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A Search for Pulsars and an Exploration of Dispersion Measure Within the Milky Way Galaxy

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A Search for Pulsars and an Exploration of Dispersion Measure Within the Milky Way Galaxy

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Abstract

A pulsar is a rapidly rotating neutron star which emits electromagnetic radiation from its magnetic poles. Upon detection from Earth, these signals have been dispersed in phase due to electron interactions in transit. The extent of this dispersion indicates information about both the distance to and the location of the pulsar, with respect to Earth and the Galactic plane. This project makes use of radio data from the 100m Robert C. Byrd Green Bank Telescope (GBT), presented in the form of *prepfold* plots assembled by the Pulsar Science Collaboratory (PSC). 1,007 of these plots were analyzed in order to determine if the depicted source was noise, radio frequency interference (RFI), maybe a new pulsar, a previously known pulsar, or a previously unknown pulsar. In addition to this analysis, data from the Australia Telescope National Facility (ATNF) catalogue of known pulsars were used to illustrate the relationship between dispersion measure (DM) and the location of a pulsar, using the galactic coordinate system (l, b). It is shown that a higher DM corresponds to locations nearer to the Galactic plane.

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Introduction

The object that came to be known as a pulsar was first observed in 1967 by then graduate student Jocelyn Bell, and her supervisor, Antony Hewish. The initial discovery was found to have a pulse signal duration of 0.3 s and a pulse period of 1.337 s. At the time of publishing, three additional similar objects had been found, indicating that a pulsar is not an uncommon occurrence (Hewish et al. 1968). As of this year, there are at least 3,400 known pulsars (Reddy 2024).

A pulsar is defined as a rapidly rotating neutron star which emits bursts of electromagnetic radiation, most commonly measured in the radio range with frequencies between 20 MHz and 10 GHz, and is named in reference to its position in the sky using right ascension and declination. As an example, the first discovered pulsar is referred to as PSR 1919+21 (Carroll & Ostlie 2017). These neutron stars are the remnants of massive stars with an initial mass between 10 and 25 times the mass of the Sun (Heger et al. 2003). Once these stars reach the end of their lives on the main sequence, expand into a supergiant, and subsequently collapse in a supernova explosion, only the extremely dense remains of the iron core are left, prevented from collapsing further by the neutron degeneracy pressure (Carroll & Ostlie 2017). Due to the principle of conservation of angular momentum, the large decrease in radius between the core of the initial supergiant and the resulting neutron star indicates that these objects must rotate very rapidly. Neutron stars must also have very strong magnetic fields, as the magnetic flux through the surface of the object is conserved as it collapses (Carroll & Ostlie 2017). Both these ideas are observed to be true and contribute to the defining characteristics of the pulsar. Pulsars rotate between a range of periods, with the fastest known rotation at 716 Hz (Hessels et al. 2006), and the longest known rotation period of 75.88s, or 13.2 mHz (Caleb et al. 2022). The strong magnetic fields are also believed to be the driving mechanism behind the characteristic electromagnetic emission of the pulsar, as the neutron star is a very quickly rotating magnetic dipole (Condon & Ransom 2018). Pulsars are also, on occasion, found in a binary pair with another object—often either a white dwarf or another neutron star. The first binary pulsar, PSR B1913+16, was discovered by Hulse and Taylor in 1975 (Hulse & Taylor 1975), and, as shown in the Australia Telescope National Facility (ATNF) Catalogue, many more binary pulsars have been located today, although they are still known to be relatively uncommon (The ATNF Pulsar Catalogue 2024; Manchester et al. 2005).

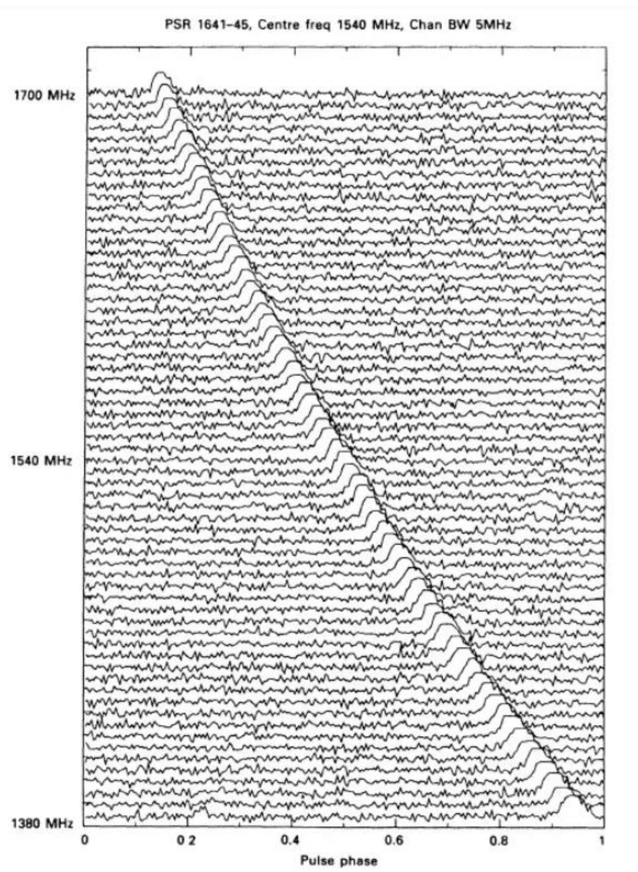

Figure 1: An example of the dispersion of a pulsar signal upon reaching Earth, from the pulse of PSR 1641-45. The pulse phase on the horizontal axis is plotted against the pulse frequency, measured in MHz. (Lyne & Graham-Smith 1990, as cited in Carrol & Ostlie 2017)

Due to the presence of the interstellar medium, the signal from a pulsar is dispersed in phase upon being detected from Earth. The electromagnetic waves from the pulsar interact with the electrons in the interstellar medium, with more energy being lost from lower frequencies, and the overall signal dispersion increases as the signal travels farther (Carroll & Ostlie 2017). A visual depiction of this dispersion is shown in Figure 1. This phenomenon yields a value referred to as dispersion measure (DM), which communicates information relating to both the distance to the detected pulsar from the Earth, and the density of electrons in the path of the signal, depending on the relative positions of the Earth, the pulsar, and the galactic center.

Pulsar Search

The completion of this project relied on radio data taken by the 100 meter Robert C. Byrd Green Bank Telescope (GBT), managed by the Green Bank Observatory in West Virginia. This telescope is sensitive to frequencies in the range of 0.1 to 100 GHz and is most often used for radio astronomy purposes (Telescopes). The Pulsar Search Collaboratory, now known as the Pulsar Science Collaboratory (PSC), is a partnership between the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), the National Radio Astronomy Observatory (NRAO), and West Virginia University whose purpose is to allow the analysis of these radio data for the purpose of searching for pulsars (Rosen et al. 2010).

For the purposes of this project, the radio data was presented in the form of a *prepfold* plot. These plots are so named due to the technique known as folding the data, where many pulses are stacked on top of each other in order for an observer to see a visible signal above the noise. In order to determine a period for the potential pulsar signal, a Fourier transform is also employed in transforming the initial signal-time data to a signal-frequency set, where a pulse signal is more evident. The PSC uses a software referred to as PRESTO to take these Fourier transforms, which in turn uses the *prepfold* program to fold the signal-time data at the proper period and generate a plot, as demonstrated in Figure 2 (Lynch). This is a fairly ideal plot, with very clear markers that the observed signal is a pulsar.

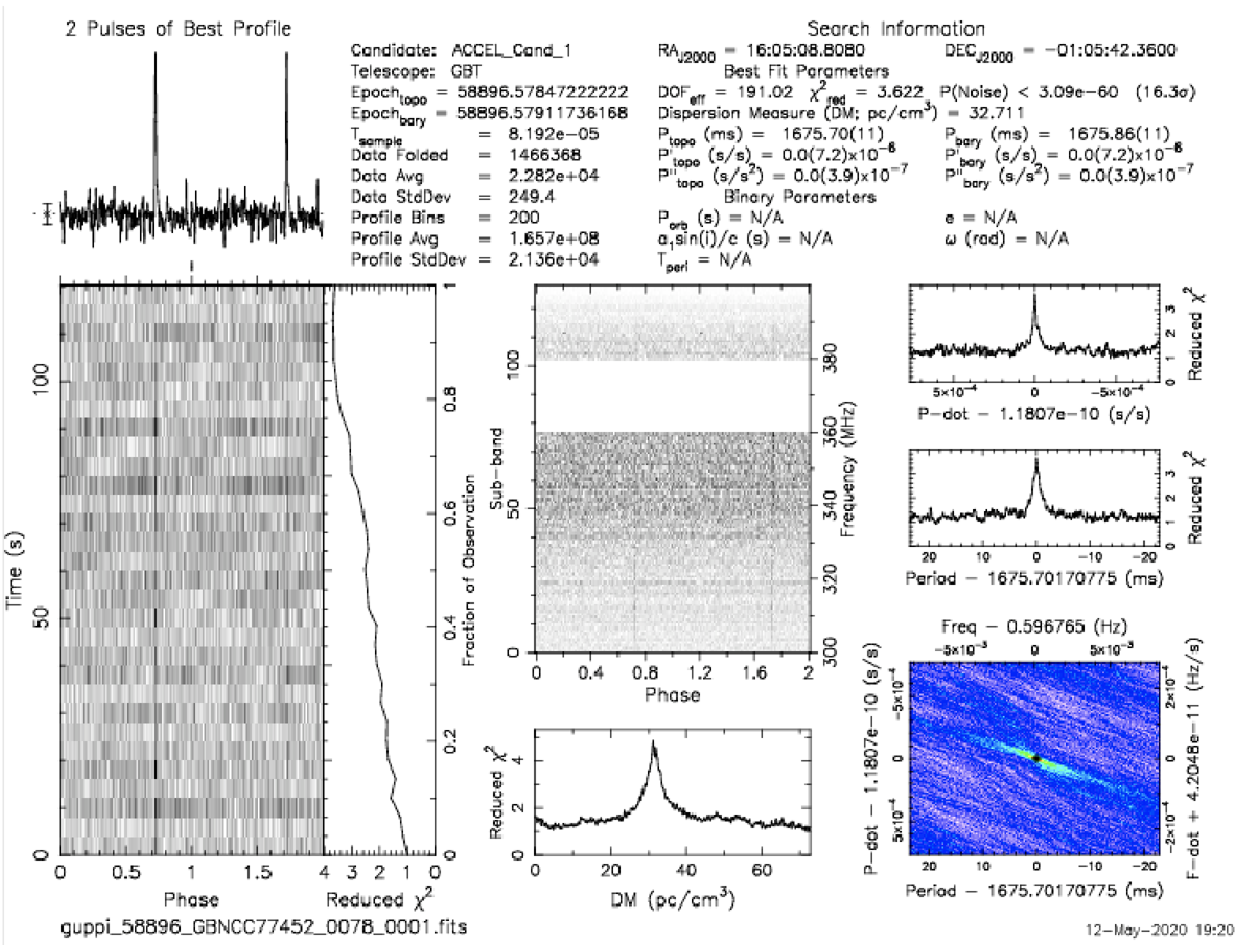

Figure 2: A *prepfold* plot representing recently discovered pulsar J1605-01. There are two pulses shown, clearly above the noise, and the observed radio frequency, in MHz, is a broadband signal. The DM, in pc/cm^3, is measured to be 32.711 (GBNCC Discoveries 2021).

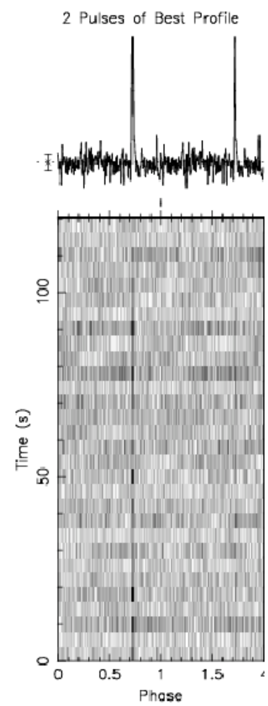

Figure 3: The time domain and pulse profile from the *prepfold* plot of pulsar J1605-01

In analyzing these plots, certain parts of the plot are used to determine the likelihood that the signal originated from a pulsar, as opposed to radio frequency interference (RFI) originating from Earth, or simply noise. The first of these is the time domain and pulse profile, as shown in Figure 3. For the plot to be representative of a pulsar, the pulse peaks must be clearly visible above the background noise, which is the case here. This chart also demonstrates vertical lines in the time-phase chart, corresponding in phase with the pulses visible in the pulse profile; another indication that this signal is a pulsar. The frequency-phase chart, as shown in Figure 4, is viewed next. This chart displays the measured frequency of the received signal in MHz, and should show, for a pulsar, a broadband signal that corresponds in phase with the time domain and pulse profile.

Also shown in Figure 4 is the Reduced χ^2-DM chart. As the Reduced χ^2 is a statistical quantity showing the agreement between the data and a model (Andrae et al. 2010), its value is

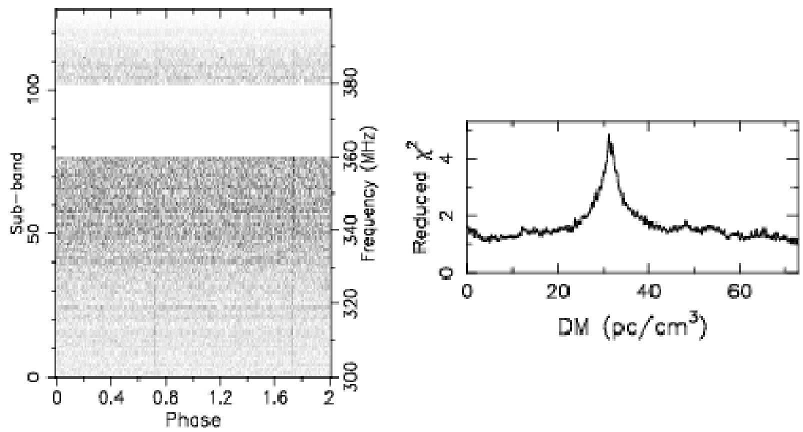

Figure 4: The frequency-phase chart (left) and the dispersion measure (DM) chart (right) from the *prepfold* plot of pulsar J1605-01.

close to 1 when this agreement is present. Since the model, in this case, is the absence of a pulsar, the Reduced χ^2 value is high when a pulsar signal is detected (Lynch). The width of the peak in the DM curve comes about due to the dispersion of the signal as it travels through space, but the peak itself shows a clear maximum Reduced χ^2 value. This, along with the DM value at the peak being appropriate for the direction from which the signal seems to originate, is indicative that the source is genuinely a pulsar.

Non-Pulsar Sources

While analyzing the *prepfold* plots, it is very common to encounter instances of radio frequency interference (RFI). These signals have a tendency to resemble a pulsar signal very closely, as evidenced by the example shown in Figure 5. The pulse profile clearly shows two pulses above the background noise, and the time domain chart shows the vertical lines, corresponding in phase, but there are anomalous dark spots which show up around 140 s. The frequency-phase chart is, however, indistinguishable from that of an actual pulsar signal. The

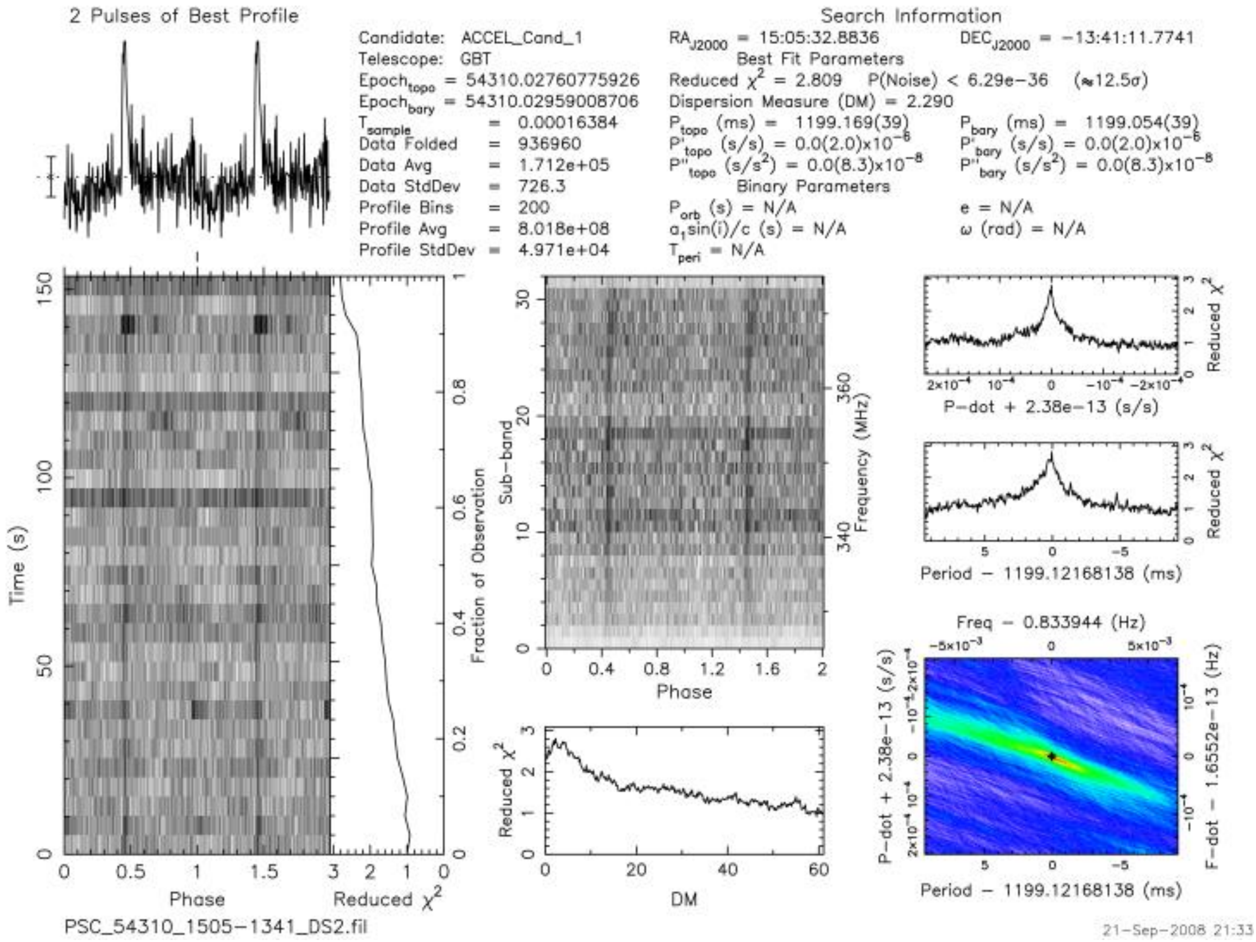

Figure 5: A known source of Radio Frequency Interference (RFI). The plot closely resembles that of a true pulsar, apart from the location of the peak in the DM curve (Example Plots 2022).

true indication that this signal is RFI remains the DM curve. The peak is not clear, and it appears to occur very near to zero. As the DM value is strongly related to the distance traveled by the signal, this near-zero value indicates that the signal has not traveled through space, but most likely originated on Earth. Thus, this plot demonstrates a human-made radio source.

The last source, which comprises most of the plots available for grading, is background noise. These are signals that seemed to have a recurring pattern, according to the PRESTO software, but do not truly contain a pulsar signal. This is often visually obvious, as the error bars are quite large on the pulse profile, indicating a low signal-to-noise ratio. The time domain chart

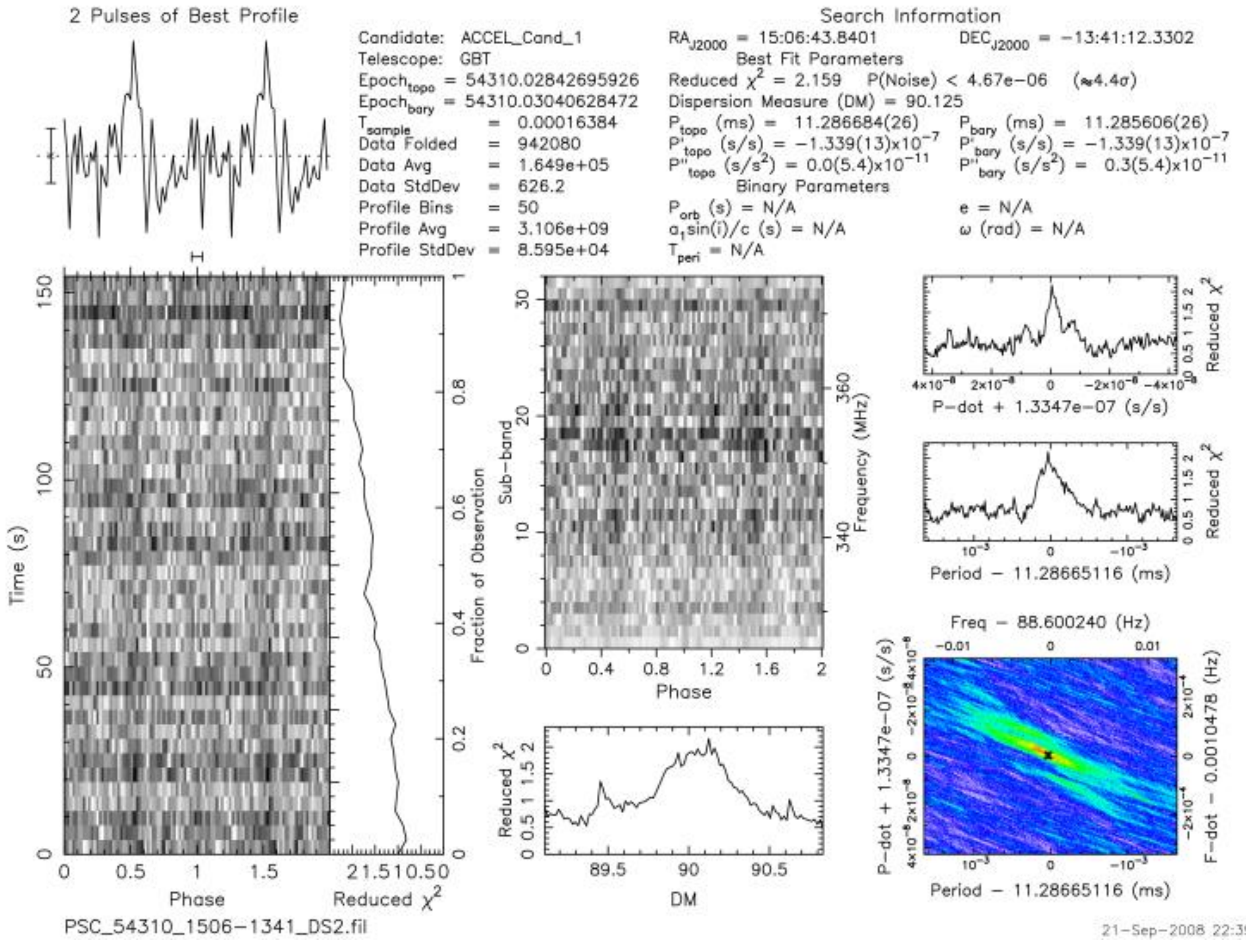

Figure 6: An example of a signal known to be noise. There are clear 'pulses,' but they are quite small relative to the background noise. The DM is also marked as being 90.125 pc/cm^3, which is too high for this direction in the sky (Example Plots 2022).

may have vertical lines, but they are often either very faint, or horizontally dispersed, indicating that the association between supposed pulse and phase is low. The frequency-phase chart may also show some pattern, but these lines are often very faint or not present at all. Often, the most obvious indicator that a plot is depicting noise is the DM. These plots have DM charts with either multiple peaks or no clear peak, and often display a DM that is much too high for the direction from which the signal is detected. Figure 6 demonstrates these traits, and thus has been labelled as noise.

Individually Graded Plots

Upon the completion of the PSC certification, the process of grading individual *prepfold* plots was begun. For each plot, the procedure was to evaluate each of the four sections explained in previous sections (the time domain and pulse profile, the frequency-phase chart, and the reduced χ^2-DM curve), and grade them individually on a scale from 0 to 2, with 0 being "not," 1 "maybe," and 2 "pulsar." These individual grades were less important than, and only meant to better inform the overall plot grade, which included labels of "noise," "RFI," "maybe," "new," and "known." Noise and RFI were determined as previously explained, paying attention to the markers highlighted above. If a source could not be definitively categorized as RFI, and the pulses showed more structure than could be easily categorized as noise, the DM curve and its peak value were then more closely examined. If the curve had a clear peak, the Galactic Dispersion Model was used, attached to the Pulsar Survey Scraper, to ascertain whether the peak DM value was within a reasonable range for that particular direction (Kaplan 2022). Each *prepfold* plot, as can be seen in the top right of each Figure, displays right ascension (denoted as α, or here, RA_{J2000}) and declination (denoted as δ, or here, DEC_{J2000}). The DM Model then uses these coordinates, along with the data from known pulsars, to calculate the maximum DM along the line of sight. This procedure would rule out noise when the DM curve on the *prepfold* plot peaks at a value that is much too high. Known pulsars would be identified in much the same way, by inputting the coordinates and peak DM, along with a search radius, into the Pulsar Survey Scraper to determine if the unknown data matches any known sources. This would also be combined with a similar search in the ATNF Pulsar Catalogue (The ATNF Pulsar Catalogue 2024; Manchester et al. 2005). The "maybe" label was given to any plots that did not clearly fit into any of these categories but could still possible be depicting a true pulsar signal, and the "new" label was reserved only for those that were undoubtedly a previously unidentified pulsar.

The plots that I graded were created from radio data originating from the PSC GBT 820 Drift survey. I graded 1,007 plots, out of which I labelled 824 as noise, and 171 as RFI. Only 12 were marked as maybe, and I neither came across any known pulsars, nor found any new. There were many plots that were difficult to categorize, as I could tell that they did not depict a pulsar signal but was unsure whether the source was RFI or noise. Figure 7, however, clearly depicts an RFI source. The signal contains pulses, but they are not cleared from noise as one from a pulsar would be. The time domain chart shows vertical lines, but there is a horizontal feature around

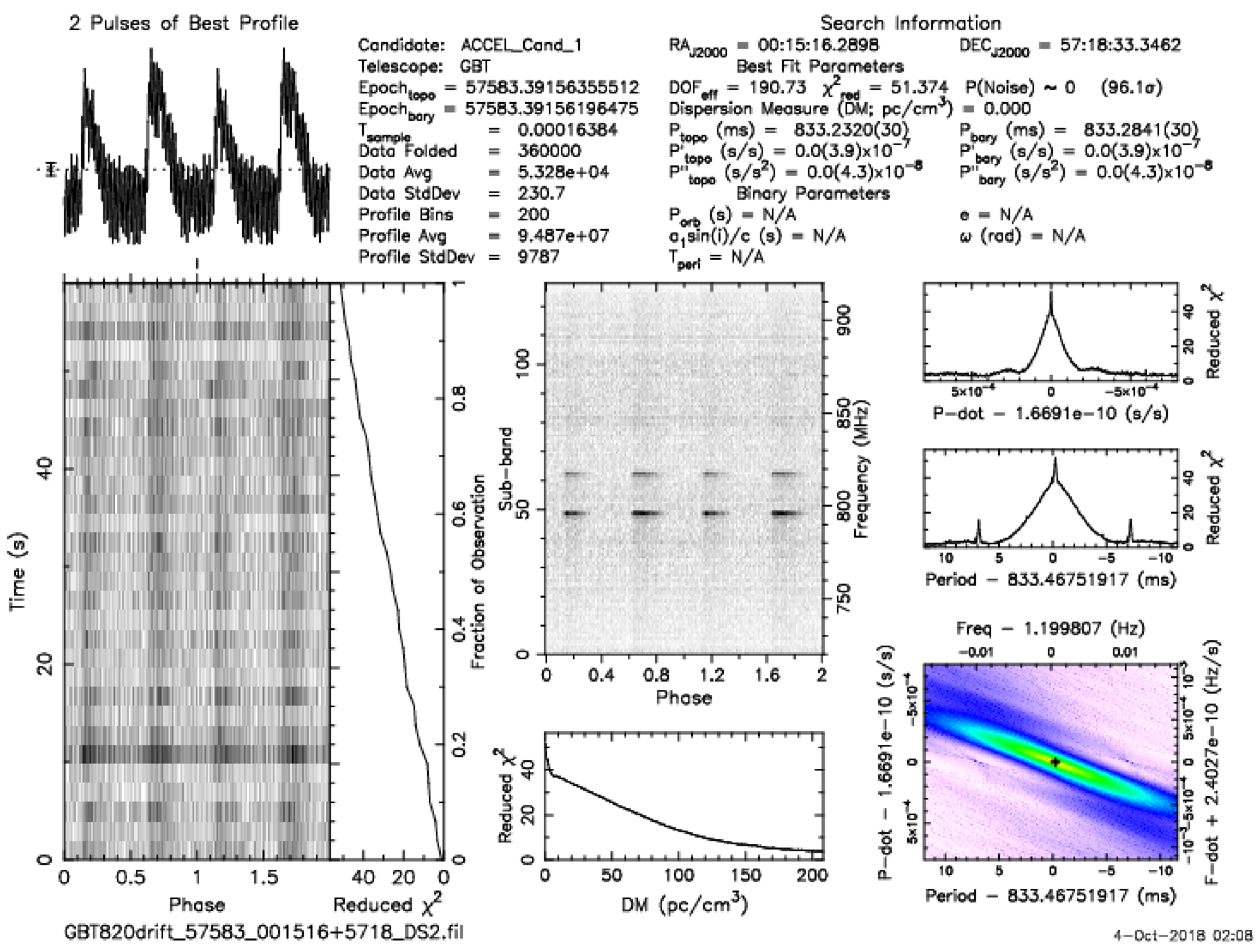

Figure 7: A *prepfold* plot depicting a signal that is clearly RFI. There are pulses present, but there is a large amount of noise. The observed signal only shows up around two particular frequencies, and the DM curve clearly peaks at zero.

10s that is more prominent. The frequency-phase chart does not show a broadband signal, but one that occurs at two distinct frequencies. The most obvious tell is that the DM curve is exceptionally smooth, and clearly peaks at zero.

A clear example of noise is shown in Figure 8. The pulse profile demonstrates a very low signal-to-noise ratio, and there is no identifiable ‘pulse.’ Neither the time domain nor the frequency-phase chart displays any structure, indicating that there is no strong signal within the data. The DM curve solidifies the classification of this plot as noise. While the chart displays a clear maximum, the curve itself is very jagged in shape, indicating that this peak may just be

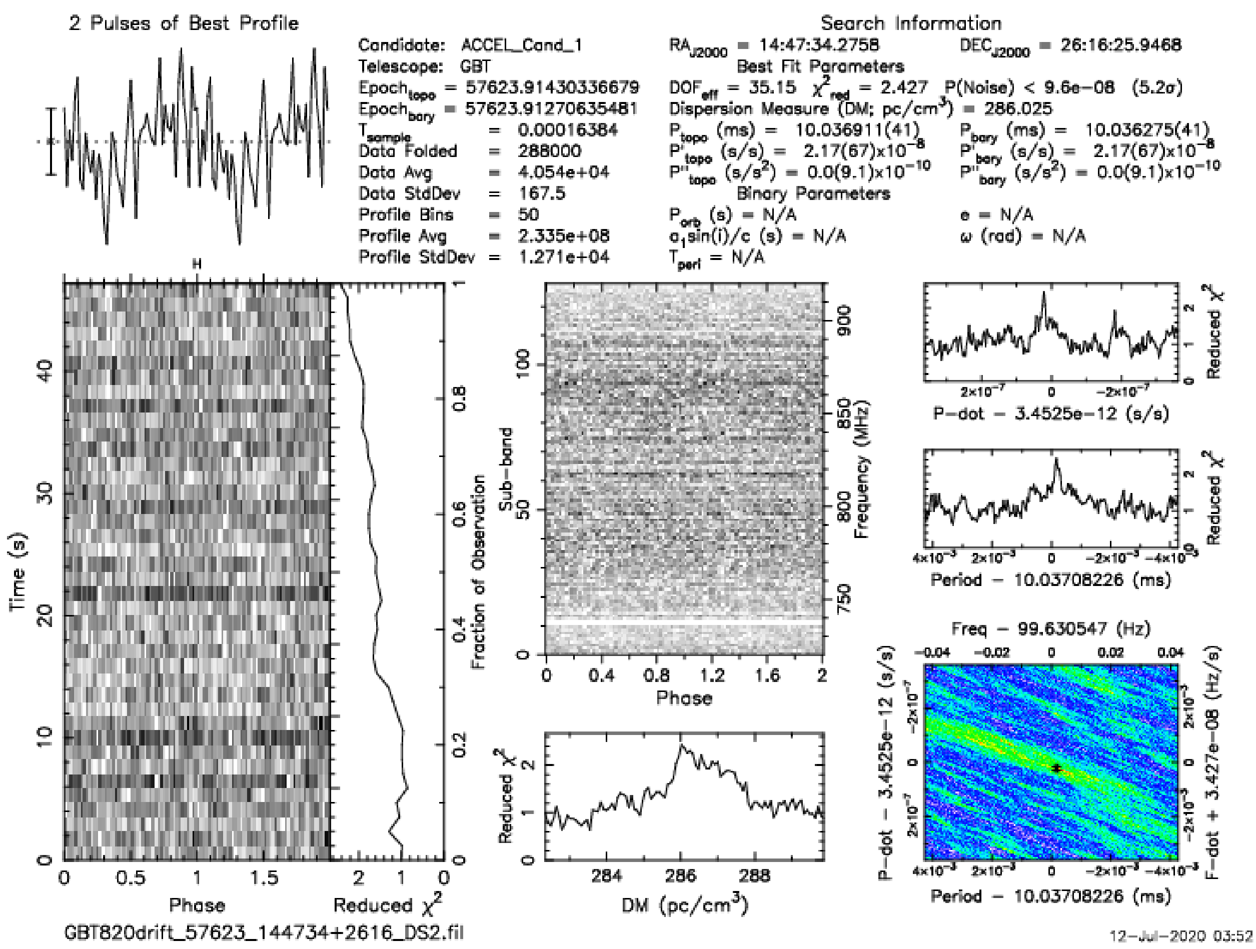

Figure 8: A *prepfold* plot depicting only noise. There are no identifiable patterns in the time domain or frequency-phase charts. The DM curve does have a peak, but it is not very distinct, nor is it within the correct range.

variation within the noise. The DM Model calculates the maximum DM for this line of sight as 22.3 pc/cm^3 (Kaplan 2022), which, compared with the 286.025 pc/cm^3 here, indicates that this is noise.

Figure 9 shows my most promising plot. Although it does not include obvious characteristics which would indicate a pulsar, it is not RFI, and it seems too structured to be noise. Thus, I marked it as ‘maybe.’ The pulse profile, while it displays a large error bar and thus has a low signal-to-noise ratio, does show two clear pulses. The time domain chart shows,

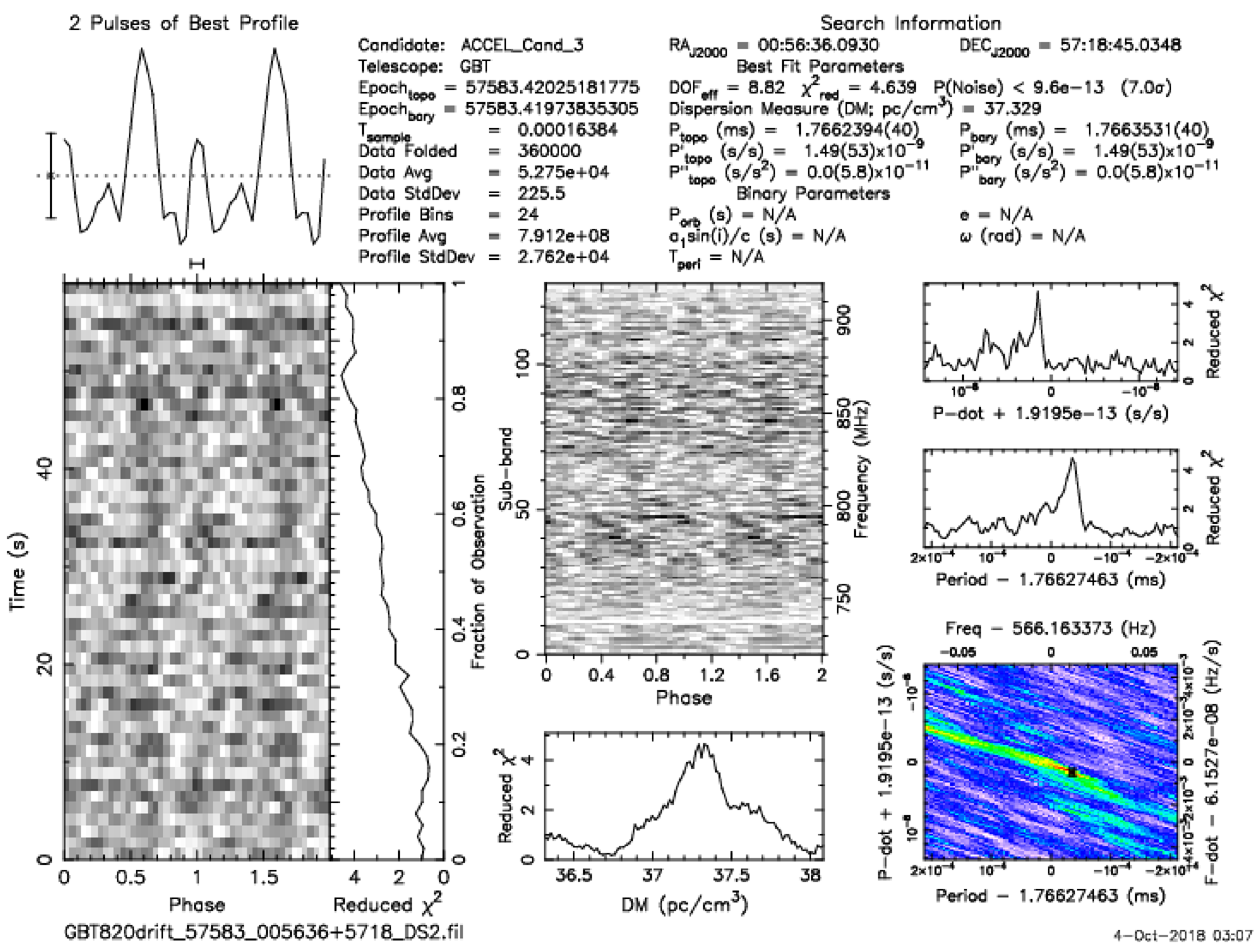

Figure 9: A *prepfold* plot that I labeled as ‘maybe.’ This plot showed the most pulsar-like elements across all four graded sections out of those that I graded.

although faint, a vertical structure corresponding in phase with the pulse profile, and the frequency-phase chart shows a corresponding broadband signal. The DM curve, while not smooth, does have a clear peak at 37.329 pc/cm^3, which is within the range reasonable for this line of sight: 210.1 pc/cm^3 (Kaplan 2022). Out of the 12 plots graded as "maybe," this one came closest to representing a pulsar signal, and thus has been marked for further review.

Dispersion Measure and the Galactic Plane

When considering the location of objects relative to the plane of the Milky Way Galaxy, or to the Galactic center, the use of the galactic coordinate system (*l*, *b*), galactic longitude and latitude, respectively, is necessary. This system is defined as shown in Figure 10. As a conclusion to this project, I have included an investigation into the correspondence between the measured DM value for a pulsar, and its location, as currently known, with respect to the Galactic plane. As discussed in previous sections, the best-fit DM value is important in determining whether a signal originates from a pulsar, from human-made RFI, or from background radio noise. As this is a measurement of the amount of electron interaction the signal experiences as it travels, the DM values of known pulsars must correlate with the different stellar densities in and out of the

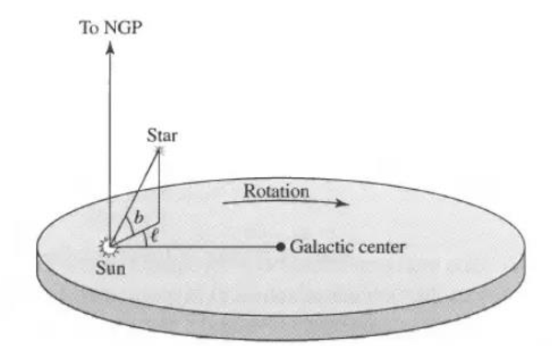

Figure 10: A definition of galactic coordinates, with the Sun as the origin. *l* is galactic longitude, *b* is galactic latitude, and NGP is north Galactic pole. Direction of Galactic rotation is also included (Carroll & Ostlie 2017).

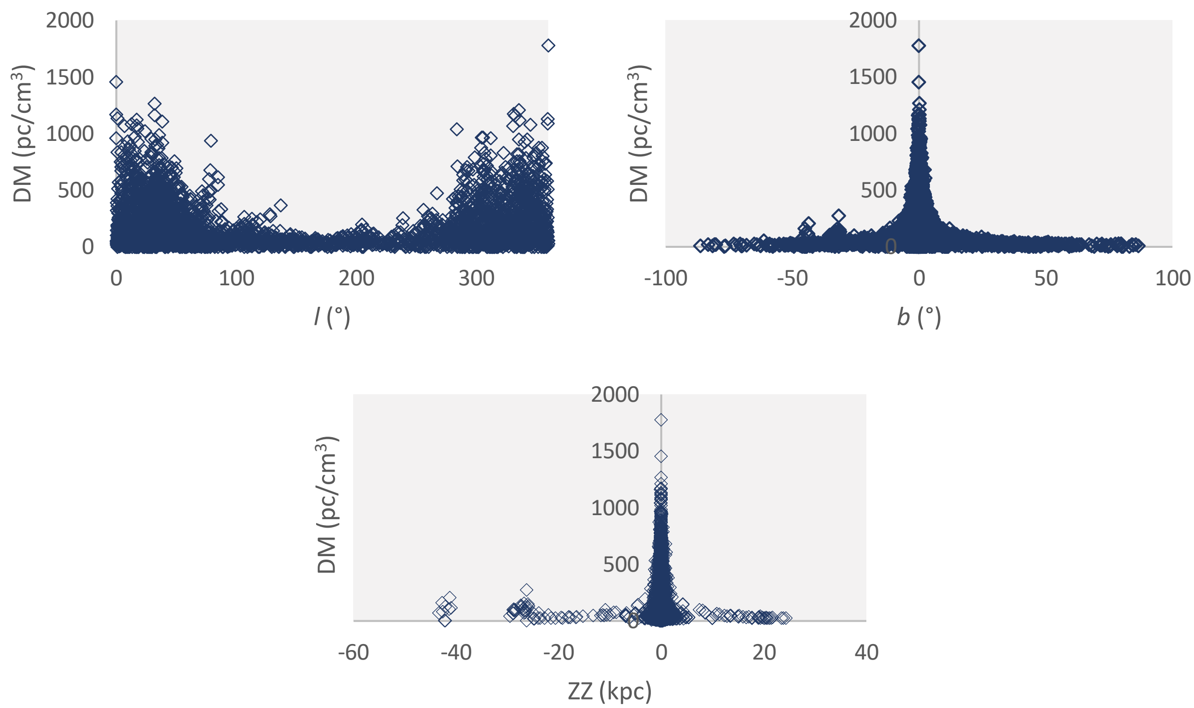

Figure 11: A series of charts depicting the relationship between DM (pc/cm^3), depicted on the vertical axes, and quantities relating to the position of the pulsar in the Galaxy. Top left depicts DM against *l* (°), top right depicts DM against *b* (°), and bottom center depicts DM against a quantity referred to as ZZ (kpc), a representation of the linear distance from the Galactic plane. Each data point is representative of one known pulsar. Pulsar data courtesy of the ATNF Catalogue (The ATNF Pulsar Catalogue 2024; Manchester et al. 2005).

Galactic plane. Figure 11 displays the results of this investigation.

Beginning with the upper left chart displaying the relationship between DM and galactic longitude, we see there is a correlation between higher DM values and both high and low *l* values, indicating a higher concentration of pulsars near the Galactic center. The upper right chart, displaying the relation between DM and galactic latitude, shows both a higher density of pulsars and a trend toward higher DM values when $b = 0$. Together, these charts indicate both a higher pulsar density and generally higher DM values for those pulsars nearer to the Galactic center. The lower center chart depicts DM against the quantity ZZ, in units of kpc. ZZ, as defined by the ATNF catalogue, is a linear distance from the Galactic plane, calculated based on the best estimate of the distance to a pulsar based on its DM (The ATNF Pulsar Catalogue 2024; Manchester et al. 2005). This chart displays similar results to those of the DM-*b* chart, but provides a linear coordinate as opposed to an angular one. Pulsars within the Galactic plane have a higher DM than those outside of it. These results support the common understanding that a high DM correlates with a high electron density along a line of sight, and that the general density in the Galactic center is high.

Conclusions

Pulsars are rapidly rotating neutron stars from which are detected bursts of electromagnetic energy at frequencies generally ranging from 20 MHz to 10 GHz. The analysis of radio data in the search for these objects is a long process in which few pulsars are found. It is common to find RFI, which originates from Earth and can very closely resemble a pulsar. Instances of noise are most common, occurring in more than half of my graded plots. Out of my 1,007 plots, only one stood out as having any possibility of depicting a pulsar signal, however it is a weak candidate.

In graphing the DM value of pulsars in the ATNF database against their corresponding galactic coordinates, it is made clear that the closer a pulsar is to the Galactic plane, the higher its DM is likely to be. This also works in the reverse. It is well known that the density of the Galactic plane is higher than that of the surrounding space, so this was an expected result, but the charts illustrate this in a clearer manner.

Data analysis of this sort, with the goal of identifying previously unknown pulsars, will undoubtedly continue.

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