Discovery of Eleven Millisecond Pulsars

Using Jerk Searches on Unassociated Fermi-LAT Sources

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INTRODUCTION

Finding new millisecond pulsars (MSPs) is one of the main science drivers of current pulsar surveys. In the past decade, the most successful approach to search for MSPs has been to look for radio pulsations in the error boxes of Gamma-ray sources identified by the Large Area Telescope (LAT) aboard the Fermi satellite. Here we present the Discovery of 11 MSPs as a result of such a search done under the Pulsar Search Consortium (PSC). Eight of the discovered MSPs were found using Jerk searches while three were found during preliminary acceleration searches. One of these MSPs is in a tight binary and might not have been discovered without a jerk search having been done.

A CASE FOR JERK SEARCH

Binary MSPs can be used to study a wide variety of scientific phenomena including the testing and constraining of General Relativity, equation of state of nuclear matter, and properties of matter at extreme densities.

A problem which arises when observing MSPs in binary systems is the smearing of the pulse signal in different spectral bins due to Doppler shift in period resulting from orbital motion. Fourier domain acceleration search is a standard technique used to account for the smearing of pulses by assuming a constant acceleration for the system [1]. However, the assumption of a constant acceleration is not sufficient for binary systems with smaller periods when the observation length is longer than about 10% of the orbital period. The large number of "spider" systems, with orbital period << 1 day, discovered in searches of Fermi sources suggests there may be many more tight binaries than previously thought.

This is why searching for jerk, the second time derivative, is needed. The Fourier domain jerk search algorithm by Andersen and Ransom [2] is sensitive to changes in the period of the pulsed signal up to its second derivative caused by the orbital motion (shown in Equation 1), resulting in increased sensitivity to tight binary systems for observations lasting between 5% and 15% of the orbital period with only a slight penalty for less accelerated systems. Jerk search was implemented as an option in the standard "accelsearch" routine in the PRESTO software package in 2018 [3].

Equation 1: The Jerk component of orbital motion in terms of the period (P), period derivative ($\dot{P}$) and period second derivative ($\ddot{P}$).

$$j \approx \left(\frac{\ddot{P}}{P} - \frac{2\dot{P}^2}{P^2}\right)c$$

OBSERVATIONS

All the initial observations were done using the Green Bank Telescope (GBT) at a central frequency of 820 MHz and a bandwidth of 200 MHz, using 2048 channels. The sampling time was 61.44 µs. They were done from 01-28-2017 to 02-11-2017, with a total of 72 sources being observed. The confirmation observations were done using the GBT at 820 MHz when needed. For some sources, archival Arecibo or GBT sources were used to confirm the candidates.

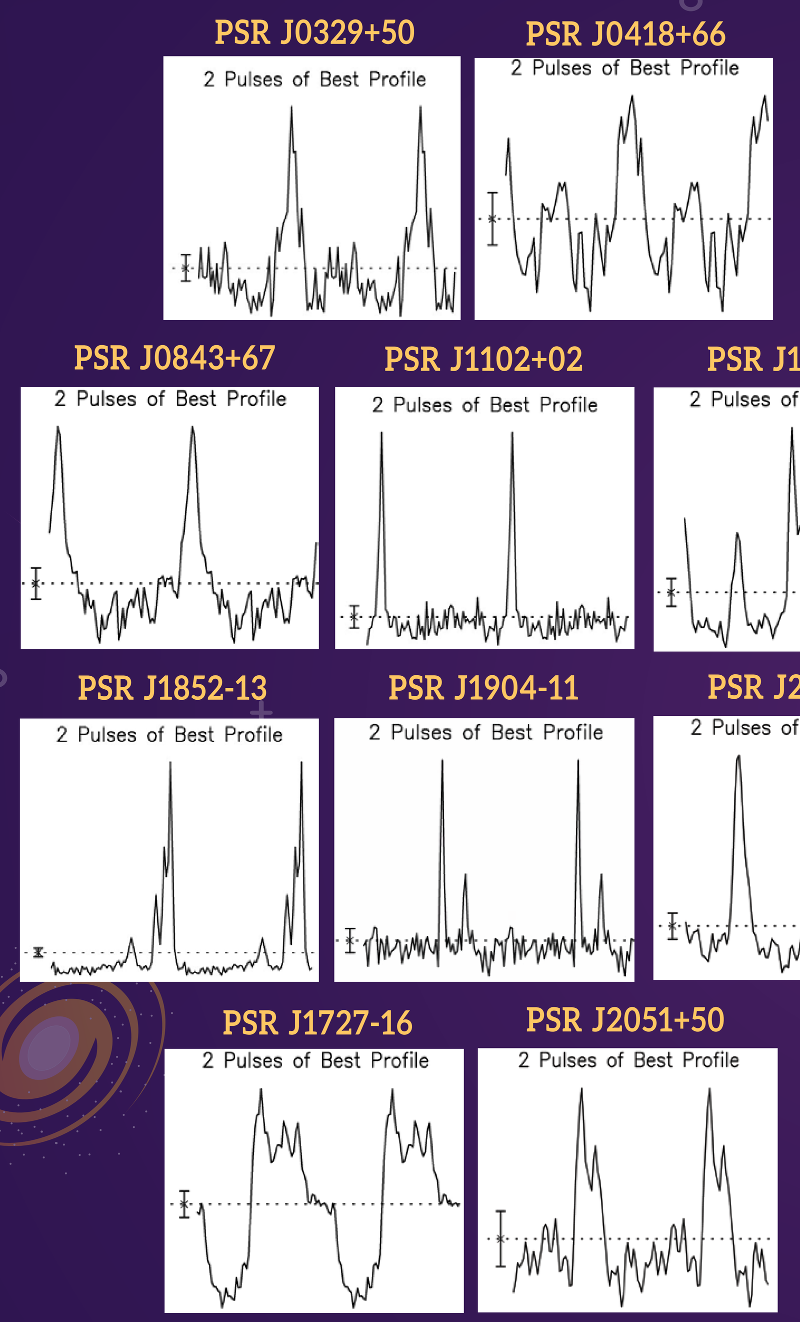

Figure 1: Pulse Profiles for 10 of the discovered MSPs

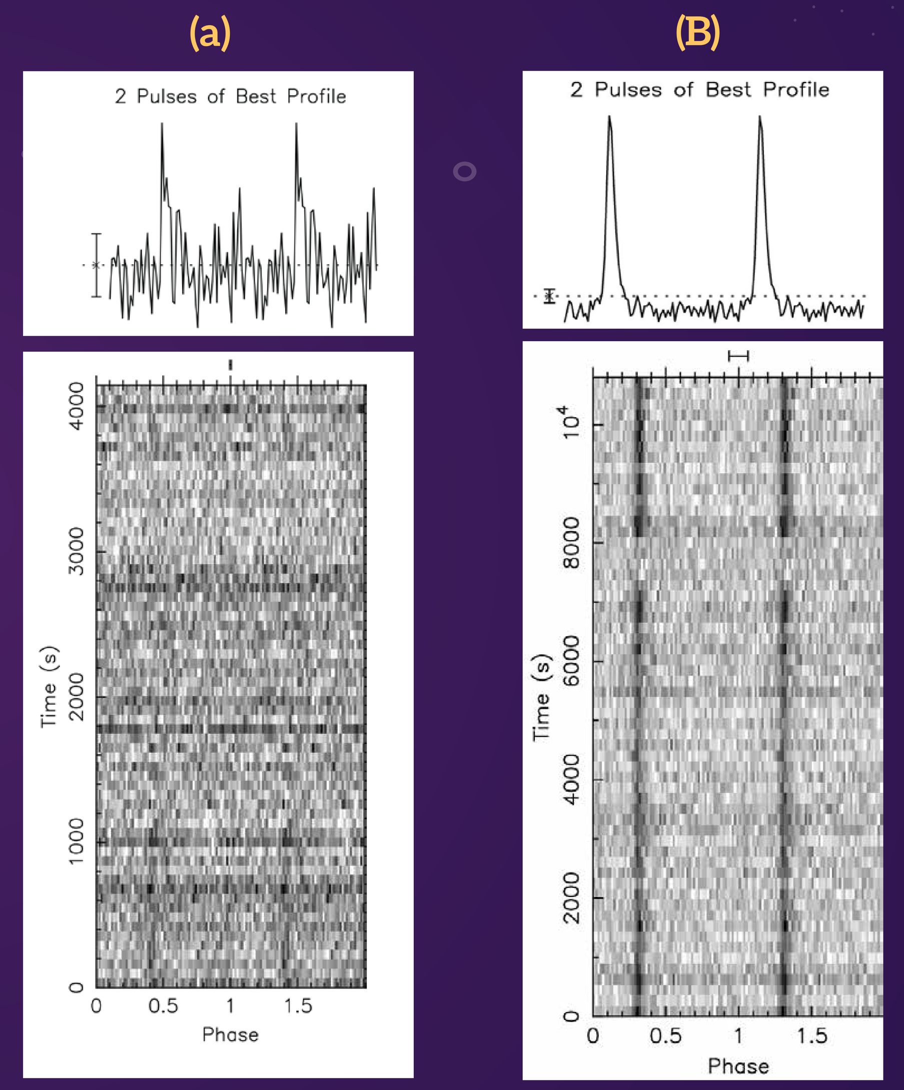

Figure 2: Waterfall plots for PSR J0312-09. In (a) the eclipse can be seen. (b) is a fold without searching for jerk and it can be seen that the MSP is only faintly detected, drifting in phase space.

Pulsar	Period (ms)	Right Ascension (4FGHL)	Declination (4FGHL)	95% error (arcmin)	DM (pc cm-3)	Dist (kpc)
PSR J0312-09	3.704	03:12:07.77	-09:20:13.34	2.9	20.53	0.82
PSR J0329+50	3.06	03:29:57.65	50:36:28.12	4.1	7.374	0.30
PSR J0418+66	2.91	04:18:54.1	66:36:00	1.4	77.56	2.20
PSR J0843+67	2.846	08:43:23.5	67:12:48	1.83	20.73	1.90
PSR J1102+02	4.053	11:02:20.9	02:44:17.11	8.9	27.39	1.30
PSR J1624-39	2.96	16:24:22.104	-39:52:39	2.75	77.48	2.63
PSR J1727-16	2.455	17:27:59.1	-16:09:09	4.2	93.1	3.8
PSR J1852-13	4.31	18:52:17.832	-13:09:21.6	3.47	44.95	1.27
PSR J1904-11	2.626	19:04:27.5	-11:29:54	7.3	97.67	1.70
PSR J2036-02	1.911	20:36:15.1	-02:07:59	5.5	52.19	1.16
PSR J2051+50	1.681	20:51:43.67	50:50:43.4	-	60.99	3.1

Table 1: Properties of the eleven newly discovered Millisecond Pulsars. Distances were obtained from YMW16 model except for J1102+02 and J2051+50 for which NE2001 was used since observed DM is beyond the maximum for the YMW16 model in this direction. The 95% error is the size of the semi-major axis of the Fermi-LAT source's error ellipse.

RESULTS

These searches resulted in the discovery of 11 new pulsars. Eight of these were found through jerk searches while 3 of these were found during preliminary acceleration searches. Table 1 shows the properties of these MSPs and Figure 1 shows their pulse profiles.

Among these is PSR J0418+66 (P = 2.91ms) which was also independently discovered as a γ-ray pulsar and thus has a 11-year timing solution which shows that it is an isolated pulsar. Timing solutions remain to be obtained for the rest of the ten MSPs. However, for PSR J0312-09 (P = 3.704 ms), PSR J0329+50 (P = 3.06 ms), PSR J0843+67 (P = 2.846ms) and PSR J1102+02 (P = 4.053 ms) we have orbital solutions through preliminary timing analysis. PSR J0843+67 is in a 7.35 day orbit with a companion of mass $M_c \geq 0.27\,M_\odot$. PSR J0329+50 is in a 11.75 days orbit with a companion of mass $M_c \geq 0.35\,M_\odot$, which is higher than what is expected from binary evolution models. PSR J1102+02 is also in a long orbit with an orbital period of 22.39 days and a companion of mass $M_c \geq 0.26\,M_\odot$. PSR J1102+02 and PSR J1904-11 show exceptionally narrow pulses, indicating suitability for pulsar timing arrays. PSR J1624-39 has an inter-pulse at a phase offset of 0.5 from the main pulse, suggesting a likelihood for it to be an orthogonal rotator. This would make it an especially good candidate for pulsar evolution studies. PSR J2051+50 showed variations in pulse profile which remain to be studied. Accounting for re-detection of already known pulsars among the observed sources, our survey had a detection fraction of 20.8%, comparable to that of other surveys of unassociated Fermi-LAT γ-ray sources. [4].

PSR J0312-09

PSR J0312-09 is in a 2.34 hr orbit with companion mass $M_c \geq 0.009\,M_\odot$, which makes it a black widow. It was discovered as a highly accelerated system with a significant jerk component. Folding the discovery observation without specifying the jerk component resulted in a smeared fold with a significance below the detection threshold in our pipeline, as can be seen in Figure 2 (b). Hence, the cost of a jerk search was justified in the discovery of this unique binary system. Figure 2 (a) shows the waterfall plot for J0312-09 which shows that it eclipses for ~11% of the orbit.

CONCLUSION

J0312-09 was a much weaker candidate when folded without a jerk search, with a gaussian significance of only 4.7σ compared to 13.6σ when folded with a jerk search on the same observation data. Hence, it probably would not have been discovered without jerk search. Therefore, these results show that even though jerk searches are computationally intensive, they can help uncover systems which would not have been found using solely acceleration searches. Furthermore, these results reiterate the efficiency of using Fermi-LAT γ-ray sources to search for pulsars.

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