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TIMING OF FIVE PALFA-DISCOVERED MILLISECOND PULSARS

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ABSTRACT

We report the discovery and timing results for five millisecond pulsars (MSPs) from the Arecibo PALFA survey: PSRs J1906+0055, J1914+0659, J1933+1726, J1938+2516, and J1957+2516. Timing observations of the five pulsars were conducted with the Arecibo and Lovell telescopes for time spans ranging from 1.5 to 3.3 years. All of the MSPs except one (PSR J1914+0659) are in binary systems with low eccentricities. PSR J1957+2516 is likely a redback pulsar, with a $\sim$0.1 $M_\odot$ companion and possible eclipses that last $\sim$10% of the orbit. The position of PSR J1957+2516 is also coincident with a near-infrared source. All five MSPs are distant (>3.1 kpc) as determined from their dispersion measures, and none of them show evidence of γ-ray pulsations in a fold of *Fermi Gamma-Ray Space Telescope* data. These five MSPs bring the total number of MSPs discovered by the PALFA survey to 26 and further demonstrate the power of this survey in finding distant, highly dispersed MSPs deep in the Galactic plane.

Key words: pulsars: general – pulsars: individual (PSR J1906+0055, PSR J1914+0659, PSR J1933+1726, PSR J1938+2516, J1957+2516)

1. INTRODUCTION

In recent years, several large-scale pulsar surveys have been undertaken to search for new pulsars (Cordes et al. 2006; Keith et al. 2010; Barr et al. 2013; Boyles et al. 2013; Deneva et al. 2013; Coenen et al. 2014; Stovall et al. 2014). One of the drivers for such surveys is the discovery of millisecond pulsars (MSPs). MSPs are formed through accretion from a companion during an X-ray binary phase (Alpar et al. 1982; Bhattacharya & van den Heuvel 1991) in which the pulsar is "recycled." This accretion phase spins the pulsar up to very fast rotational rates (spin periods $P \lesssim 30$ ms). Such pulsars are useful for a variety of physical applications. Examples include tests of theories of gravity using MSP–white dwarf systems such as PSR J1738+0333 and PSR J0348+0432 (Freire et al. 2012; Antoniadis et al. 2013) and triple systems like PSR J0337+1715 (Ransom et al. 2014); tests of general relativity using double neutron star systems, such as J0737−3039 (Kramer et al. 2006) and PSR B1913+16 (Weisberg et al. 2010); the study of binary systems such as eccentric MSPs like PSRs J1903+0327 (Champion et al. 2008) and J1950+2414 (Knispel et al. 2015) which are interesting due to their peculiar binary evolution; and constraining the equation of state of dense matter using measurements of neutron star masses (Demorest et al. 2010; Antoniadis et al. 2013). Another major driver for the discovery of new MSPs is the effort to detect gravitational wave emission using an array of pulsars (NANOGrav Collaboration et al. 2015; Lentati et al. 2015; Reardon et al. 2016). The large-scale pulsar surveys mentioned above, combined with targeted searches of unidentified gamma-ray sources from the *Fermi Gamma-Ray Space Telescope* (e.g., Hessels et al. 2011; Keith et al. 2011; Ransom et al. 2011; Kerr et al. 2012), have resulted in the discovery of about 90 new MSPs in the past 5 years, an increase of 40% in the known Galactic MSP population. A subset of the newly discovered sources are eclipsing systems that appear to fall into two categories (e.g., Freire 2005; Roberts 2012). The first category, known as black widow systems, has very low mass, degenerate companions ($\lesssim 0.05\, M_\odot$) believed to be the result of ablation by the pulsar. The second, known as redback systems, has low to moderate mass, non-degenerate companions ($M \sim 0.15 - 0.7\, M_\odot$).

The PALFA survey (Cordes et al. 2006; Lazarus et al. 2015) is an ongoing search for new pulsars and transients in the Galactic plane ($|b| < 5°$) that is accessible to the Arecibo Observatory William E. Gordon 305 m Telescope using the ALFA 7-beam receiver. The survey consists of an inner-Galaxy region ($32° \lesssim l \lesssim 77°$) and an outer Galaxy region ($168° \lesssim l \lesssim 214°$). The relatively high observing frequency used in the survey (1.4 GHz) mitigates the deleterious effects introduced by the interstellar medium (ISM) that can prevent detection of rapidly spinning pulsars. This makes the PALFA survey well suited to discovering highly dispersed (distant) MSPs in the Galactic plane. Hence, PALFA is providing a view of the Galactic MSP population that complements what is being found at high Galactic latitudes by all-sky and targeted searches. PALFA began in 2004 and to date has discovered 165 radio pulsars (Cordes et al. 2006; Nice et al. 2013; Lazarus et al. 2015), including 26 MSPs (e.g., Champion et al. 2008; Knispel et al. 2010, 2011; Crawford et al. 2012; Deneva et al. 2012; Allen et al. 2013; Knispel et al. 2015; Scholz et al. 2015) and the so far unique repeating fast radio burst (Spitler et al. 2014, 2016).

Here we present the discovery and follow-up timing of five MSPs found in the PALFA survey: PSRs J1906+0055, J1914+0659, J1933+1726, J1938+2012, and J1957+2516. In Section 2, we describe the observations used to discover and time these systems. In Section 3, we describe the details of each pulsar system. In Section 4, we present our conclusions.

2. OBSERVATIONS AND ANALYSIS

2.1. Discovery

The MSPs described here were discovered in the inner-Galaxy region of the PALFA survey between 2010 September and 2012 September. During this time, the PALFA survey used the Mock spectrometers[25] to record data from the 7-beam ALFA receiver centered at 1375 MHz with 322.617 MHz of bandwidth across 960 channels and a sample time of 65.476 μs. PALFA uses 268 s integrations per pointing in the inner-Galaxy. Additional details can be found in Lazarus et al. (2015).

The PALFA survey uses three pipelines to search for radio pulsars: (1) a full-resolution[26] `PRESTO`-based pipeline (Lazarus et al. 2015), (2) the Einstein@Home pulsar search pipeline (Allen et al. 2013), and (3) a `PRESTO`-based reduced-time-resolution "Quicklook" pipeline (Stovall 2013). The five MSPs presented here were all discovered using pipeline (1) on the Guillimin supercomputer operated for Compute Canada by McGill University, so it is the only pipeline we describe in some detail.

[25] http://www.naic.edu/~astro/mock.shtml

[26] http://www.cv.nrao.edu/~sransom/presto/

Prior to searching the data for pulsars, pipeline (1) performs radio frequency interference (RFI) excision which consists of multiple components. The first removes known RFI that is specific to electronics at the Arecibo Observatory. Then narrow-band RFI is identified in both the time- and frequency-domain using `PRESTO`'s `rfifind` routine. The narrow-band RFI is masked out of subsequent processing. Next, broadband signals are identified by analyzing the DM = 0 pc cm^{-3} timeseries. Bad time intervals are identified as samples whose values are more than six times larger than the local standard deviation. Such samples are replaced with the local median bandpass. At this stage, the data are de-dispersed into trial dispersion measures (DMs) ranging from 0 to $\sim$10,000 pc cm^{-3}. The DM steps were chosen to balance the contributions to pulse broadening from the sample duration, the despersive smearing within a single frequency channel, the dispersive smearing within a frequency sub-band, and the dispersive smearing due to the finite DM step size. We used the `DDplan.py` tool from `PRESTO` to determine the step sizes versus trial DM. The minimum step size was chosen by allowing smearing up to 0.1 ms. The resulting maximum DM smearing is about 0.1 ms at DMs of a few tens of pc cm^{-3}, increases to 1 ms for DMs of a few hundred pc cm^{-3}, and reaches 10 ms for DMs of about 10,000 pc cm^{-3}. After de-dispersion, two additional RFI excision steps are performed. The first is to remove "red" noise from each de-dispersed time-series using `PRESTO`'s `rednoise` routine which performs a median removal using logarithmically increasing block sizes in the frequency domain. The second is to remove from the power spectrum, Fourier bins of RFI identified in lists of identified RFI that are generated dynamically from the combined ALFA beams and for each beam individually from the entire observing session, which typically consist of about 30 pointings. Each de-dispersed timeseries is searched for periodic signals using common Fourier search techniques and for individual pulses in the time domain using the `PRESTO` software package (Ransom et al. 2002). The periodic signal search has two components: the first is a zero-acceleration search and the second searches for signals with constant accelerations up to $\sim$1650 m s^{-2} (Lazarus et al. 2015). The best candidates (roughly 100 per search pointing) are folded into diagnostic plots for further evaluation. Due to the large number of candidates that are generated by this pipeline, we have investigated multiple ways of sorting through them. One method uses machine learning algorithms to sort through the candidates using image pattern recognition (Zhu et al. 2014). PSR J1938+2012 was identified using this image pattern recognition technique, while the other four MSPs were identified by sorting on various heuristic ratings (see Table 4 of Lazarus et al. 2015).

2.2. Timing Observations

After discovery, follow-up observations of each of the five new MSPs were conducted in order to determine rotational, astrometric, and binary parameters where applicable. This is done by accounting for every rotation of the pulsar over the entire data span by observing at appropriate spacings in time such that the number of pulses between observations is unambiguous. Once we obtained phase-connected solutions spanning more than one month, we observed each pulsar on a roughly monthly basis. PSRs J1906+0055, J1933+1726, J1938+2012, and J1957+2516 were timed using the 305 m

William G. Gordon Telescope at the Arecibo Observatory while PSR J1914+0659 was timed using the 76 m Lovell Telescope at the Jodrell Bank Observatory.

From 2011 September 9 to 2013 September 20, observations of PSRs J1906+0055 and J1957+2516 at the Arecibo Observatory were performed using the ALFA receiver with the Mock spectrometers. These observations were typically conducted as test pulsars for the PALFA survey and were therefore recorded in the same mode as search observations described in Lazarus et al. (2015) and had integration times of between 268 and 600 s.

After 2012 February 18, follow-up observations of PSRs J1906+0055, J1933+1726, J1938+2012, and J1957+2516 were conducted using the L-wide receiver with the Puerto Rican Ultimate Pulsar Processing Instrument (PUPPI), which is a clone of the Green Bank Ultimate Pulsar Processing Instrument (GUPPI).[27] Initial observations consisted of incoherent search mode observations with 800 MHz of bandwidth that was split into 2048 channels with a sample time of 40.96 μs. These data were then folded using the `fold_psrfits` routine from the `psrfits_utils` software package.[28] Later observations were performed using PUPPI in coherent fold mode with the same 800 MHz of bandwidth split into 512 frequency channels and were written to disk every 10 s. RFI was excised from both incoherent and coherent PUPPI files using a median-zapping algorithm included in the PSRCHIVE[5] software package (van Straten et al. 2012).

Follow-up timing observations of PSR J1914+0659 at Jodrell Bank were done using a dual polarization cryogenic receiver with a center frequency of 1525 MHz and bandwidth of 350 MHz. Data were processed by a digital filter bank producing 700 frequency channels of 500 kHz bandwidth. The output of each channel was folded at the nominal topocentric period of the pulsar and the resultant profiles written to disk every 10 s. RFI was removed using a median-zapping algorithm and the data were then incoherently de-dispersed at the pulsar's DM and folded profiles were produced for total integration times of typically 40 minutes.

2.3. Timing Analysis

In order to construct the initial timing solutions for the four binary pulsars, we performed a fit of the observed periods from early observations to orbital Doppler shifts for circular orbits. For each of the five pulsars, we constructed pulse templates by summing together data from multiple observations and fitting Gaussian components to the summed profiles. Examples of summed profiles for each of the pulsars presented here were previously included in Lazarus et al. (2015). For each observation, we generated pulse times-of-arrival (TOAs) using `pat` from the PSRCHIVE software package to cross-correlate the pulsar's template profile with the data in the Fourier domain (Taylor 1992). The observations from Arecibo were split into 2–4 frequency sub-bands depending on the pulsar's brightness, and each sub-band was used to generate a TOA allowing us to fit for the DM. The TOAs were then fitted to a model for each pulsar to get the final timing solutions using TEMPO[30] For all timing solutions, we used the DE421 solar system ephemeris and the BIPM clock timescale. The final timing solutions are given in Table 1 and the timing residuals are shown in Figure 1.

All of the binary pulsars presented here are in highly circular orbits (eccentricity $<10^{-4}$). Since there is a strong correlation between the longitude of periastron (ω) and the epoch of periastron passage (T_0) in low-eccentricity binaries, we used the ELL1 binary model in TEMPO (see the appendix of Lange et al. 2001). The ELL1 model removes this correlation by using the parameterization $\epsilon_1 = e \sin \omega$, $\epsilon_1 = e \cos \omega$, and $T_{\rm asc} = T_0 - \omega P_b / 2\pi$ where e is the eccentricity and P_b is the orbital period. This parameterization is superior for cases where xe^2 (x is the projected semimajor axis) is much smaller than the error in the TOAs, as is the case for all binary pulsars presented here. The timing residuals as a function of orbital period are presented in Figure 2.

The procedure described in Section 2.3 is known to often result in the underestimation of TOA errors. Therefore, the TOA uncertainties for each recording instrument mode were multiplied by a scaling factor to produce a fit with χ^2 equal to 1 for that subset of residuals. This results in more conservative estimates for the timing parameter uncertainties. The scaling factors (EFACs) used for each pulsar are given in Table 1.

2.4. Mean Flux Density Measurements

For the PUPPI observations taken in coherent mode we also obtained observations of a noise diode, which are suitable for use in polarization calibration. Such observations were made for PSRs J1906+0055, J1933+1726, and J1957+2516. We used observations of the bright quasar B1442+10 made by the NANOGrav Collaboration (NANOGrav Collaboration et al. 2015) for flux calibration. The calibration of polarization and flux were performed using the `pac` tool from the PSRCHIVE analysis package using the *SingleAxis* model. We searched for rotation measures in the range −2,000 to 2,000 rad m^{-2}, but did not detect substantial polarization for any of these three MSPs. The mean flux densities are included in Table 1.

3. DISCUSSION

We have reported the timing solutions for five MSPs discovered in the PALFA survey. These MSPs consist of four highly circular binary systems and one isolated system. The DMs of these MSPs range from 44 to to 236 pc cm^{-3}. Two of them have DM/P ratios greater than 30 pc cm^{-3} ms^{-1} (see Figure 3), adding to the population of high-DM MSPs being discovered by the PALFA survey (Crawford et al. 2012; Scholz et al. 2015). The eccentricities of PSRs J1906+0055 and J1938+2012 are near the expected values for their respective orbital periods from the relation in Phinney & Kulkarni (1994) indicating these systems have been circularized through long-term mass transfer from the companion in a low-mass X-ray binary (LMXB). PSR J1957+2516 is also likely to have undergone the same process, but its eccentricity is currently unconstrained. The parameters for PSR J1933+1726 system are not consistent with this relation, but this is expected for an intermediate mass binary pulsar (IMBP). Also, the three low mass systems (J1906+0055, J1938+2012, and J1957+2516) are all consistent with the expected companion mass–orbital period relation for HeWD-MSP systems formed

[27] https://safe.nrao.edu/wiki/bin/view/CICADA/GUPPIUsersGuide
[28] http://github.com/scottransom/psrfits_utils
[29] http://psrchive.sourceforge.net/
[30] http://tempo.sourceforge.net

Table 1
Timing Solutions and Derived Parameters for Five PALFA-discovered MSPs

Parameter	PSR J1906+0055	PSR J1914+0659	PSR J1933+1726	PSR J1938+2012	PSR J1957+2516
Timing Parameters					
R.A. (J2000)	19:06:48.68051(4)	19:14:17.647(2)	19:33:22.9828(3)	19:38:40.0803(1)	19:57:34.6115(3)
Decl. (J2000)	00:55:07.886(1)	07:01:11.00(7)	17:26:49.606(9)	20:12:50.827(3)	25:16:02.076(3)
Pulsar Period (s)	0.0027895524236884(2)	0.01851182255144(3)	0.02150723378644(1)	0.0026341351275486(6)	0.003961655342404(1)
Period Derivative (s s^{-1})	$3.32(1) \times 10^{-21}$	$3.1(3) \times 10^{-20}$	$4.9(1) \times 10^{-20}$	$7.5(6) \times 10^{-22}$	$2.744(9) \times 10^{-20}$
Dispersion Measure (pc cm^{-3})	126.8317(9)	225.3(2)	156.90(3)	236.909(5)	44.137(3)
Reference Epoch (MJD)	56408.0	56351.0	56466.0	56511.0	56408.0
Span of Timing Data (MJD)	55814–57001	55873–57101	56186–56746	56186–56834	55814–57001
Number of TOAs	187	61	45	96	151
rms Residual (μs)	7.84	245.61	33.95	20.19	19.15
EFAC (JB/Mock/PI/PC)[a]	–/1.0/1.0/1.4	1.0/1.1/–/–	–/–/1.1/–	–/–/1.1/–	–/1.5/2.0/2.1
1400 MHz Mean Flux Density (mJy)	0.1	···	0.04	···	0.02
Binary Parameters					
Orbital Period (days)	0.6096071304(3)	···	5.15393626(2)	16.2558195(1)	0.2381447210(7)
Orb. Per. Derivative (s s^{-1})	···	···	···	···	$12(2) \times 10^{-12}$
Projected Semimajor Axis (lt-s)	0.6250279(9)	···	13.67353(1)	8.317778(4)	0.283349(6)
Epoch of Ascending Node (MJD)	56407.5586451(1)	···	56466.1820553(6)	56514.938959(1)	56407.8681189(6)
ECCsin(OM)	$-1.0(3) \times 10^{-6}$	···	$-1.8(1) \times 10^{-5}$	$9.9(8) \times 10^{-6}$	$2(3) \times 10^{-5}$
ECCcos(OM)	$1(2) \times 10^{-6}$	···	$6.5(1) \times 10^{-5}$	$-3.2(9) \times 10^{-6}$	$2(2) \times 10^{-5}$
Mass Function ($M_\odot$)	0.0007055	···	0.1033	0.002338	0.0004307
Min. Companion Mass ($M_\odot$)	0.12	···	0.79	0.18	0.099
Med. Companion Mass ($M_\odot$)	0.14	···	0.96	0.21	0.12
Derived Parameters					
Galactic Longitude (°)	35.51	41.79	53.18	56.2	62.77
Galactic Latitude (°)	−3.0	−1.85	−1.02	−0.76	−1.97
Eccentricity	1.4×10^{-6}	···	6.7×10^{-5}	9.4×10^{-6}	2.8×10^{-6}
DM Derived Distance[b] (kpc)	3.3	6.1	5.5	7.7	3.1
Surface Mag. Field Strength (G)	0.97×10^{8}	7.7×10^{8}	10.4×10^{8}	0.45×10^{8}	3.3×10^{8}
Spindown Luminosity (erg s^{-1})	60.4×10^{32}	1.96×10^{32}	1.95×10^{32}	16.2×10^{32}	174.0×10^{32}
Characteristic Age (Gyr)	13.3	9.34	6.92	55.6	2.29

Note. Numbers in parentheses represent 1σ uncertainties in the last digits as determined by TEMPO, scaled such that the reduced $\chi^2 = 1$. All timing solutions use the DE421 Solar System Ephemeris and the UTC(BIPM) time system. Derived quantities assume an $R = 10$ km neutron star with $I = 10^{45}$ gm cm^2. Minimum companion masses were calculated assuming a 1.4 $M_\odot$ pulsar. The EFAC values correspond to subsets of TOAs from observations from Jodrell Bank (JB), Mock spectrometers, and the ALFA receiver (Mock), PUPPI with L-wide in incoherent search mode (PI), and PUPPI with L-wide in coherent search mode (PC). The DM derived distances were calculated using the NE2001 model of Galactic free electron density, and have typical errors of ∼20% (Cordes & Lazio 2002).

in an LMXB (Tauris & Savonije 1999). Below, we discuss details of each individual MSP.

3.1. PSR J1906+0055

PSR J1906+0055 is a 2.8 ms pulsar with a DM of 127 pc cm^{-3}. It is in a highly circular, 14.6 hr orbit with a companion having a minimum mass of 0.12 $M_\odot$ (assuming a pulsar mass of 1.4 $M_\odot$) and a median mass of 0.14 $M_\odot$ (assuming a pulsar mass of 1.4 $M_\odot$). Therefore, the companion is likely a He white dwarf. The DM-derived distance for J1906+0055 from the NE2001 model (Cordes & Lazio 2002) for the Galactic electron density is 3.3 kpc. PSR J1906+0055's 14.6 hr orbit makes it a potential candidate for detection of orbital decay and for constraining dipolar gravitational radiation (Freire et al. 2012).

3.2. PSR J1914+0659

PSR J1914+0659 is an isolated, partially recycled pulsar with a spin period of 18.5 ms and a DM of 225 pc cm^{-3}. Its DM-derived distance is 6.1 kpc. Based on the spin period and period derivative, it is likely the result of a disrupted double neutron star system (Lorimer et al. 2004).

3.3. PSR J1933+1726

PSR J1933+1726 is a partially recycled pulsar with a spin period of 22 ms and a DM of 157 pc cm^{-3} in a highly circular, 5

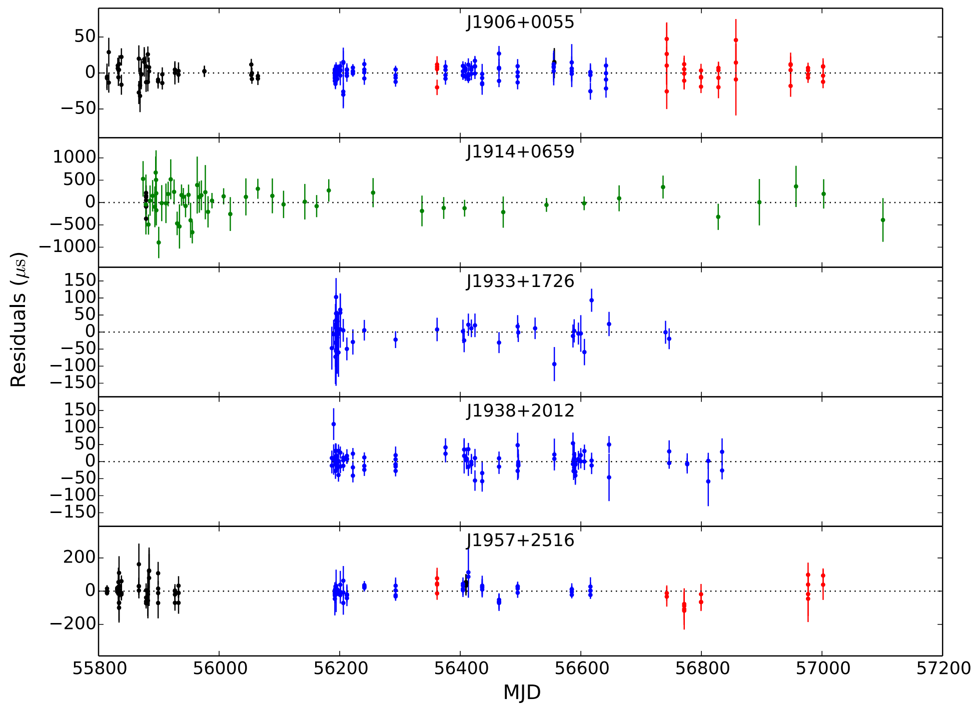

Figure 1. Post-fit timing residuals vs. modified Julien date (MJD) for five MSPs discovered in the PALFA survey. Green points are from Jodrell Bank observations, black points are from Arecibo Mock spectrometer observations, blue points are from Arecibo PUPPI observations in incoherent search mode, and red points are from PUPPI observations in coherent fold mode.

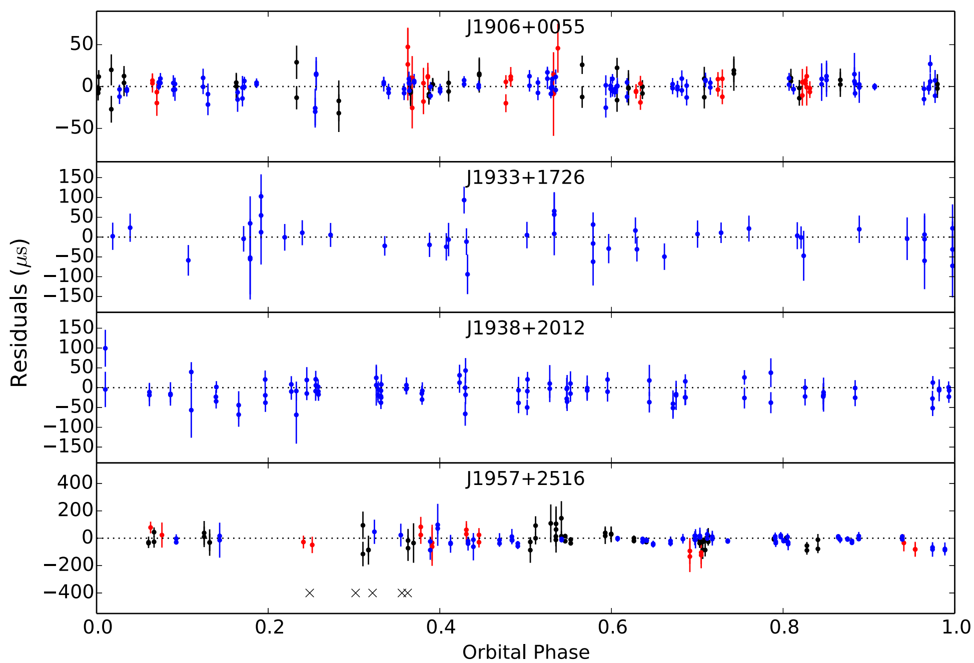

Figure 2. Post-fit timing residuals vs. orbital phase for four binary MSPs discovered in the PALFA survey. PSR J1957+2516 is often eclipsed between orbital phases 0.15 and 0.4. Non-detections with observing times of at least 600 s are shown as black Xs at the bottom of the plot. There are, however, also detections within this orbital phase range. Black points are from Arecibo Mock spectrometer observations, blue points are from Arecibo PUPPI observations in incoherent search mode, and red points are from PUPPI observations in coherent fold mode.

day orbit with a fairly high-mass companion. The companion's minimum mass is 0.8 $M_{\odot}$. This companion mass combined with the low orbital eccentricity indicates the companion is likely to be a CO white dwarf (Camilo et al. 2001). The DM-derived distance for this system is 5.5 kpc. The relatively high companion mass makes this system a candidate for a future Shapiro delay measurement if it has a favorable orbital inclination angle.

3.4. PSR J1938+2012

PSR J1938+2012 is a 2.6 ms pulsar with a DM of 237 pc cm^{-3} and is in a highly circular, 16 day orbit. The companion's minimum mass is 0.2 $M_{\odot}$ and is therefore likely a He white dwarf. Its DM is among the highest known for rapidly rotating MSPs ($P \leqslant 5$ ms; see Figure 3) The DM-derived distance for this system is 7.7 kpc.

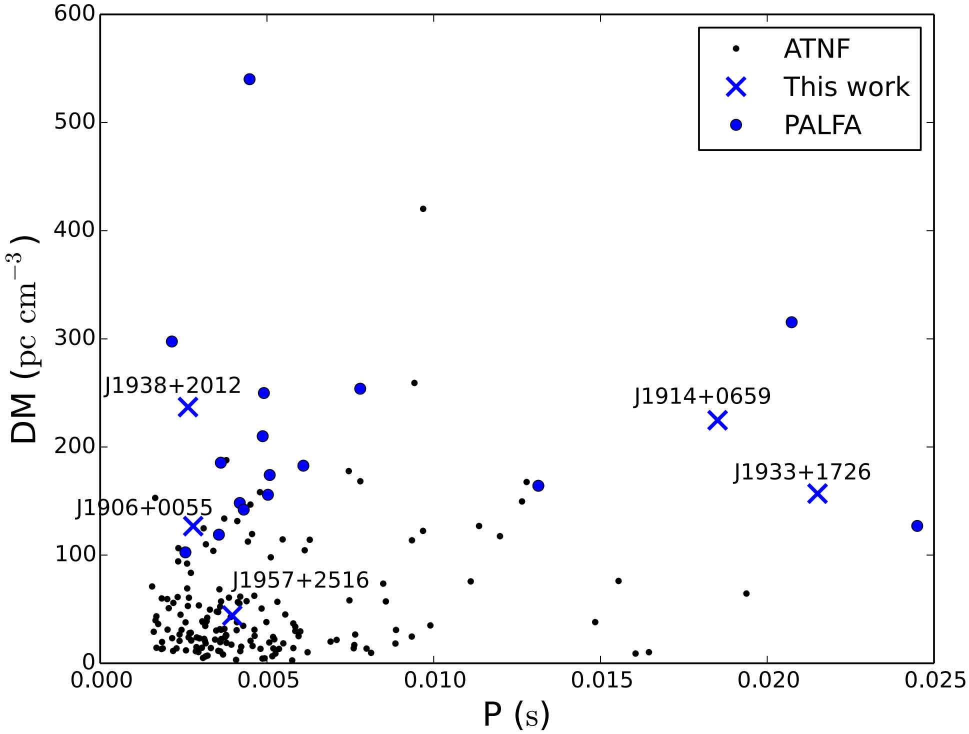

Figure 3. Spin period vs. DM for the five MSPs presented here are shown along with known Galactic MSPs (cf. Figure 5 of Crawford et al. 2012 and Figure 1 of Scholz et al. 2015). The Galactic MSPs are from the ATNF pulsar catalog (Manchester et al. 2005).

3.5. PSR J1957+2516

PSR J1957+2516 is a 4.0 ms pulsar with a DM of 44 pc cm^{-3} that is in a highly circular, 6.8 hr orbit. The eccentricity of the system is unconstrained by the timing solution presented here, but has an upper limit of 4×10^{-5}. We have plotted the orbital phase of non-detections of PSR J1957+2516 during observations of 600 s or longer in Figure 2 as black Xs. These non-detections are consistent with eclipsing as they occur near the orbital phase of 0.25 which corresponds to superior conjunction. However, we cannot rule out that these non-detections are not due to scintillation, since the pulsar has a fairly low DM. There have also been detections of the pulsar during portions of the orbit where it appears to have been eclipsed at other times (see Figure 2). However, we note that the detections that occured near an orbital phase of 0.25 are from the top of the band only (i.e., the pulsar was not detected below about 1.4 GHz in that session). In addition to the possible eclipses, we also detected an orbital period derivative of 12×10^{-12}, making this a likely redback or black widow system. PSR J1957+2516's companion mass is $\approx 0.1\,M_\odot$ and is consistent with this being a redback system. However, as shown in Figure 4, it lies between the black widow and redback populations in the orbital period versus minimum companion mass diagram.

3.6. Counterparts at Other Wavelengths

For all of the binary pulsars presented here, we examined archival optical and infrared data[31] for possible counterparts at the locations given in Table 1. Only PSR J1957+2516 was found to have a potential counterpart. We identified a potential near-infrared counterpart to PSR J1957+2516 from the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006). 2MASS J19573440+2516014 lies 2$''$.5 away from the pulsar. This is considerably larger than the typical 2MASS astrometric uncertainty of $\sim$0$''$.1, but it led us to further examine the field. On visually inspecting the 2MASS image the source appeared extended in the east-west direction by $\sim 5''$, overlapping with the position of PSR J1957+2516. Therefore we obtained further near-infrared imaging with the WIYN High Resolution Infrared Camera (WHIRC; Meixner et al. 2010) on the WIYN 3.5 m telescope in order to resolve the extended source. Our data consist of 14×30 s exposures with the J filter and 11×30 s exposures with the K_s filter on the night of 2014 May 10. The data were reduced according to standard procedures and calibrated relative to 2MASS. We very clearly show (Figure 5) that the single 2MASS source is actually a blend of three sources: two relatively bright stars and one fainter star. The position of the pulsar is between one of the brighter stars and the fainter star but inconsistent with all of them given the uncertainties (the WHIRC astrometry is accurate to $\pm$0$''$.1). Further investigation to subtract the brighter stars and look for a source coincident with the pulsar is ongoing.

None of the five MSPs presented here are positionally coincident with γ-ray sources from the *Fermi* Large Area Telescope (LAT) 4-Year Point Source Catalog (3FGL; see Acero et al. 2015). This is not surprising given the relatively small spin-down rates and much larger distances of these MSPs compared to the current sample of γ-ray detected MSPs (Abdo et al. 2013), as well as the strong diffuse γ-ray background in the Galactic plane. The only exception is PSR J1957+2516, which is relatively nearby ($D = 3.1$ kpc) and has a moderately high spin-down rate ($\dot{E} = 1.74 \times 10^{34}$ erg s^{-1}). To look for high-energy emission from this MSP, we retrieved all Pass8

[31] http://irsa.ipac.caltech.edu

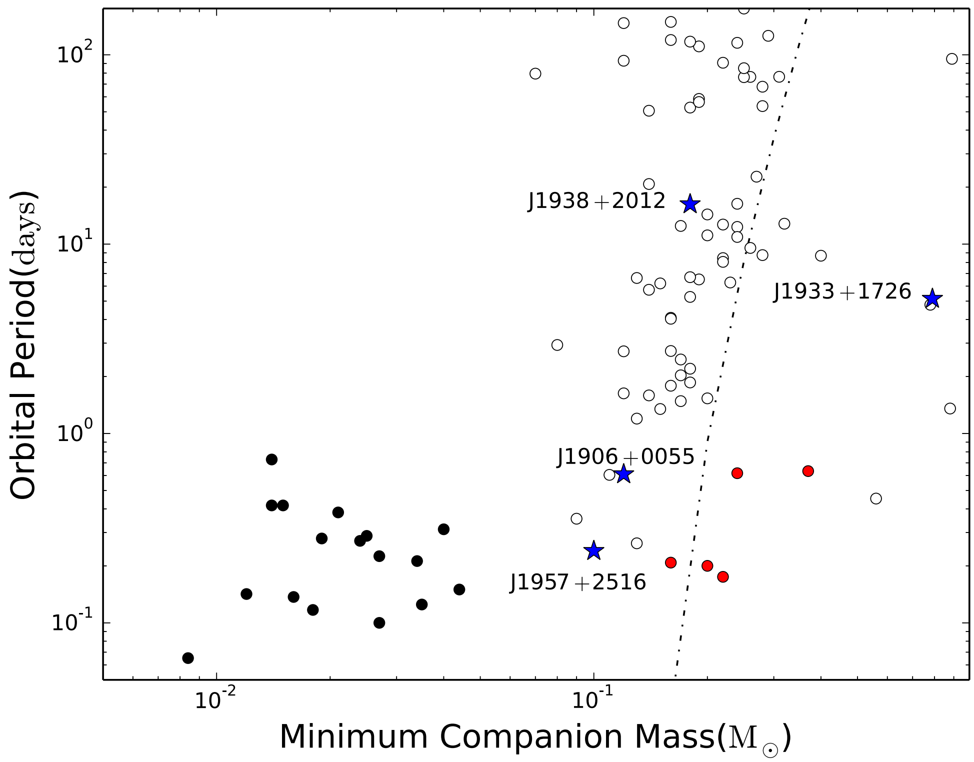

Figure 4. Orbital period vs. minimum companion mass for the four binary PALFA MSPs presented here (blue stars) and known Galactic field MSPs. Plotted are MSPs from the ATNF pulsar catalog (unfilled black circles; Manchester et al. 2005), known redbacks (filled red circles), and known black widows (filled black circles). The dashed line shows the relation between companion mass and orbital period for systems formed through long-term mass transfer in LMXBs (Tauris & Savonije 1999). As expected, the three MSPs with low mass companions are near the relation.

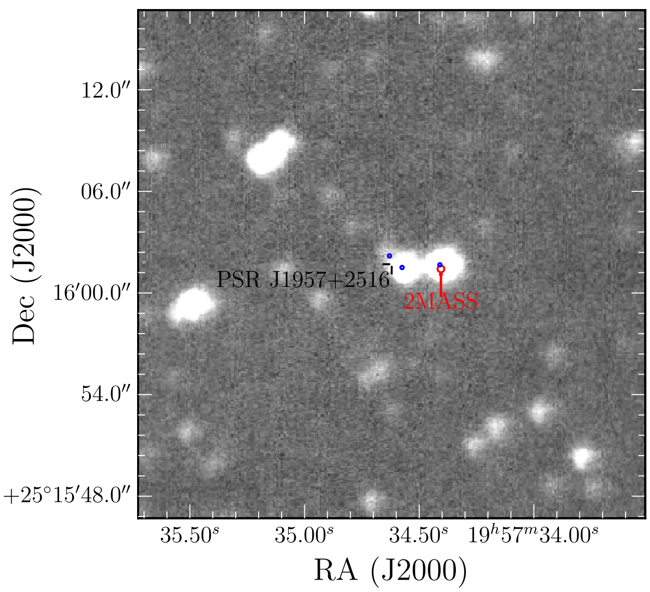

Figure 5. WIYN 3.5 m observation of the field containing PSR J1957+2516. The position obtained from the radio timing of PSR J1957+2516 is shown using black tick marks. The positions of the three stars described in Section 3.6 are shown using blue circles.

Fermi LAT data within 8° of the radio timing position of PSR J1957+2516 spanning from the start of the mission through 2016 March 16. The data products were first filtered with the Fermi Science Tools v10r0p5 using the event selection criteria recommended by the Fermi Science Support Center.[32] Using the counts, exposure, source maps, and live-time cube generated from these data as well as a spatial/spectral source model taken from the 3FGL catalog, we carried out a binned likelihood analysis to test for the presence of a γ-ray source at the pulsar position. We further include a new source at the pulsar position modeled with an exponentially cut-off power-law, as appropriate for a pulsar. The best-fit model from the binned likelihood analysis results in a negative value for the test significance for a source at the pulsar position. This is an indication that the addition of a γ-ray source coincident with PSR J1957+2516 is not warranted by the data, which in turn, suggests that this MSP does not produce γ-ray emission that is detectable above the background level. We also folded the *Fermi* photons for each of the five MSPs using the *Fermi* plugin for `tempo2`[33] and the pulsar ephemerides presented here. For the fold we selected events $\leqslant 0\overset{\circ}{.}8$ from the MSP position and used events with energies ranging from 0.1 to 10 GeV, however there was no evidence of pulsations for any of the five MSPs. We note that in the case of the likely redback PSR J1957+2516, the orbital period derivative may have varied over the timespan of the *Fermi* data. Therefore, detection of pulsations in *Fermi* data for this pulsar may still be possible with a more extensive pulsation search with varying orbital period derivative.

4. CONCLUSIONS

We have presented timing solutions for five MSPs discovered in the PALFA survey, which continues to discover some of the most distant MSPs known. The most distant MSP

[32] See http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/ for details.

[33] http://fermi.gsfc.nasa.gov/ssc/data/analysis/user/Fermi_plug_doc.pdf

presented here is PSR J1938+2012, which has a DM-derived distance of 7.7 kpc. Four of the MSPs were found to be in highly circularized binary orbits while the other system (PSR J1914+0659) is an isolated, partially recycled pulsar indicating that it is likely the result of a disrupted double neutron star system. One of the binary systems, PSR J1933+1726, has a high-mass companion that is likely to be a CO white dwarf. Two others, PSRs J1906+0055 and J1938+2012, have low-mass companions that are likely to be He white dwarfs. The remaining binary system, PSR J1957+2516, is likely to be a redback system. It is an eclipsing system in a tight orbit with a low-mass companion and we have detected a change in the orbital period. PSR J1957+2516 was found to be close to a near-infrared source which appeared to be extended in archival data. Higher resolution images revealed multiple point sources near the position of PSR J1957+2516, but further follow-up is ongoing to determine if the pulsar is associated with one of the near-infrared point sources. As is the case for all PALFA-discovered MSPs, these MSPs show no signs of γ-ray emission significantly above the background emission in the Galactic plane. This indicates that the PALFA survey is complementary to the ongoing *Fermi* searches for MSPs.

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