Instructor Lab Manual: Pulsars

Introduction

When a massive star (between about 8 - 25 times the mass of the sun) reaches the end of its life, it dies in a spectacular explosion called a **supernova**. During the supernova, the gravity of the collapsing star crushes the core into an extremely dense object called a **neutron star**, a sphere just a few kilometers wide but with more mass than the sun! It's made almost entirely of neutrons packed together so tightly that a single teaspoon would weigh about a billion tons.

If the neutron star has a strong magnetic field and is spinning rapidly, it can become a **pulsar**. Pulsars emit powerful beams of radio waves from their magnetic poles; as the neutron star spins, those beams of radio waves sweep through space like a lighthouse. If Earth happens to lie in the path of one of those beams, we can observe regular pulses of radio waves, once per rotation. These pulses are so consistent that pulsars are among the most precise natural clocks in the universe.

In this lab, you'll analyze data from a pulsar located about 3,500 light-years from Earth called B0329+54, one of the first pulsars ever discovered, and one of the brightest in the northern sky. Because it's so bright and regular, B0329+54 is often used as a calibration source by radio telescopes around the world. This pulsar was observed by the Green Bank Telescope (GBT), the largest movable radio telescope in the world, which allows us to see (and hear) the individual pulses. To analyze the data, you'll use a software called GNU Radio, installation instructions can be found here: `https://wiki.gnuradio.org/index.php/InstallingGR`. Make sure to download the data file `B0329DATA.dat` before beginning the lab.

Exploring the Signal in GNU Radio

In this section, you'll use GNU Radio to read the data file, apply some basic filtering, and generate a plot of the time-series. This will let you visualize and listen to the pulses from B0329+54 and give you a look at what the telescope recorded.

Open GNU Radio Companion and create a new flowgraph using the button on the far left of the top control panel. Using the search tool (magnifying glass icon in the control panel), search for and **add the following blocks to your workspace**. Once you've added a block to your workspace, double-click to **open the properties window and make the modifications below.**

- Edit the existing `samp_rate` variable.
  - Value: `2861`
- **File Source**
  - File: your path to the downloaded `B0329DATA.dat` file.
  - Output Type: `float`
- **Multiply Const**

- IO Type: `float`
- Constant: `1e-3`

- **Low Pass Filter**
  - FIR Type: `Float` → `Float (Decimating)`
  - Cutoff Freq: `200`
  - Transition Width: `100`
- **QT GUI Time Sink**
  - Type: `Float`
  - Number of Points: `samp_rate*5`
  - Y min: `15`
  - Y max: `25`
  - Config → Control Panel: `Yes`
- **Audio Sink**
  - Sample Rate: `samp_rate`

These blocks can be connected to create a flowgraph; connect the blocks by first selecting the **out** port of one block, then the **in** port of the other. Organize and **connect the blocks to match Figure 1**. The connecting arrows should be black. If they're red, then there's a mismatch between the data types being used in each block. If this happens, double check the data type of each block, they should all have orange ports indicating the `float` data type.

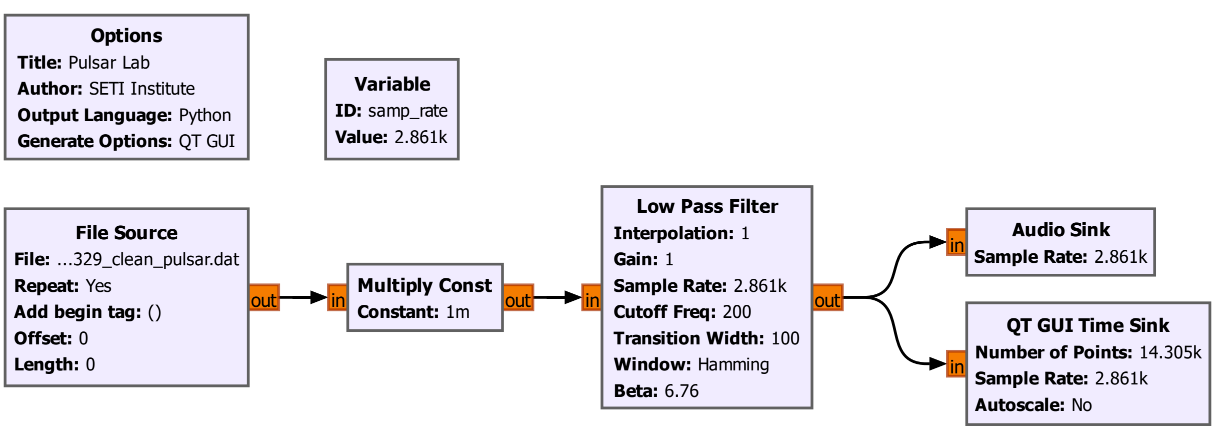

Figure 1: GNU Radio Companion flowgraph to visualize and sonify the signal from B0329+54.

Run the flowgraph using the play button on the control panel, you should see a plot similar to Figure 2 and hear a repeating click sound. Each peak in the time-series and audio click is a pulse from B0329+54!

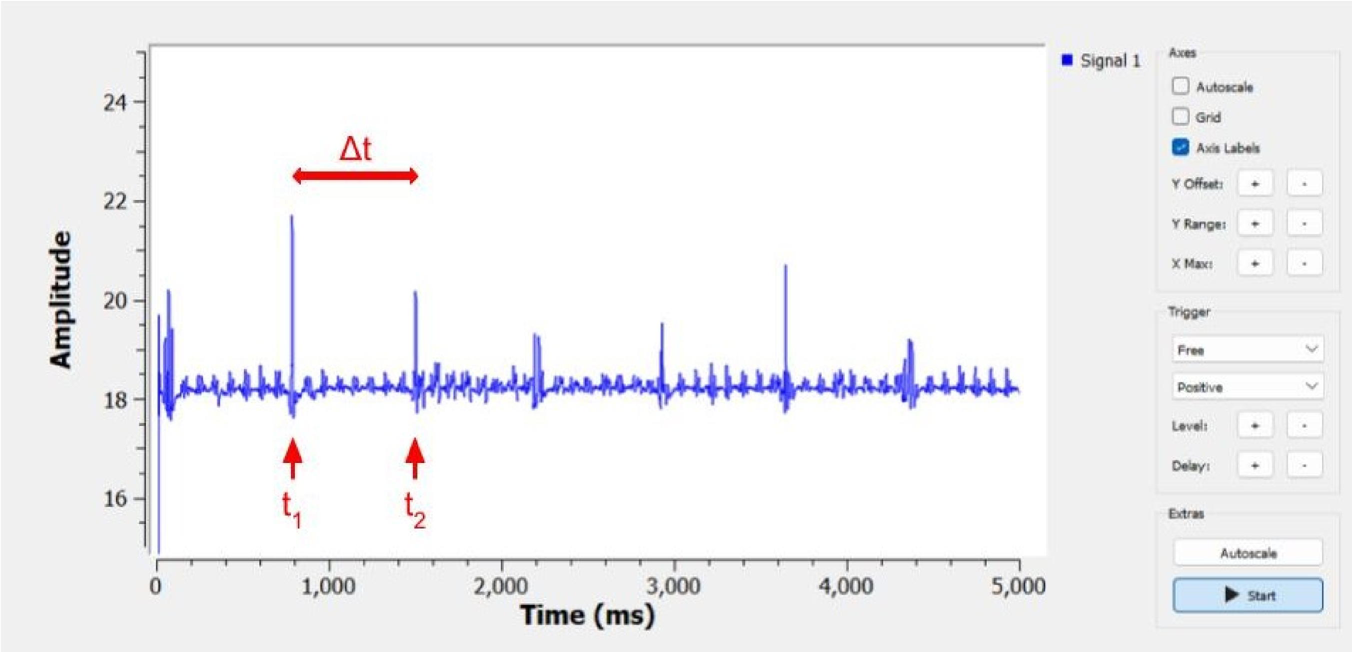

Figure 2: GNU Radio Companion time-series plot of the pulsar signal.

Measuring the Period

Next, determine the pulsar's rotation period by using the time-series plot generated in GNU Radio. Each pulse appears as a distinct peak in the signal. By identifying the arrival time of several consecutive pulses and calculating the time difference between each pair, you can estimate the pulsar's rotation period. Your cursor will display the time at its location on the plot. In the table below, **record the arrival times of at least 5 pairs of consecutive pulses** to an accuracy of at least 4 significant figures, calculate the differences $\Delta t = t_2 - t_1$, and then compute the average (mean) of those values. The time-series plot will automatically update every 5 seconds, you can stop the plot at it's current location using the **Stop** button at the bottom of the control panel. Zoom into a region of the plot by dragging a box around the region of interest in order to get a more accurate measurement of the pulse time.

The process of identifying and measuring pulse periodicity is not only important in studying pulsars, but it's also an integral tool in SETI. Repeating signals are one of the most intriguing types of potential technosignatures, signs of technology that would indicate the presence of intelligent life in the universe. Learning to analyze the periodic patterns of pulsars helps astronomers build the foundational tools to evaluate whether a signal is natural or artificial.

Arrival Time t_1 (ms)	Arrival Time t_2 (ms)	$\Delta t = t_2 - t_1$ (ms)
787.6525	1503.1604	715.5079
2958.8413	3673.5474	716.7061
2984.3602	3699.6709	715.3107
3740.2051	4454.6685	714.4634
1522.1500	2236.9710	714.8210
	Average Period (ms):	715.4

Table 1: Pulse arrival time measurements and period estimation.

Constraining the Size of a Pulsar

When pulsars were first discovered in 1967, astronomers didn't know what was causing them. Imagine you're an astronomer in the 1960's trying to explain these regular pulses. One idea is that they're coming from a rotating object with a beam of radiation, like a lighthouse. Every time the beam sweeps past Earth, we detect a pulse. If that's true, the pulse rate is just the rotation rate of the object. One of the first questions astronomers asked was: what kind of object could be spinning so fast without flying apart?

According to Einstein's theory of special relativity, there's a hard limit in the universe, nothing can travel faster than the speed of light (c), which is about 300,000,000 m/s. If the surface of a spinning star was moving faster than the speed of light, then the laws of physics as we know them would be wrong! So we can turn this around and ask the question: what's the largest possible radius the star could have, while keeping the equator moving slower than the speed of light?

The formula for the speed (v) at the surface of a spinning sphere along the equator is:

$$v = \frac{2\pi R}{P} \tag{1}$$

where R is the radius of the star (in meters), and P is the rotation period (in seconds). In order to satisfy the conditions of special relativity, this speed must be less than the speed of light (c):

$$\frac{2\pi R}{P} \leq c \tag{2}$$

Solving for the radius (R), we get:

$$R \leq \frac{cP}{2\pi} \tag{3}$$

This line of reasoning gives us a simple but powerful tool. If we know how fast the object is spinning, we can calculate the maximum size it can be.

Using the average rotation period you found for B0329+54 and Equation 3, **calculate the maximum radius of this pulsar**. Remember to convert the period from milliseconds to seconds (1 second = 1,000 milliseconds) for this calculation.

$$R \leq \frac{cP}{2\pi}$$

$$R \leq \frac{(3 \times 10^8)(0.7154)}{2\pi}$$

$$R \leq 3.42 \times 10^7 \text{ meters}$$

This approach for constraining the size of a pulsar only sets a upper limit, and works better for faster rotating objects. As far as pulsars go, B0329+54 rotates rather slowly, only about 0.7 seconds. Currently, the fastest rotating pulsar ever discovered is PSR J1748-2446ad, which has a rotation period of only 1.396 milliseconds! Using the same method, **calculate the maximum radius for pulsar PSR J1748-2446ad.**

$$R \leq \frac{cP}{2\pi}$$

$$R \leq \frac{(3 \times 10^8)(0.001396)}{2\pi}$$

$$R \leq 6.67 \times 10^4 \text{ meters}$$

More precise methods for determining the size of a pulsar have since been developed, and further constrained the size of these objects. The NICER (Neutron Star Interior Composition Explorer) experiment has estimated the radius of PSR J1748-2446ad to be about 1.3×10^4 meters. Using this radius and Equation 1, **calculate the rotational speed at the surface of this pulsar**, as a percentage of the speed of light.

$$v = \frac{2\pi R}{P}$$

$$v = \frac{2\pi(1.3 \times 10^4)}{0.001396} = 58,471,630 \text{ m/s}$$

$$\frac{v}{c} = \frac{58,471,630}{300,000,000} \approx 0.195 \rightarrow v \approx 19.5\% \text{ c}$$

The average density (ρ) of a pulsar can be found if we know both its mass (M) and volume (V).

$$\rho = \frac{M}{V} \tag{4}$$

Assuming the neutron star is a sphere, the volume is:

$$V = \frac{4}{3}\pi R^3 \tag{5}$$

Pulsars are thought to have a mass of about 1.4 times the mass of the sun, which is about 2.785×10^{30} kg. Using this and the radius found by NICER (1.3×10^4 m) **calculate the density of pulsar PSR J1748-2446ad**. For comparison, water has a density of 1000 kg/m^3, and an atomic nucleus has a density of about 2.3×10^{17} kg/m^3.

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi(1.3 \times 10^4)^3 \approx 9.203 \times 10^{12} \text{ m }^3$$

$$\rho = \frac{M}{V} = \frac{2.785 \times 10^{30}}{9.203 \times 10^{12}}$$

$$\rho \approx 3.02 \times 10^{17} \text{ kg/m}^3$$

Characteristic Age of a Pulsar

The spin of a pulsar will gradually slow down as it emits energy into space in the form of electromagnetic radiation and particle winds. This process causes the rotation period P to increase very slowly over time. The rate at which the period is changing is called $\dot{P}$, the period derivative. This can be used to find the characteristic age (τ, measured in seconds) of the pulsar, an approximation of how old the pulsar is, assuming it was spinning faster than it is today and has been slowing down at a constant rate.

$$\tau = \frac{P}{2\dot{P}} \tag{6}$$

The pulsar B0329+54 has been studied extensively and been found to have a period rate of change of $\dot{P} = 2.05 \times 10^{-15}$ seconds per second. Using this, the average period you found earlier, and Equation 6, **calculate the characteristic age of B0329+54**. Convert your answer from seconds to years (1 year $\approx 3.156 \times 10^7$ seconds).

$$\tau = \frac{P}{2\dot{P}} = \frac{0.7154}{2(2.05 \times 10^{-15})} \approx 1.74478 \times 10^{14} \text{ seconds}$$

$$\tau = \frac{1.74478 \times 10^{14} \text{ seconds}}{3.156 \times 10^7 \text{ seconds/year}} \approx 5.528 \text{ million years}$$

Determining the age of a pulsar helps place it in the broader history of the galaxy, and can help inform SETI strategies. For example, long-lived, stable systems may be good candidates for targeted SETI searches, while very young systems may be less likely to host or preserve life.

Extension and Discussion

In this lab, you've studied the properties and physics behind neutron stars/pulsars, one of the most extreme objects in the universe. While you've calculated the rotation period, surface speed, density, and age, these topics connect to much larger ideas at the forefront of research in astrophysics, quantum mechanics, relativity, and the search for extraterrestrial intelligence (SETI). The following topics highlight a few of the many ways pulsars are being used to help scientists explore the universe.

SETI and Technosignatures

When pulsars were first discovered, their extreme regularity led some astronomers to consider artificial origins. The first pulsar discovered, B1919+21, was nicknamed "LGM-1" for "Little Green Men". In modern SETI, pulsars are used as a reference point for what natural signals can look like. Their consistency, repetition, and astrophysical origin help define the baseline when searching for technosignatures, signals that indicate the presence of technology, and therefore intelligence, in the universe. Any signal that deviates from known astrophysical patterns, such as irregular repetition, non-natural modulation, or directionally targeted transmissions, must be examined in the context of what we already know about sources like pulsars.

Pulsars remind us that not every strange signal is a message, but every message would be a strange signal. Learning to distinguish natural astrophysical sources from artificial ones is central to SETI, and pulsars provide one of the clearest benchmarks for what nature can produce.

The Nature of Neutron Star Matter

Neutron stars are formed during a supernova, when the core of the massive star collapses under the extreme force of gravity. The collapse is only stopped by neutron degeneracy pressure, a quantum mechanical effect that resists further compression. Without the neutron degeneracy pressure to stop the collapse, the supernova would result in a black hole, as is the case for even more massive stars with more violent supernova that can overcome this pressure. At these extreme densities, matter enters a state that cannot be recreated on Earth, making neutron stars an invaluable resource to study the most extreme forms of matter.

The exact composition of neutron stars isn't fully known. In the outer layer, neutrons may exist alongside a thin crust of ions, but deeper inside the structure becomes more uncertain. Some models predict the presence of exotic particles like hyperons, particles containing strange quarks, or deconfined quark matter, where the neutrons dissolve into their constituent quarks. These possibilities are governed by the unknown equation of state (EoS) for ultra-dense matter, which remains an important open problem in physics.

Magnetic Fields and Emission Mechanisms

Pulsars have incredibly strong magnetic fields, trillions of times stronger that Earth's. These fields are misaligned with the rotation axis, causing charged particles to be accelerated along the magnetic poles. This acceleration creates focused beams of radiation, including radio waves, that sweep across space as the pulsar rotates. The jets of charged particles emitted by the magnetic field can also be seen in some cases, such as the Chandra X-Ray Telescope's image of the Vela pulsar.

The precise mechanism by which this radiation is generated is still not fully understood. The region above the magnetic poles, called the magnetosphere, hosts complex interactions between electric and magnetic fields, and high-energy particles. Understanding precisely how the beam is created, and why only some neutron stars emit detectable pulses, remains an active area of research.

Pulsars as Astrophysical Tools

Pulsars are more than just interesting objects, they can be used as tools for many other areas of astrophysics. Millisecond pulsars, such as PSR J1748-2446ad that you studied in this lab, are so stable that they rival atomic clocks on Earth. By carefully monitoring the arrival times of their pulses, astronomers can detect tiny shifts in timing caused by external influences.

The first exoplanets ever discovered were detected in 1992 by using this pulsar timing method, as the planets orbit around a pulsar called PSR B1257+12. The gravitational influence of these exoplanets caused the pulsar to wobble slightly, resulting in a very small but periodic shift in the arrival times of the pulses.

Another application is pulsar timing arrays, where networks of pulsars across the galaxy are used in conjunction to search for gravitational waves. These waves stretch and compress space, subtly altering the pulse arrival times across the sky in a correlated way. In 2023, astronomers used a pulsar timing array to discover the gravitational wave background, a low-frequency ”hum” throughout the universe, thought to be caused by binary supermassive black holes.

Pulsars also help us study the interstellar medium (ISM), the matter that lies between stars. As the radio waves travel through space, they are dispersed by electrons along their path, casing lower frequencies to be delayed relative to higher frequencies. By carefully measuring this dispersion, astronomers can map the ISM and study the plasma environment throughout the galaxy.