Draft version January 17, 2019
Typeset using LaTeX default style in AASTeX62

Searching for Black Widow and Redback Pulsar Analogues with the Long Wavelength Array

Christopher DiLullo,[1] Kevin Stovall,[1, 2] Gregory B. Taylor,[1] Jayce Dowell,[1] and Aquib Moin[3]

[1] *Department of Physics and Astronomy*
University of New Mexico
1919 Lomas Blvd NE
Albuquerque, NM 87131, USA
[2] *National Radio Astronomy Observatory*
1003 Lopezville Road
Socorro, NM 87801-0387, USA
[3] *Department of Physics*
United Arab Emirates University
Sheik Khalifa Bin Zayed Street, Al Ain, Abu Dhabi, UAE

Abstract

There exists a well known connection between gamma-ray emission and millisecond pulsars (MSPs) and there is also some evidence for a connection between gamma-ray emission and black widow and redback pulsar systems. These black widow and redback pulsar systems have been shown to have periodic dispersion measure (DM) variations on timescales near that of the binary period. This variation in DM arises from the pulse traveling through material present within the systems. The exact conditions which separate "normal" MSP systems from black widows and redbacks are not well understood. We have observed four binary pulsar systems, two of which show gamma-ray emission, which have known white dwarf companions in order to search for similar periodic DM variations. The expected DM variations are small as white dwarfs contribute little material to the system due to their strong gravity and theoretically weak stellar winds. The low frequencies observed by the Long Wavelength Array (LWA) make us highly sensitive to DM variations. We report changes in DM nearly 3 orders of magnitude smaller than seen in black widow systems, but find no periodic variations.

1. INTRODUCTION

Pulsars in binary systems offer a unique chance to study the material contained within these systems. If the binary system has a large enough inclination angle from the plane of the sky, then the system will exhibit a transit with respect to Earth, where the companion star comes between Earth and the pulsar. During this transit phase, the pulse will have to traverse any material contained within the system that would arise from stellar winds from the companion. This should manifest itself as a periodic variation in dispersion measure (DM) on timescales near that of the binary orbital period. The maximum variation will occur when the companion transits the pulsar and no variation should be seen when the pulsar transits the companion star.

These types of eclipsing binary systems are broken into two populations differentiated by the companion mass. The two populations are known as "black widow" (BW) and "redback" (RB) systems. BW pulsars have very low mass degenerate companions ($0.02\ M_\odot \leq M \leq 0.05\ M_\odot$) and RB pulsars have slightly more massive companions ($0.2\ M_\odot \leq M \leq 0.4\ M_\odot$). The companions of these types of pulsars are ablated by the pulse, which heats and strips material off of the companion's surface into the surrounding medium. This increases the electron column density along the pulse's propagation path and causes a variation in DM, as described above. The companions in BW systems are degenerate stars which are highly ablated, while RB companions tend to be non-degenerate and are less ablated. The different populations can be clearly seen in Figure 1[1].

Periodic variations in DM have been measured in both black widow systems (Freire et al. 2003) and redbacks (Zanon et al. 2018). Black widow and redback systems have also been connected with gamma-ray emission, but the exact emission mechanism is still not understood (Caraveo 2014). There is also an established connection between

---

[1] Data taken from https://apatruno.wordpress.com/about/millisecond-pulsar-catalogue/

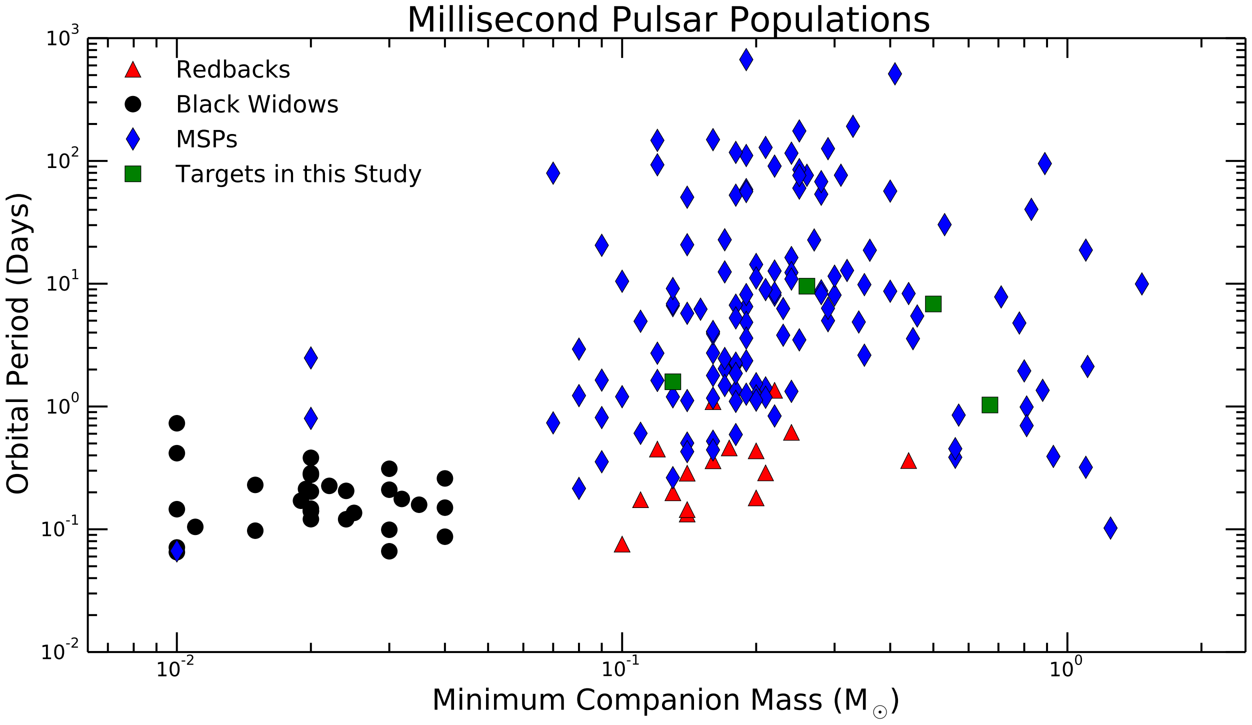


Figure 1. Binary orbital period vs. minimum companion mass for 184 millisecond pulsar (MSP) systems. The black widows can been seen with distinctly lower mass companions than the redback systems. It is unclear which parameters differentiate redbacks from "regular" MSP systems.

millisecond pulsars (MSPs) and gamma-ray emission. MSPs are older "recycled" pulsars which have been spun back up to millisecond rotational periods by accreting material from a companion star. Recent studies of unidentified Fermi gamma-ray sources have yielded many MSPs, with a considerable fraction of these being black widow and redback systems (Cromartie et al. 2016; Pletsch et al. 2012; Guillemot et al. 2011). This suggests that gamma-ray emission can be used as an indicator of a possible MSP or a pulsar system with black widow/redback-like behavior.

We present a study of four binary pulsar systems with known white dwarf companions. Three out of four sources are MSPs and two of those MSPs show gamma-ray emission and are therefore candidates to exhibit some type of black widow/redback-like behavior. We investigate this by searching for similar periodic DM variations that have been observed in black widow systems. The location of each of our targets in Figure 1 suggest these systems may display some sort of redback behavior. However, the expected variations in DM should be small since the white dwarf companions of all our targets should have high surface gravity and should not have an appreciable stellar wind.

2. OBSERVATIONS

We have observed four binary pulsar systems using the LWA1 station of the Long Wavelength Array (LWA; Taylor et al. 2012). The low frequencies observed by the LWA offer high sensitivity to changes in DM since dispersion is proportional to ν^{-2}. The observations lasted for one hour each and consisted of one dual-polarization beam with two frequency tunings, centered at 64.5 and 79.2 MHz, each with a bandwidth of 19.6 MHz. Lower frequencies were avoided due to potential scattering from the ISM. These observations were supplemented with archival data from the LWA Pulsar Archive (Stovall et al. 2015). Only observations taken at large angles from the Sun were used in order to avoid systematic variations in DM due to the solar wind.

The four targets chosen were J0034–0534, B0655+64, J1400-1431, and J2145–0750. All four targets are MSPs with identified white dwarf companions. J0034–0534 and J1400–1431 both have detected gamma-ray emission via the *Fermi* Large Area Telescope (LAT). J0034–0534 shows two γ-ray peaks that are very nearly aligned with the radio peaks, a feature previously only seen in the Crab pulsar (Abdo et al. 2010). J1400–1431 shows weak evidence for pulsed emission, but its positional coincidence with the *Fermi* source 3FGL J1400.5–1437 strongly supports a connection (Swiggum et al. 2017). This connected emission could suggest a possible black widow/redback-like variation in DM

Table 1. Orbital Parameters of Target Sources

Parameter	J0034–0534	B0655+64	J1400–1431	J2145–0750
Orbital Period (days)	1.58928182532(14)	1.0286696980(2)	9.5474676743(19)	6.8389025099(4)
Projected Semi-major Axis, $a_p sin(i)$, (lt − s)	1.4377662(5)	4.124976(28)	8.4212530(6)	10.1641056(6)
Best Fit Inclination Angle, i	Unknown	62° or 84°	$\geq 60°$	$< 61°$
Minimum Companion Mass ($M_\odot$)	0.13	0.67	0.26	0.50
Disperion Measure (pc cm^{-3})	13.765199	8.774268	4.932640	9.004509
Reference	Desvignes et al. (2016)	Losovskii et al. (2016)	Swiggum et al. (2017)	Löhmer et al. (2004)

for these systems given their orbital inclinations. The other two sources were included for completeness. These targets have all been previously detected with LWA1 and have orbital periods which allow for the observation of a full orbit. Relevant orbital parameters and dispersion measures for the four sources are listed in Table 1.

3. DATA ANALYSIS

The raw data were reduced using routines available in the LWA Software Library[2] (LSL; Dowell et al. 2012). RFI was excised via a median zapping routine that excises any data that lies 6σ outside the median. The pulse times of arrival (TOAs) were found using the `pat` application distributed with the PSRCHIVE[3] package (van Straten et al. 2012). Finally, variations in DM (ΔDM) were fit by the TEMPO[4] program using the DMX parameter. The fits were computed over one hour intervals so each observation yielded one measurement of DM.

These solutions are plotted against the date (MJD) of observation and a linear fit is computed to search for any time dependent drift in the DM of the pulsar. This drift is then subtracted from the data to isolate binary-related DM variations. We then plot the drift-corrected data against binary orbital phase, using the epoch of periastron as reference. Any periodic variations in DM should be evident in this plot. We use a Lomb-Scargle periodogram analysis (Lomb 1976; Scargle 1982) to search for statistically significant power on frequencies corresponding to the orbital periods of the systems. The mean DM variation is computed and plotted. We also verify the avoidance of systematics introduced by our own solar wind by plotting the data against angle from the Sun on the given MJD. This clearly indicates that the Sun introduces no systematic effects.

4. RESULTS

Each binary system is modeled using the ELL1 binary model (see TEMPO documentation), thus we expect to see greatest ΔDM at 25% orbital phase. It is visually apparent that we do not detect periodic DM variations across an entire orbit for any of the sources observed. The ΔDM plots are presented in Figure 2. The Lomb-Scargle periodograms for each pulsar also show no statistically significant periodicity on relevant timescales. These are shown in Figure 3. We also compute reduced-χ^2 between the drift-corrected data and the mean ΔDM "fit". If the mean is a good fit to the data, then there is little variation.

Table 2. Results

Parameter	J0034–0534	B0655+64	J1400–1431	J2145–0750
ΔDM, (pc cm^{-3})	$(6.04 \pm 2.59) \times 10^{-5}$	$(1.40 \pm 1.39) \times 10^{-4}$	$(1.21 \pm 1.42) \times 10^{-4}$	$(2.30 \pm 0.52) \times 10^{-4}$
Linear fit slope, (pc $cm^{-3}day^{-1}$)	$(1.20 \pm 2.19) \times 10^{-7}$	$(5.86 \pm 10) \times 10^{-8}$	$(1.31 \pm 1.06) \times 10^{-6}$	$(-2.46 \pm 3.46) \times 10^{-7}$
Linear fit intercept, (pc cm^{-3})	-0.01 ± 0.01	-0.003 ± 0.006	-0.08 ± 0.06	0.01 ± 0.02

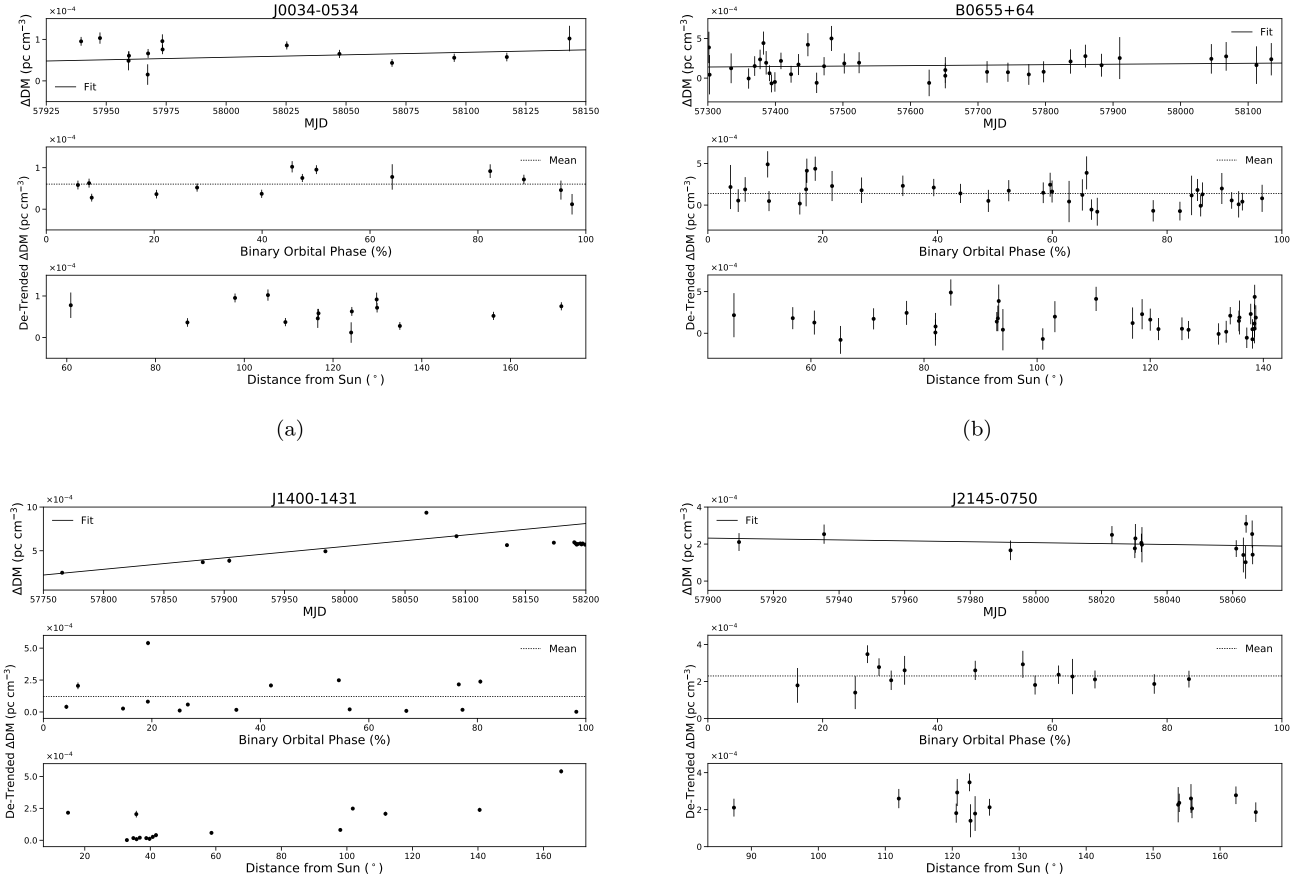
---

[2] http://fornax.phys.unm.edu/lwa/trac/wiki

[3] http://psrchive.sourceforge.net/

[4] http://tempo.sourceforge.net

The Lomb-Scargle periodograms and reduced-χ^2 of each fit for each source are presented and discussed in the following sections. The measured ΔDM values and linear fit parameters for each source are succinctly presented in Table 2.



(a)

(b)

(c)

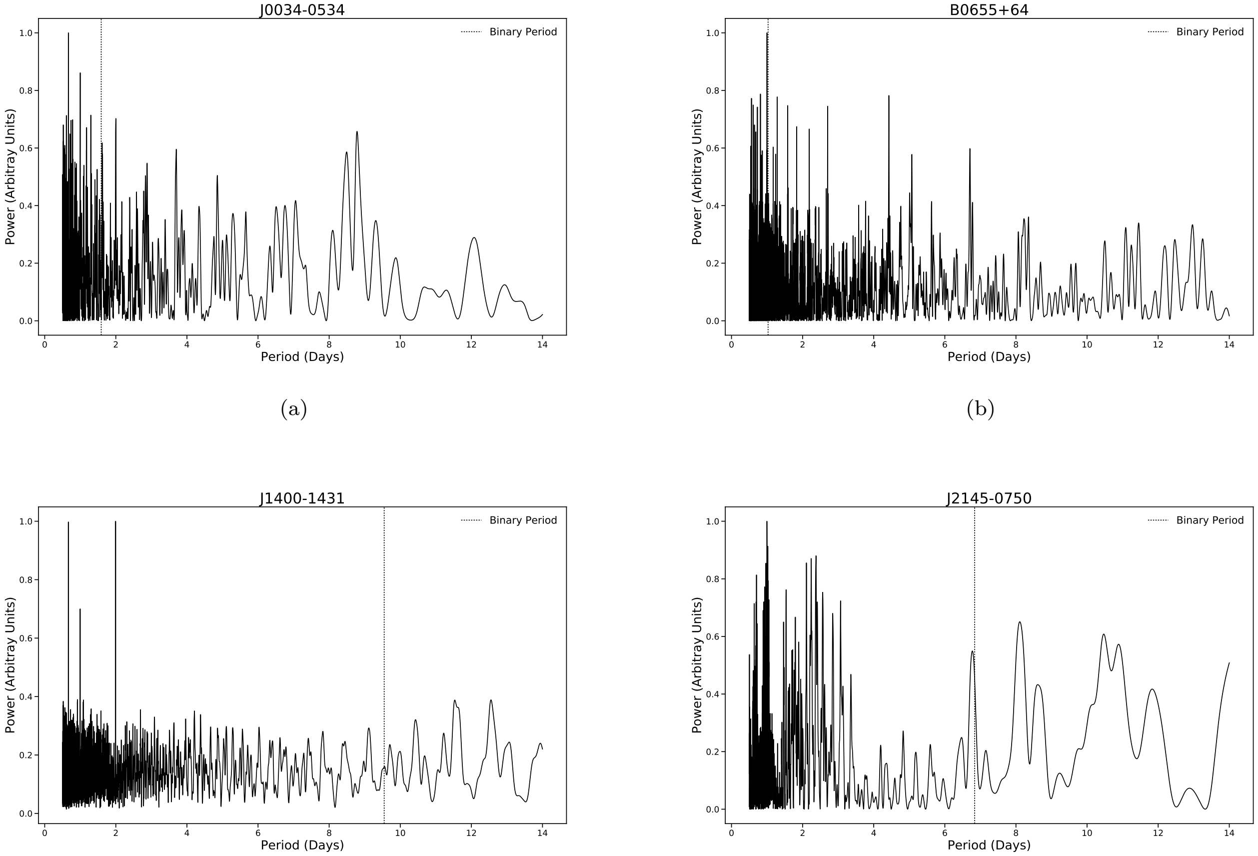
(d)

Figure 2. ΔDM plots. The top plot in each subfigure shows ΔDM vs. MJD and shows the linear fit that is computed to find any time dependent DM drifts. The middle plot shows the data after the linear fit is subtracted and the mean ΔDM vs. orbital phase. Finally, the bottom plot shows ΔDM vs. angular distance from the Sun.

4.1. *J0034–0534*

The results for J0034–0534 are presented in Figure 2a. There is a total of 15 hours of observations for J0034–0534. One low signal to noise data point was removed after it was determined that this observation was at a low elevation above the horizon. The sensitivity of LWA1 decreases at lower elevations due to beam projection effects. We find a drift in DM, however after subtracting this drift we still find no periodic change in DM. The reduced-χ^2 of the data with respect to the mean is $\chi^2_\nu = 4.26$. This shows there is some variability in the DM of the pulsar. There also appears to be no systematics introduced by our solar wind.

The lack of power present at the orbital period in the Lomb-Scargle periodogram, shown in Figure 3a, shows a lack of periodicity at this timescale. We see a consistent spike in power around 1 day timescales in the periodograms of all sources and conclude this is due to instrumental systematics. The statistical significance of power at a given timescale is verified via a jack knifing routine. We achieve this by iteratively computing the periodogram while randomly omitting approximately 25% of the data for each iteration. The number of iterations is equal to the number of data points for each observation. The value of the periodogram at the orbital period is recorded during each iteration and a mean value, with 1σ deviations, is computed. The mean periodogram value is then used to compute an effective signal to



(a)

(b)

(c)

(d)

Figure 3. Lomb-Scargle periodgrams. The red lines represent the binary period of each system. No significant power is present at any of these periods.

noise ratio, defined to be the ratio of the mean to the standard deviation of the entire periodogram with no data points omitted. The mean value of the periodogram at the orbital perdiod of J0034-0534, along with 1σ bounds, is found to be $1.917 \pm 1.295 \times 10^{-9}$. The signal to noise ratio is 0.458. This low value implies that the power on this timescale is not statistically significant.

We find the mean ΔDM with 1σ limits to be

$$\Delta DM = 6.04 \pm 2.59 \times 10^{-5} \text{ pc cm}^{-3}.$$

4.2. *B0655+64*

This pulsar is circumpolar from LWA1, which allows for many observations over multiple years. There is a total of 35 hours of observations for B0655+64. The results for B0655+64 are presented in Figure 2b. Again, after correcting for the drift in DM over time, we find little variation about the mean change in DM. The reduced-χ^2 of the mean "fit" has a value $\chi^2_\nu = 0.977$. There appears to be no systematics introduced by our solar wind.

The Lomg-Scargle periodogram for B0655+64 is shown in Figure 3b. It is clear there is no significant power on timescales near that of the orbital period. This is confirmed by the same jack knifing analysis used for the rest of the sources in this study. The mean value, with 1σ bounds, is $4.144 \pm 2.890 \times 10^{-8}$ which gives a signal to noise ratio of 1.226.

We measure ΔDM to be

$$\Delta DM = 1.40 \pm 1.39 \times 10^{-4} \text{ pc cm}^{-3}.$$

4.3. *J1400–1431*

The results for J1400–1431 are presented in Figure 2c. We have 16 hours of observations for J1400–1431. After subtracting the drift in DM, we find variations in DM, but no periodic variations. The reduced-χ^2 of the fit is large, with a value of $\chi^2_\nu = 85.614$. The large value of χ^2_ν is likely due to a slow variation in the DM caused by the interstellar medium that is not well described by a simple linear fit. The Lomb-Scargle periodogram is presented in Figure 3c. We see no significant power on the orbital period. The jack knifing routine gives a mean value of the periodogram with 1σ limits of $3.501 \pm 1.689 \times 10^{-7}$. This corresponds to a SNR of 2.267.

We measure ΔDM to be

$$\Delta DM = 1.21 \pm 1.42 \times 10^{-4} \text{ pc cm}^{-3}.$$

4.4. *J2145–0750*

The results for J2145–0750 are presented in Figure 2d. There are 14 hours of observations for J2145–0750. We again find a drift in DM, but no periodic changes after removing the drift. This is evident in the Lomb-Scargle periodogram presented in Figure 3d. There is a small rise in power close to the orbital period, represented by the red line, but our jack knifing routine shows no statistical significance to this peak. The mean value of the periodogram, with 1σ bounds, is $1.266 \pm 0.385 \times 10^{-7}$. This gives a signal to noise ratio of 1.932. The reduced-χ^2 of the mean fit to the drift-corrected data is $\chi^2_\nu = 0.896$. This shows there is very little variation in DM on any timescale. We see no systematic error introduced by our solar wind.

We measure ΔDM to be

$$\Delta DM = 2.30 \pm 0.52 \times 10^{-4} \text{ pc cm}^{-3}.$$

5. DISCUSSION AND CONCLUSIONS

We have carried out a systematic study of the four binary pulsar systems J0034–0534, J2145–0750, J1400–1431, and B0655+64 to search for periodic variations in dispersion measure. Two of these sources (J0034–0534 and J1400–1431) show pulsed gamma-ray emission which is connected to black widow and redback systems in which the pulse may be interacting with the stellar wind of the companion star.

We find no significant periodicity on timescales near that of the orbital periods for the four sources presented in this study. The amplitude of DM variations are small, with 6×10^{-5} pc cm^{-3} being the smallest. This is roughly a factor of 200 below the DM variations detected by Freire et al. (2003), which are of order of 10^{-2} pc cm^{-3}. This suggests that there is not enough material present within these systems to effectively change the DM of the pulsar, presumably the result of the strong gravity of the white dwarf systems and consequent weak stellar winds. Thus, it is unlikely these systems have similar interior conditions to those inside black widow and redback systems. If black widow and redback systems can be detected at low frequencies, we have demonstrated that measurements of the DM can be obtained with much improved precision at low frequencies.

6. ACKNOWLEDGMENTS

Construction of the LWA has been supported by the Office of Naval Research under Contract N00014-07-C-0147 and by the AFOSR. Support for operations and continuing development of the LWA1 is provided by the Air Force Research Laboratory and the National Science Foundation under grants AST-1711164 and AGS1708855. K.S. is supported by the NANOGrav Physics Frontiers Center (NSF award 1430284).

REFERENCES

Abdo, A., Ackermann, M., Ajello, M., et al. 2010, The Astrophysical Journal, 712, 957

Caraveo, P. A. 2014, Annual Review of Astronomy and Astrophysics, 52

Cromartie, H., Camilo, F., Kerr, M., et al. 2016, The Astrophysical Journal, 819, 34

Desvignes, G., Caballero, R., Lentati, L., et al. 2016, Monthly Notices of the Royal Astronomical Society, 458, 3341

Dowell, J., Wood, D., Stovall, K., et al. 2012, Journal of Astronomical Instrumentation, 1, 1250006

Freire, P., Camilo, F., Kramer, M., et al. 2003, Monthly Notices of the Royal Astronomical Society, 340, 1359

Guillemot, L., Johnson, T., Venter, C., et al. 2011, The Astrophysical Journal, 744, 33

Löhmer, O., Kramer, M., Driebe, T., et al. 2004, Astronomy & Astrophysics, 426, 631

Lomb, N. R. 1976, Astrophysics and space science, 39, 447

Losovskii, B. Y., Dumskii, D., & Logvinenko, S. 2016, Astronomy Reports, 60, 204

Pletsch, H., Guillemot, L., Fehrmann, H., et al. 2012, Science, 338, 1314

Scargle, J. D. 1982, The Astrophysical Journal, 263, 835

Shahbaz, T., Linares, M., & Breton, R. 2017, Monthly Notices of the Royal Astronomical Society, 472, 4287

Stovall, K., Ray, P., Blythe, J., et al. 2015, The Astrophysical Journal, 808, 156

Swiggum, J. K., Kaplan, D. L., McLaughlin, M. A., et al. 2017, The Astrophysical Journal, 847, 25

Taylor, G., Ellingson, S., Kassim, N., et al. 2012, Journal of Astronomical Instrumentation, 1, 1250004

van Straten, W., Demorest, P., & Osłowski, S. 2012, arXiv preprint arXiv:1205.6276

Zanon, A. M., Burgay, M., Possenti, A., & Ridolfi, A. 2018in , IOP Publishing, 012004