Analyzing Archival Terzan5 Data Through Polarization Calibration

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Abstract

Redback Pulsars are eclipsing pulsars that are frequently lost due to their quasi-random orbital variability. In this project we endeavored to use new software to gather detections of two pulsars in the globular cluster, Terzan 5. Then using these new detections we were able to investigate the polarization of these sources through calibration of the data. We attempted to verify whether PSR J1748−2446ad is truly the fastest-spinning radio pulsar by using the polarization information, and were unsuccessful. The polarization information of PSR J1748−2446P was more illuminating and provided some evidence of the pulsar having circular polarization.

Contents

Chapter 1

Introduction

There is currently archival data as well as contemporary data from the Green Bank Telescope (GBT) on almost 40 millisecond pulsars in Terzan5. That group of pulsars includes many interesting systems, including the two Redback Pulsars that this paper investigates.

Redback (RB) pulsars are eclipsing binary millisecond pulsars that interact with a not yet degenerate companion star. The eclipses of these pulsars can be attributed to ionized material of the companion obscuring the pulsar. A companion of a RB pulsar will be a fluffy star that fills its own Roche lobe during the whole orbit due its circular orbit. The Roche lobe is a teardrop shaped region surrounding a star in a binary system. Inside the lobe is material that is bound to the star by gravity, anything outside of the star can escape the system, orbit the stars, or fall into the binary companion. The wind of the pulsar will fill the magnetosphere of the companion with relativistic particles causing evaporation which in turn results in the eclipse of the radio waves in the cyclotron resonances of the plasma [Stappers et al., 2001].

J1748−2446ad, or Ter5ad, and J1748−2446P, or Ter5P, are two such pulsars that are located in the globular cluster Terzan 5. Ter5ad is known as the fastest spinning radio pulsar, but it experiences extreme eclipsing and is not present for most observations. Ter5P has less extreme eclipsing, but is sometimes still missing from observations. Due to the strong orbital variability and orbital periods that change quasi-randomly, there were very few detections of these two pulsars. `SPIDER_TWISTER` is software that performs pulsar searches in orbital phase through the automatic folding of data, using multiple trial values for the time of passage at the ascending mode ($T_{\rm asc}$). Then, the value corresponding with the highest signal to noise is returned [Ridolfi]. By using `SPIDER_TWISTER`, these pulsars were able to be detected across several years of archival data.

In this project we endeavored to search through all of the archival data for Ter5ad and Ter5P to gather more detections. In addition to doing this, we also analyzed the archival data through folding the raw data using the updated orbital ephemerides gathered from `SPIDER_TWISTER`. These folds of the raw data were then calibrated in an effort to gather polarization information on both pulsars. Ter5ad while being known as the fastest-spinning radio pulsar, could possibly be oriented edge-on or could possibly have a similar interpulse to the main pulse exactly at 180 degrees separated in rotation, resulting in the spin period to seem twice as fast as in reality. By gathering polarization information and folding the raw data for this pulsar at two-times the spin period, we could test this theory by looking for polarization differences between the two peaks resulting from the two-times-folded data. Gathering polarization information for Ter5P would be similarly interesting as the polarization of RB pulsars is not well-studied, especially as a function of orbital period with their variable eclipses. Through this investigation we were unable to gather polarization information for Ter5ad, but we did find that both Ter5P and Ter5ad lack linear polarization, and while Ter5ad seemingly has no polarization at all Ter5P has some circular polarization.

Chapter 2

Data

2.1 History of Ter5ad and Ter5P

Ter5ad was discovered in 2006 using the Green Bank Telescope, and this discovery subsequently unseated B1937+21 (642-Hz) as the fastest spinning neutron star ever found at 716 Hz. This pulsar was difficult to detect due to it's very low flux density and high eclipse fraction (∼40%), which inherently suggests that even faster spinning neutron stars may exist. Ter5P has a spin frequency of 579 Hz, and while it is similarly an RB pulsar, it has a less sizeable eclipsing fraction. [Hessels et al., 2006]

2.1.1 Data Processing

The observational data we analyzed of Ter5ad and Ter5P spanned from 2009 to 2020. All of the data were taken on the GBT with the GUPPI instrument, and most observations are in either the Lband (1-2 GHz) or Sband (2-4 GHz) frequencies.

As mentioned previously, `SPIDER_TWISTER` performs an orbital phase search using multiple trial values in orbital phase and returns the value with the highest signal to noise [Ridolfi]. This provides the user with an updated orbital ephemeris that can be used for other investigations. We used `SPIDER_TWISTER` to process all of the archival and contemporary data by utilizing the old orbital ephemeride file and the time series of each epoch. Due to the unique searching protocols of `SPIDER_TWISTER` we were able to gather more detections than have ever been seen before for each pulsar, the exact epochs of detection can be seen in the table in the results section.

After gathering all of updated orbital ephemerides, we then tested the subbanded data to see what effect the new epehemerides would have when folding the data using prepfold.

Once we confirmed the positive effects of using the updated ephemerides for the purposes of data folding, we then folded the available raw data with those ephemerides. A portion of the archival data was not available to be folded on the computing cluster we were processing data on, so there is some information missing from the analysis. Those data were deleted as they are extremely voluminous, approximately a terabyte of data per hour on the cluster. Where available, we used previous raw data folds to calibrate.

There is limited data available on the topic of polarization information for RB pulsars, and until recently Ter5ad and Ter5P had similar limitations. Gathering polarization information for Ter5ad would either reaffirm or dispute the validity of its label of fastest spinning radio pulsar, and gathering polarization information for Ter5P would expand the limited data about RB pulsars polarization information.

Using `PSRCHIVE` we calibrated the data and then set the rotation measure (RM) of the pulsars respectively. All pulsars in the globular cluster, Terzan5, have a rotation measure around $180\,\mathrm{rad\,m^{-2}}$ and so for epochs where we could not accurately estimate the RM we set it to $180\,\mathrm{rad\,m^{-2}}$. After setting the rotation measure, we used `PSRCHIVE` to create plots that display the polarization of the pulsars. For Ter5P, we found evidence of circular polarization, but no evidence of linear polarization. For Ter5ad, we found no evidence of polarization, but that doesn't concretely prove that Ter5ad lacks polarization, and further discussion of this topic is available in chapter 4.

2.2 Eclipsing Pulsars

Redback pulsars and Black Widow (BW) pulsars are distinct populations of eclipsing binary millisecond pulsars. The mechanisms of eclipses are not currently well known. In Chen et al. [2013], the formation of these systems is associated with converging low mass X-ray binaries (LMXB), and the factor determining the production of a BW pulsar vs a RB pulsar

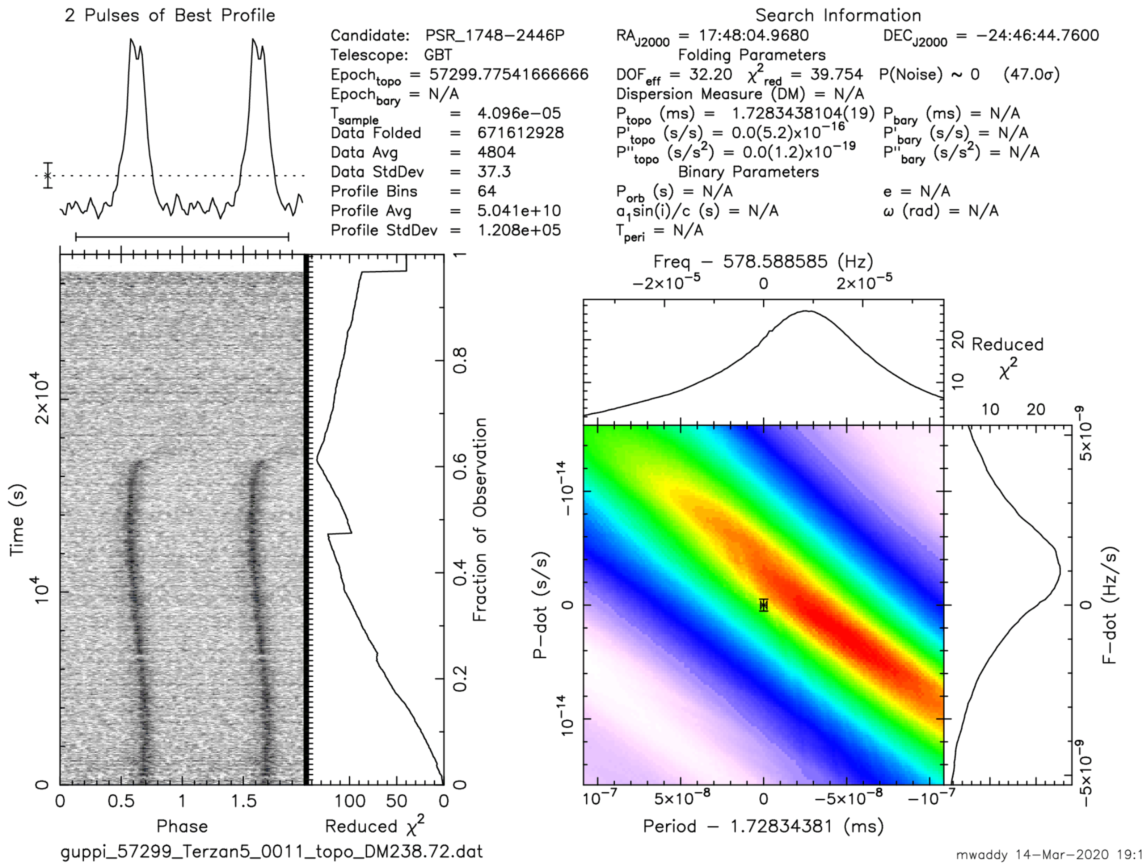

Figure 2.1: A plot of one of the stronger Ter5P detections on 57299 using the updated ephemerides from SPIDER_TWISTER.The first diagram on the left of this plot displays a time vs. phase plot that shows the pulsar gong into eclipse 60% of the way through the observation. Beside that diagram is a brief list of information about the folding process. In the top right corner, there is another brief list detailing the pulsar search parameters. Lastly, in the right bottom corner there is a period-period derivative diagram.

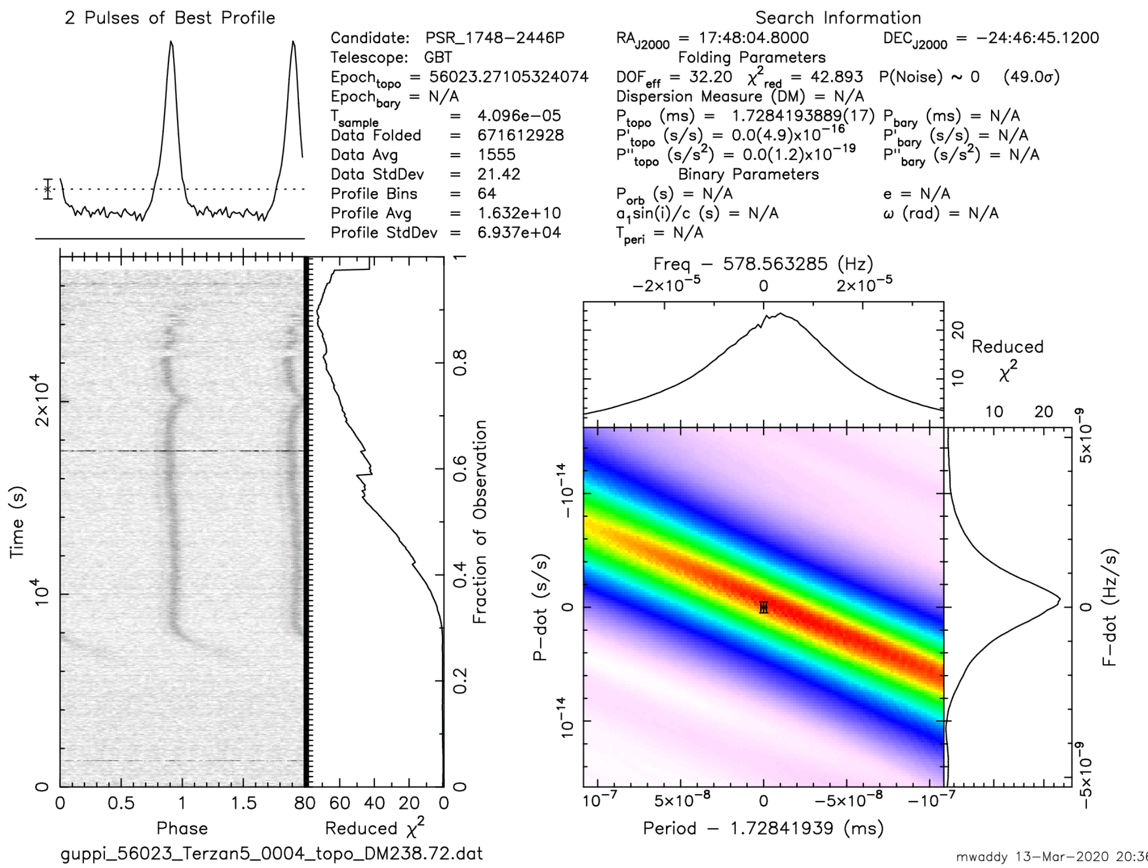

Figure 2.2: A plot of one of the stronger Ter5P detections on 56023 using the updated ephemerides from `SPIDER_TWISTER`.

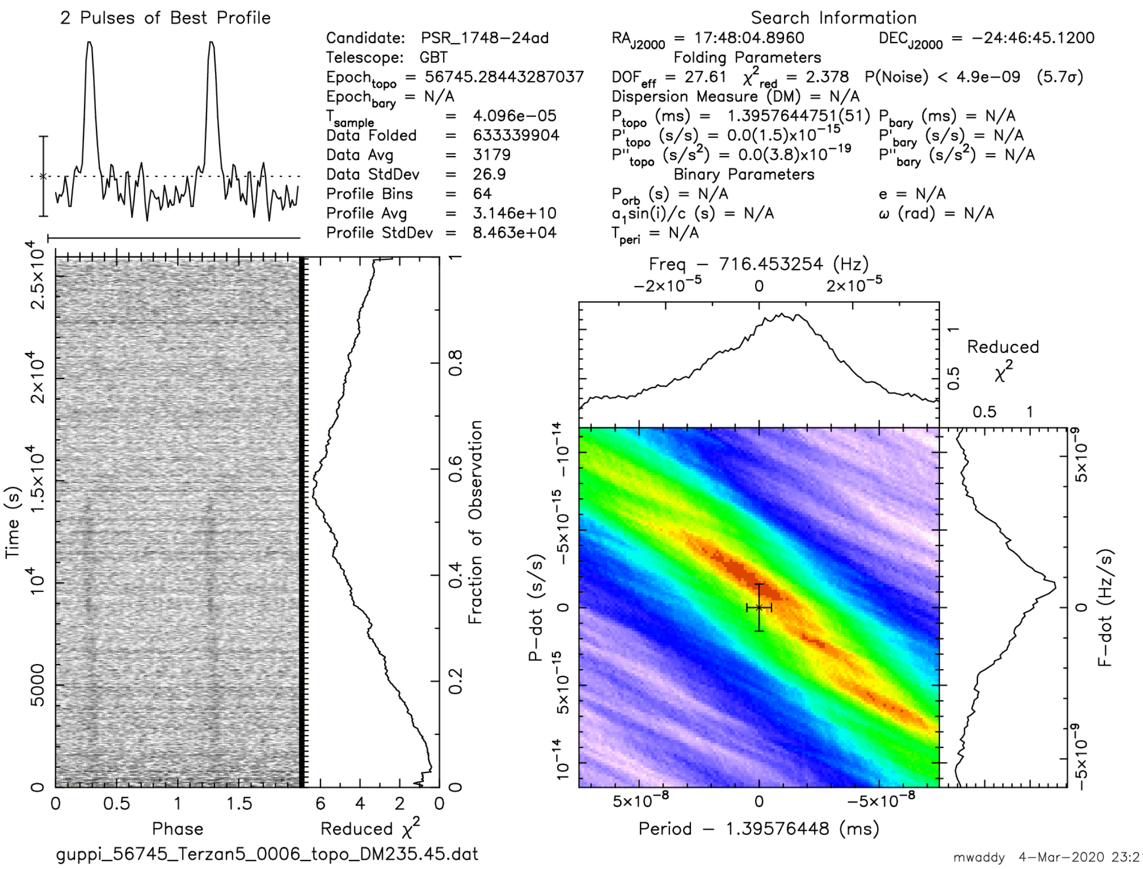

Figure 2.3: A plot of the 56745 Ter5ad detection using the updated ephemerides from `SPIDER_TWISTER`.

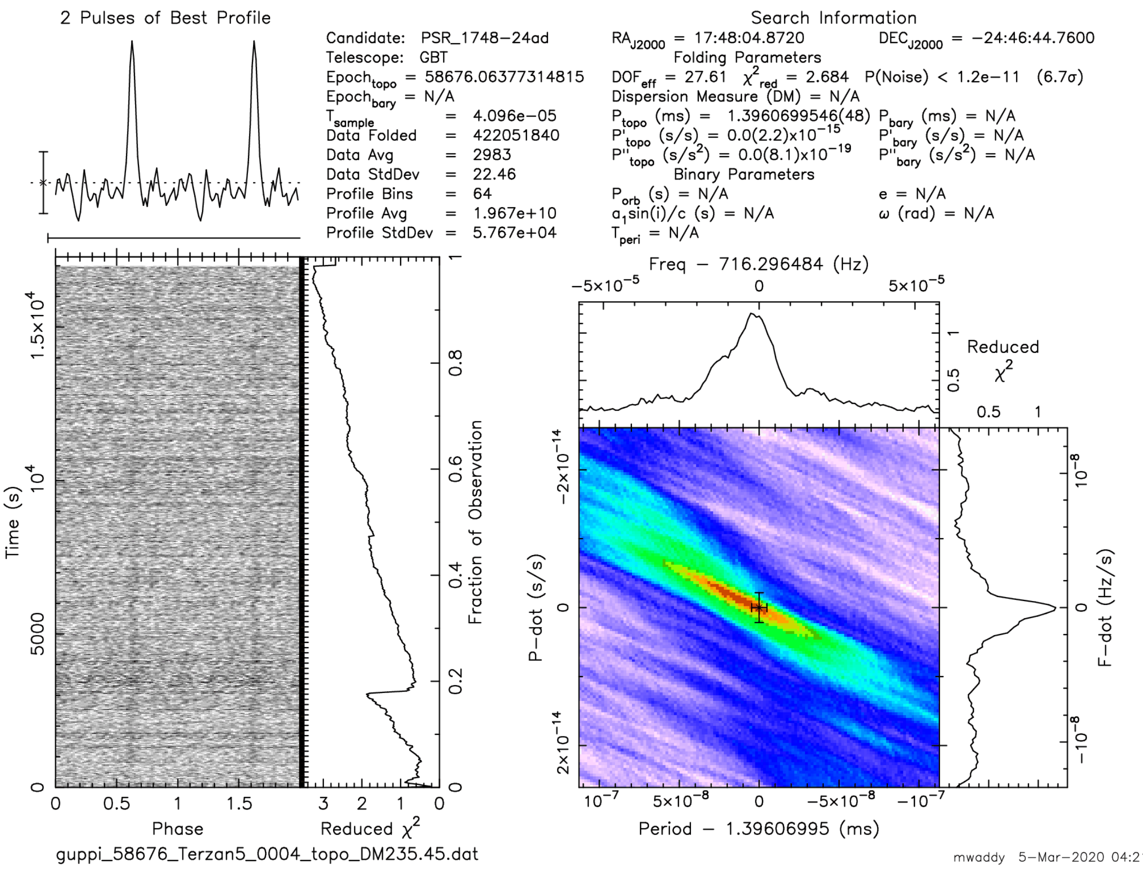

Figure 2.4: A plot of the 58676 Ter5ad detection using the updated ephemerides from `SPIDER_TWISTER`.

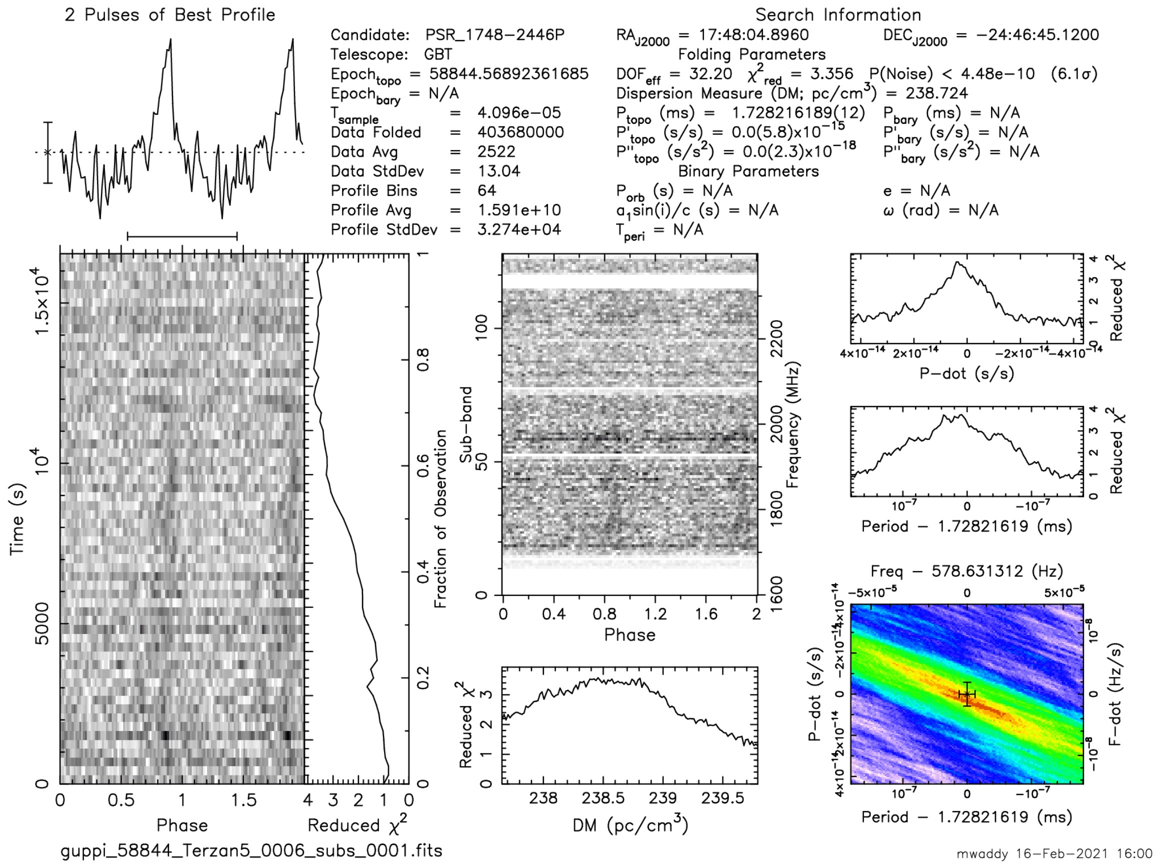

Figure 2.5: A plot of the 58844 folded subband Ter5P detection using the updated ephemerides from `SPIDER_TWISTER`. The first diagram on the left of this plot displays a time vs. phase plot that shows the pulsar gong into eclipse 70% of the way through the observation. Beside that diagram is a brief list of information about the folding process. There are two diagrams in the middle, the top diagram shows the phase vs. the frequency, and the bottom diagram visualizes the the dispersion measure vs. the reduced χ^2. χ^2 is related to measuring the signal-to-noise, as it measures how well a model fits the data. In the top right corner, there is another brief list detailing the pulsar search parameters. Lastly, in the right bottom corner there are three diagrams - a period derivative vs. χ^2, a period vs. χ^2, and a period-period derivative diagram.

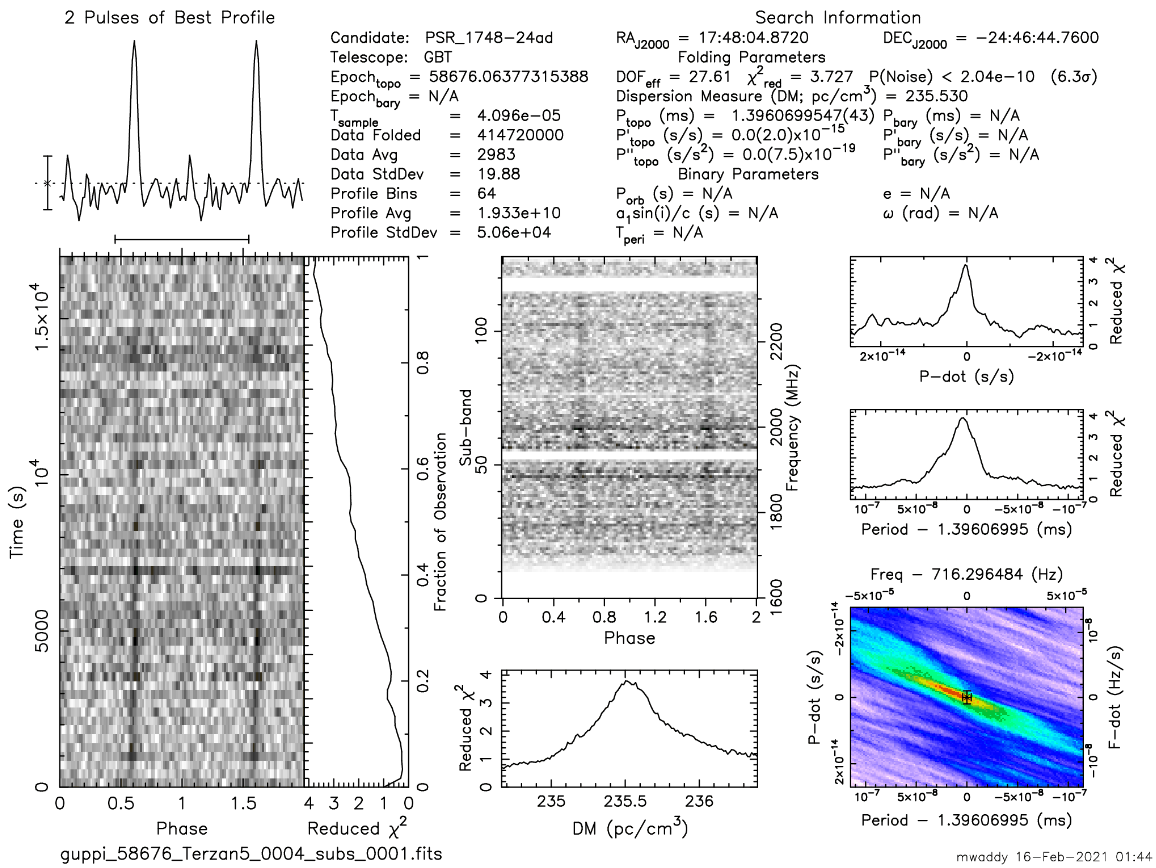

Figure 2.6: A plot of the 58676 folded subband Ter5ad detection using the updated ephemerides from `SPIDER_TWISTER`.

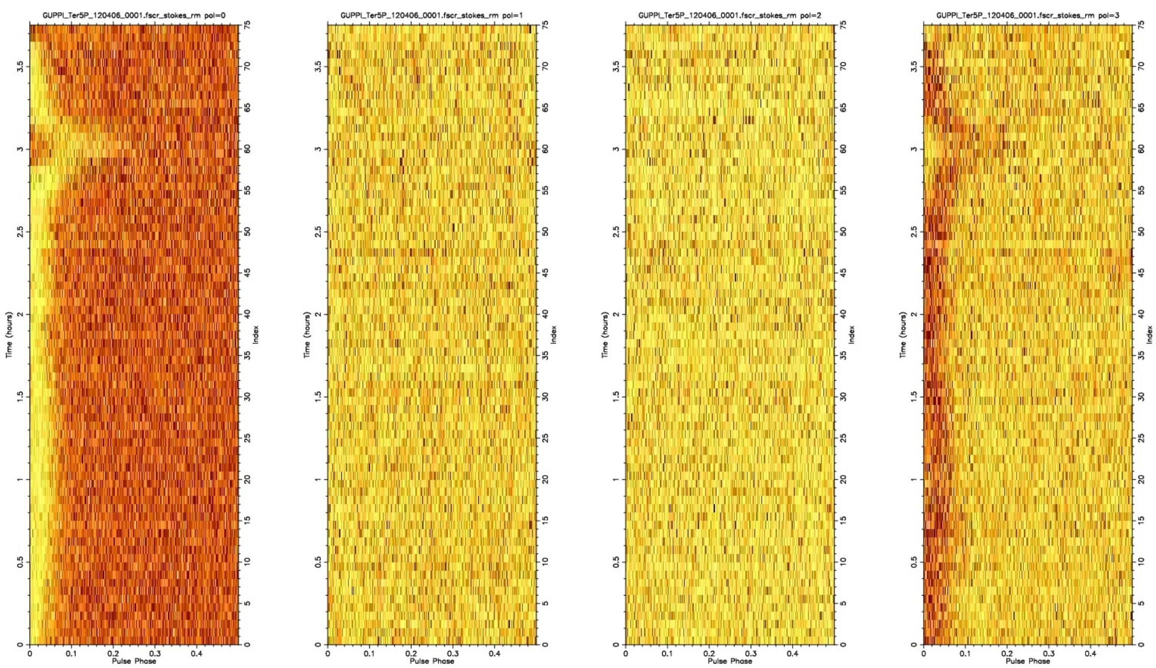

Figure 2.7: A plot of stokes parameters analyzed for Ter5P on 56023, from left to right the first panel shows the total intensity (I), the second and third panels show the linear polarization (Q and U), and the last panel shows the circular polarization (V).

is the efficiency of the irradiation process. RB pulsars absorb a larger fraction of the emitted spin-down energy of the radio pulsar, causing more efficient mass loss via evaporation [Chen et al., 2013].

In order to form an eclipsing millisecond pulsar (MSP) system, the neutron star must be capable of spinning up its period to a millisecond rate and the companion star must be ablated to produce the orbital eclipses. When the companion star decreases to 0.2-0.3 solar masses, it becomes fully convective. It is then assumed that the magnetic braking stops and the mass transfer is temporarily halted. When the neutron star is spun up enough from accretion, it becomes an MSP, then it begins to evaporate the companion star [Chen et al., 2013].

Different values of efficiency in evaporation of the companion star can be related to the distribution of angles between the orbital angular momentum axis and the pulsar magnetic axis. This determines the geometric beaming of the outflow consisting of charged particles from the pulsar magnetosphere [Chen et al., 2013]. Determining the magnetic inclination angle from polarization measurements could test this, but unfortunately for MSPs and especially for RB pulsars this is very difficult due to the eclipse effects.

Chapter 3

Analysis

3.1 Polarization for Redbacks

3.1.1 GUPPI Malfunction

The GUPPI instrument on the GBT first started malfunctioning in 2014, and it shows up in our data on March 29th 2014. This malfunction of the sampler caused most of the data after that date to not have viable polarization information. The GUPPI malfunction is semi-random, so for some epochs the polarization is still viable, for example June 30th, 2014 (56838), October 11th, 2014 (56941), and October 4th, 2015 (57299). There are pulsars in Terzan 5 with intrinsic Stokes V, for example PSR 1744–24A and PSR J17482446N, and when the polarization fluctuates as a function of frequency that means the data is unusable, but if the polarization stays constant as a function of frequency the data is usable.

3.1.2 Examples of Polarization from Pulsars in Terzan5

The largest population of known MSPs in globular clusters is hosted in Terzan 5 [Hessels et al., 2006, Lyne et al., 2000, Prager et al., 2017], so comparing the polarization of Ter5P and Ter5ad to other pulsars in Terzan 5 will help contextualize the data.

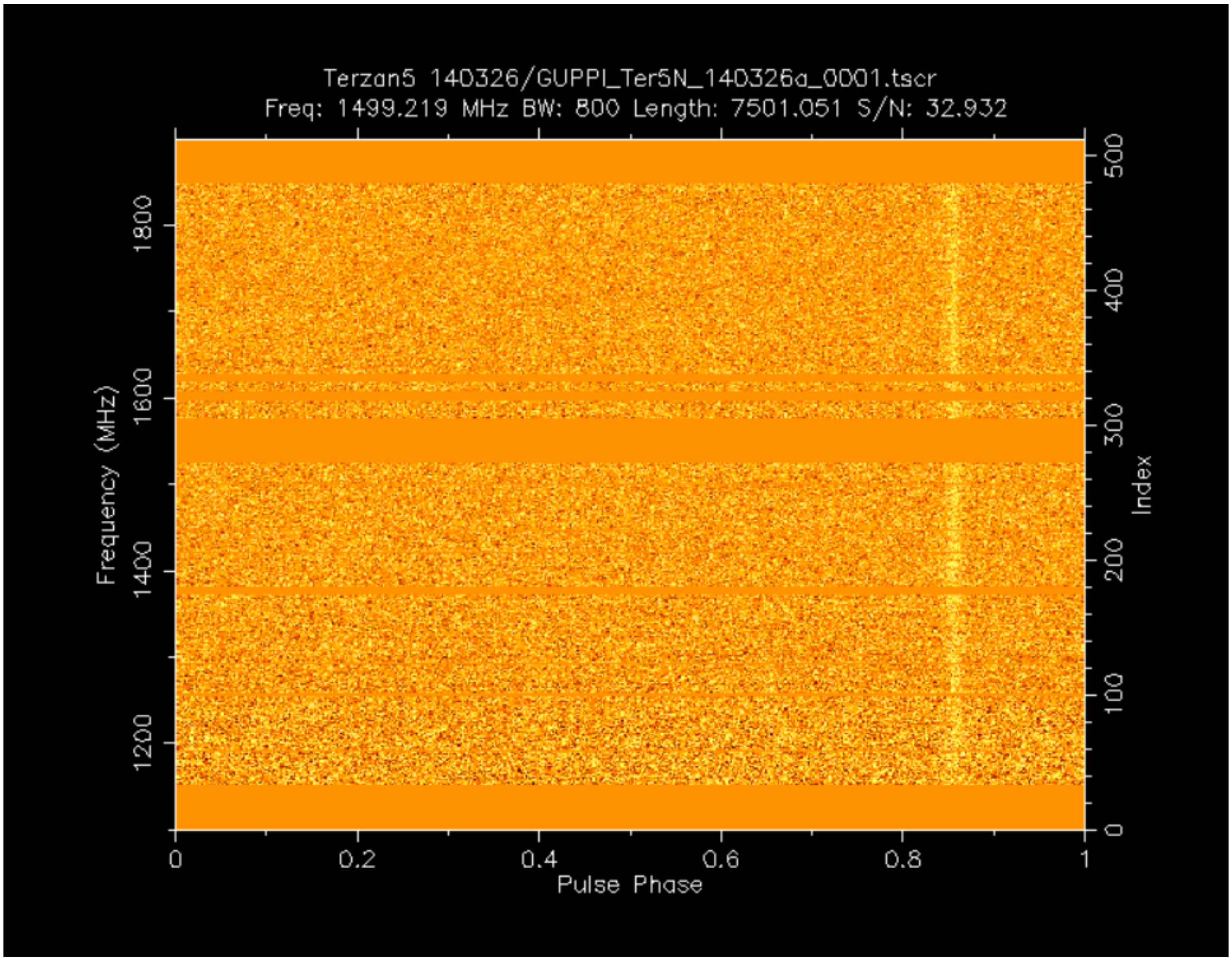

Figure 3.1: A plot showing constant polarization as a function of frequency throughout an epoch in 2014 for PSR J17482446N, therefore confirming this portion of the data on this date likely have good polarization information.

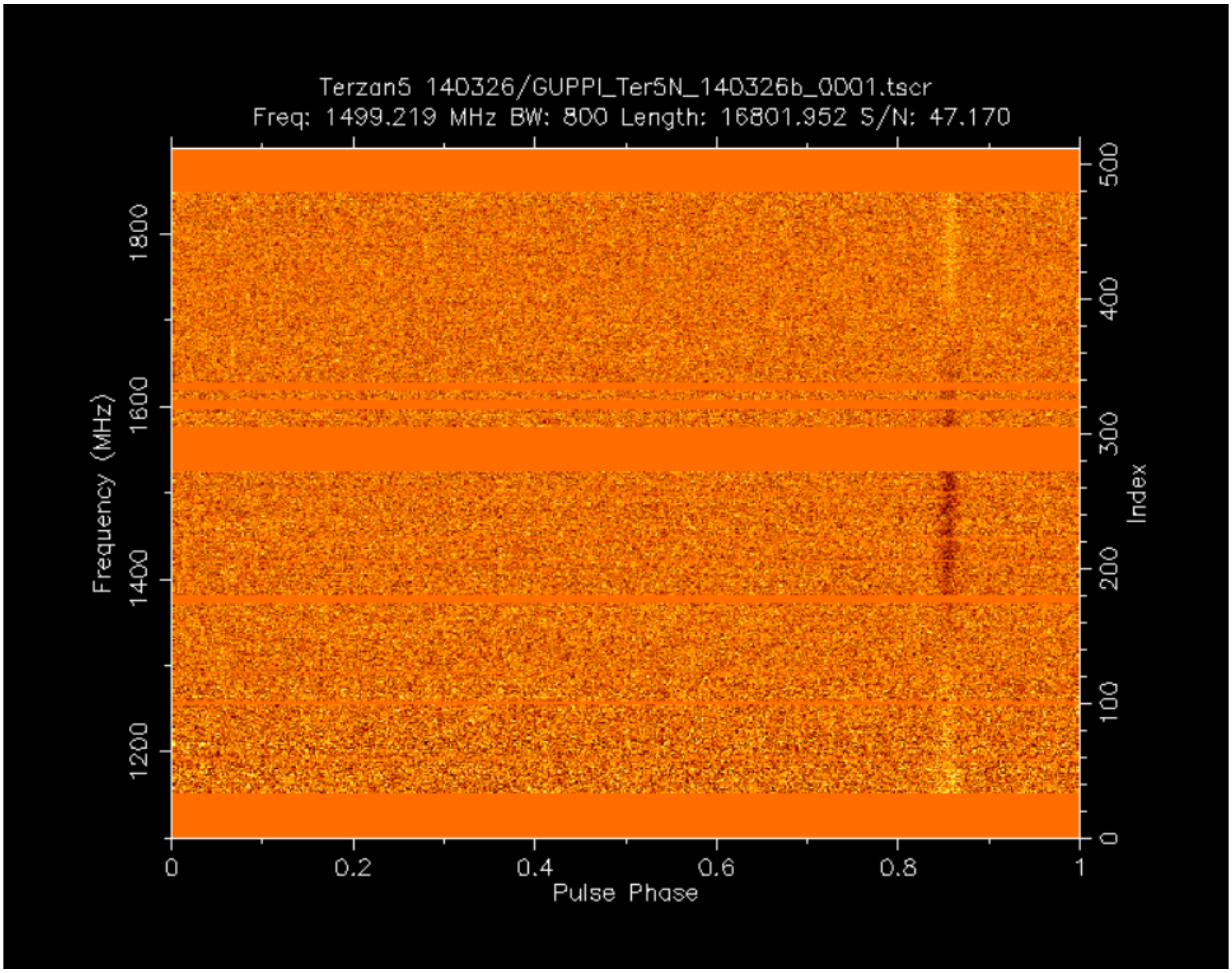

Figure 3.2: A plot showing polarization fluctuation as a function of frequency for PSR J17482446N. This shows that the polarization information for this portion of the data on this date would be unusable.

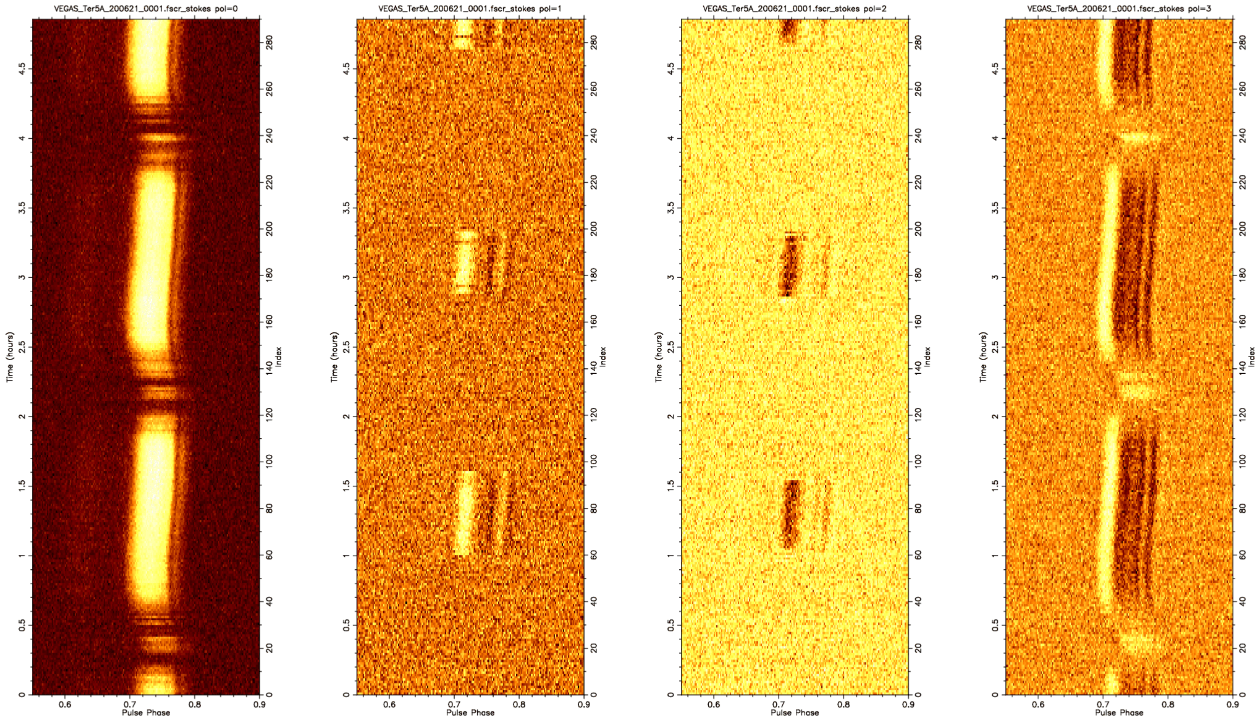

Figure 3.3: A plot of stokes parameters analyzed for Ter5A, from left to right the first panel shows the total intensity (I), the second and third panels show the linear polarization (Q and U), and the last panel shows the circular polarization (V).

Ter5A

PSR B1744–24A, or Ter5A, is an eclipsing MSP with a 11.56 ms spin period in a compact binary system presumably with a man sequence star companion [Bilous et al., 2019]. It shows both linear and circular polarization, but when it eclipses the linear polarization disappears at the edges of the eclipse.

Ter5N

PSR J17482446N, or Ter5N, is an 8.66 ms MSP [Ransom et al., 2005] that shows both linear and circular polarization. This pulsar doesn't eclipse, and so it should show a baseline of what the polarization should look like under normal circumstances.

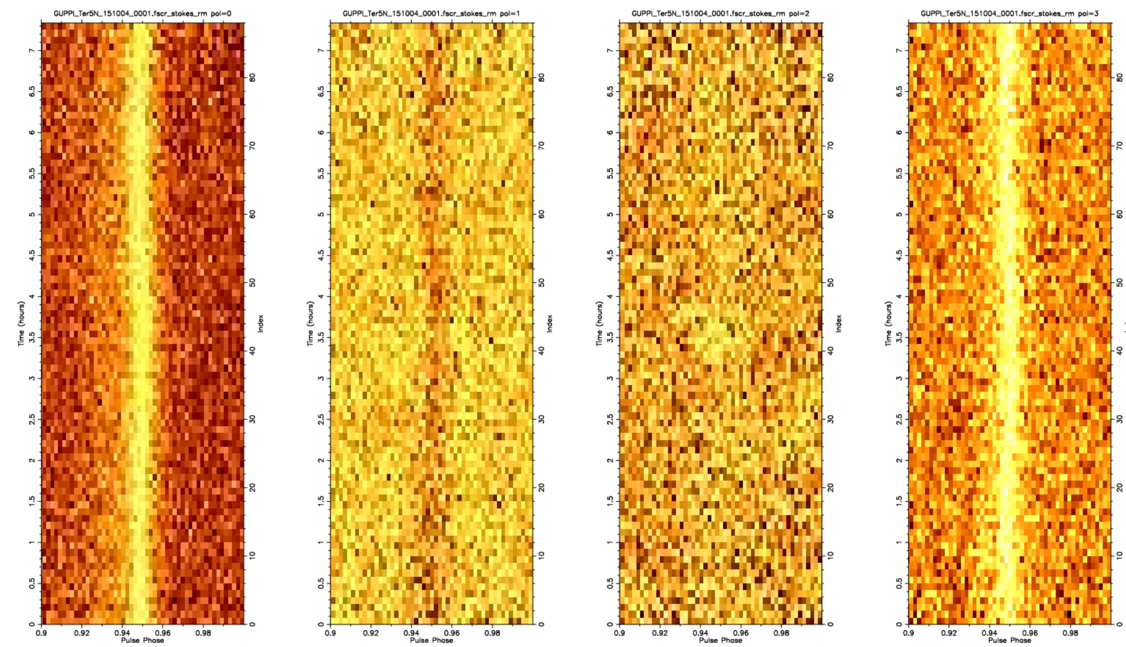

Figure 3.4: A plot of stokes parameters analyzed for Ter5N, from left to right the first panel shows the total intensity (I), the second and third panels show the linear polarization (Q and U), and the last panel shows the circular polarization (V).

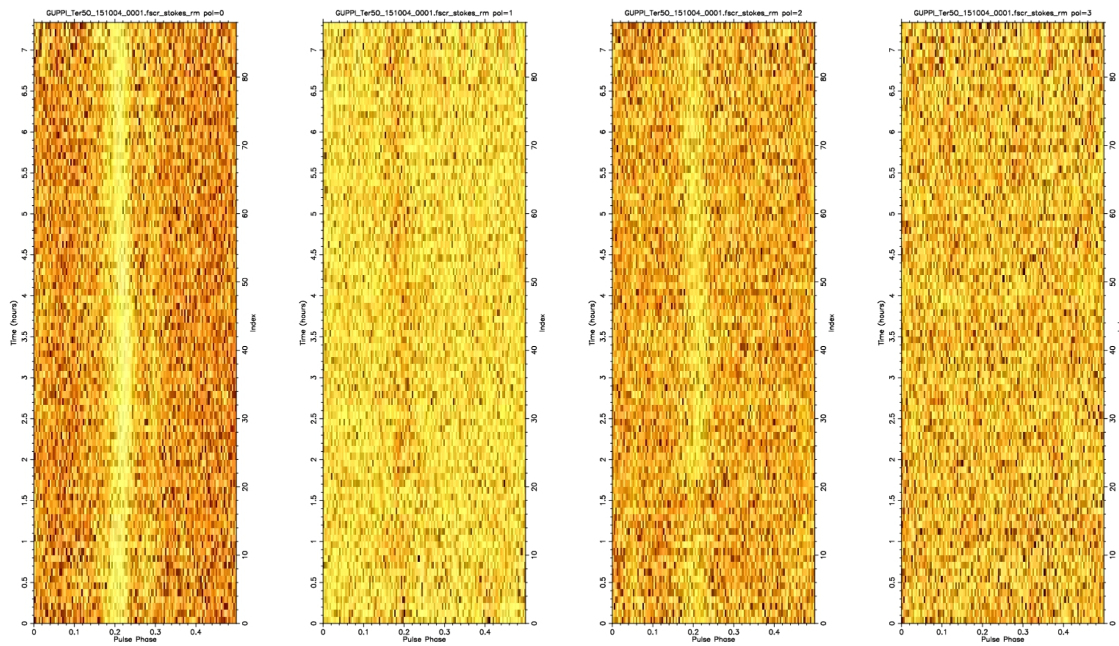

Figure 3.5: A plot of stokes parameters analyzed for Ter5O, from left to right the first panel shows the total intensity (I), the second and third panels show the linear polarization (Q and U), and the last panel shows the circular polarization (V).

Ter5O

PSR J174824460, or Ter5O, is an 1.67663 ms eclipsing BW MSP [Ransom et al., 2005]. This pulsar only shows linear polarization.

3.2 Polarization Calibration of Ter5P and Ter5ad

As mentioned previously, Ter5P shows evidence of circular polarization demonstrated in figures 3.6 and 3.7. Pulsars are highly polarized sources, but circular polarization isn't as common, and so to see a pulsar have no linear polarization and pronounced circular

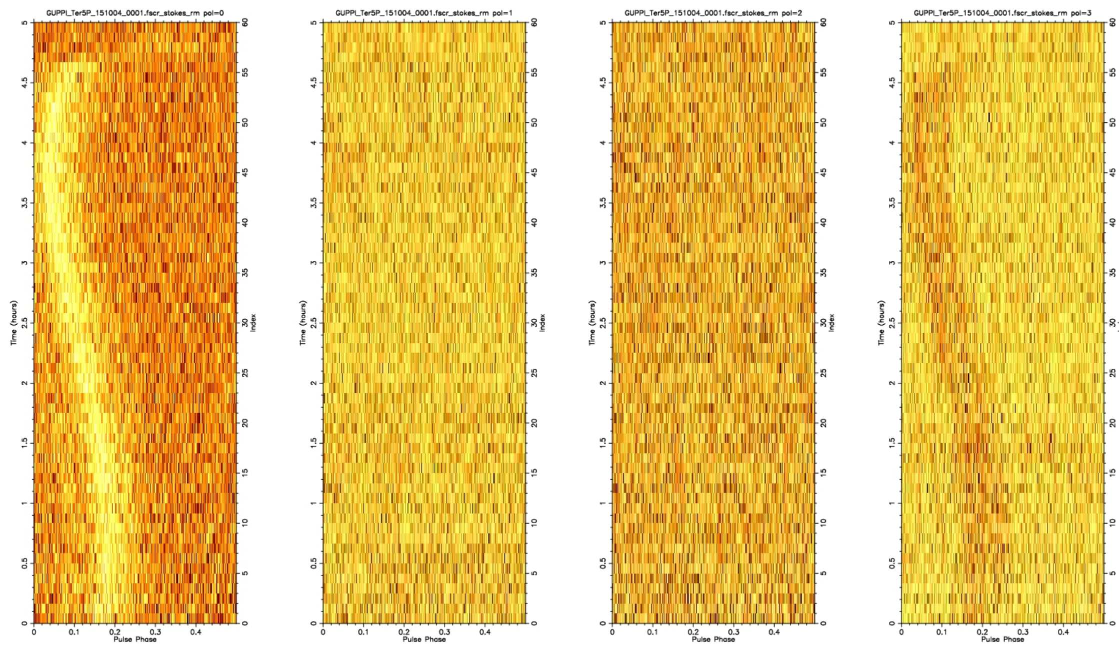

Figure 3.6: A plot of stokes parameters analyzed for Ter5P taken in the same epoch as the above figure for Ter5O. From left to right the first panel shows the total intensity (I), the second and third panels show the linear polarization (Q and U), and the last panel shows the circular polarization (V).

polarization is highly unusual. The trend stays consistent through all of the epochs of strong detection that we were able to calibrate, adding interesting information to the sparsely populated topic of study that is RB pulsar polarization.

Also mentioned previously was the fact that there is no evidence of polarization for Ter5ad. This is due to a combination of issues, the issue of GUPPI malfunctioning in 2014, the issue of Ter5ad's faintness, and the issue of Ter5ad's eclipse fraction. These issues will be further discussed in chapter 4. Despite getting clear detections similar to the one in figure 3.8, we were still unable to gather any polarization information as seen in figure 3.9.

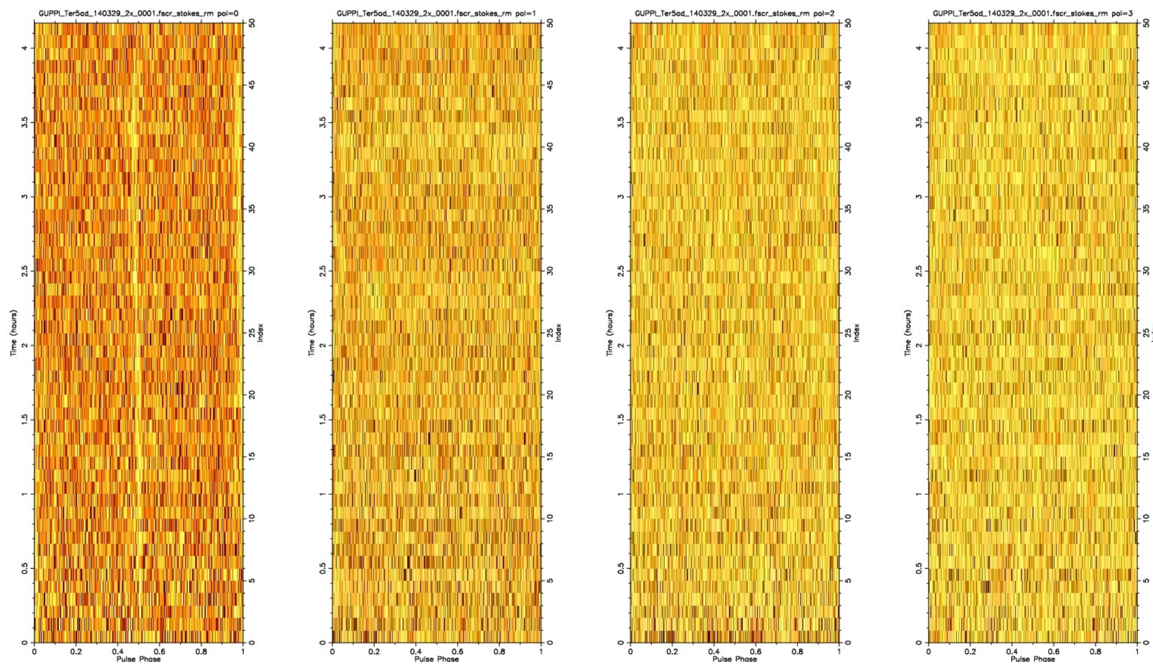

Figure 3.7: A plot of stokes parameters analyzed for Ter5ad. From left to right the first panel shows the total intensity (I), the second and third panels show the linear polarization (Q and U), and the last panel shows the circular polarization (V).

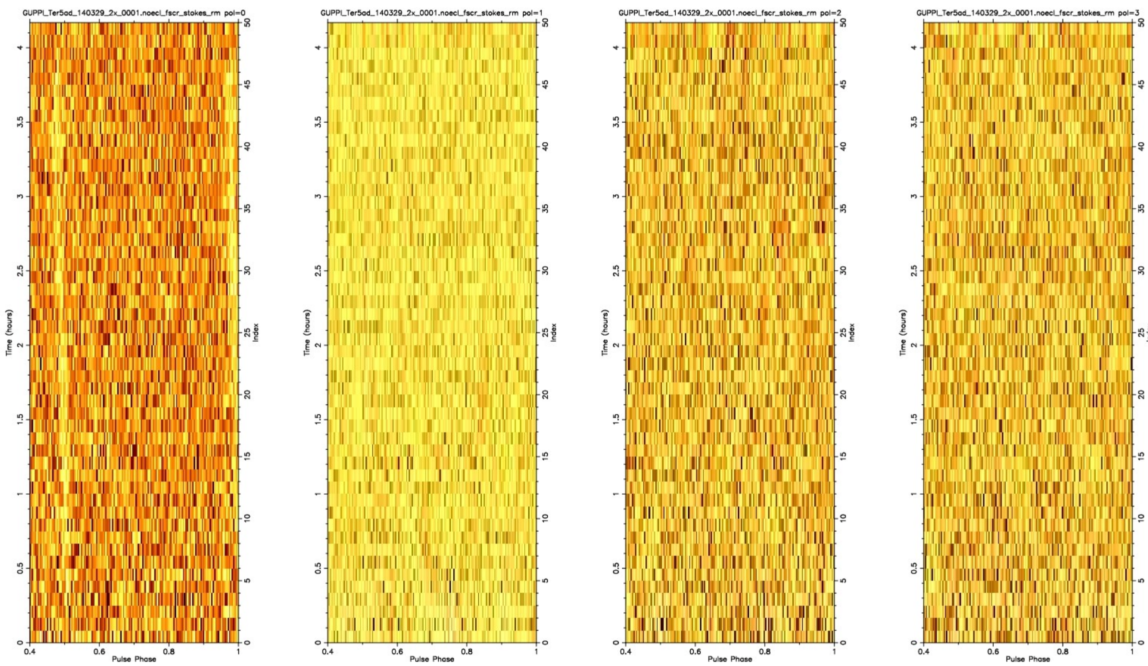

Figure 3.8: A plot of stokes parameters analyzed for Ter5ad from the same epoch as above, but the raw data has been folded at twice the spin period confirming that there s no evidence of polarization in this epoch. From left to right the first panel shows the total intensity (I), the second and third panels show the linear polarization (Q and U), and the last panel shows the circular polarization (V).

Chapter 4

Results

4.1 Discussion & Conclusions

There are more questions than answers after analyzing the data for polarization information on Ter5ad and Ter5P. To start with Ter5ad, despite our best efforts we consistently found no evidence of polarization and so we could neither confirm nor deny that Ter5ad is the fastest spinning radio pulsar using polarization information. This is due to a combination of issues, in 2014 the GUPPI sampler malfunctioned causing problems specifically for polarization, the pulsar is very faint and usually doesn't reach above 10 σ for detections, and the eclipses are frequent. The frequent eclipses meant that Ter5ad was eclipsed critically through most epochs from 2009-2020. These eclipses could also possibly be eliminating any of the already faint polarization information. The linear polarization disappearing at the edges of eclipses that happens for Ter5A could also be happening to Ter5ad. Additionally, the lack of raw data for epochs that actually had Ter5ad detections ended up being an unfortunate coincidence that impeded our polarization analysis. The questions of Ter5ad's polarization merit more investigation in the future because it is still unclear whether the polarization doesn't exist or is imperceptible to our analyses.

The results of Ter5P's polarization is quite interesting, the polarization being solely circular is uncommon even in comparison to the other Terzan 5 MSPs. As mentioned previously, the differentiating factor of whether an MSP becomes a BW or a RB is the efficiency of the irradiation process. Ter5O, a BW pulsar exhibits only linear polarization, while Ter5P only exhibits circular polarization. The questions about the polarzaton of eclipse pulsars also merits more investigation, as there is little information currently dedicated to it.

In addition to the polarization studies, there are now several detections of both Ter5ad and Ter5P in the archival data that can be used for future investigation, and the documentation of this can be seen in the table below.

Epoch (MJD)	Epoch (YYMMDD)	Was Ter5ad detected?	Was Ter5P detected?	Is the polarization viable?	Are there polarization folds for Ter5N?	Are there polarization folds for Ter5A?
55057	090814	N	N	Bad epoch	No	No
55058	090815	N	N	Bad epoch	No	No
55136	091101	Y	Y	Bad epoch	Yes	No
55183	091218	N	N	No folds	No	No
55317	100501	no data available	no data available	Good epoch	Yes	Yes
55324	100508	N	N	Good epoch	No	No
55422	100814	N	Y (weak)	Bad epoch	No	No
55472	101003	N	N	Bad epoch	No	No
55496	101027	N	Y	Good epoch	No	No
55614	110222	N	Y	Good epoch	No	No
55653	110402	N	Y (weak)	Good epoch	No	No
55743	110701	N	Y	Good epoch	Yes	No
55829	110925	N	Y	Good epoch	No	No
55931	120105	N	Y (strong)	Good epoch	No	No
56023	120406	N	Y (strong)	Good epoch	Yes	No
56028	120611	N	Y	Good epoch	No	No
56032	120615	N	Y	Good epoch	No	No
56113	120705	N	Y	Good epoch	No	No
56206	121006	N	Y	Good epoch	No	No
56299	130107	N	Y	Good epoch	No	No
56389	130607	N	Y	Good epoch	No	No
56399	130617	N	Y (weak)	Good epoch	No	No
56474	130701	N	Y	Good epoch	No	No
56587	131022	Y	Y (weak)	Good epoch	No	No
56671	140114	N	Y (weak)	Bad epoch	No	No
56742	140326	N	Y	Bad epoch	No	No
56745	140329	Y (strong)	Y (strong)	Bad epoch	Yes	No
56778	140501	Y	Y	Bad epoch	No	No
56787	140510	N	Y	Bad epoch	No	No
56798	140521	N	N	Bad epoch	No	No

Epoch (MJD)	Epoch (YYMMDD)	Was Ter5ad detected?	Was Ter5P detected?	Is the polarization viable?	Are there polarization folds for Ter5N?	Are there polarization folds for Ter5A?
56838	140630	N	Y (strong)	Good epoch	Yes	Yes
56941	141011	N	Y (strong)	Good epoch	Yes	Yes
56943	141013	N	Y (weak)	Bad epoch	No	No
57026	150104	N	Y (weak)	Bad epoch	No	No
57119	150607	N	Y (weak)	Bad epoch	No	No
57209	150706	N	Y	Bad epoch	No	No
57299	151004	N	Y (strong)	Good epoch	Yes	Yes
57305	151010	N	Y(strong)	Bad epoch	No	No
57387	151231	N	Y (strong)	Bad epoch	No	No
57573	160704	N	Y (strong)	Bad epoch	No	No
57769	170116	Y	Y (weak)	Bad epoch	No	No
57791	170207	Y (strong)	Y	Bad epoch	No	No
57875	170502	N	Y	Bad epoch	No	No
58030	171004	N	Y	Bad epoch	No	No
58113	171226	Y (weak)	N	Good epoch	No	No
58215	180607	Y (weak)	Y	Bad epoch	No	No
58305	180706	N	Y	Bad epoch	No	No
58320	180721	Y (weak)	N	Bad epoch	No	No
58384	180923	Y (weak)	Y	Bad epoch	No	No
58412	181021	N	Y	Bad epoch	No	No
58480	181228	N	N	Bad epoch	No	No
58491	190108	N	N	Good epoch	No	No
58582	190609	N	Y	Bad epoch	No	No
58676	190712	Y (strong)	N	Bad epoch	No	No
58753	190927	N	Y	Bad epoch	No	No
58844	191227	N	Y	no data available	No	No
58933	200325	N	Y	no data available	No	No
59021	200621	N	Y	no data available	No	No
59037	200707	Y (weak)	N	no data available	No	No
59075	200814	N	N	no data available	No	No
59146	201024	N	N	no data available	No	No
59233	210119	N	N	no data available	No	No
59246	210201	N	N	no data available	No	No

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