Proper Motion Measurements of Radio-Quiet Pulsars Using γ-ray Single Photons

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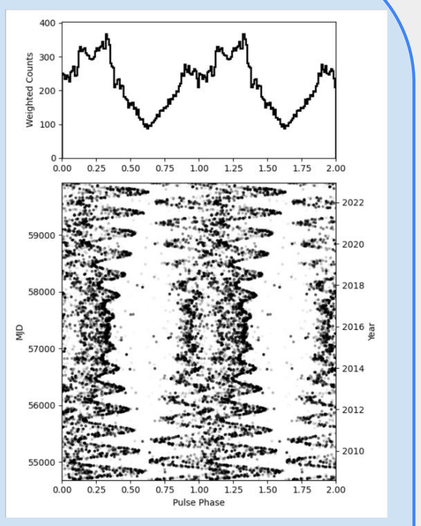
Goals

We are trying to measure the proper motion of young, slow pulsars that have been detected in γ-rays but not in radio. For the pulsars that we do measure a proper motion, we are searching for potential associations with any nearby nebulae.

Pulsar Selection: *Fermi* 3PC

- Pulsar Criteria:
  - No previous proper motion measurements
  - No radio measurements
  - No glitches
  - Relatively low timing noise



The growing sinusoidal signal in the phaseogram above is the proper motion signature that we have to account for in our timing.

Event optimize

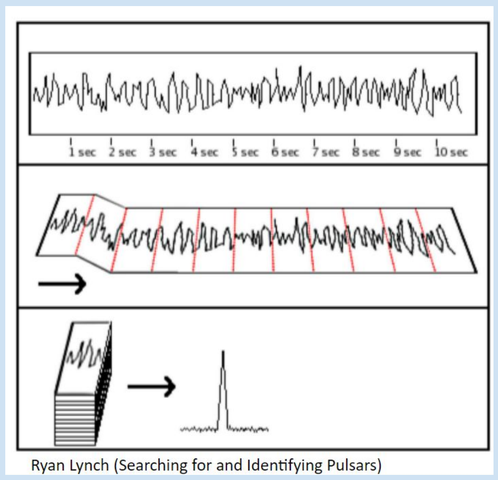
- Our goal is to do a joint nonlinear analysis of red noise and the timing analysis using individual photons to measure the proper motion

Radio Timing

- Radio TOA: 10^2 to 10^3 pulses (slow pulsars) or 10^4 to 10^6 pulses (MSPs)
- Typical integration time: 5-60 minutes

γ-ray Timing

- High background source emission
- Emission rate: ~ 1 photon per day



Ryan Lynch (Searching for and Identifying Pulsars)

- It is far more difficult to conduct pulsar timing with γ-rays than with radio due to the massive difference in the number of photons detected and the high source background.

To maximize the amount of information we can extract from each photon, we are using MCMC techniques and likelihood analysis to time γ-ray pulsars using Fermi single photon data through PINT, a new high precision pulsar timing software (see QR code)

Acknowledgements

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- D. A. Smith, et al 2023, ApJ, 958, 191
- Ajello, M., Atwood, W.B., et al. 2022, Science, 376, 521.
- Faherty, J., Walter, F.~M., & Anderson, J. 2007, Astrophysics and Space Science, 308, 225.
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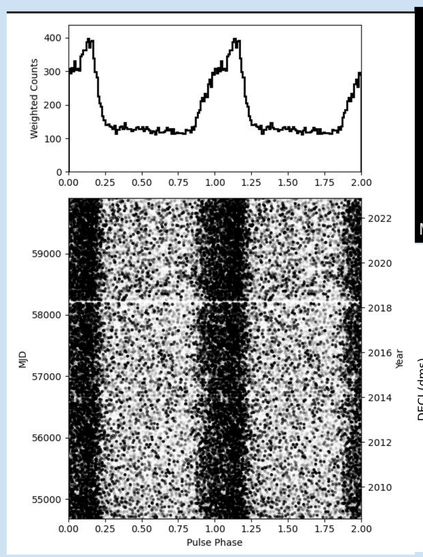
Proper Motion Measurements

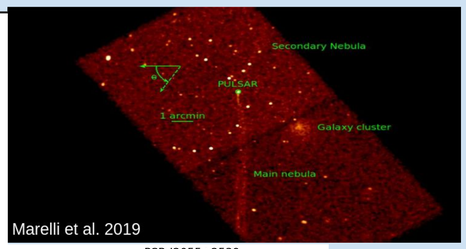
We have timed 12 γ-ray pulsars as of date. 5 of them (marked green) have >3σ measurements. 3 of them (marked orange) have nearby nebulae or nebulae features.

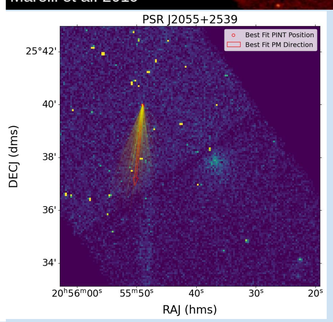
Name	PMRA (mas/yr)	PMDEC (mas/yr)	PM (mas/yr)	Sigma	PA (deg)
J0633+0632	20 (9)	174 (62)	176 (61)	2.87	84
J0734-1559	-66 (34)	-114 (60)	132 (54)	2.43	60
J1623-5005	-12 (19)	-71 (34)	72 (34)	2.11	80
J1624-4041	-17 (20)	85 (78)	87 (77)	1.13	-79
J1641-5317	-127 (67)	-102 (125)	162 (94)	1.72	39
J1827-1446	-63 (110)	-135 (753)	149 (685)	0.22	65
J1836+5925	-37 (7)	-14 (7)	39 (7)	5.97	21
J1954+2836	15 (6)	-44 (9)	46 (9)	5.42	-71
J2028+3332	59 (12)	-57 (13)	82 (13)	6.58	-44
J2055+2539	24 (43)	-240 (72)	242 (72)	3.35	-84
J2030+4415	-18 (16)	72 (15)	74 (15)	4.85	-76
J1746-3239	61 (47)	248 (326)	255 (317)	0.8	76

J2055+2539

- There is a two-tail nebula morphology associated with the pulsar
- Our proper motion measurement points into the tail, implying that it could be a jet.
- Our measurement is consistent with previously established upper limits

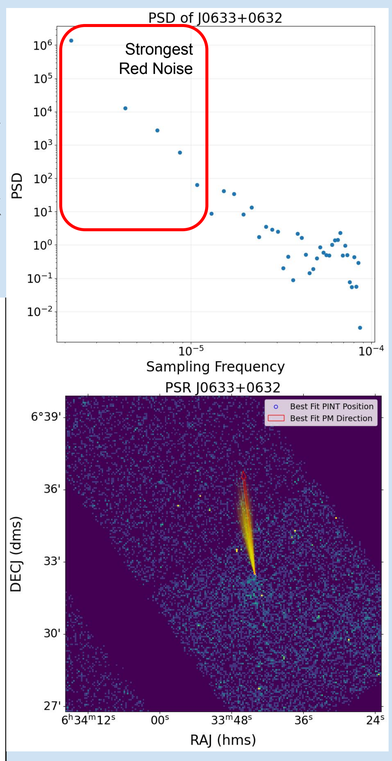


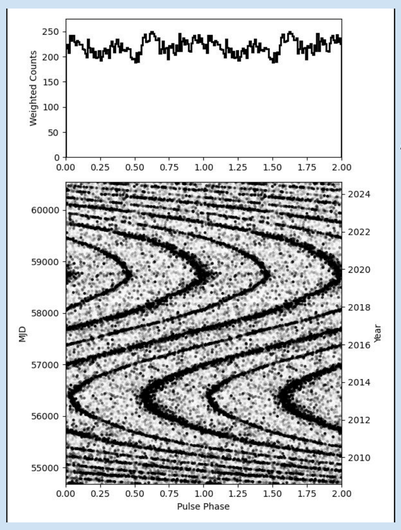




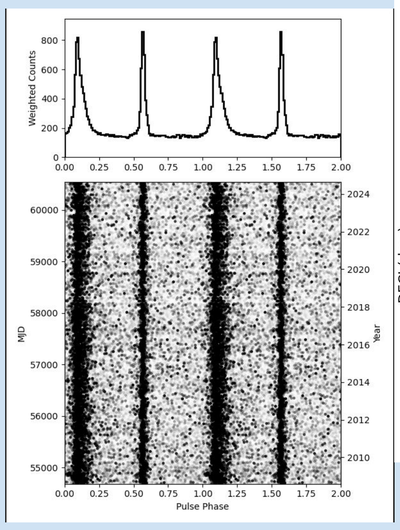
J0633+0632 and Red Noise Fitting

- Several of the slow pulsars that we are trying to measure proper motion for show significant red noise
- We can account for the red noise by using a Fourier based spectral decomposition alongside the MCMC analysis
- For the brighter pulsars, I can do a rough TOA analysis (similar to radio) in PINT and fit our residuals to acquire a starting phase-connected timing model, but this analysis does not work with faint pulsars





Accounting for Red Noise



Reading a Phaseogram

- **The top plot is a binned histogram of all the photons plotted with rotation phase.**
- **The bottom plot is a scatter plot of all the detected photons across the *Fermi*-LAT observation**
- **The transparency on the scatter plot denotes the probability i.e. weight that the photon (dot) is associated with the pulsar as opposed to a background source**