist of the following parts: an integrated pulse profile (upper left), which is the result of folding the data at the period of the candidate; a plot of pulse phase versus observation time (left), which shows the phase of the pulses as they arrive throughout the observation, as well as accumulated χ^2 versus observation time (for the definition of χ^2, see Equation (7.3) in Lorimer & Kramer 2005); pulse phase versus frequency

[1] Also adjunct at the National Radio Astronomy Observatory, Green Bank, WV 24944, USA.
[2] Current address: Department of Physics, Western Kentucky University, Bowling Green, KY 42101, USA.
[3] http://einstein.phys.uwm.edu/radiopulsar/html/PMPS_discoveries/
[4] http://sigproc.sourceforge.net
[5] http://www.github.com/swinlegion
[6] http://www.cv.nrao.edu/~sransom/presto

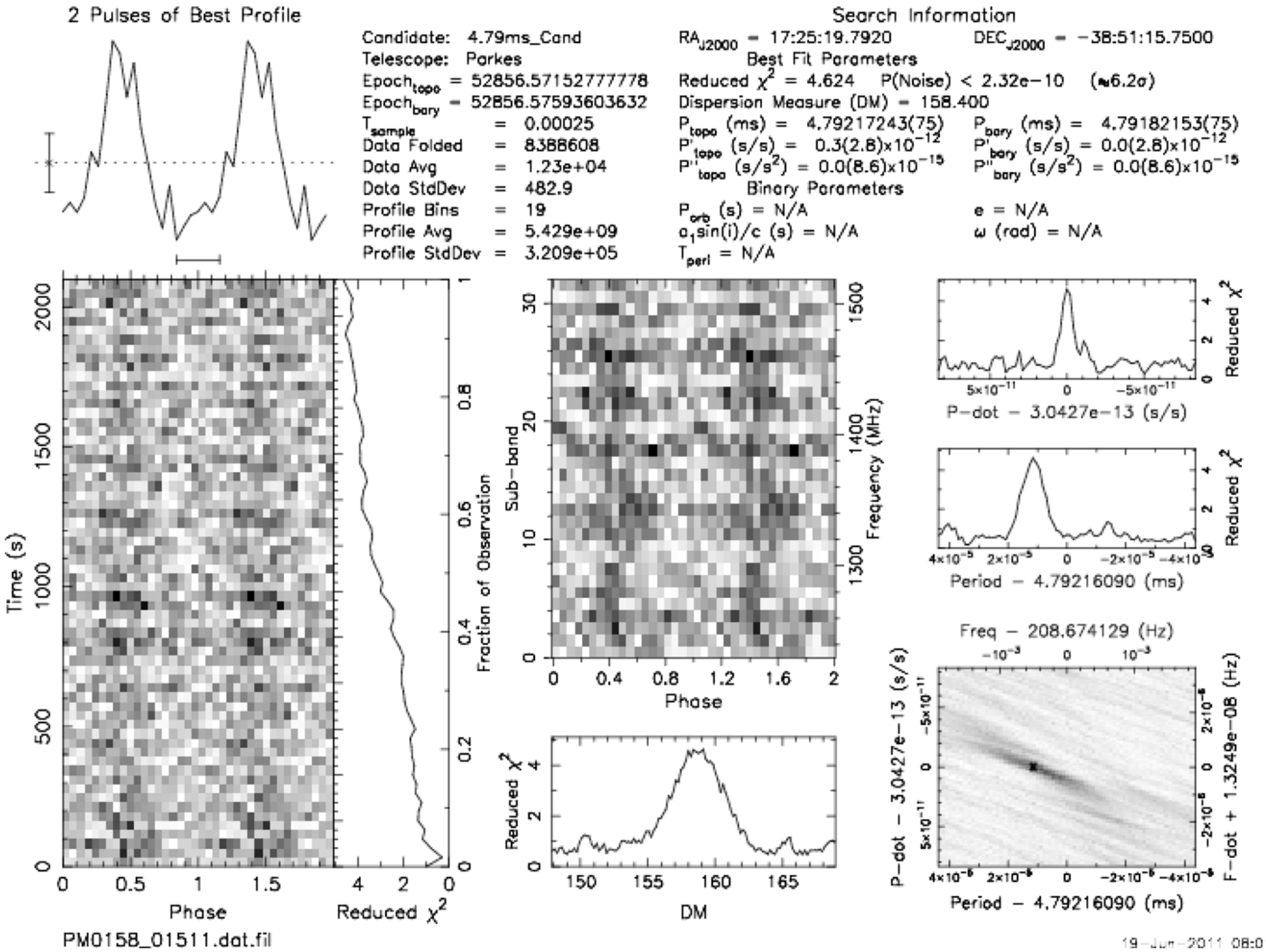

Figure 1. Diagnostic plot from `prepfold` showing the discovery of PSR J1725−3853. For a description of the subplots, see Section 2.

(middle), which shows the phase of the pulses across the observing band; period versus χ^2 (middle right), which shows the χ^2 value resulting from folding the data at many trial periods; period derivative versus χ^2 (upper right), which shows the χ^2 value resulting from folding the data with many trial period derivatives; DM versus χ^2 (lower middle), which shows the χ^2 resulting from dedispersing the data at many trial DMs; and period versus period derivative (lower right), which shows the χ^2 intensity in period–period derivative space.

No acceleration searches were carried out in this reduction. To reduce the number of plots that needed to be inspected by eye, we selected candidates with periods under 50 ms, DMs greater than 10 pc cm^{-3}, and spectral S/Ns greater than nine for viewing, resulting in ∼270,000 candidates, five of which have already been confirmed as pulsars. Since this processing was never intended to be rigorous, we assumed that most pulsars with periods greater than 50 ms had been discovered, and that most candidates with a DM that peaked under 10 pc cm^{-3} were interference.

3. NEWLY DISCOVERED PULSARS

From our inspection of the `prepfold` plots, we identified five very promising pulsar candidates and have subsequently been able to confirm these as new pulsars and perform follow-up observations as described below.

3.1. PSR J0922−52

PSR J0922−52 has a period of 9.68 ms and a DM of 122.4 pc cm^{-3}. The spectral S/N and χ^2 of the profile from the discovery observation, reported by `seek` and `prepfold`, are 9.1 and 2.7, respectively. The inferred distance from the NE2001 model (Cordes & Lazio 2002) is 0.8 kpc. It was confirmed on MJD 56102 with a 35 minute observation using the Parkes telescope at 1400 MHz. The FWHM of the profile from the confirmation observation (Figure 2) is 790 μs. Since the position is not well constrained by the observations we have been able to carry out, we can only estimate, using the radiometer equation (Lorimer & Kramer 2005), a lower limit on the mean flux at 1400 MHz, which is 0.16 mJy. Further observations are needed in order to time this pulsar and determine its physical parameters.

3.2. PSR J1147−66

PSR J1147−66 has a period of 3.72 ms and a DM of 133.8 pc cm^{-3}. The spectral S/N and χ^2 of the profile from the discovery observation, reported by `seek` and `prepfold`, are 10.9 and 6.0, respectively. The inferred distance from the NE2001 model is 2.7 kpc. It was confirmed on MJD 56158 with a 20 minute observation using the Parkes telescope at 1400 MHz.

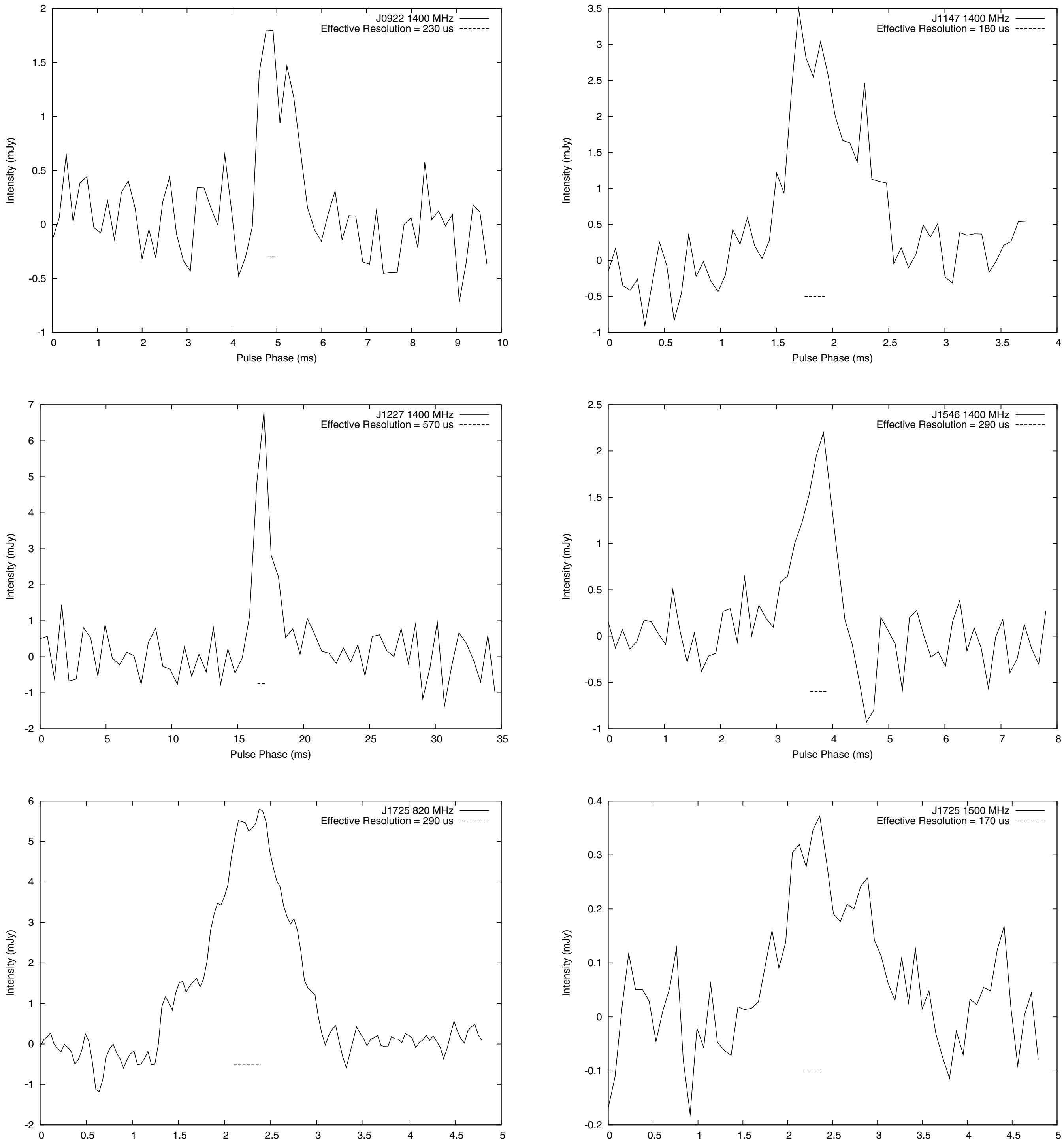

Figure 2. Upper left: folded profile from the 35 minute confirmation observation of PSR J0922−52 on MJD 56102 at 1400 MHz. The effective resolution of the profile (given by $t_{\rm eff} = \sqrt{t_{\rm samp}^2 + t_{\rm scatt}^2 + t_{\rm DM}^2}$, where $t_{\rm samp}$ is the sampling time, $t_{\rm scatt}$ is the scattering time from the NE2001 model (Cordes & Lazio 2002), and $t_{\rm DM}$ is the DM smearing across a single channel) is given in the plot and is shown by the bar beneath the profile. Upper right: folded profile from the 20 minute confirmation observation of PSR J1147−66 on MJD 56158 at 1400 MHz. Middle left: folded profile from the 15 minute confirmation observation of PSR J1227−6208 on MJD 55857 at 1400 MHz. Middle right: folded profile from the 35 minute confirmation observation of PSR J1546−59 on MJD 56102 at 1400 MHz. Lower left: composite profile for PSR J1725−3853 at 820 MHz, with a total integration time of 113 minutes. Lower right: folded profile from the 15 minute 1500 MHz observation of PSR J1725−3853 on MJD 55876.

The FWHM of the profile from the confirmation observation (Figure 2) is 795 μs. The estimate of the lower limit on the mean flux at 1400 MHz is 0.80 mJy. As with PSR J0922−52, further observations are needed for timing and determining its physical characteristics.

3.3. PSR J1227−6208

PSR J1227−6208 has a period of 34.53 ms and a DM of 362.6 pc cm^{-3}. The spectral S/N and χ^2 of the profile from the discovery observation, reported by `seek` and `prepfold`,

Table 1
Observational Parameters for the Confirmation and Timing Observations of PSR J1725−3853

MJD	Frequency (MHz)	Bandwidth (MHz)	Sampling Time (μs)
55660	820	200	81.92
55707	820	200	81.92
55780	820	200	81.92
55825	820	200	81.92
55876	1500	800	81.92
56005	820	200	40.96
56031	820	200	40.96

are 12.6 and 4.6, respectively. The inferred distance from the NE2001 model is 8.3 kpc. It was confirmed on MJD 55857 with a 15 minute observation using the Parkes telescope at 1400 MHz, and was independently detected by the High Time Resolution Universe (HTRU) pulsar survey (Keith et al. 2010), as well as the ongoing processing by Einstein@Home (B. Knispel et al., in preparation). A full timing solution will be given by D. Thornton et al. (in preparation), who found it to be in an approximately circular binary orbit of period 6.7 days with a $\gtrsim 1.3\, M_{\odot}$ companion. Since a companion of this mass could be a neutron star, we searched both the original PMPS data and our confirmation observation for another pulsar, but found none down to a flux limit of 0.16 mJy, assuming a detection significance of 6σ. Unlike previous searches of this kind (e.g., Lorimer et al. 2006), no correction for acceleration is needed, as the orbital period is substantially longer than the survey integration time (35 minutes). The FWHM of the profile from the confirmation observation (Figure 2) is 1.3 ms. The estimate of the lower limit on the mean flux at 1400 MHz is 0.27 mJy. Further details of this pulsar will be published by Thornton et al. (in preparation).

3.4. PSR J1546−59

PSR J1546−59 has a period of 7.80 ms and a DM of 168.3 pc cm^{-3}. The spectral S/N and χ^2 of the profile from the discovery observation, reported by `seek` and `prepfold`, are 9.4 and 3.4, respectively. The inferred distance from the NE2001 model is 3.3 kpc. It was confirmed on MJD 56102 with a 35 minute observation using the Parkes telescope at 1400 MHz. The FWHM of the profile from the confirmation observation (Figure 2) is 670 μs. The estimate of the lower limit on the mean flux at 1400 MHz is 0.20 mJy. As with PSR J0922−52 and PSR J1147−66, further observations are needed for timing and determining its physical characteristics.

3.5. PSR J1725−3853

PSR J1725−3853 has a period of 4.79 ms and a DM of 158.2 pc cm^{-3}. The spectral S/N and χ^2 of the profile from the discovery observation, reported by `seek` and `prepfold`, are 10.2 and 4.6, respectively. The inferred distance from the NE2001 model is 2.8 kpc. Both the confirmation observation on MJD 55660 and timing observations were done with the 100 m Robert C. Byrd Green Bank Telescope (GBT) at 820 MHz, with one timing observation at 1500 MHz. The observational parameters are listed in Table 1. All observations were taken using the Green Bank Ultimate Pulsar Processing Instrument (GUPPI; DuPlain et al. 2008), which is built from reconfigurable off-the-shelf hardware and software available from the Collaboration for Astronomy Signal Processing and Electronics Research (Parsons et al. 2009). GUPPI samples data with eight-bit precision over bandwidths as large as 800 MHz, and is capable of recording all four Stokes parameters. The observations taken on MJDs 55825 and 56031 were done in a gridding format (see, e.g., Morris et al. 2002), where we took four observations around the position of the pulsar in order to better constrain the position, which greatly facilitated the timing analysis described below.

Table 2
Timing and Derived Parameters for PSR J1725−3853

Timing Parameters	
Right ascension (J2000)	17:25:27.27(8)
Declination (J2000)	−38:53:04.20(5)
Spin period (s)	0.004791822704(3)
Period derivative (s s^{-1})	$5(3) \times 10^{-20}$
Dispersion measure (pc cm^{-3})	158.2(7)
Reference epoch (MJD)	55846
Number of TOAs	13
Span of timing data	55660 − 56031
Derived Parameters	
Galactic longitude (deg)	349.3(7)
Galactic latitude (deg)	−1.8(6)
Distance (kpc)	2.8
Surface magnetic field (Gauss)	$5(1) \times 10^{8}$
Spin-down luminosity (ergs s^{-1})	$6(3) \times 10^{33}$
Characteristic age (yr)	$1.6(9) \times 10^{9}$
820 MHz flux density (mJy)	1.1
Pulse FWHM at 820 MHz (ms)	0.865
Pulse FWHM at 1500 MHz (ms)	1.2

Note. Errors quoted are twice the nominal values reported by TEMPO and reflect the uncertainties in the least significant digit.

The GBT data were initially optimized by a fine search in period and DM to produce integrated pulse profiles. Using a simple Gaussian template, we extracted times of arrival (TOAs) from each profile via the Fourier-domain template matching algorithm (Taylor 1992) as implemented in the `get_toa.py` routine in the PRESTO package. The Gaussian template for the 820 MHz observations was made from the composite 820 MHz profile, and the template for the 1500 MHz observation was made from the one observation at that frequency. Gaussian templates were used because a template made from the composite profile underestimated the errors on the residuals by a factor of nine. In total, a set of 13 TOAs spanning 371 days was then fit to a simple isolated pulsar timing model using the TEMPO analysis package.[7] Following a number of iterations, we were able to converge on a timing model in which the TOAs are fit by an isolated pulsar with parameters listed in Table 2. The TOA uncertainties were multiplied by a factor of three to ensure a reduced χ^2 value in the fit of unity. The root-mean-square timing model residuals were 88 μs. The positional uncertainty resulting from this fit is 0″.05 in declination and 1″.2 in R.A., while the frequency derivative is only marginally significant, given the current baseline. The final fit parameters are typical for an isolated millisecond pulsar with a characteristic age of approximately 1.6 Gyr and a surface magnetic field of 5×10^8 Gauss (see, e.g., Lorimer 2008).

No coincident sources were detected in any HEASARC catalogue,[8] and no γ-ray source was detected in 371 days of folded γ-ray photons from the *Fermi* Large Area Telescope

[7] http://tempo.sourceforge.net
[8] http://heasarc.gsfc.nasa.gov

(Atwood et al. 2009). The FWHM of the composite profile made from adding all of the profiles at 820 MHz is 865 μs, and the FWHM of the 1500 MHz profile is 1.2 ms (Figure 2). The estimated mean flux at 820 MHz is 1.1 mJy. We were unable to compute a reliable flux density at 1500 MHz given the 0.15 mJy detection threshold of the PMPS (Manchester et al. 2001). These flux estimates have large errors, and further observations are required to reliably calculate a spectral index.

In addition to the five pulsars confirmed so far, the search analysis described in Section 2 resulted in a large number of statistically significant candidate pulsar signals. A list of these candidates, which will be subject to follow-up observations with the GBT and Parkes, can be found at http://astro.phys.wvu.edu/pmps.

4. CONCLUSIONS

Reprocessing of the PMPS resulted in the discovery and confirmation of five new pulsars, PSR J0922−52, PSR J1147−66, PSR J1227−6208, PSR J1546−59, and PSR J1725−3853. PSR J1227−6208 was independently confirmed by Einstein@Home as well as the HTRU team in their medium-latitude survey and will be presented by Thornton et al. (in preparation). Our discovery of PSRs J0922−52, J1147−66, J1227−6208, J1546−59, and J1725−3853 brings the total number of millisecond pulsars found in the PMPS to 25. We present a timing solution for PSR J1725−3853, and continued timing observations will allow us to further improve this solution.

Our discovery of these five pulsars emphasizes the value of archiving pulsar search data and indicates that there are a number of as-yet-undiscovered pulsars present in the PMPS data. Given the number of pulsar candidates present, automated searches are the most efficient way to reduce the number of candidates to an amount that can be viewed in a reasonable amount of time. Due to the fact that they have both high DMs and short periods, many of our candidates are weak and close to the detection threshold, so there is a good chance they were not ranked highly by previous automated searches. Keith et al. (2009) found that weak pulsars and pulsars with high DMs were ranked highly by automated searches. However, most of these pulsars have long periods, i.e., periods on the order of hundreds of milliseconds. As the ratio of DM to period increases, the detected pulse profile is significantly broadened and begins to look more sinusoidal. These candidates are harder to select via ranking systems. We note that Eatough et al. (2010) found that artificial neural networks have difficulty detecting short period pulsars, with their own detecting only 50% of pulsars with periods less than 10 ms. In our search strategy, every single candidate is being inspected by eye. In many of the earlier analyses of the PMPS data (e.g., Manchester et al. 2001), the candidates were also viewed by eye and it is not clear why these were not found earlier. Perhaps they were simply missed due to human fatigue. In the following year, we hope to follow up and confirm many of our candidates. Along with the re-analysis of the PMPS survey data presented here, and the ongoing search by Einstein@Home, we expect the sample of millisecond pulsars found in the PMPS to increase further.

We thank the HTRU team and in particular Michael Keith, Matthew Bailes, Sam Bates, and Dan Thornton for their information on the binary parameters of PSR J1227−6208. We also thank Matthew Bailes for making `dedisperse_all` available to us. We thank Bruce Allen and Michael Kramer for directing our attention to the Einstein@Home Web site. We particularly thank Ben Knispel for very useful discussions about the Einstein@Home discoveries. We thank George Hobbs and Fernando Camilo for useful discussions concerning the timing of PSR J1725−3853, and the referee for very helpful comments on the manuscript. Pulsar research at WVU is supported by a WVEPSCoR research challenge grant awarded to M.A.M. and D.R.L. In addition, A.C., L.H., and C.T. were supported by a Cottrell Scholar award to DRL. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

REFERENCES

Atwood, W. B., Abdo, A. A., Ackermann, M., et al. 2009, ApJ, 697, 1071
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156
DuPlain, R., Ransom, S., Demorest, P., et al. 2008, Proc. SPIE, 7019, 70191D
Eatough, R. P., Keane, E. F., & Lyne, A. G. 2009, MNRAS, 395, 410
Eatough, R. P., Kramer, M., Lyne, A. G., & Keith, M. 2011, in AIP Conf. Proc. 1357, Radio Pulsars: An Astrophysical Key to Unlock the Secrets of the Universe, ed. M. Burgay, N. D'Amico, P. Esposito, A. Pellizzoni, & A. Possenti (Melville, NY: AIP), 58
Eatough, R. P., Molkenthin, N., Kramer, M., et al. 2010, MNRAS, 407, 2443
Faulkner, A. J., Stairs, I. H., Kramer, M., et al. 2004, MNRAS, 355, 147
Hobbs, G., Faulkner, A., Stairs, I. H., et al. 2004, MNRAS, 352, 1439
Keane, E. F., Kramer, M., Lyne, A. G., Stappers, B. W., & McLaughlin, M. A. 2011, MNRAS, 415, 3065
Keane, E. F., Ludovici, D. A., Eatough, R. P., et al. 2010, MNRAS, 401, 1057
Keith, M. J., Eatough, R. P., Lyne, A. G., et al. 2009, MNRAS, 395, 837
Keith, M. J., Jameson, A., van Straten, W., et al. 2010, MNRAS, 409, 619
Kramer, M., Bell, J. F., Manchester, R. N., et al. 2003, MNRAS, 342, 1299
Lorimer, D. R. 2008, Living Rev. Rel., 11, 8
Lorimer, D. R., Faulkner, A. J., Lyne, A. G., et al. 2006, MNRAS, 372, 777
Lorimer, D. R., & Kramer, M. 2005, Handbook of Pulsar Astronomy (Cambridge: Cambridge Univ. Press)
Manchester, R. N., Lyne, A. G., Camilo, F., et al. 2001, MNRAS, 328, 17
McLaughlin, M. A., Lyne, A. G., Lorimer, D. R., et al. 2006, Nature, 439, 817
Morris, D. J., Hobbs, G., Lyne, A. G., et al. 2002, MNRAS, 335, 275
Parsons, A., Werthimer, D., Backer, D., et al. 2009, arXiv:0904.1181v1
Ransom, S. M., Eikenberry, S. S., & Middleditch, J. 2002, AJ, 124, 1788
Taylor, J. H. 1992, Phil. Trans. R. Soc. A, 341, 117