

Searching for and Identifying Pulsars

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1. Introduction

Welcome to the Pulsar Search Collaboratory! As part of the **PSC**, you will be helping to identify new pulsars in data collected using the Green Bank Telescope. This guide is designed to help you in three ways:

1. By teaching you about the amazing and unique properties of pulsars
2. By explaining why astronomers are interested in pulsars
3. By giving you tips on how to identify pulsars in our data

Your job in the PSC will focus on this last point, but it is very important to understand what you are looking for and why. So just what is a pulsar?

Pulsars are a special class of **neutron star**. Neutron stars are the remnants of stars that are several times more massive than our own Sun. Such stars end their lives in an explosion that astronomers call a **supernova**. This explosion destroys all the outer layers of the star, leaving behind only a super-dense core. This core is the neutron star. We call these remnants neutron stars because they are made of **neutrons**—the subatomic particles that can be found in the nucleus of an atom. You may be asking yourself, “If neutrons are found in atoms, shouldn’t all stars contain neutrons?” The answer to this question is yes, but neutron stars are unique because they are made almost *entirely* of neutrons. Furthermore, these neutrons are not contained *within* atoms, but rather exist on their own.

It is impossible to create anything resembling a neutron star in a laboratory here on Earth. That is because neutron stars can only be made by squeezing normal atoms together *very* tightly, so that the density gets very high. Most neutron stars are a bit more massive than our Sun, but are only 20 miles across. Neutron stars are so dense that just one teaspoonful would weigh over one billion tons! Here’s another example: to make something as dense as a neutron star, you would have to squeeze the entire human population (some 7 billion

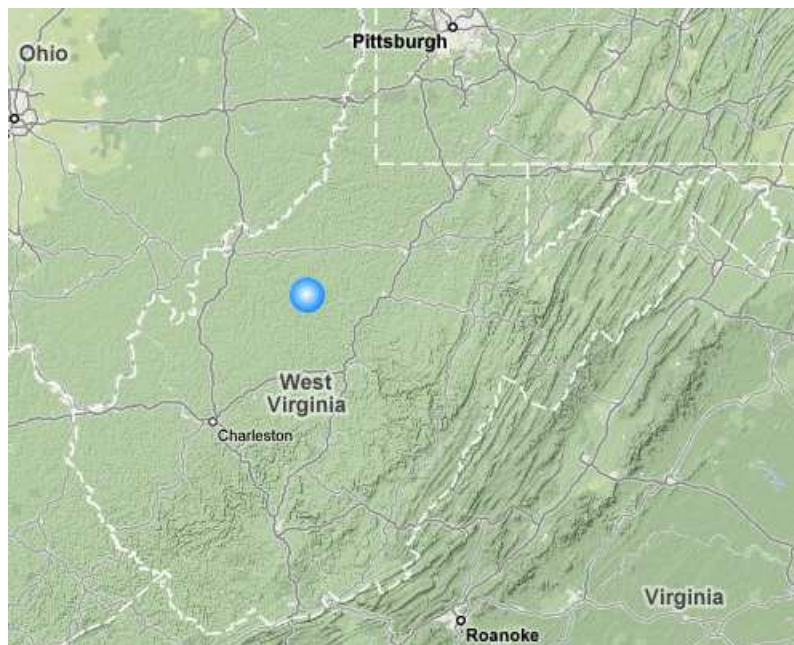


Fig. 1.— A scale picture of a neutron star overlay-ed on a map of West Virginia. A neutron star is only about 12 miles across, yet it contains almost one-and-a-half times as much matter as our Sun. Map from Google Maps.

people) into a *single sugar cube*! Now imagine a large city filled from top to bottom with these ultra-dense human sugar cubes, and you'll start to get some idea of what a neutron star is like.

Because they have so much mass in such a small volume, neutron stars have extremely strong gravitational fields. The gravity on the surface of a neutron star is 100 billion times stronger than on the surface of the Earth. If you could somehow visit the surface of a neutron star you would be crushed into a very flat pancake! It is this self-gravity of the neutron star that is responsible for squeezing so much mass into such a small area. It is believed that neutron stars with masses greater than about three times that of our Sun cannot support their own weight, and ultimately collapse to become black holes.

As we said, pulsars are a special class of neutron stars. **What separates pulsars from other neutron stars?** For starters, pulsars have very strong **magnetic fields**. Many objects in the universe have magnetic fields—Earth has a magnetic field that helps to protect us from radiation emitted by the Sun, and the Sun has its own magnetic field that causes solar flares and Sun spots. But the magnetic fields around pulsars are *much* stronger than the Earth's or the Sun's. In fact, pulsars have magnetic fields that are between one billion and one *quadrillion* times stronger than the Earth's! These uber-strong magnetic fields produce

some very interesting phenomena¹. The most important of these phenomena for us is that radiation is beamed from the magnetic poles of the pulsar.

Let's take a moment to discuss this more fully. If you have ever played with a bar magnet before, you know that magnets have a north and south pole. This is true of Earth's magnetic field, and it is this fact that allows compasses to work. Magnetic fields are strongest at these poles, and **the magnetic fields at the poles of pulsars are so strong that a lot of amazing things happen**. One such amazing thing is that radiation is produced in the form of **radio waves** (see the Appendix for a discussion of the nature of light and radio waves). These radio waves are emitted from the poles in a very tight beam of radiation, almost like a flashlight.

Another property of pulsars now becomes important—**pulsars spin very quickly**. They can spin anywhere from once every few seconds to as many as hundreds of times in a single second! Take a moment to try and visualize what is going on here. We have a neutron star that is sending radio waves out in beams from its two magnetic poles, while at the same time rotating very quickly. If you think about it, you will realize that this is a lot like a lighthouse, leading many people to describe pulsars as interstellar beacons. But we can only carry this analogy so far. Lighthouses on Earth create visible light, but when we look at pulsars we are usually² looking for radio waves. Lighthouses on Earth are also much smaller and much, much less powerful than pulsars are. And finally, pulsars can spin several hundred times a second. Lighthouses on Earth certainly don't spin this fast!

Every time the pulsar's beam points towards us, we will see a brief "flash" of radio waves. Just as with a lighthouse, if we had "radio eyes" we would see pulsars blink, or pulse. This is precisely where the name pulsar comes from. Of course, the pulsar's beam has to actually be at the proper orientation so that it points towards us. Otherwise, we would see no pulse of radio waves, and hence no pulsar.

All of this is very interesting, but the last property of pulsars that we are going to discuss is what really makes them useful to astronomers — **pulsars are very *precise* clocks**. It may sound strange to call a city-sized ball of spinning neutrons a clock, and to be sure, pulsars don't have hour and minute hands or a face that reads 1–12. However, a clock really is nothing more than something that lets us keep time by *ticking* at regular, well known intervals. The tick of a pulsar is simply the brief pulse of radio waves, and the regular interval is the **period** of the pulsar, which is the time it takes for the pulsar to spin around once. It turns out that

¹The magnetic field of a pulsar is so strong that it would erase every hard drive and credit card on Earth, even if the pulsar were placed as far away as the Moon!

²Some pulsars can also be seen in X-rays and gamma-rays, and a very small number have been detected using optical light and infrared radiation

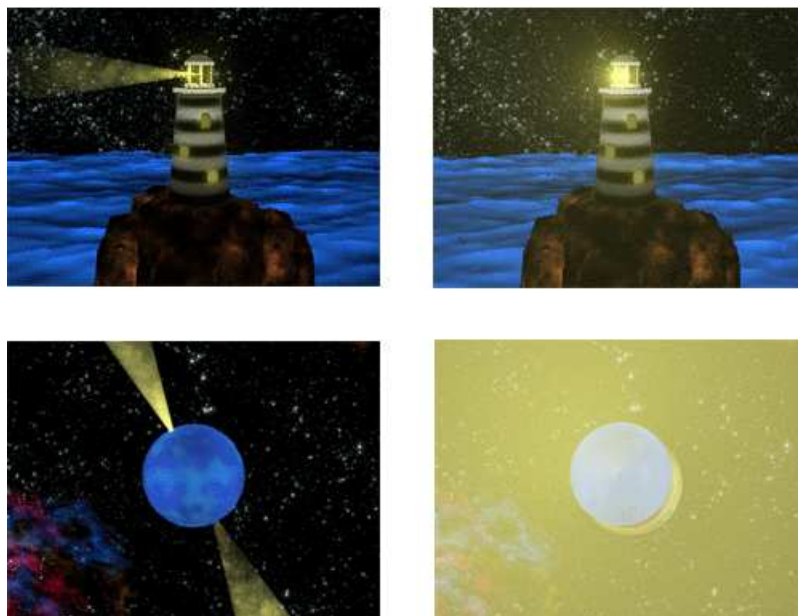


Fig. 2.— Here we see two different points in the pulsar’s rotation. On the left, the beam is pointing away from Earth and we see no radio emission. On the right, the pulsar’s beam is pointing right at us, so we see an increase in radio emission. The top panels show the corresponding situations for a lighthouse. Image from <http://www.airynothing.com/high-energy-tutorial/sources/pulsars.html>.

when we average over many pulses, pulsars have *extremely* stable periods, and as such we can predict with very high precision when any given pulse *should* arrive at Earth. However, a gradual slowing down of the pulsar’s spin period, the presence of a companion star or planet, a large acceleration between the Earth and the pulsar, shifts in the outer layers of the neutron star, and many other things can cause the true **time of arrival** of a given pulse to be different than the prediction. Astronomers can model all of these effects and bring our prediction back in line with observations. This is how astronomers use pulsars as tools for studying the universe. Since we could never create anything even coming close to a pulsar here on Earth, these are *unique* tools that allow us to answer *unique* questions. This is the true importance of pulsars to astronomy. Of course, in order to use pulsars to do science, we have to find them, and that is exactly where your help is needed.

2. Finding Pulsars

At first, you might think that finding pulsars would be fairly easy. All one should have to do is point a radio telescope at the sky and look for objects that blink. But **there are several reasons why that isn’t possible**. To start with, the strength of any one individual pulse is usually very weak. In fact, for most pulsars, a single pulse is not even strong enough to

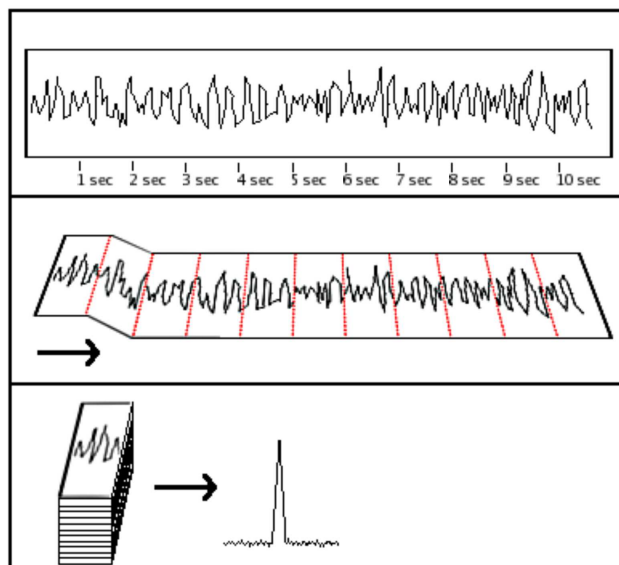


Fig. 3.— Here we illustrate the technique of folding. In the top panel, we place ticks every 1 second in our data. In the middle panel, we fold over at these tick marks. In the bottom panel, we add up the signal in each layer of our fold. In this way, we can find a weak pulsar that would otherwise be lost in the noise. However, we must know the period of the pulsar ahead of time. In this example, we used a period of one second.

detect—it gets swamped by background radio waves (what astronomers refer to as noise). It is not all that different from trying to see stars in the day time. The bright light from the Sun makes the stars impossible to see. In the case of pulsars, the noise that is inherent in our instruments makes a single pulse very difficult to see, except in the case of the brightest pulsars.

In order to solve this problem, astronomers must combine many pulses together in order to build up a detectable signal. This is commonly referred to as **folding**. To get an idea for how it works, imagine having a long strip of paper. On this paper we make a mark that indicates the strength of a signal detected with our radio telescope—the higher the mark is on the paper, the stronger the signal. Now imagine that we make these marks continuously while someone pulls the strip of paper along underneath our pen. What we would have in the end is a record of how strong our signal was during the course of our observation. On the left of the paper is the first mark that we made, and on the right is the last mark. Each mark represents the strength of the signal detected by our telescope at some point in time. The paper might look something like Figure 3. Now because the pulsar is so weak, this just looks like a bunch of random marks—that is the noise, or the background. Somewhere buried in that noise is the signal from our pulsar. Let's say that we *know ahead of time*

that our pulsar has a period of one second. Then we could make a mark on our paper that represents one second of time, i.e. one period of the pulsar. We can then imagine folding our paper on-top of itself, so that these marks line up. If we then had a way of adding the signals from different layers of this fold together, we would eventually see the signal from the pulsar getting stronger and stronger, while the noise would stay the same strength³. Finally, we would be able to see our pulsar.

But this is a difficult task when you can't actually tell *where* the individual pulses are. In other words, *this technique only works efficiently if we know the period of the pulsar ahead of time*. If we don't have that knowledge, we would have to fold every observation at every *possible period* and look to see if a pulsar signal emerged. This is an impossible task, so we have to find another way.

2.1. Fourier Transforms

Luckily, there is a tool called the **Fourier transform** that can help us. Fourier transforms are mathematical operations that are perfectly suited for finding periodic signals (that is, something that repeats in a given set of data). The important thing for you to know is that the Fourier transform does what its name suggests—it *transforms* the data from one form into another. In the case of pulsar searches, the transformation takes data that is in a form of signal vs. time, and turns it into something in the form of signal vs. **frequency**. Frequency is related to time as

$$\text{frequency} = \frac{1}{\text{time}} \tag{1}$$

Stated differently, *the frequency tells us how many times something repeats in a given second*. If something spins with a period of exactly one second, then its frequency is once per second. If it spins faster, say going around 20 times per second, then the frequency is 20 per second. Scientists define a unit called the Hertz, abbreviated as Hz, that is equal to one cycle per second. So in the second example above, our frequency would have been 20 Hz.

What would the frequency be of something that has a period of 0.01 seconds? Well, 0.01 second is one-hundredth of a second, meaning that in a full second the object would make 100 full rotations. So our frequency is 100 Hz. Mathematically, we could also have divided by the period— $1/(0.01\text{seconds}) = 100\text{Hz}$. We can make a general formula to illustrate this

³You may wonder why the noise doesn't get stronger if you add it it together, too. The reason is that the noise is a *random process*, and it is just as likely to cancel itself out in each fold as it is to get stronger. The signal from the pulsar, however, always gets stronger

point.

$$f_{\text{spin}} = \frac{1}{P_{\text{spin}}} \quad (2)$$

where f_{spin} is the **spin frequency** and P_{spin} is the spin period.

When we Fourier transform a set of pulsar data, we can look for signals in the frequency domain. If we find one, we can then go back and fold our data in the time domain and determine if our signal came from a real pulsar. For example, suppose we see a signal at a frequency of 100 Hz in our Fourier transformed data. We would then fold our data at a spin period of 0.01 seconds. This is a more efficient way of searching for pulsars than doing blind folds.

When we work in the frequency domain, we can also take advantage of **harmonics**. The harmonic of a signal occurs at an integer multiple of the main frequency. For example, if a pulsar has a rotational frequency of 100 Hz, we will also detect a signal at 200 Hz, 300 Hz, 400 Hz, and so on. We say that the spin frequency is the fundamental or first harmonic. Mathematically, the frequency of the n^{th} harmonic is $n \times f$, where f is the spin frequency. Harmonics occur naturally in most periodic signals, not just pulsars. You are probably familiar with harmonics, even if you don't know it. Musical instruments, like violins, pianos, or the human voice, produce sound waves, and waves are periodic. So when a violin player plays a note, say an A-flat, what you hear is actually all the harmonics of an A-flat. These harmonics give the instrument a rich, pleasing sound.

Harmonics add a richness to pulsar signals as well (although keep in mind that radio waves are not sound waves). Some, and often quite a bit, of the power from a pulsar signal is in the higher harmonics. If we only used the first harmonic (the spin frequency), then we would lose precious sensitivity, especially to weak pulsars.

Modern computers are very good at taking the Fourier transform of a set of data. Still, the transformed data set is pretty big, and it would be very difficult, if not impossible, for a person to look for every possible pulsar signal. Instead, we have written computer programs that look at the Fourier transformed data and try to find the signals from pulsars. These computer programs are very good at what they do. Unfortunately, it isn't as simple as hitting **Enter** on the keyboard and receiving all the information about a pulsar. There are many things that may *look like* a pulsar at first glance, but which are in fact something entirely different (and usually much more ordinary). Separating the true pulsars from these impostors requires a human touch, and this is one of the most important tasks that you will be undertaking. But before we talk more about that, we should talk about these impostors, and why we need to worry about them.

3. Radio Frequency Interference

Pulsars emit much of their radiation as radio waves. These radio waves travel through space before being collected by our telescopes. However, we live in a world that is *full* of other sources of radio waves. You can probably think of a few right now—when you turn on your car radio, you are picking up radio waves sent out by the station. Satellite TV uses radio waves to send its information. So do cell phones and wireless Internet transmitters. There are other, less obvious sources of radio waves. The power lines that carry electricity to your house give off radio waves (if you ever noticed an AM station picking up a lot of static while driving by a power station, that is why). Even the spark plugs in a gasoline-powered car give off radio waves! There are cosmic sources of radio waves too, like our very own Sun. Most of these sources of radio waves have become vital to our every day lives, and so from this point of view they are a very good thing. But from the point of view of a radio astronomer, this is all very bad. These sources of radio waves get in the way, and make some observations almost impossible. For this reason, astronomers refer to these man-made sources of radio waves as **Radio Frequency Interference**, or RFI. RFI is similar to light pollution. In large cities, light pollution can make it impossible to see faint stars, and RFI can make it similarly difficult to see faint sources of radio waves.

Astronomers have found ways to reduce the effects of RFI. The best way is to build telescopes far away from the sources of RFI, which usually means going to remote locations where there aren't very many people. Sometimes, certain parts of the radio spectrum are simply avoided all together. Sometimes we can make filters that block RFI that we know exists at a certain point in the spectrum. And sometimes computers try to identify obvious sources of RFI and then ignore it in a given set of data.

RFI is especially problematic for pulsar searches because it can often look like a pulsar signal in the Fourier transformed data. Why is this the case? Remember that the Fourier transform helped us find the repeating signal of the pulsar. But these man-made sources of RFI often repeat as well. For example, the alternating current (AC) that supplies your home with power changes polarity at a frequency of 60 Hz. Power lines that carry this current therefore give off RFI at a frequency of 60 Hz if they are not shielded. For this reason, we always see a large signal in our Fourier transformed data at 60 Hz. Luckily, we can simply tell a computer to ignore that frequency. Other sources of RFI may not be as easy to handle, because we don't always know what frequency they will show up at.

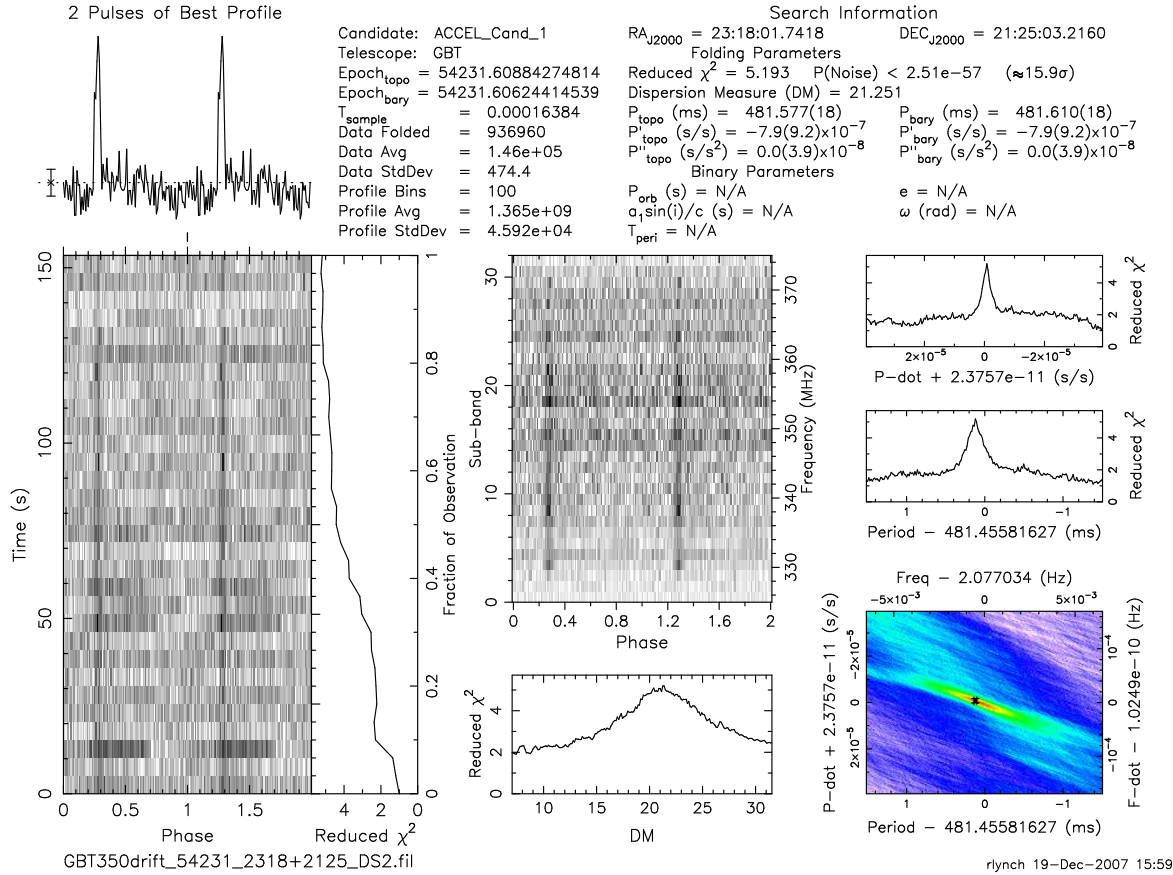


Fig. 4.— A prepfold plot of an actual pulsar. This pulsar spins with a period of 0.481 seconds. Each part of this plot contains a lot of information that you will be learning to use so that you can identify real pulsars.

4. PRESTO and Finding Pulsars

As you may have begun to realize, there is an awful lot of work done on computers when it comes to finding pulsars. There are many different packages of software designed for this task, and the one you are going to use is called **PRESTO**. **PRESTO** takes the Fourier transform of a data set and uses some clever algorithms to search for pulsars. When **PRESTO** finds a promising candidate, it can go back to the time domain data and use a program called **prepfold** to fold the data at the period of our candidate. What comes out is a plot like the one in Figure 4. There is a lot of information on this plot, and at first it can look pretty intimidating. So let's take each piece of the plot and break it down, explaining what it shows us and why the information is important. When we put it all together, you will be able to look at one of these plots and decide if it shows a true pulsar.

4.1. The Time Domain and Pulse Profile

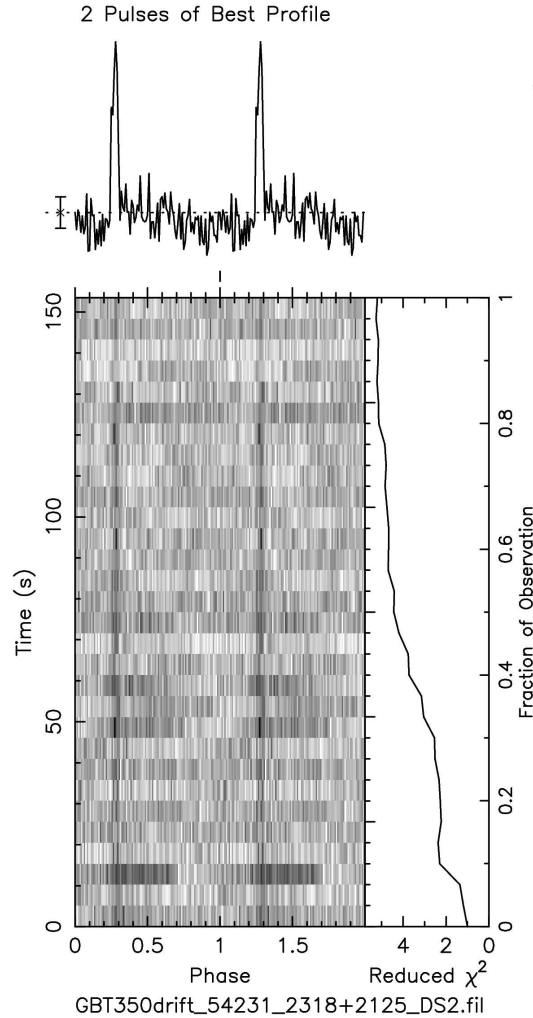


Fig. 5.— This panel shows the time series and pulse profile. The time series represents the strength of the signal as a function of phase and time. If we add up all the power we collect over our whole observation for a single phase, then we will have the pulse profile. In other words, the pulse profile is the folded signal from the pulsar that was collected over the entire observation.

Figure 5 shows one of the most important parts of a **prepfold plot**. This is the **time domain and pulse profile**. The time domain plot shows us how the strength of our signal varies during the course of our observation. Each gray square represents the strength of the signal in some small piece of the data (we refer to this small piece as a **bin**). The darker the bin, the stronger the signal. A white bin indicates that no signal was detected in that bin. This plot is a representation of our folding process. Each row on this plot is a **sub-fold**, i.e. a fold of a small chunk of our data that is a few seconds long. This small chunk is simply

the “height” of a bin, and is called a **sub-integration**. The “width” of each row is equal to the length of the fold, which is nothing more than the period of our candidate. If you go back to Figure 3, you will recognize a sub-fold as being a few layers of our folded paper.

The y-axis is labeled as “Time (s)” and is simply the time in seconds since the start of our observation. The x-axis is labeled as “**Phase**” and goes from 0 to 2.0. The phase tells us how far we are through the pulsar’s rotation. A phase of 0.5 means that the pulsar has gone through half a rotation; a phase of 1.0 indicates one full rotation; a phase of 1.5 indicates one and a half rotations, and so on. Each sub-fold is equal to one full rotation, so showing the phase going from 0.0 to 1.0 is the same as showing a full sub-fold. We have shown two full rotations for clarity—if we only showed one rotation, and the pulse landed just at the end of this rotation (i.e. at a phase of 1.0) then it would be on the edge of our plot and hard to see.

Every time the pulsar beam passes in front of us, we will see an increase in the strength of our signal. Furthermore, the beam will always pass in front of us at the same point in the pulsar’s rotation, or the same phase. This explains why there is a dark line in the time series. It is telling us that, from the beginning of our observation all the way until the end, we got a sudden increase in the strength of our signal, and that this always occurred at the same phase.

Now let’s look at the top of this plot. This is known as the pulse profile. and it gives us the strength of the pulse as a function of phase. This is nothing more than the result of our full folding process. To make it, we add up, or integrate, the results of all the sub-folds. The peak corresponds to when the pulsar is “on”, and the random lines that you see when we are “off-pulse” is the background noise. Ideally, we should see a pulse that is much stronger than the noise level, indicating a strong pulsar. If the pulse is not much stronger than the noise, then we simply can’t say with confidence that we have a real detection.

4.2. Frequency and Sub-bands

Figure 6 shows us another part of our PRESTO plot—we still have phase on the x-axis, and the darker bins still mean that we detected a stronger signal. However, time on the y-axis has been replaced with frequency, or **sub-band**. We already talked about *spin frequency*, which is how many times a pulsar goes around in one second. In the current plot, though, we are actually talking about our **observing frequency**. This is the frequency of the radio waves that we are actually collecting with our telescope. You may notice that the frequency is measured in megahertz (MHz). Your car radio typically picks up signals with a frequency of 88–107 MHz (the FM band). It is important to realize that this is different than the spin

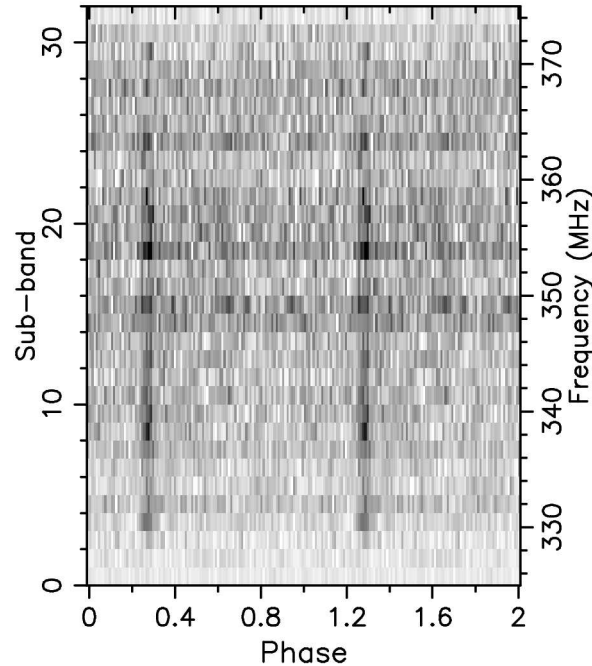


Fig. 6.— This panel shows the strength of our signal as a function of both phase and observing frequency. The sub-band tells us how our instruments are breaking down the wide range of frequencies into small chunks. As you can see, there is an increase in the strength of the signal at a single phase, and it is spread across all frequencies.

frequency (which is usually no higher than a few hundred hertz). Now, you will notice that in addition to being labeled with “Frequency (MHz)”, the y-axis is also labeled as “Sub-band”. The instruments we use to collect and measure our radio signals actually break down the signal into small chunks of observing frequency. Each one of these chunks is called a sub-band. It is typical for us to use 32 or 64 sub-bands, and if you look closely, you should see that this in fact the number of sub-bands on the plot. Each gray bin in this image represents the power collected in a single sub-band over the full observation. You can also think about it as the power collected in some small chunk of our observing frequency. If you look closely, you should see an increase in signal strength, which appears as a dark line on our plot. You should see it at the same phase in both the time series and frequency/sub-band plots. Examining the characteristics of this signal helps us to determine if we are looking at a real pulsar or some source of RFI (we will talk about that later on).

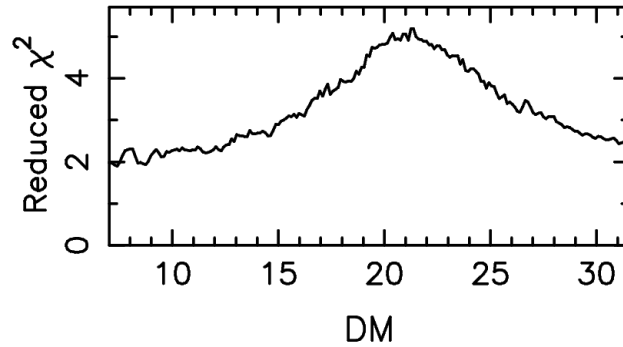


Fig. 7.— This panel shows the Dispersion Measure, or DM. The DM is a way of quantifying the number of electrons that the pulsar’s signal must travel through to reach the Earth. The y-axis is the Reduced χ^2 . A real pulsar should have a peak value of Reduced χ^2 at a non-zero DM.

4.3. The Dispersion Measure

Figure 7 shows another part of the `prepfold` plot, and this one is much different than the previous two. The x-axis is labeled as “DM”, and the y-axis as “**Reduced χ^2** ”. First, let’s talk about the DM. DM stands for **Dispersion Measure**, and it is a very important quantity that we can measure with our signal. The dispersion measure doesn’t actually have anything to do with the pulsar itself. Instead, the dispersion measure tells us something about *the space between Earth and the pulsar*. We often think of space as being empty, but that isn’t quite true. Space is filled with many things, though the density is so low that compared to Earth, space is *almost* empty. One of the things that we find in space are electrons—subatomic particles that normally orbit the nucleus of an atom. These electrons disperse the pulsar’s signal (hence the name “dispersion measure”), causing lower observing frequencies to arrive later than higher observing frequencies. The electrons can also scatter the signal in much the same way smoke scatters visible light. The dispersion measure is a way of telling us how many electrons the signal encountered on it’s way to Earth. The larger the dispersion measure, the more electrons the signal encountered. This could happen for two reasons – either the pulsar is very far away, or the *density* of electrons in the space between Earth and the pulsar is relatively high. Both will cause an increase in the dispersion measure.

What about the “Reduced χ^2 ”? First off, the symbol “ χ ” (pronounced “Kigh”, or /kaɪ/ in the phonetic alphabet) is simply a Greek letter “X”. The Reduced χ^2 is a statistical value that indicates how well a *model* agrees with some actual *data*. A large value of Reduced χ^2 means that the model and data are not in good agreement, and a Reduced χ^2 of one means that they are. We use the Reduced χ^2 in an uncommon way. Our model *doesn’t* include

a pulsar, because we don’t know the properties of the pulsar ahead of time. So when we compare this pulsar-less model to data that *does* contain a pulsar, we see a high Reduced χ^2 , which is exactly what we want.

Now that we know what the axes are, what does the dispersion measure plot tell us? The peak of the curve tells us the most likely value of DM. Ideally, we would like to see a sharp peak at one value of DM. This would mean that the DM is pretty well measured. If the peak is broader, it means that the DM measurement is less certain.

It is important to note where the DM curve is peaking when you are trying to determine if your pulsar candidate is real. If the curve reaches its highest point at a DM of zero, then the signal must not have traveled through *any* electrons to get to Earth. But that must mean that the signal actually originated at the Earth, and since there are no pulsars on the surface of our planet (a very good thing!) then we know that we must *actually* be looking at RFI. For this reason, the DM of a signal is one of the best ways we have of distinguishing between RFI and a true astronomical signal from space.

4.4. The Period and Period Derivative

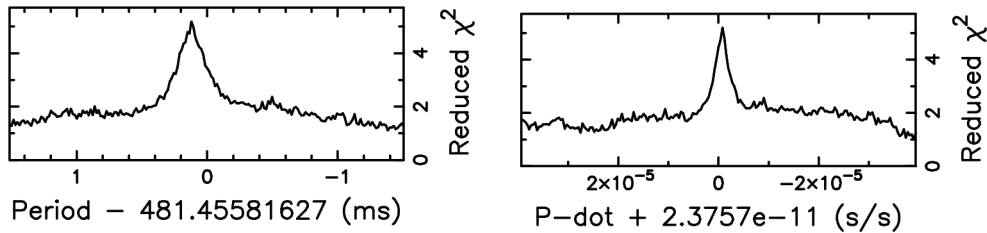


Fig. 8.— These two panels show the Period and P -dot. The y-axis is the Reduced χ^2 . Ideally, you should see a sharp peak in Reduced χ^2 , which indicates that the Period or Period derivative have been well measured.

Now we turn our attention to the last three plots. Take a look at the two panels in Figure 8. They look similar to the plot of dispersion measure, once again having “Reduced χ^2 ” on the y-axis. However, in the panel on the left the x-axis is labeled as “Period (ms)” and in the panel on the right the x-axis is labeled as “ P -dot (s/s)”. You will also notice that Period and P -dot have a number being subtracted from them. This number is simply the center of the plot, and we subtract it so that we can easily tell how far the peak of the curve lies from this central value. Once again, we want to see a nice, sharp peak, telling us that we have measured the period well.

The P -dot, or **Period Derivative**, is the first *time derivative* of the period. This is a

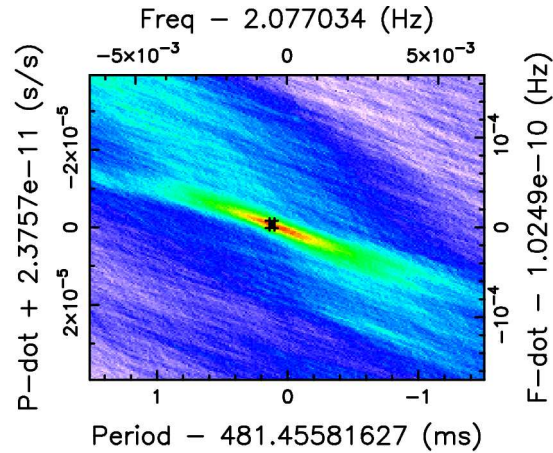


Fig. 9.— In this panel, the Period and Period-dot are on the x- and y-axes, and the Reduced χ^2 is represented by the different colors. A high value of the Reduced χ^2 is shown in red and a lower value in white or purple. This is similar to a topographic map that shows elevation using closely spaced lines. You will notice that the x- and y-axis are also labeled with Frequency and Frequency-dot. Remember that frequency is essentially one divided by the period, so it is fairly easy to go between using Period and Period-dot and Frequency and Frequency-dot.

mathematical quantity, but it simply tells us how much the period is changing over time. It has units of “seconds per second”—in other words, the number of seconds by which the pulsar’s rotation speeds up or slows down over the course of a single second⁴. The period of a pulsar changes very slowly, so these numbers are very small. The Period Derivative is an important quantity to measure when really trying to understand an individual pulsar. Generally speaking, pulsars ought to be slowing down, but the motion of the pulsar relative to our solar system can cause the rotation to appear to speed up. This motion could be induced by something like a companion star or planets orbiting the pulsar. When determining whether a candidate is a true pulsar or RFI you should look for a sharp peak in the Reduced χ^2 vs. P-dot curve. This indicates that the candidate has a well defined Period Derivative. Isolated pulsars typically have a P-dot that is too small to measure in a short observation, and hence appears to be zero. If the P-dot is non-zero and the pulsar is real, then you have found an exciting binary pulsar!

Finally, we turn our attention to Figure 9. This may seem like a very complicated plot, but it is really nothing more than the previous two plots put together. The x-axis is the Period or Spin Frequency, once again shifted so that the center of the plot corresponds to zero. The

⁴Can you think of what the P-dot would be if it were in different units, say years/year?

y-axis is P-dot or F-dot (F-dot being the change in spin frequency). The colors represent the Reduced χ^2 , with red meaning a high Reduced χ^2 and purple meaning a low Reduced χ^2 . This is very similar to an elevation map. Instead of lines of constant elevation, we have colors of constant Reduced χ^2 . To make this plot, we take the two curves from the previous two plots, and combine them. If you imagined the plot coming out of the page and being three dimensional, the red areas would correspond to the peaks and the purple areas to the “lowlands” in the Reduced χ^2 curves. You can also think of the two plots in Figure 8 as cross-sections of the peak of Figure 9.

Ideally, we should see a well defined region of red, and only one well defined region of red, in this plot. If there are other well defined regions of red, then our measurements might not be very good. Usually, this is only an issue for weak pulsars or strong, variable RFI.

4.5. The Search Information

If you look at the original `prepfold` plot, you will also see a lot of text at the top. All of this is information about the search, the observations, and the candidate pulsar. The part that you should be most familiar with is the Dispersion Measure and Period, which is labeled as P_{topo} or P_{bary} ⁵. While both of these numbers can be determined by looking at the plots, they are also printed in the Search Information area for you. You will also notice that there are numbers in paranthesis at the end of each value. This paranthetical number is simply the error in the last decimal place. If you are interested in what the other terms mean, I have included them in the glossary, but in most cases you won’t need to worry about them.

5. Getting Down to Business: Telling Real Pulsars from RFI

Now that you understand just what a `prepfold` plot tells us, you are ready to begin looking for real pulsars. As you will see, sometimes it can be easy to identify RFI, and sometimes it can be a little trickier. Of course, experience will help you to make better judgments about

⁵ P_{topo} is the period measured at the telescope, while P_{bary} is the period that would be measured if our telescope were placed at the center of mass of the solar system (also called the Barycenter). The solar system center of mass is actually just beyond what we typically think of as the edge of the Sun, called the photosphere, so this correction is made on computers. Why should the two be different? The answer is that the telescope is accelerating as the Earth rotates on its axis and orbits around the Sun. In effect, the telescope is “running” towards or away from the pulsar, affecting when pulses appear to arrive. The solar system center of mass isn’t accelerating very much, and so doesn’t suffer from this problem. It is a reference frame that all observers can agree on.

what is a real pulsar and what isn't, but there are also some characteristics of RFI and pulsar signals that you can use. But **you should keep in mind that there are exceptions to almost every rule!** Sometimes, real pulsars can have characteristics that we usually associate with RFI, and vice versa. This is part of the challenge, and the fun, and trying to find new pulsars.

5.1. Using the Time Domain Plot and Pulse Profile

It can always be useful to think back to our analogy between pulsars and lighthouses. Just as a lighthouse is only visible for a small fraction of their rotation (when the beam points at us), so too are most pulsars. This is equivalent to saying that the pulsar should only appear within some small phase, and that phase should be the same throughout the observation in most cases (we will see an important exception shortly). In other words, the pulse profile should be a narrow peak, not a broad bump. Figure 10 shows an example of RFI that is spread out in phase, and consequently doesn't have a narrow pulse profile. Here is our first exception, though—the beams of some pulsars can point at the Earth throughout most of the pulsar's rotation, so some pulsars have fairly broad beams. Also, some pulsars don't have a single, narrow beam, but instead have complicated beams with many different bright and dim patches. This can cause the pulsar to have many peaks at different phases. **The lesson: don't judge a pulsar candidate by its pulse profile alone!!**

Here's another exception—it is possible for a pulsar's signal to drift in phase. This will happen when the pulsar is highly accelerated, possibly due to a nearby companion star. We call these binary systems, and you can see this in Figure 11. The time domain plot for binary pulsars will exhibit this wave-like structure. The signal still shows up as a narrow curve, and it is smooth without any sudden jumps from one phase to another. Contrast this with Figure 12, which is actually RFI. At first glance it seems to have a wave-like structure, but the signal abruptly jumps in phase. This is something a real pulsar doesn't do.

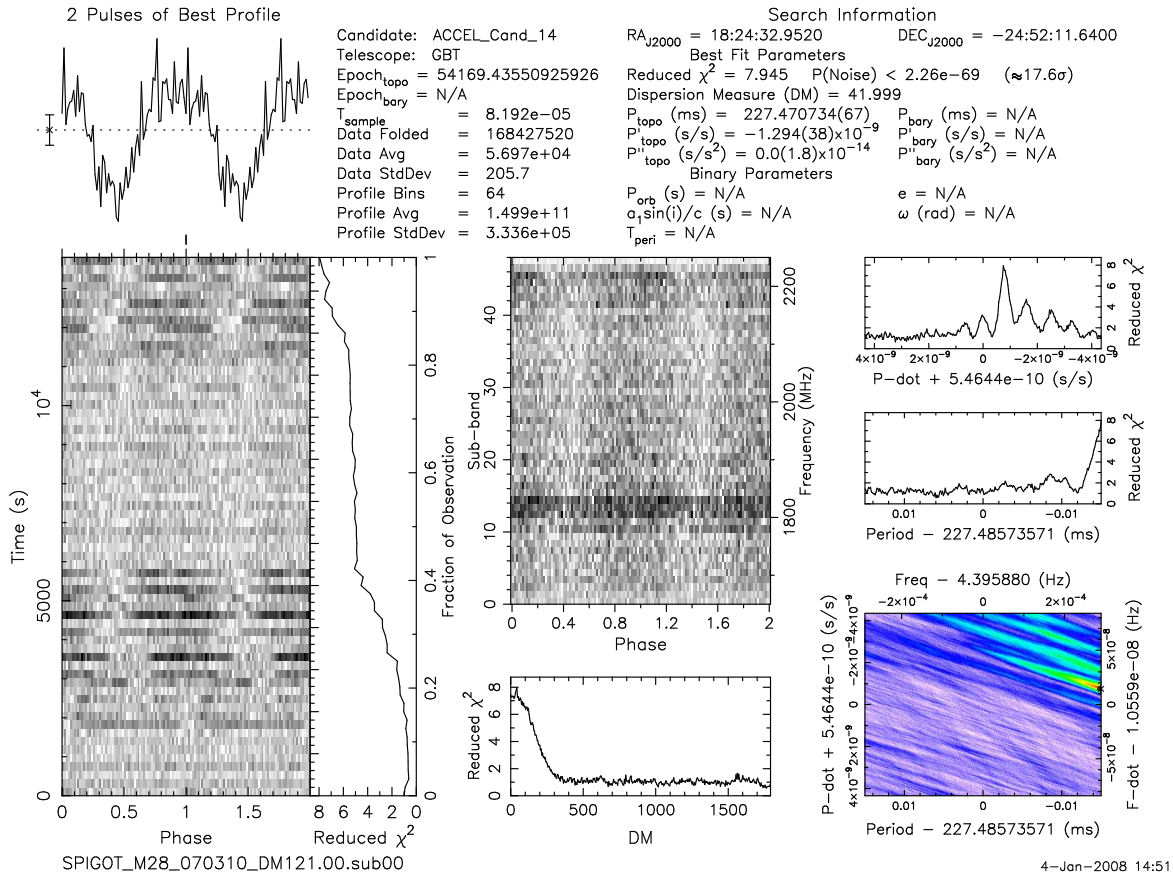


Fig. 10.— A prepfold plot of some broadband RFI that shows up at a variety of phases. This RFI is also transient. Another clue that this is RFI is that the DM curve peaks at zero.

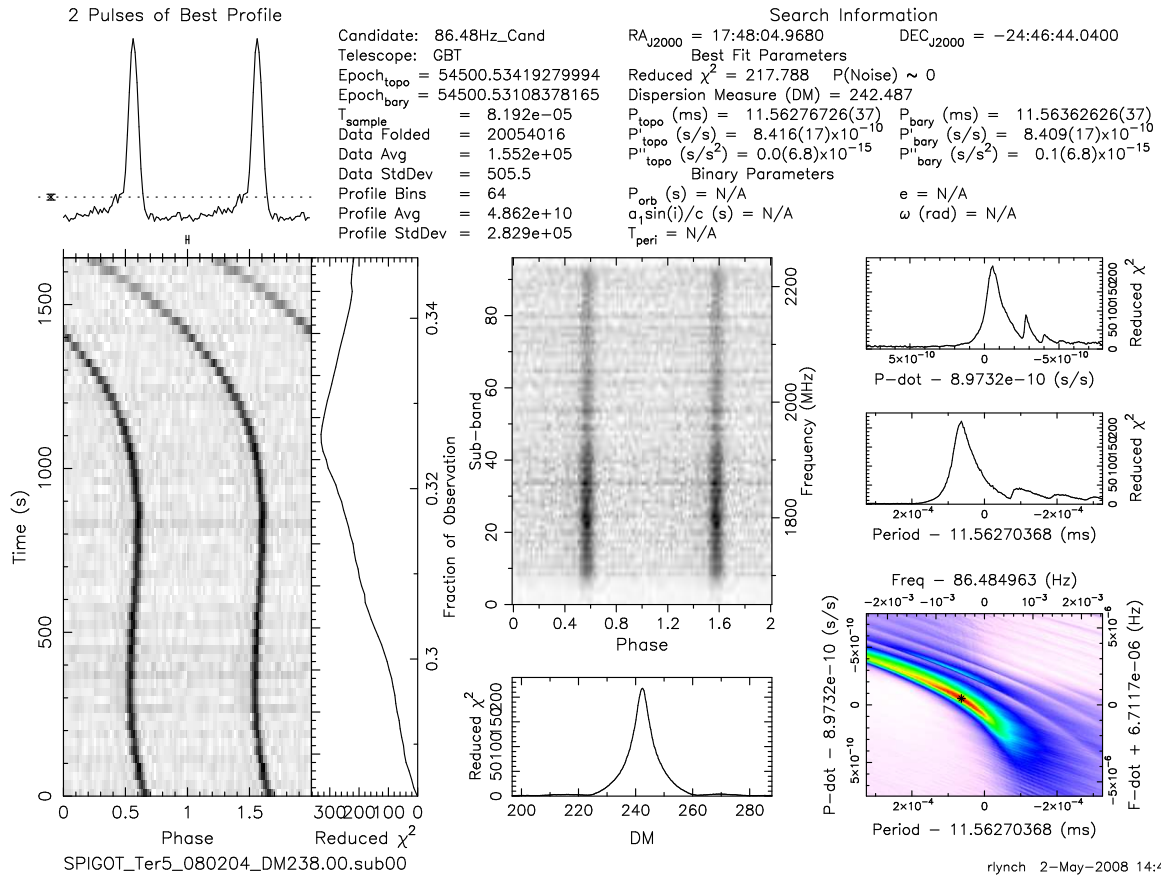


Fig. 11.— A prepfold plot of a binary pulsar. You can see the effects of the pulsar’s orbit as a wave-like structure in the time domain plot.

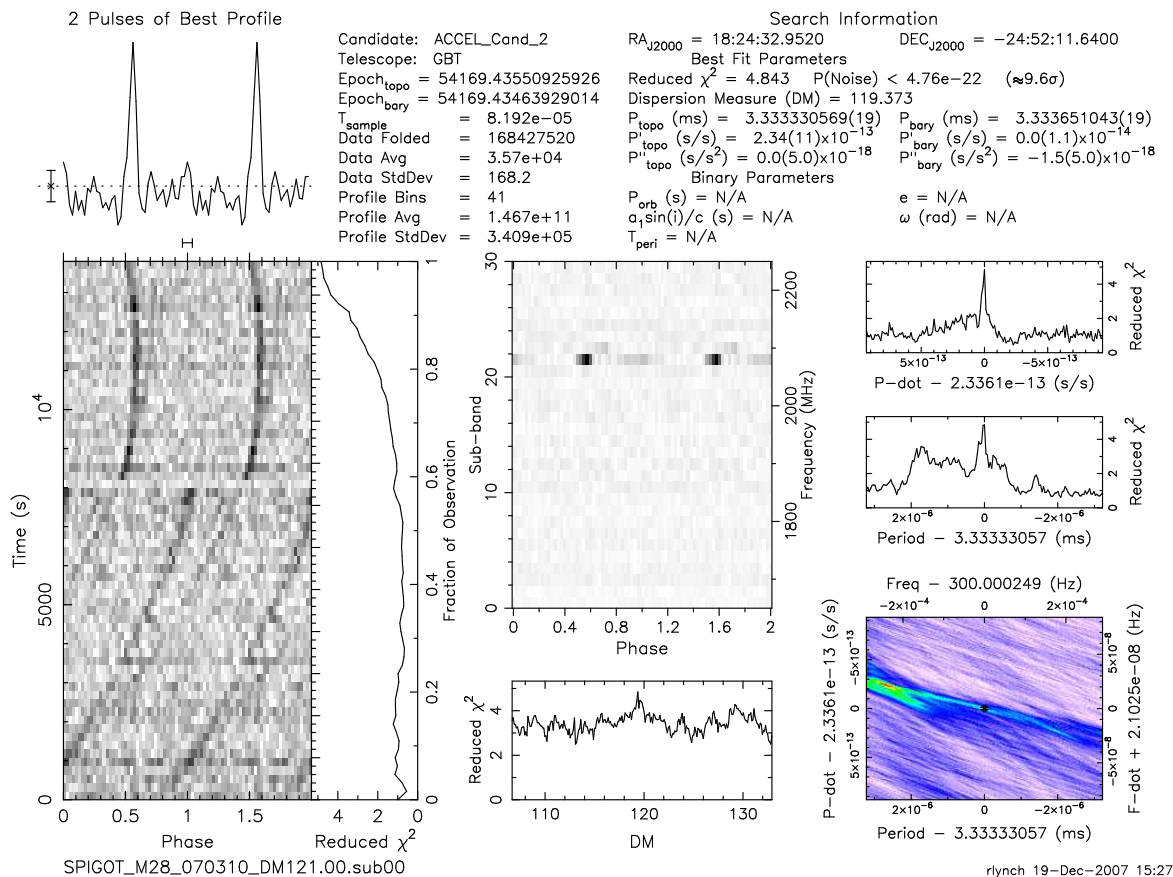


Fig. 12.— A prepfold plot of some RFI that drifts in phase. Notice the phase jump at 8000 seconds. There are other indications that this is RFI. The signal is narrow band, the DM curve is flat, and the Reduced χ^2 vs. Period curve doesn't peak at one period. Also, notice that the period is almost exactly $3\bar{3}$, corresponding to a spin frequency of almost exactly 300 Hz. This is a suspiciously “convenient” period.

5.2. Broadband vs. Narrowband Signals

When you tune your car radio to your favorite radio station, you usually have to get the frequency right to within 0.1 MHz. For example, 103.1 MHz may play country, while 103.3 MHz plays classic rock. The fact that a given radio station only broadcasts its signal in a very narrow range of frequencies is no accident—it is done purposely to avoid overlapping with other stations, and to avoid wasting energy by dumping it into frequencies that people don't have to listen to. These are examples of **narrowband** signals, and they are very common amongst RFI. Pulsars, on the other hand, don't have a way of restricting their emission to a very narrow range of *observing frequency* (remember, this is different than spin frequency). As a result, pulsars beam radiation at a wide range of frequencies, and this is

known as **broadband** emission. Can you think of how this might be helpful to us when looking at a **prepfold** plot?

If you said that pulsars and RFI would look different in the Frequency/Sub-band plot, you'd be right. **Since pulsar emission is broadband, we will see power at all the observing frequencies.** We may see more power at some frequencies and less at others, but there should still be a clear increase in signal strength at all of our observing frequencies. On the other hand, narrowband emission from RFI will only show up in a very narrow range of frequencies and often only in one sub-band. Going back to Figure 12, you will see an example of narrowband RFI. If you see that the emission is narrowband, then you can be sure that the signal is in fact from RFI, and not from a real pulsar.

5.3. Transient Emission

Sometimes, the source of RFI that is masquerading as a real pulsar is only turned on for some small fraction of our observation. This may occur if the source of RFI (like a communications satellite) is only active for a brief period of time. If this is the case, then you won't see a continuous line in the Time Series. Instead, the signal will appear broken, sometimes being on and sometimes being off. We call this **transient emission**. If you see this, you should be cautious about labeling the detection as a real pulsar. *But there are important exceptions to this rule!*

Pulsar emission can actually turn off during an observation. In some cases, the pulsar itself suddenly stops sending out radio waves for reasons that astronomers still don't entirely understand. In other cases, something may block the signal from reaching the Earth. This can occur in binary systems if the orientation between the Earth and the pulsar is just right. In these cases, the pulsar's companion star will sometimes pass in front of the pulsar, stopping the signal from reaching us. This is known as an **eclipsing system**, because we say that the pulsar is being eclipsed by its companion. The same principle applies when the moon blocks the light from the Sun, resulting in a solar eclipse. Eclipsing systems will have transient emission. Sometimes, you may see the pulsar signal disappear and reappear in the same observation. Sometimes, the pulsar may only appear part of the way through the observation. Figure 13 shows an example of an eclipsing pulsar.

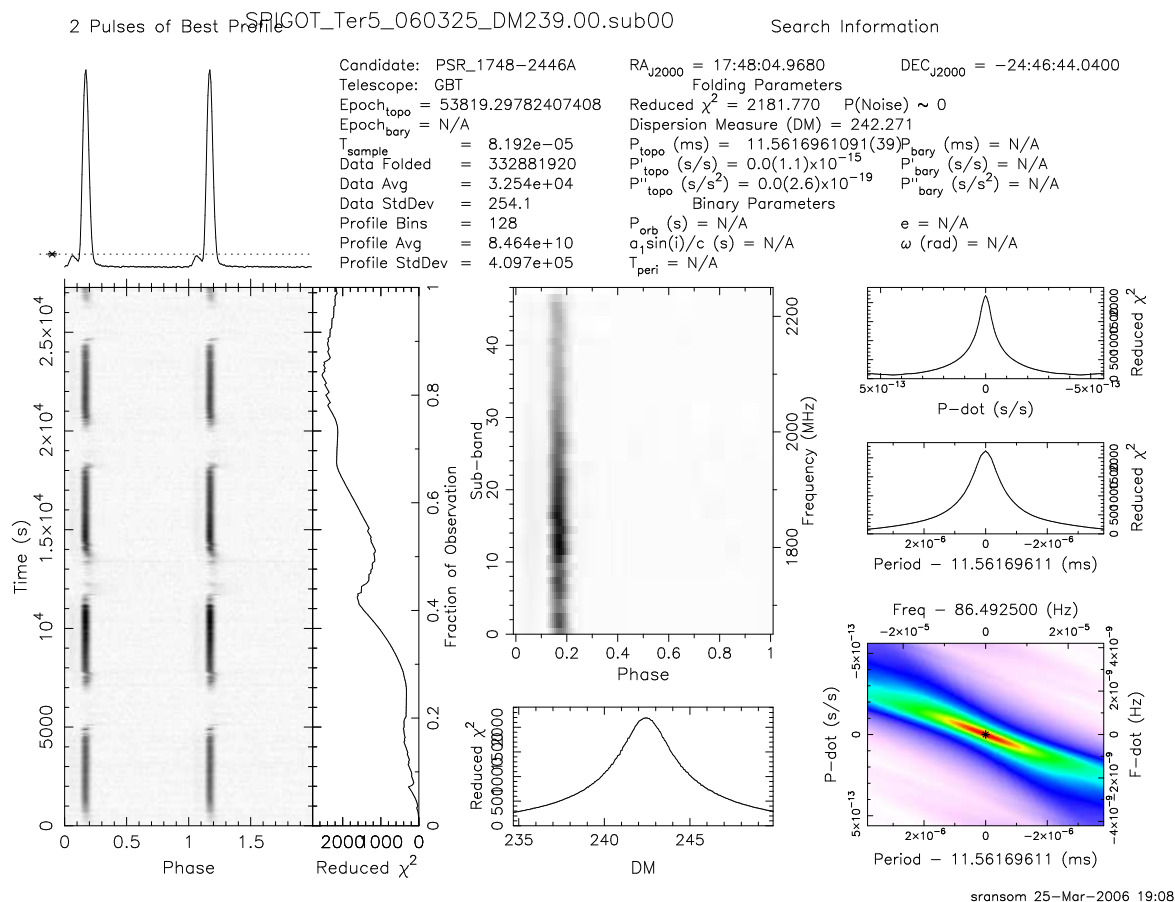


Fig. 13.— A prepold plot of an eclipsing pulsar. This is actually the same pulsar as in Fig. 11, but the effects of the binary on the phase have been removed and a longer observing time has been displayed so that you can see the pulsar “turning off” as it is eclipsed. Notice that the pulsar seems to fade away rather than turn off abruptly. This is because of a wind from the pulsar’s companion star that acts like a cloud, slowly causing the pulsar to diminish in brightness before disappearing completely.

So if you see transient emission, it could be a sign of RFI. But it could also be a sign of an eclipsing system or **nulling pulsar**. To tell them apart, you will need to examine other parts of the plot, such as the Frequency/Sub-bands and the Dispersion Measure. Experience will also help.

5.4. The Dispersion Measure

One of the most useful ways of identifying RFI is to look at the DM curve. Recall that any real pulsar signal must travel through space to reach us, and in doing so will certainly encounter some electrons. On the other hand, a signal originating near the Earth will not

encounter any electrons and will have a DM very nearly zero. So if the DM curve peaks at zero, then you almost certainly have found RFI, not a real pulsar. It is important to note that some pulsars can have a fairly low DM (under 10 pc cm^{-3})⁶, so be sure to examine the plot closely to make sure you know where the DM curve is truly peaking. You must also be aware that some sources of RFI can *appear* to have a non-zero DM (see Figures 10 and 12. So seeing a signal that has a non-zero DM does not necessarily mean that the signal is from a real pulsar. As always, you should carefully examine other parts of the prepfold plot before making a judgement.

5.5. Some Other Things to Consider

In some cases, you will see a signal that has a “convenient” spin period or frequency. By this, I mean that the period or frequency seems very close to a nice, round number that humans might like to use. Some simple examples are a period of almost exactly 10 milliseconds (corresponding to a frequency of 100 Hz), or a frequency of 300 Hz (corresponding to a period of $3.\bar{3}$ milliseconds). A pulsar certainly could have these spin frequencies, but there is no reason why they should be more common than any other spin frequencies. As you examine many candidate pulsars, you will begin to recognize some common spin frequencies that correspond to RFI.

6. Putting it All Together

While all of the things discussed in this guide should be used to determine the authenticity of a pulsar candidate, you will no doubt begin to fall into your own unique routine for examining PRESTO plots and deciding whether or not a candidate is “good”. To help you get to that stage, I have included my own scheme for examining these plots:

1. Look at the pulse profile. Is the signal sufficiently high above the noise level? Is the profile free of strange signals that do not normally show up in real pulsars?

⁶These units stand for “parsecs per centimeter cubed”. A parsec is a unit of length used commonly in astronomy, and is equal to about 3.3 light years. You may notice that since we are dividing a distance by another unit of distance cubed, what we actually have is a number per distance squared. Astronomers commonly refer to this as “column density”. If you are familiar with calculus, you may recognize this as the number density of electrons integrated along the path from the telescope to the pulsar. See if you can answer the following question: if the DM is 17 pc cm^{-3} and we know that the average number density of electrons is $0.01 \text{ electrons cm}^{-3}$, what is the distance to the pulsar?

2. Look at the time series. Is the signal persistent? Does it occur at the same phase, or drift in phase in the way a binary pulsar would? Are there obvious sources of RFI?
3. Look at the sub-bands. Does the signal occur at a wide range of frequencies or is it narrowband?
4. Look at the DM curve. Does it peak at a non-zero DM? Is the DM well measured, or is there considerable uncertainty in the measurement?
5. Look at the period and frequency. Are they round or “convenient” numbers, such as $P = 10$ milliseconds or $f = 100$ Hz?
6. Look at the period and P-dot information. Are these well measured? Is there a strong peak in the Period vs P-dot plot?

The first few items in the above list tend to be more obvious indicators of a real pulsar or an obvious source of RFI, so that is what I look at first. But it is important to consider *all* of the above points before deciding whether or not a candidate is real. Remember that the answer may not always be obvious, and sometimes there is no way of saying for sure. These “maybe” cases are still important to classify, because we can follow them up with more observations that will be able to definitively pin down whether or not a candidate is real.

By now, you might be thinking, “What did I get myself into?” There is a lot to consider when you are looking for pulsars, and it can all seem pretty complicated at first. Don’t give up! As you gain more experience, sorting through PRESTO plots will become second nature. You will learn to pick up on signatures of RFI quickly, and will be able to recognize the characteristics of an actual pulsar. Sometimes the answer may not be very clear cut, and that is perfectly OK! In fact, that is one of the best parts about science. Most of the time, we don’t know the answers to our questions ahead of time. We have to work with what nature gives us in order to try and put the pieces of the puzzle together. Some puzzles are easier than others, but the challenge is what makes science, and astronomy in particular, so much fun. Hopefully, this guide will help to get you started. And hopefully, you will find some new and very exciting pulsars.

GOOD LUCK AND HAPPY HUNTING!

7. APPENDIX: The Nature of Light

We are used to thinking of light as that which allows us to see. But this is much too restrictive a definition. What we normally call light is better described as **visible light**. Light, in general, includes all parts of the **electromagnetic spectrum**—from radio and microwaves, to infrared, visible, and ultraviolet light, to x-rays and gamma-rays. These are all different types of the same basic phenomenon. Figure 14 is a representation of the electromagnetic spectrum, with different types of light labeled.

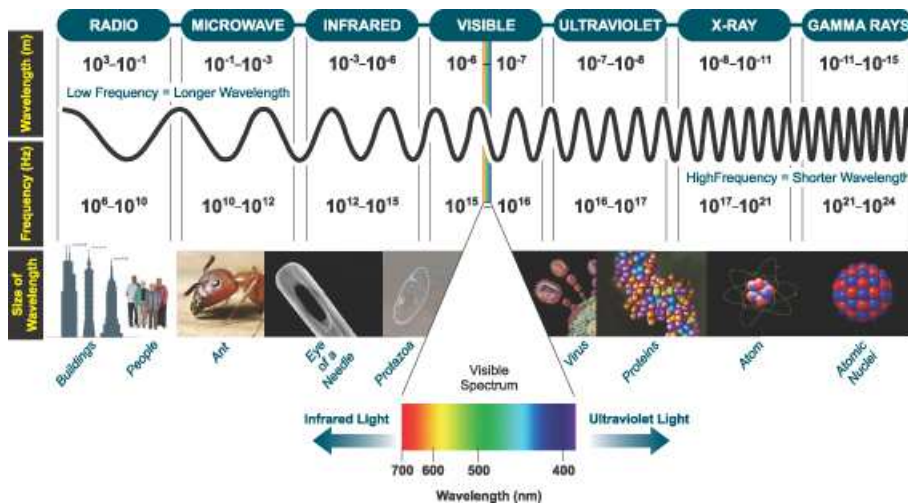


Fig. 14.— A representation of the electromagnetic spectrum. Radio waves have the longest wavelength and lowest frequency, while gamma-rays have the shortest wavelength and highest frequency. The pictures at the bottom show real-world objects that are about the same size as the wavelength of light in each different part of the spectrum. Image from <http://www.andor.com/library/light/>.

The electromagnetic spectrum is a word that scientists use to refer to the wide range of **electromagnetic waves**. Electromagnetic waves are simply waves of energy. This energy is carried by electric and magnetic fields. Figure 15 is a representation of one of these waves. All waves can be characterized by their **wavelength** and **frequency**. The wavelength is the distance between two peaks on the wave. Radio waves have a very long wavelength while gamma-rays have a very short wavelength. Frequency is the number of peaks that pass by an observer every second. Since the peaks of radio waves are separated by a large distance, few of them pass by an observer in a second, i.e. they have a low frequency. Gamma-rays, on the other hand, have a short wavelength, and thus a high frequency. Color is really nothing more than the response of our eyes to different frequencies of visible light. Red light has the lowest frequency and blue light the highest. In radio astronomy, when we talk about the observing frequency, we are referring to the frequency of the light that we are observing.

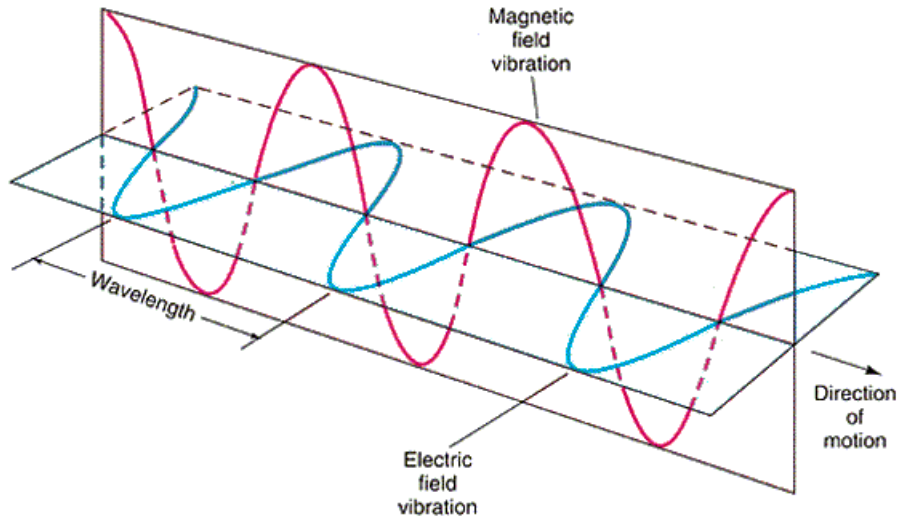


Fig. 15.— A representation of an electromagnetic wave. The electric field and magnetic field waves are always perpendicular to each other, and to the direction in which they travel. The wavelength is the distance between any two peaks. Image from <http://www.pas.rochester.edu>.

It is a common misconception that radio waves are somehow related to sound. The only similarity is that sound also travels in waves. Other than that, there is no more similarity between radio waves and sound than there is between visible light and sound. However, it is possible to encode information in radio waves (or any form of light), and that information can then be *changed into sound*. This is how a car radio or cell phone operate.

The fact that light carries electromagnetic energy is a clue to how light is produced. The simple description is that light is produced any time there is source of accelerating electrical charge. This is why electronic equipment tends to give off radio waves. Whenever the current flowing through the system changes speed or direction, it will give off light. And most electronic equipment gives off light in the form of radio waves. For this reason, electronic equipment around a radio telescope must be well shielded or removed completely. Otherwise, it will be a source of RFI.

GLOSSARY

Bin: A small piece of data. We usually refer to time bins (data collected in a small chunk of time) or frequency bins (data collected in a small chunk of observing frequency).

Binary Systems: A system consisting of a pulsar and companion star in orbit around one another.

Broadband: Emission that occurs over a wide range of observing frequencies.

Dispersion Measure: A way measuring the number of electrons that a pulsar signal must pass through while traveling through space to the Earth. The units are parsecs per centimeter cubed.

Eclipsing Systems: A system consisting of a pulsar and companion star, in which the companion star sometimes blocks radio emission from the pulsar.

Electromagnetic Spectrum: The wide range of electromagnetic waves, or different types of light.

Electromagnetic Waves: Waves of energy carried by electric and magnetic fields. This is another term for light.

Fourier Transform: A mathematical tool that transforms data from one form to another. In pulsar astronomy, we use Fourier transforms to take our data from the time domain to frequency domain. Fourier transforms are very useful for finding repeating signals in a set of data.

Frequency: The number of times some event repeats in a single second. The units are hertz.

Magnetic Fields: A way of describing the influence of magnetic force. All magnetic fields have a north and south pole, just like a household bar magnet. Magnetic fields on Earth are relatively weak compared to those found around pulsars.

Narrowband: Emission that occurs in only a small range of observing frequencies.

Neutrons: Subatomic particles that carry no electrical charge. Neutrons can be found in the nuclei of atoms, and are the primary constituent of neutron stars.

Neutron Star: A very dense star made almost entirely out of neutrons. Neutron stars are produced when massive stars die in large explosions.

Observing Frequency: The radio frequency that astronomy observations are made at, typically measured in MHz or GHz.

Period Derivative: The rate of change in the rotational period of the pulsar per unit time, which is unitless but usually written as seconds per second.

Phase: The fraction of a full rotation that a pulsar has gone through.

Pulse Profile: The strength of a pulsar signal as a function of phase. Pulse profiles are made by folding the time domain data and adding up all the power at a given phase.

Radio Frequency Interference: Radio signals from man-made sources that can often look like a pulsar signal. RFI can come from a variety of sources, and if there is a lot of it radio astronomy observations can be nearly impossible.

Radio Waves: Energy carried in the radio part of the electromagnetic spectrum. Radio waves are actually a form of light, fundamentally no different than the light we see with our eyes. However, radio waves carry less energy than visible light. Radio waves are *not* sound waves, but they are often used by humans to carry information that can then be turned into sound (for example, by a car radio).

Reduced χ^2 : A mathematical tool for determining how well some data fit to a given model. Normally, a Reduced χ^2 of one is desirable. However, we want a high value for Reduced χ^2 , because in our case the model is data with *no* pulsar, so a high Reduced χ^2 indicates that a pulsar (or at least RFI masquerading as a pulsar) *does* exist.

Spin Frequency: The frequency at which a pulsar rotates. Spin frequency is equal to the number of times a pulsar rotates in a single second.

Spin Period: The length of time it takes a pulsar to complete one rotation.

Sub-band: A small range of observing frequencies integrated together. Radio astronomy instruments typically break down the observing frequency into sub-bands.

Supernova: A huge explosion that occurs when stars several times more massive than our Sun exhaust the fuel that keeps them burning. Supernovae are among the most powerful explosions in our universe.

Transient Emission: Radio wave signals that are only present for part of an observation.

Time of Arrival: The moment that a pulsar signal is detected on the Earth. Astronomers can predict the time of arrival very accurately for pulsars. By comparing this prediction to the actual time of arrival, astronomers learn about pulsars, the environments in which they are found, and the properties of the galaxy between the pulsar and Earth.

Time Series: A representation of how the signal from a pulsar changes in time. Time series are plotted as the power at a given phase vs. time.

Visible Light: Light that our eyes are sensitive to. Although we cannot see them, radio waves, microwaves, and X-rays are all types of light.

Wavelength: The distance between two peaks in an electromagnetic wave, and a way of characterizing light.

GLOSSARY OF PRESTO SEARCH INFORMATION

$a_1 \sin(i)/c$: A way of describing the size of the pulsar’s orbit if it is in a binary system.

Candidate: The name or label assigned to the current pulsar candidate.

Data Avg: The average value of the data.

Data Folded: The size of the data set being worked on.

Data StdDev: The standard deviation, a way of characterizing the spread in the values of the data.

Dec_{J2000}: The declination of the source in the J2000 coordinate system. Declination is like a line of constant latitude on the sky.

Dispersion Measure: See the glossary above.

e: The eccentricity of the pulsar’s orbit, if it is in a binary system. Eccentricity measures how elliptical the orbit is, with a high eccentricity indicating a very elliptical orbit.

Epoch_{bary}: The Modified Julian Date of the start of the observation accounting for slight shifts due to the motion of the Earth.

Epoch_{topo}: The Modified Julian Date of the start of the observation.

Profile Avg: The average value of the pulse profile.

Profile Bins: The number of phase bins in the pulse profile.

Profile StdDev: A way of characterizing the spread in the values of the pulse profile.

P_{bary}: The period of the pulsar, adjusted as if it were measured from the center of mass of the solar system.

P’_{bary}: The P-dot of the pulsar, adjusted as if it were measured from the center of mass of the solar system..

P’’_{bary}: The second derivative of the period of the pulsar, adjusted as if it were measured from the center of mass of the solar system. The P-double-dot is the rate of change of the P-dot.

P_{orb}: The orbital period of the pulsar, if it is in a binary system. This is the length of time it takes for the pulsar to go through one full revolution.

P_{topo}: The period of the pulsar as measured from the observatory.

\mathbf{P}'_{topo} : The P-dot of the pulsar as measured from the observatory.

\mathbf{P}''_{topo} : The P-double-dot of the pulsar as measured from the observatory. The P-double-dot is the rate of change of the P-dot.

\mathbf{RA}_{J2000} : The right ascension of the source in the J2000 coordinate system. Right ascension is like a line of constant longitude on the sky.

Reduced χ^2 : See the glossary above.

Telescope: The name of the telescope used to make the current observation.

\mathbf{T}_{peri} : A way of describing when the pulsar is closest to the center of mass of its system, if it is in a binary system.

ω : The longitude of periastron. This is a way of describing the orientation of the pulsar's orbit, if it is in a binary system. (This symbol is the Greek letter omega.)