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Discovery of five pulsars in a pilot survey at intermediate Galactic latitudes with FAST

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ABSTRACT

We present the discovery and timing results of five pulsars discovered in a pilot survey at intermediate Galactic latitudes with the Five-hundred Aperture Spherical Telescope (FAST). Among these pulsars, two belong to the category of millisecond pulsars (MSPs) with spin periods of less than 20 ms. Two others fall under the classification of 'mildly recycled' pulsars, with massive white dwarfs as companions. Remarkably, this small survey, covering an area of 4.7 square degrees, led to the discovery of five pulsars, including four recycled pulsars. Such success underscores the immense potential of future surveys at intermediate Galactic latitudes. In order to assess the potential yield of MSPs, we conducted population simulations and found that both FAST and Parkes new Phased Array Feed surveys, focusing on intermediate Galactic latitudes, have the capacity to uncover several hundred new MSPs.

Keywords: pulsars: general

1. INTRODUCTION

Radio pulsars, which are rapidly rotating neutron stars (NSs) emitting radio pulses, provide an exceptional opportunity for investigating profound aspects of physics. This includes exploring gravitational theories in intensely strong fields (e.g., Venkatraman Krishnan et al. 2020; Kramer et al. 2021) and gaining insights into the state of matter under incredibly high densities

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(e.g., Demorest et al. 2010; Antoniadis et al. 2013; Özel & Freire 2016; Fonseca et al. 2021). Pulsars also enable us to investigate the characteristics of the interstellar medium (ISM; e.g., Coles et al. 2015; Abbate et al. 2020; Kumamoto et al. 2021; Zhang et al. 2023) and examine the formation and evolution of NSs within binary and other dense systems (e.g., Bhattacharya & van den Heuvel 1991). Among these pulsars, a particularly crucial group is the millisecond pulsars (MSPs), with spin periods usually shorter than approximately 20 milliseconds. The remarkable stability of their rotation allows for exceptional timing precision, enabling us to detect ultra-low frequency gravitational waves (e.g., Agazie et al. 2023; Antoniadis et al. 2023; Reardon et al. 2023a; Xu et al. 2023a). The extensive applications of pulsars in astrophysics have made the search for new pulsars a fundamental focus for current and future large radio telescopes (Nan 2006; Keane et al. 2015; Padmanabh et al. 2023; Wang et al. 2023).

While the majority of pulsars are situated near the Galactic plane, it is widely recognised that MSPs, or more generally "recycled" pulsars, exhibit significantly greater scale heights than regular pulsars (e.g., Levin et al. 2013). As we venture away from the Galactic plane, the density of ISM decreases, leading to reduced effects like scattering and dispersive smearing. This significant decrease in these effects enhances our ability to detect rapidly spinning MSPs, making our observations much more sensitive. Consequently, researchers have identified intermediate Galactic latitudes as the optimal region for MSP searches (Levin et al. 2013; McEwen et al. 2020). In the past, the Parkes High Time Resolution Universe (HTRU) survey (Keith et al. 2010) and drift-scan surveys conducted by various telescopes have covered these intermediate latitudes (e.g., Boyles et al. 2013; Deneva et al. 2013). Thanks to these surveys, the discovery of 79 MSPs has been achieved within $5^\circ < |gb| < 15^\circ$ (excluding globular clusters, see ATNF pulsar catalogue [1], Manchester et al. 2005).

Currently, the Five-hundred-meter Aperture Spherical Telescope (FAST) is carrying out two major surveys with a focus on radio pulsars, the Commensal Radio Astronomy FasT Survey (CRAFTS, Li et al. 2018a) and the Galactic Plane Pulsar Survey (GPPS, Han et al. 2021). So far, CRAFTS has discovered 179 radio pulsars, including 45 MSPs [2] (Qian et al. 2019; Zhang et al. 2019; Cameron et al. 2020; Cruces et al. 2021; Wang et al. 2021a,b; Tedila et al. 2022; Wen et al. 2022; Miao et al. 2023; Wu et al. 2023), and GPPS has discovered 618 radio pulsars, including 148 MSPs [3] (Han et al. 2021; Zhou et al. 2023; Su et al. 2023). While these two surveys complement each other and GPPS is expected to cover Galactic latitudes up to 10°, a large fraction of intermediate Galactic latitudes (10 to 15°) that are particularly rich in 'good-timer' MSPs, are still not covered with sufficient sensitivity. In this paper, we present the discovery of five pulsars in a pilot survey at intermediate Galactic latitudes and the results from our initial follow-up observations. In §Section 2 we describe the survey and the timing campaign. In §Section 3 we present the results and discuss their implications. Some perspectives are discussed in §Section 4.

2. OBSERVATIONS AND DATA REDUCTION

2.1. *A pilot survey at intermediate Galactic latitudes with FAST*

The 19-beam L-band focal plane array of FAST (Li et al. 2018b) was used to survey an area along the Galactic plane at a Galactic latitude of $gb = 5.2^\circ$. The observing band covers a frequency range from 1.05 to 1.45 GHz (Jiang et al. 2020). A total of 30 pointings were carried out and we listed their pointing centres in Table 1. We utilised the FAST snapshot observing mode (Han et al. 2021) for the survey, and therefore each pointing consists of four observations offset from each other to fully cover the region. The integration time of each observation is 390 s. The full pilot survey consists of 2280 beams. The FAST ROACH backend was used in its pulsar-search mode, with 4096 channels across 500 MHz of bandwidth and 49 μs sampling rate. The total intensity was recorded with 8-bit sampling.

A periodicity search was carried out with the pulsar searching software package *PRESTO* (Ransom 2001). The dispersion measure (DM) range that we searched was 0–1000 pc cm^{-3}. In order to account for possible orbital modulation of pulsar periodic signals, we searched for signals drifting by as much as $\pm 200/n_{\rm h}$ bins in the Fourier domain by setting $zmax = 200$ (Ransom et al. 2002), where $n_{\rm h}$ is the largest harmonic at which a signal is detected (up to 8 harmonics were summed). We also searched for single pulse candidates with a signal-to-noise ratio (S/N) larger than seven using the *single_pulse_search.py* routine for each de-dispersed time series and boxcar filtering parameters with filter widths ranging from 1 to 300 samples. Burst candidates were manually examined, and narrow band and impulsive

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[1] https://www.atnf.csiro.au/research/pulsar/psrcat/

[2] http://groups.bao.ac.cn/ism/english/CRAFTS/202210/t20221026_719407.html

[3] http://zmtt.bao.ac.cn/GPPS/GPPSnewPSR.html

radio-frequency interference (RFI) were manually removed.

Five pulsar candidates were detected with our periodicity search. Follow-up observations of these candidates were performed using FAST and the Parkes radio telescope, Murriyang. All five candidates were successfully confirmed. In Table 2, we presented the measured parameters of these pulsars.

2.2. *Follow-up timing observations*

Two of the bright pulsars, J1826−0049 and J1849+1001, were followed up with the Parkes telescope. The Ultra-Wideband Low (UWL) system (Hobbs et al. 2020) was used in the coherently de-dispersed search-mode where data were recorded with 2-bit sampling every 64 μs in each of the 1 MHz wide frequency channels covering a total bandwidth of 3328 MHz between 704 and 4032 MHz. Only the total intensity was recorded. The integration time is 1 hr for J1826−0049 and 2 hr for J1849+1001. PSRs J1837+0419 and J1839+0543 were observed and timed with FAST using the central beam of the 19-beam receiver. Data were recorded in the pulsar search mode with configurations the same as the survey. Full polarization information was recorded. The integration time for each pulsar is 240 s.

To derive coherent timing solutions, search-mode data were folded with the apparent spin period of each pulsar determined at each observing epoch using the DSPSR software package (van Straten & Bailes 2011) with a sub-integration length of 30 s. We manually excised data affected by narrowband and impulsive RFI for each sub-integration. Each observation was averaged in time to create sub-integrations with a length of a few minutes and pulse time of arrivals (ToAs) were measured for each sub-integration using the `pat` routine of PSRCHIVE software package (van Straten et al. 2012). Timing analysis was carried out using the TEMPO2 software package (Hobbs et al. 2006). We used the Barycentric Coordinate Time (TCB) units, TT(TAI) clock standard, and the JPL DE438 solar system ephemeris for our timing analysis.

For pulsars that a coherent timing solution can be obtained, we re-folded the search-mode data and averaged each observation in time and frequency to produce a high S/N pulse profile. ToAs were measured using these high S/N profiles and we repeated our timing analysis to measure their spin, astrometric, and binary parameters. Throughout our timing analysis, TEMPO2 fitting with ToA errors (known as 'MODE 1') was used and the weighted root-mean-square (Wrms) of timing residuals were reported in Fig. 2 and Table 2. To refine our DM measurements, for each pulsar we selected a high S/N observation and divided the bandwidth into four frequency subbands. We then measured a ToA from each subband and fitted for the DM using TEMPO2. Our timing results will be presented in Section 3.

To perform polarimetric calibration for FAST observations, we conducted noise diode observations prior to each observation. A 100% linearly polarized diode signal with a period of 0.100663296 s was injected into the receiver system as the telescope points towards a sky region offset by 10 arc-min from the target source (Jiang et al. 2020). The PAC routine of PSRCHIVE was used to calibrate the polarization of each observation. The Stokes parameters are in accordance with the astronomical conventions described by van Straten et al. (2010). Stokes V is defined as $I_{\rm LH} - I_{\rm RH}$, using the IEEE definition for the sense of circular polarization. The linear polarization and the position angle (PA) of linear polarization were calculated following Dai et al. (2015) After the polarimetic calibration, we searched for the Faraday Rotation Measure (RM) for each pulsar using the RMFIT routine of PSRCHIVE. We carried out a brute-force search for peak linear polarization with RMFIT in an RM range of $\pm 1000\,{\rm rad\,m^{-2}}$.

3. RESULTS

With 13.5 hr of observing time that covers 4.7 square degrees of area, we discovered five new pulsars and detected all six known pulsars in this region. Two of the new discoveries (PSRs J1826−0049 and J1852+1200) are MSPs with spin periods shorter than 20 ms. Three of them (PSRs J1826−0049, J1849+1001, and J1839+0543) are confirmed to be in binary systems. So far, coherent timing solutions have been obtained for three pulsars (J1826−0049, J1849+1001, and J1837+0419). PSR J1828−0003 was previously discovered as a Rotating RAdio Transient (RRAT; Zhou et al. 2023) and we detected its periodic signals with a period of 3.8071 s. In the following sections, we will discuss each pulsar separately.

3.1. *J1826−0049*

PSR J1826−0049 is an MSP with a period of 4.59 ms and a DM of 42.67 $\rm pc\,cm^{-3}$. In Fig. 1 we show its time and frequency averaged pulse profile using a Parkes observation with 1 hr of integration. With follow-up Parkes timing observations, we successfully obtained a coherent timing solution for PSR J1826−0049 (Table 2). Best-fit timing residuals are shown in Fig. 2. Our current timing showed that it is in a binary system with an orbital period of 6.7 days. The minimum, median, and maximum companion mass are 0.2332, 0.2738, and 0.6185 $\rm M_{\odot}$, respectively. Here we assumed the pulsar

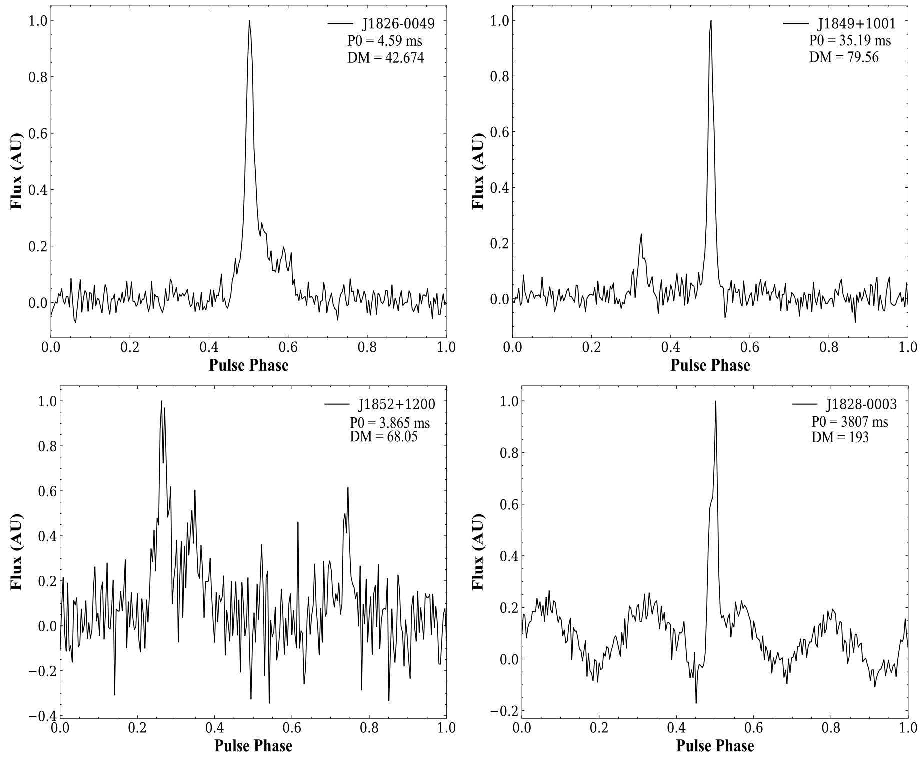

Figure 1. Time and frequency averaged pulse profiles of PSRs J1826−0049, J1849+1001, J1852+120 and J1828−0003.

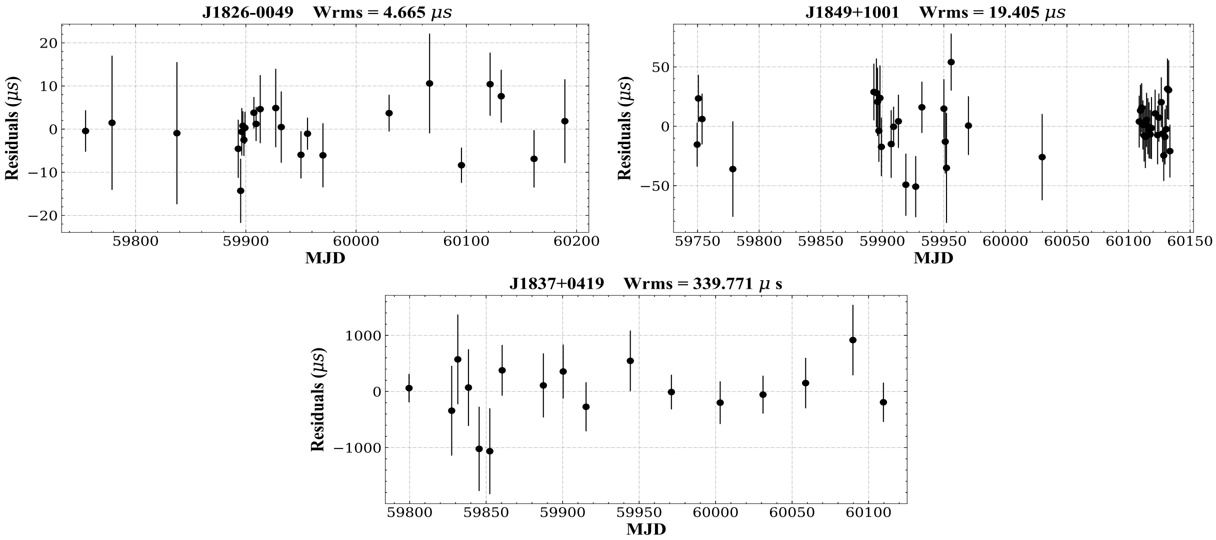

Figure 2. Timing residuals for three new pulsars as a function of MJD. The weighted root-mean-square (Wrms) of the timing residuals of each pulsar is reported.

mass to be $M_\mathrm{p} = 1.35\,\mathrm{M}_\odot$, and the minimum, median, and maximum companion masses were estimated with an inclination angle of $i = 90$, 60 and 26 degrees, respectively (Lorimer & Kramer 2004). This suggests that the companion to PSR J1826−0049 is likely a white dwarf (WD). Our timing analysis yields a large proper motion of $346(94)\,\mathrm{mas\,yr^{-1}}$ for this system. However, for a DM distance of 1.3 kpc (Yao et al. 2017), this gives an apparent acceleration due to the proper motion (the so-called Shklovskii effect, Shklovskii 1970) of $\sim 1.1 \times 10^{-7}\,\mathrm{m\,s^{-2}}$, which corresponds to an apparent $\dot{P}_{Shk}$ of $\sim 1.7 \times 10^{-18}\,\mathrm{s\,s^{-1}}$. This is almost two orders of magnitude larger than the measured $\dot{P}$ of $\sim 2.3 \times 10^{-20}\,\mathrm{s\,s^{-1}}$, suggesting that the proper motion was significantly overestimated. Continued timing

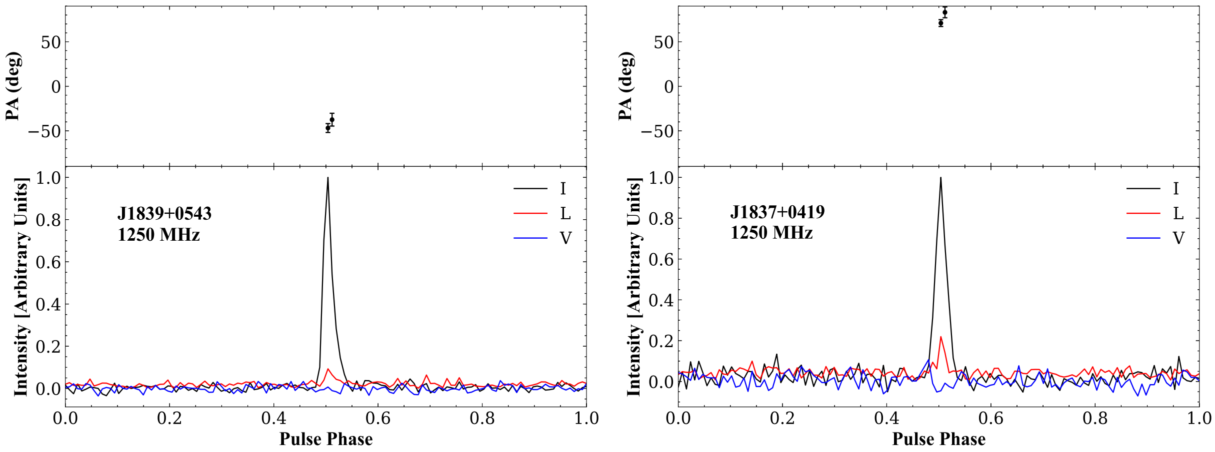

Figure 3. Polarization profiles of PSRs J1839+0543 and J1837+0419. The black, red and blue lines show the total intensity, linear polarisation and circular polarisation, respectively.

observations and a longer timing baseline are required to constrain the proper motion of this pulsar.

3.2. *J1849+1001*

PSR J1849+1001 has a spin period of 35.189 ms and a DM of 79.56 $\mathrm{pc\,cm^{-3}}$. In Fig. 1 we show its time and frequency averaged pulse profile using a Parkes observation with 2 hr of integration. We carried out a high cadence timing campaign with Parkes in 2022 and successfully obtained a coherent timing solution for PSR J1849+1001 (Table 2). Best-fit timing residuals are shown in Fig. 2. Our current timing showed that it is in a binary system with an orbital period of 26.16 days. The minimum, median and maximum companion mass are 0.8902, 1.0873 and 3.3440 $\mathrm{M_{\odot}}$, respectively. The system's low eccentricity (e $\sim$ 0.008) excludes the possibility that this is a double NS system; it is very likely to be a member of the sub-class of mildly-recycled pulsars and has a massive WD companion (e.g., Gautam et al. 2022).

3.3. *J1837+0419*

PSR J1837+0419 is an isolated pulsar with a spin period of 504.74 ms and a DM of 174.75 $\mathrm{pc\,cm^{-3}}$. PSR J1837+0419 was followed up and timed with FAST and a coherent timing solution has been obtained (Table 2). Best-fit timing residuals are shown in Fig. 2. Our current timing showed that its spin-down rate is $\dot{\nu} = -5.33(4) \times 10^{-15}\,\mathrm{Hz\,s^{-1}}$, which indicates a characteristic age of $\tau_{\mathrm{c}} = 6\,\mathrm{Myr}$ and a surface magnetic field strength of $B_{\mathrm{s}} = 8.4 \times 10^{11}$ G. These suggest that PSR J1837+0419 is a normal pulsar. With the timing solution, we co-added all FAST observations and obtained a high S/N pulse profile, which enabled us to measure its rotation measure (RM) to be $156 \pm 17\,\mathrm{rad\,cm^{-2}}$. In Fig. 3 we show the time and frequency averaged polarisation profile of PSR J1837+0419.

3.4. *J1839+0543*

PSR J1839+0543 has a spin period of 57.927 ms and a DM of 113.83 $\mathrm{pc\,cm^{-3}}$. While a coherent timing solution has not been obtained so far, our follow-up FAST observations confirmed that it is in a binary system with an orbital period of 28.517 days. The minimum, median and maximum companion mass are 0.87, 1.06 and 3.22 $\mathrm{M_{\odot}}$, respectively. Similar to J1849+1001, the eccentricity of this system (e $\sim$ 0.004) is low and is likely to be a mildly-recycled pulsar with a massive WD companion. Using measured pulsar parameters, we co-added all FAST observations and obtained a high S/N pulse profile, which enabled us to measure its RM to be $211 \pm 20\,\mathrm{rad\,cm^{-2}}$. In Fig. 3 we show the time and frequency averaged polarisation profile of PSR J1839+0543.

3.5. *J1828−0003*

PSR J1828−0003 was previously discovered as an RRAT by the FAST GPPS survey (Zhou et al. 2023). We detected nine single pulses ($> 9\sigma$) at a DM of 193 $\mathrm{pc\,cm^{-3}}$ from this pulsar through our single-pulse search. In Fig. 4, we show our initial detection of single pulses of this pulsar. We searched for periodicity with detected single pulses and identified a period of 3.8 s. Subsequently, we folded our FAST data with the period and successfully detected its pulsed emission (shown in Fig. 1). This confirmed that PSR J1828−0003 is likely to be an isolated normal pulsar with RRAT-like activities.

3.6. *J1852+1200*

PSR J1852+1200 is an MSP with a spin period of 3.866 ms and a DM of 68.05 $\mathrm{pc\,cm^{-3}}$. While FAST ob-

Table 1. A List of covers by the survey at intermediate Galactic latitudes.

Pointing	GL (degree)	GB (degree)	RA (J2000) (hh:mm:ss)	DEC (J2000) (±dd:mm:ss)
1	26.215	5.233	18:20:30.47	−03:33:31.4
2	27.025	5.233	18:22:00.38	−02:50:38.6
3	27.835	5.233	18:23:29.97	−02:07:43.7
4	28.645	5.233	18:24:59.24	−01:24:46.8
5	29.455	5.233	18:26:28.24	−00:41:47.9
6	30.265	5.233	18:27:57.00	+00:01:12.7
7	31.075	5.233	18:29:25.23	+00:44:15.1
8	31.885	5.233	18:30:53.86	+01:27:19.2
9	32.695	5.233	18:32:22.04	+02:10:24.7
10	33.505	5.233	18:33:50.07	+02:53:31.6
11	34.315	5.233	18:35:17.99	+03:36:39.8
12	35.125	5.233	18:36:45.83	+04:19:49.1
13	35.935	5.233	18:38:13.61	+05:02:59.5
14	36.745	5.233	18:39:41.36	+05:46:10.9
15	37.555	5.233	18:41:09.11	+06:29:23.1
16	38.365	5.233	18:42:36.89	+07:12:36.0
17	39.175	5.233	18:44:04.72	+07:55:49.6
18	39.985	5.233	18:45:32.64	+08:39:03.7
19	40.795	5.233	18:47:00.67	+09:22:18.2
20	41.605	5.233	18:48:28.83	+10:05:33.1
21	42.415	5.233	18:49:57.17	+10:48:48.2
22	43.225	5.233	18:51:25.70	+11:32:03.4
23	44.035	5.233	18:52:54.46	+12:15:18.6
24	44.845	5.233	18:54:23.48	+12:58:33.6
25	45.645	5.233	18:55:52.79	+13:41:48.5
26	46.465	5.233	18:57:22.41	+14:25:03.0
27	47.275	5.233	18:58:52.39	+15:08:17.1
28	48.085	5.233	19:00:22.75	+15:51:30.7
29	48.895	5.233	19:01:53.52	+16:34:43.6
30	49.705	5.233	19:03:24.74	+17:17:55.7

servations have confirmed the discovery, timing observations of this pulsar have not yet commenced, leaving its binary system status unknown.

4. DISCUSSION AND CONCLUSION

It is generally believed that MSPs in binary systems have been "recycled" by the accretion of matter and transfer of angular momentum from their binary companion, spinning up their rotation to millisecond periods (e.g., Bhattacharya & van den Heuvel 1991). In some cases, this accretion process can stop before the pulsar gets fully recycled, leading to so-called "mildly-recycled" pulsars with rotational periods between 20 and 100 ms. This process happens mostly if the companion stars are more massive: such stars evolve more rapidly and therefore any accretion episodes will generally be much shorter (Berthereau et al. 2023). Two of our discoveries, PSRs J1849+1001 and J1839+0543, fall under this category.

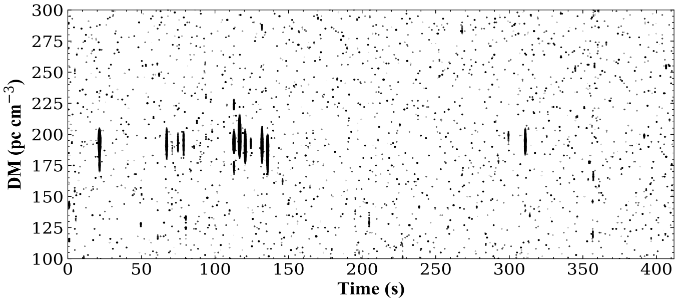

Figure 4. Detected single pulses of PSR J1828−0003. Each circle represents a detection above a threshold of 5σ. The diameter of each circle is proportional to the significance of the detection.

Their massive companions ($> 1\mathrm{M}_{\odot}$) and low orbital eccentricities suggest that PSRs J1849+1001 and J1839+0543 can be classified as an intermediate-mass binary pulsar (IMBP, see Tauris et al. 2012). More interestingly, our current analysis suggests that the WD companion of these two pulsars could be significantly more massive than $1\mathrm{M}_{\odot}$. This means that PSRs J1849+1001 and J1839+0543 could be very similar to PSR J2045+3633 (McKee et al. 2020). Precise measurements of their companion masses and orbital parameters are therefore important for us to understand their evolutionary history and the general evolution of IMBPs.

Because of their massive companions and non-negligible orbital eccentricity, PSRs J1849+1001 and J1839+0543 could be ideal systems to measure "Post-Keplerian" (PK) parameters through pulsar timing (e.g., Damour & Taylor 1992). If we assume that GR describes adequately these effects, then two PK parameters suffice to determine the masses of both components of a binary. Such measurements are of great importance for probing the equation of state of neutron stars. Currently, our timing baseline of approximately one year is too short to measure any relativistic perturbations to the pulsar's orbit, and longer timing with high precision is required.

With sub-arcsec precision timing positions of PSRs J1826−0049 and J1849+1001, we searched for their multi-wavelength counterparts in publicly available optical, X-ray and γ-ray surveys. No counterparts have been identified. Given their substantial Galactic latitudes, these binary systems represent promising candidates for dedicated deep optical observations. In addi-

Table 2. Parameters of six pulsars. The minimum, median, and maximum companion masses for binary systems were estimated assuming a pulsar mass of 1.35 $M_{\odot}$ and an inclination angle of 90, 60, and 26 degrees, respectively.

Pulsars with timing solutions			
	J1826−0049	J1849+1001	J1837+0419
RAJ (J2000)	18:26:16.546(1)	18:49:00.7303(4)	18:37:34.328(8)
DECJ (J2000)	−00:49:50.07(5)	+10:01:01.07(2)	+04:19:26.2(6)
ν (Hz)	217.8248734478(2)	28.41772282880(1)	1.98120365183(4)
$\dot{\nu}$ (Hz/s)	$-1.1(2) \times 10^{-15}$	$-4(1) \times 10^{-17}$	$-5.31(2) \times 10^{-15}$
PMRA (mas/yr)	149(43)		
PMDEC (mas/yr)	312(102)		
EPOCH (MJD)	59971.98	59950.05	59944.24
Time span (MJD)	59754−60189	59749−60133	59799−60109
DM ($\mathrm{cm^{-3}\,pc}$)	42.674(8)	79.56(1)	174.750(4)
RM ($\mathrm{rad\,m^{-2}}$)			156(17)
Reduced χ^2	1.5628	0.8893	0.8381
Wrms (μs)	4.7	19.4	339.8
Binary parameters			
	ELL1 model	DD model	
P_{b} (days)	6.73497259(4)	26.1656358(1)	
χ (ls)	5.978283(2)	44.751772(7)	
T_{ASC} (MJD)	59972.1346047(5)		
T_0 (MJD)		59932.3275(1)	
EPS1	$-1.0(8) \times 10^{-6}$		
EPS2	$1.1(7) \times 10^{-6}$		
OM		336.079(1)	
ECC		0.0080940(2)	
Derived parameters			
GL (degree)	29.313	41.596	35.211
GB (degree)	5.215	5.082	5.051
$\dot{E}$ (erg $\mathrm{s^{-1}}$)	9.5×10^{33}	4.5×10^{31}	4.1×10^{32}
B_{s} (G)	3.3×10^{8}	1.3×10^{9}	8.4×10^{11}
τ_{c} (Myr)	3000	11500	5.9
$\mathrm{DIST_{YMW16}}$ (kpc)	1.3	3.2	9.8
P (ms)	4.59084393858(5)	35.18930795490(2)	504.74366886(1)
$\dot{P}$ ($\mathrm{s\,s^{-1}}$)	$2.3(4) \times 10^{-20}$	$5(1) \times 10^{-20}$	$1.352(7) \times 10^{-15}$
Companion mass ($\mathrm{M_{\odot}}$)	$0.2332 < 0.2738 < 0.6185$	$0.8902 < 1.0873 < 3.3440$	
Pulsars without timing solutions			
	J1839+0543	J1852+1200	J1828−0003
RAJ (J2000)	18:39:00(20)	18:52:58(20)	18:28:44(20)
DECJ (J2000)	+05:43(2)	+12:00(2)	−00:03(2)
ν (Hz)	17.26282301(1)	258.687554(7)	0.262666(7)
EPOCH (MJD)	58447.77	60127	59310
Time span (MJD)	58643−59792		
DM ($\mathrm{cm^{-3}\,pc}$)	113.83(1)	68.05(5)	193(3)
RM ($\mathrm{rad\,m^{-2}}$)	211(20)		
Binary parameters			
P_{b} (days)	28.517(1)		
χ (ls)	46.55(3)		
T_0 (MJD)	59821.97(6)		
OM	166(8)		
ECC	0.0039(5)		
Derived parameters			
GL (degree)	36.620	43.812	30.292
GB (degree)	5.362	5.106	5.027
$\mathrm{DIST_{YMW16}}$ (kpc)	5.3	2.7	10.6
P (ms)	57.927974(5)	3.8657782(1)	3807.1(1)
Companion mass ($\mathrm{M_{\odot}}$)	$0.8662 < 1.0568 < 3.2190$		

tion, our current measurement of the $\dot{P}$ of J1826−0049 gives a large spin-down power of $\dot{E} \approx 9.5 \times 10^{33}\,\mathrm{erg\,s^{-1}}$, suggesting that this it could also be an X-ray and/or γ-ray pulsar.

One of the motivations to find more MSPs is to improve the sensitivity of current pulsar timing arrays (PTAs) to detect ultra-low frequency gravitational waves (Xu et al. 2023b; Reardon et al. 2023b). PSR J1826−0049 is a comparatively bright MSP, which can be detected with high S/N by FAST in ~ 5 min and by Parkes in ~ 1 hr. Therefore, it can be a good candidate for (PTAs) in the future. Our continued timing of this pulsar at Parkes will allow us to refine its parameters and evaluate its timing precision. The other MSP, J1852+1200, is much fainter than J1826−0049 and can only be timed by large telescopes like FAST.

The discovery of two MSPs (PSRs J1826−0049 and J1852+1200) and two recycled pulsars (PSRs J1849+1001 and J1839+0543) in our pilot survey further stressed the importance of sensitive pulsar surveys at intermediate Galactic latitudes. To demonstrate this, we utilised the *PSRPOPPY* software package (Bates et al. 2014) to predict the number of MSP discoveries for FAST surveys covering $5^\circ < |gb| < 10^\circ$ and $10^\circ < |gb| < 15^\circ$, assuming that the integration time per pointing is identical to our pilot survey (i.e. 390 s). Here, we followed the procedure described in Dai et al. (2017) to perform the population simulation and used MSP Galactic, spin period, luminosity, and spectral distributions presented by previous studied (e.g., Yusifov & Küçük 2004; Faucher-Giguère & Kaspi 2006; Lorimer et al. 2006; Levin et al. 2013; Lorimer et al. 2015). Our simulations showed that ~ 616 MSPs are expected to be detected by FAST within $5^\circ < |gb| < 10^\circ$, and ~ 322 MSPs within $10^\circ < |gb| < 15^\circ$. So far, 25 and 12 Galactic MSPs have been discovered in these two regions, respectively.

A new cryogenically cooled Phase Array Feed (cryoPAF) is currently being commissioned at the Parkes radio telescope. The cryoPAF has a field-of-view (FoV) four times larger than the legacy Parkes multi-beam receiver and therefore allows us to carry out much deeper pulsar surveys with the same amount of observing time as previous surveys. We carried out a simulation assuming that the cryoPAF repeats the Parkes HTRU mid-lat survey ($3.5^\circ < |gb| < 15^\circ$) with an integration time of 2160 s, which is four times longer than that of HTRU mid-lat (Keith et al. 2010). Our simulation indicates that the cryoPAF survey is anticipated to identify approximately ~ 160 MSPs. Currently, 85 Galactic MSPs have been detected in this specific area. Given the limited overlap in the sky coverage between FAST and Parkes, conducting a fresh survey at intermediate Galactic latitudes using the cryoPAF technology holds substantial promise and potential.

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REFERENCES

Abbate, F., Possenti, A., Tiburzi, C., et al. 2020, Nature Astronomy, 4, 704, doi: 10.1038/s41550-020-1030-6

Agazie, G., Anumarlapudi, A., Archibald, A. M., et al. 2023, ApJL, 951, L8, doi: 10.3847/2041-8213/acdac6

Antoniadis, J., Freire, P. C. C., Wex, N., et al. 2013, Science, 340, 448, doi: 10.1126/science.1233232

Antoniadis, J., Arumugam, P., Arumugam, S., et al. 2023, arXiv e-prints, arXiv:2306.16214, doi: 10.48550/arXiv.2306.16214

Bates, S. D., Lorimer, D. R., Rane, A., & Swiggum, J. 2014, MNRAS, 439, 2893, doi: 10.1093/mnras/stu157

Berthereau, A., Guillemot, L., Freire, P. C. C., et al. 2023, A&A, 674, A71, doi: 10.1051/0004-6361/202346228

Bhattacharya, D., & van den Heuvel, E. P. J. 1991, PhR, 203, 1, doi: 10.1016/0370-1573(91)90064-S

Boyles, J., Lynch, R. S., Ransom, S. M., et al. 2013, ApJ, 763, 80, doi: 10.1088/0004-637X/763/2/80

Cameron, A. D., Li, D., Hobbs, G., et al. 2020, MNRAS, 495, 3515, doi: 10.1093/mnras/staa1328

Coles, W. A., Kerr, M., Shannon, R. M., et al. 2015, ApJ, 808, 113, doi: 10.1088/0004-637X/808/2/113

Cruces, M., Champion, D. J., Li, D., et al. 2021, MNRAS, 508, 300, doi: 10.1093/mnras/stab2540

Dai, S., Johnston, S., & Hobbs, G. 2017, MNRAS, 472, 1458, doi: 10.1093/mnras/stx2033

Dai, S., Hobbs, G., Manchester, R. N., et al. 2015, MNRAS, 449, 3223, doi: 10.1093/mnras/stv508

Damour, T., & Taylor, J. H. 1992, PhRvD, 45, 1840, doi: 10.1103/PhysRevD.45.1840

Demorest, P. B., Pennucci, T., Ransom, S. M., Roberts, M. S. E., & Hessels, J. W. T. 2010, Nature, 467, 1081, doi: 10.1038/nature09466

Deneva, J. S., Stovall, K., McLaughlin, M. A., et al. 2013, ApJ, 775, 51, doi: 10.1088/0004-637X/775/1/51

Faucher-Giguère, C.-A., & Kaspi, V. M. 2006, ApJ, 643, 332, doi: 10.1086/501516

Fonseca, E., Cromartie, H. T., Pennucci, T. T., et al. 2021, ApJL, 915, L12, doi: 10.3847/2041-8213/ac03b8

Gautam, T., Freire, P. C. C., Batrakov, A., et al. 2022, A&A, 668, A187, doi: 10.1051/0004-6361/202244699

Han, J. L., Wang, C., Wang, P. F., et al. 2021, Research in Astronomy and Astrophysics, 21, 107, doi: 10.1088/1674-4527/21/5/107

Hobbs, G., Manchester, R. N., Dunning, A., et al. 2020, PASA, 37, e012, doi: 10.1017/pasa.2020.2

Hobbs, G. B., Edwards, R. T., & Manchester, R. N. 2006, MNRAS, 369, 655, doi: 10.1111/j.1365-2966.2006.10302.x

Jiang, P., Tang, N.-Y., Hou, L.-G., et al. 2020, Research in Astronomy and Astrophysics, 20, 064, doi: 10.1088/1674-4527/20/5/64

Keane, E., Bhattacharyya, B., Kramer, M., et al. 2015, in Advancing Astrophysics with the Square Kilometre Array (AASKA14), 40, doi: 10.22323/1.215.0040

Keith, M. J., Jameson, A., van Straten, W., et al. 2010, MNRAS, 409, 619, doi: 10.1111/j.1365-2966.2010.17325.x

Kramer, M., Stairs, I. H., Manchester, R. N., et al. 2021, Physical Review X, 11, 041050, doi: 10.1103/PhysRevX.11.041050

Kumamoto, H., Dai, S., Johnston, S., et al. 2021, MNRAS, 501, 4490, doi: 10.1093/mnras/staa3910

Levin, L., Bailes, M., Barsdell, B. R., et al. 2013, MNRAS, 434, 1387, doi: 10.1093/mnras/stt1103

Li, D., Wang, P., Qian, L., et al. 2018a, IEEE Microwave Magazine, 19, 112, doi: 10.1109/MMM.2018.2802178

—. 2018b, IEEE Microwave Magazine, 19, 112, doi: 10.1109/MMM.2018.2802178

Lorimer, D. R., & Kramer, M. 2004, Handbook of Pulsar Astronomy, Vol. 4

Lorimer, D. R., Faulkner, A. J., Lyne, A. G., et al. 2006, MNRAS, 372, 777, doi: 10.1111/j.1365-2966.2006.10887.x

Lorimer, D. R., Esposito, P., Manchester, R. N., et al. 2015, MNRAS, 450, 2185, doi: 10.1093/mnras/stv804

Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993, doi: 10.1086/428488

McEwen, A. E., Spiewak, R., Swiggum, J. K., et al. 2020, ApJ, 892, 76, doi: 10.3847/1538-4357/ab75e2

McKee, J. W., Freire, P. C. C., Berezina, M., et al. 2020, MNRAS, 499, 4082, doi: 10.1093/mnras/staa2994

Miao, C. C., Zhu, W. W., Li, D., et al. 2023, MNRAS, 518, 1672, doi: 10.1093/mnras/stac1305

Nan, R. 2006, Science in China: Physics, Mechanics and Astronomy, 49, 129, doi: 10.1007/s11433-006-0129-9

Özel, F., & Freire, P. 2016, ARA&A, 54, 401, doi: 10.1146/annurev-astro-081915-023322

Padmanabh, P. V., Barr, E. D., Sridhar, S. S., et al. 2023, MNRAS, 524, 1291, doi: 10.1093/mnras/stad1900

Qian, L., Pan, Z., Li, D., et al. 2019, Science China Physics, Mechanics, and Astronomy, 62, 959508, doi: 10.1007/s11433-018-9354-y

Ransom, S. M. 2001, PhD thesis, Harvard University

Ransom, S. M., Eikenberry, S. S., & Middleditch, J. 2002, AJ, 124, 1788, doi: 10.1086/342285

Reardon, D. J., Zic, A., Shannon, R. M., et al. 2023a, ApJL, 951, L6, doi: 10.3847/2041-8213/acdd02

—. 2023b, ApJL, 951, L6, doi: 10.3847/2041-8213/acdd02

Shklovskii, I. S. 1970, Soviet Ast., 13, 562

Su, W. Q., Han, J. L., Wang, P. F., et al. 2023, arXiv e-prints, arXiv:2305.16754, doi: 10.48550/arXiv.2305.16754

Tauris, T. M., Langer, N., & Kramer, M. 2012, MNRAS, 425, 1601, doi: 10.1111/j.1365-2966.2012.21446.x

Tedila, H. M., Yuen, R., Wang, N., et al. 2022, ApJ, 929, 171, doi: 10.3847/1538-4357/ac5f42

van Straten, W., & Bailes, M. 2011, PASA, 28, 1, doi: 10.1071/AS10021

van Straten, W., Demorest, P., & Oslowski, S. 2012, Astronomical Research and Technology, 9, 237, doi: 10.48550/arXiv.1205.6276 van Straten, W., Manchester, R. N., Johnston, S., & Reynolds, J. E. 2010, PASA, 27, 104, doi: 10.1071/AS09084

Venkatraman Krishnan, V., Bailes, M., van Straten, W., et al. 2020, Science, 367, 577, doi: 10.1126/science.aax7007

Wang, N., Xu, Q., Ma, J., et al. 2023, Science China Physics, Mechanics, and Astronomy, 66, 289512, doi: 10.1007/s11433-023-2131-1

Wang, S., Zhu, W.-W., Li, D., et al. 2021a, Research in Astronomy and Astrophysics, 21, 251, doi: 10.1088/1674-4527/21/10/251

Wang, S. Q., Wang, J. B., Wang, N., et al. 2021b, ApJL, 922, L13, doi: 10.3847/2041-8213/ac365c

Wen, Z. G., Yuan, J. P., Wang, N., et al. 2022, ApJ, 929, 71, doi: 10.3847/1538-4357/ac5d5d

Wu, Q. D., Yuan, J. P., Wang, N., et al. 2023, MNRAS, 522, 5152, doi: 10.1093/mnras/stad1323

Xu, H., Chen, S., Guo, Y., et al. 2023a, Research in Astronomy and Astrophysics, 23, 075024, doi: 10.1088/1674-4527/acdfa5

—. 2023b, Research in Astronomy and Astrophysics, 23, 075024, doi: 10.1088/1674-4527/acdfa5

Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 29, doi: 10.3847/1538-4357/835/1/29

Yusifov, I., & Küçük, I. 2004, A&A, 422, 545, doi: 10.1051/0004-6361:20040152

Zhang, D., Tao, Z., Yuan, M., et al. 2023, SCIENCE CHINA Physics, Mechanics & Astronomy, 66, 299511, doi: https://doi.org/10.1007/s11433-023-2138-5

Zhang, L., Li, D., Hobbs, G., et al. 2019, ApJ, 877, 55, doi: 10.3847/1538-4357/ab1849

Zhou, D. J., Han, J. L., Xu, J., et al. 2023, arXiv e-prints, arXiv:2303.17279, doi: 10.48550/arXiv.2303.17279