Electromagnetic radiation

Our eyes detect visible light, which is a type of *electromagnetic (EM) radiation*. Objects on Earth and in space emit other types of EM radiation that cannot be seen by the human eye, such as the radio waves. The full range of all radiating EM waves is called the *electromagnetic spectrum*.

An electron generates an electric field, and if the electron moves (that is, it vibrates back and forth), then this motion will be transferred to the field lines and they will become waves. The moving electron also generates a magnetic field that will become wavy from the motion of the electron. These combined electrical and magnetic waves reinforce one another, thus producing electromagnetic radiation. Since all matter contains electrons and all these electrons are in motion, all matter generates electromagnetic waves.

Light is made up of tiny particles called “photons”. Photons in visible light have a medium amount of energy. When photons have a little bit more energy, they become ultraviolet radiation, which cannot be seen but can give you sunburn! With more energy, photons become X-rays which travel right through you. If the photons possess even *more* energy, they become gamma rays. The electromagnetic spectrum has no upper or lower limit of frequencies. In order of increasing frequency (and decreasing wavelength), the electromagnetic spectrum includes radio frequency (RF), infrared (IR), visible light, ultraviolet (UV), X-rays, and gamma rays.

Radio astronomy

Radio astronomy is the study of celestial objects that give off radio waves. Astronomical phenomena that are often invisible or hidden in other portions of the electromagnetic spectrum can be studied through radio astronomy.

What is the radio universe made of:- Stars, the sun, planets, hydrogen clouds, the Milky Way, pulsars, star-forming regions, supernova remnants, interacting binaries, active galaxies and quasars, cosmic microwave background and many other galactic and extragalactic sources radiate not only in the visible waveband of the electromagnetic spectrum but also in the radio region. Some objects emit only dimly in the visible wavelengths and are undetectable using even the most sophisticated of optical telescopes. However, these objects can be strong radio sources and can be easily detected in other wavelengths. Radio photons have the advantage of being relatively low in energy, being emitted in larger numbers than the shorter wavelength photons for the same energy output.

History of radio astronomy

Radio astronomy was born in the early 1930s when Karl Jansky, working as a radio engineer at the Bell Telephone Laboratories in Holmdel (New Jersey), was trying to determine the origin of a source of noise that was showing up in receivers operating in the 20 MHz region of the radio spectrum.

Wavelength and Frequency

Radio astronomers use radio photons to learn about the invisible universe. The size of a photon’s wave is called a *wavelength*, which can tell us about the energy of the source. If the wave is long, it does not have much energy; if it is short, it has a lot of energy. Radio waves do not have much energy, which means they travel in big waves with long wavelengths. Radio waves can be hundreds of feet across or just a few centimeters across. Astronomers also talk about how many of these waves pass a spot every second – *frequency*. One wave per second is called 1 Hertz. A million waves per second is 1 MHz. If the waves are long, fewer of them hit you every second, so longer waves have smaller frequencies. In summary, radio waves have long wavelengths and small frequencies. The figure below shows waves with two different wavelengths.

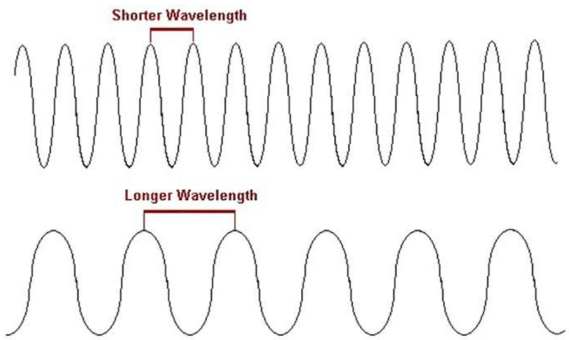

Figure 1: Shorter and Longer wavelength waves.

Jansky's experiment:

In 1931, he was assigned to study radio frequency interference from thunderstorms in order to help Bell design an antenna that would minimize static when beaming radio-telephone signals across the ocean. Jansky built a steerable antenna and began searching for the source of the noise by taking directional measurements. It was tuned to respond to radiation at a wavelength of 14.6 meters and rotated in a complete circle on old Ford tires every 20 minutes. The antenna was connected to a receiver and the antenna's output was recorded on a strip-chart recorder. To his surprise, he discovered that this noise was from extraterrestrial sources. He was able to attribute some of the static (a term used by radio engineers for noise produced by unmodulated RF radiation) to thunderstorms nearby, some to thunderstorms farther away, and some as " . . . a steady hiss type static of unknown origin." As his antenna rotated, he found that the direction from which this unknown static originated changed gradually, going through almost a complete circle in 24 hours. As he was not an astronomer himself, it took him a while to figure out that the static must be of extraterrestrial origin, since it seemed to be correlated with the rotation of Earth. With further investigation, Janksy identified the source as the Milky Way and published his findings in 1933.

Radio telescope

RF waves that can penetrate Earth's atmosphere range from wavelengths of a few millimeters to nearly 100 meters. These waves can induce a very weak electric current in a conductor such as an antenna. Most radio telescope antennas are parabolic (dish-shaped) reflectors that can be pointed toward any part of the sky. They gather up the radiation and reflect it to a central focus, where the radiation is concentrated. A radio receiver can then amplify the weak current at the focus so it is strong enough to be measured and recorded. Electronic filters in the receiver can be tuned to amplify one range (or "band") of frequencies at a time or thousands of separate narrow frequency bands. The intensity (or strength) of RF energy reaching Earth is small compared to the visible radiation, and therefore, a radio telescope must have a large "collecting area".

Electromagnetic radiation with frequencies between about 5 kHz and 300 GHz is referred to as radio frequency (RF) radiation. Radio frequencies are divided into ranges called "bands," such as "S-band," "X-band," etc. Radio telescopes can be tuned to listen for frequencies within certain bands.

Band	Range of Wavelengths (cm)	Frequency (GHz)
L	30 -15	1 - 2
S	15 - 7.5	2 - 4
C	7.5 - 3.75	4 - 8
X	3.75 - 2.4	8 - 12
K	2.4 - 0.75	12 - 40

Figure 2: Band frequencies.

Note: Band frequencies vary slightly among different sources.

<u>What can a radio telescope measure?</u>

Mapping - Mapping is the plotting of radiation intensity as a function of position, which allows an astronomer to determine where in space a radio source exists and, if the resolution is good enough, its actual structure. The position is usually noted in the form of right ascension and declination.

Frequency - While tracking a radio source, the wavelength of the receiver can be altered to allow a plot of intensity against frequency. Every astronomical object will have its own distinct plot, however those within the same class will generally have similar characteristics, which aid in identification. Analysing the spectrum can also help in understanding the physical conditions of the emitted source.

Polarisation - A radio astronomer can rotate the receiver on a telescope to determine the angle at which a maximum intensity is measured, from which we will know the orientation of the wave as it propagates through space. The polarisation will depend on the generation mechanism and material the light has passed through.

Variability **–** The intensity of most radio sources varied in some way with time. The most prominent of these time varying emitters were the pulsars, whose radio signals switched on and off at rapid regular intervals.

<u>Life cycle of a star and formation of neutron stars</u>

A star begins its life as a cloud of dust and gas (mainly hydrogen) known as a nebula. A proto-star is formed when gravity causes the dust and gas of a nebula to clump together in a process called accretion. As gravity continues to pull more matter inward towards the core, its temperature, pressure, and density increases. If a critical temperature in the core of a proto-star is reached, then nuclear fusion begins and a star is born. If the critical temperature is not reached, however, it ends up as a brown dwarf, or dead star, and never attains star status.

After millions to billions of years, depending on their initial masses, stars run out of their main fuel - hydrogen. Once the hydrogen in the core is depleted, nuclear process at the core cease and the outer layers of the star begin to collapse inward. As the material contracts, the temperature and pressure increase temporarily counteracting the force of gravity, and the outer layers of the star are now pushed outward. The star then expands to about a hundred times bigger and becomes a red giant.

Once a medium size star (such as our Sun) has reached the red giant phase, its outer layers continue to expand. The core contracts inward and the helium atoms fuse together to form carbon, releasing energy.

The atomic structure of carbon is too strong to be further compressed by the mass of the surrounding material. The star will now begin to shed its outer layers as a diffuse cloud called a planetary nebula. Eventually, only about 20% of the star's initial mass remains and the star spends the rest of its days cooling and shrinking until it is only a few thousand miles in diameter. The star has now become a white dwarf. White dwarfs are stable because the electrons in the core of the star repulsing each other balance the inward pull of gravity. With no fuel left to burn, the hot star radiates its remaining heat into the coldness of space for many billions of years. In the end, it will just sit in space as a cold dark mass sometimes referred to as a black dwarf.

The life cycle of stars, which are 10 or more times as massive as our Sun, is different. After the outer layers of the star have swollen into a red supergiant, the core begins to yield to gravity and starts to shrink. As it shrinks, the star grows hotter and denser, and a new series of nuclear reactions begin to occur, temporarily halting the collapse of the core. When the core becomes essentially just iron, it has nothing left to fuse (because of iron's nuclear structure, it does not permit its atoms to fuse into heavier elements) and fusion stops. In less than a second, the star begins the final phase of its gravitational collapse, with the core temperature rising over 100 billion degrees as the iron atoms are crushed together. The repulsive force between the nuclei overcomes the force of gravity, and the core recoils out from the heart of the star in an explosive shock wave. As the shock encounters material in the star's outer layers, the material is heated, fusing to form new elements and radioactive isotopes. In one of the most spectacular events in the Universe, the shock propels the material away from the star in a tremendous explosion called a *supernova*.

The intense pressure inside the supergiant causes the electrons to combine with the protons, forming neutrons. Thus, most of the material in the core is converted to neutrons (with some free electrons and protons) and a neutron star is formed. However, if the original star was very massive (say 20-25 times more massive than our Sun), even the neutrons will not be able to survive the core collapse and a black hole will form.

Neutron stars

Neutron stars are typically about 10 miles in diameter, have about 1.4 times the mass of our Sun, and spin very rapidly. Due to its small size and high density, a neutron star possesses a surface gravitational field about 300,000 times that of Earth.

Neutron stars also have very intense magnetic fields - about 1,000,000,000,000 times stronger than Earth's. Neutron stars may "pulse" due to electrons accelerated near the magnetic poles, which are not aligned with the rotation axis of the star. These electrons travel outward from the neutron star, until they reach the point at which they would be forced to travel faster than the speed of light in order to still co-rotate with the star. At this radius, the electrons must stop, and they release some of their kinetic energy in the form of X-rays and gamma rays. The pulses come at the same rate as the rotation of the neutron star, and thus, appear periodic. Neutron stars emitting such pulses are called pulsars.

Pulsars

In 1967, Jocelyn Bell was doing graduate research in radio astronomy at Cambridge University under the supervision of Anthony Hewish. She was studying scintillation from distant galaxies and noticed an odd radio signal with a rapid and precise pulse rate of one burst every 1.33 seconds. For a short time, scientists thought that they might be coming from an extra-terrestrial civilisation. In fact, the source of these pulses was initially referred to as Little Green Man. Over the next few months, several more pulsating radio sources were found and they were named as "pulsars", because the emission was pulsed. The pulsar discovered by Bell and Hewish is now called PSR B1919+21: PSR stands for Pulsating Source of Radio and B1919+21 indicates the position of the pulsar in the sky. Even though the pulsars were first discovered as radio sources, they have now been observed using optical, X-ray and gamma-ray telescopes. Although the astronomers were convinced that they were observing a natural phenomenon, they could not come up with a plausible hypothesis why the pulses could be so regular and rapid.

The solution to this puzzle came from the work of the Italian astronomer Franco Pacini and the Austrian-born British astronomer Thomas Gold. Their work led to the idea that a pulsar is a rapidly spinning neutron star, and soon gained support from the discovery of a pulsar at the center of the Crab Nebula.

The pulses from a spinning neutron star are produced by its magnetic field. Collapsed to such a small radius, the star's magnetic field is squeezed into a far smaller volume, amplifying the field strength to about 1 trillion times that of the Earth's magnetic field (conservation of angular momentum). A neutron star is thus an extremely powerful magnet.

When a magnetic field moves, it creates an electric field. The rapid spin of a neutron star and its intense magnetic field generates powerful electric fields, which rip positively and negatively charged particles off the star's surface and accelerate them to nearly the speed of light. The electrically charged particles are channeled by the pulsar's intense magnetic field to travel along the magnetic field lines. The magnetic field of a spinning pulsar generates two narrow beams of charged particles flowing outward at the magnetic poles. As the charged particles move along the pulsar's magnetic field, they generate radio waves along their direction of motion. This radiation is beamed because the charges are traveling along the field lines that emerge from the star's surface at each magnetic pole. Because of this beaming, we see only neutron stars that have a magnetic pole pointed towards Earth as they rotate. Pulsars radiating in other directions are invisible to us.

What makes a pulsar spin so fast? When a massive star collapses to a tiny radius, the conservation of angular momentum requires it to spin faster. This is the same effect that allows ice skaters to spin rapidly by pulling their arms and legs close to their axis of rotation.

As a pulsar spins, it drags its magnetic field through the particles that boil off its surface into the surrounding space. This drag slows down the pulsar. Astronomers measure this spindown of a pulsar by precisely timing the interval between the pulses. Such measurements indicate that the time interval – the period of spinning pulsar – gradually lengthens. The slowing rotation also reduces the energy of the radiation that the pulsar emits. Thus, young rapidly spinning pulsars emit electromagnetic waves from visible light to radio waves, whereas old, slowly spinning ones generate only radio waves.

<u>Dispersion and dispersion measure</u>

Pulsars are located far away from us and hence, their radio waves must travel through many light years of space to get to us and our telescopes. That space, however, is not truly empty, although we tend to think of it that way. The space between stars -- also known as the interstellar medium (ISM) contains a lot of electrons. When radio waves, such as those from a pulsar, encounter these electrons, the two interact. This interaction causes the radio waves to be delayed. If all the radio waves were delayed by the exact same amount, that would not be a big deal. However, low-frequency waves are delayed *more* than the high-frequency waves as in the figure.

So all the frequencies of pulsar's emission leave the pulsar itself *at the same time*, but they arrive on Earth at *different times*: the lower a wave's frequency, the more its arrival on Earth is delayed. Because of this effect, the pulses we receive are "smeared" over a period of time instead of being straight lines. That is, instead of getting signal from the pulsar all at once (which would result in a straight vertical line), we get signal from the higher frequencies first, and as time goes on, we get signal from the lower frequencies.

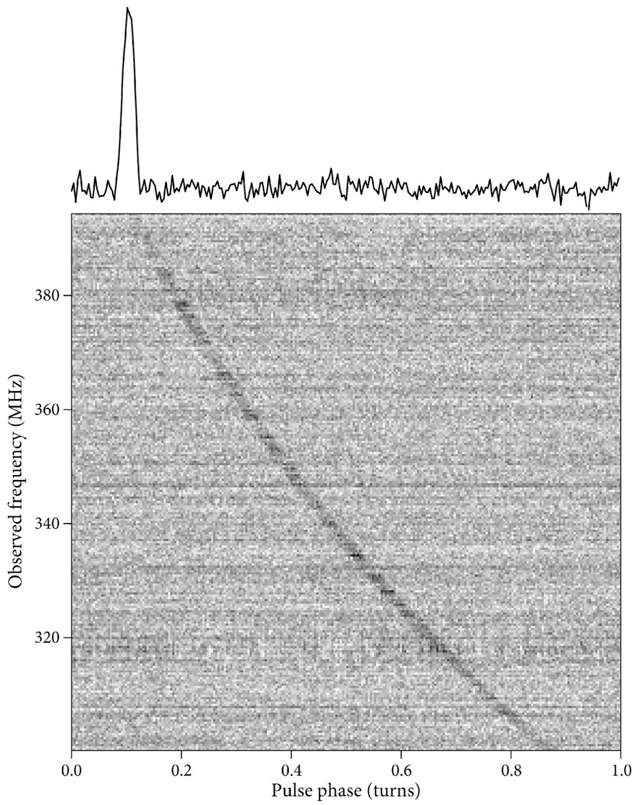

Figure 3: Dispersed signal through the ISM

This smearing makes it more difficult to detect the pulses. But, if we know *how smeared* a pulse is, we can correct it and detect the pulse. Dispersion measure tells us how much correction we need to do to line the pulses back up. The higher the DM, the more the pulse was smeared. The more the pulse was smeared, the greater the signal path through the free electrons. So, DM can be thought of as a measurement of distance -- the higher the DM, the farther the pulse traveled -- but that's a rough estimate, because some parts of the galaxy have more electrons than others. If radio waves are coming from the same object in space, we expect them to have gone through the same parts of space, meaning that they would have interacted with the same number of electrons. For this reason, if a signal comes from a pulsar, we expect it to have a distinct DM.

What is a reasonable DM: The maximum dispersion measure depends on where the candidate is in the sky. The galaxy is shaped like a disk and we are about 2/3 from the center of the disk. The DM depends on how much "stuff" is between the pulsar and us. If the pulsar is in the plane of the disk, we have to look through a lot of stuff to see it and so, the DM can be very high. If the pulsar is outside the plane of the galaxy (like above the disk), then we don't look through a lot of stuff to see the pulsar and therefore, the maximum DM is much lower. Hence, the maximum dispersion measure depends on where you are looking. To determine what the maximum DM is for your plot, go to the front page of the PSC website and scroll down to where it says **"Check the Distance to your Candidate."** Enter the RA, Dec, and DM of your plot. The last sentence will tell you what is a reasonable dispersion measure for any given RA and Dec. Since the DM value differs for every RA and Dec, one has to check for each pointing.

Locating objects in the sky

The system used by the astronomers to share information on the location of a source in the sky is by using the celestial coordinate system. The celestial sphere is an imaginary sphere of gigantic radius with the earth located at its center. The poles of the celestial sphere are aligned with the poles of the Earth: *North Celestial Pole (NCP) and the South Celestial Pole (SCP)*. The *Celestial Equator* lies along the celestial sphere in the same plane that includes the Earth's equator. An astronomer can only see half the sky at a time, that is, only half the sky is above the horizon at any time. The *horizon* changes depending on your position on earth. The point on the celestial sphere directly overhead is called the *Zenith* and the point directly below you is called the *Nadir*. The line that extends from the north point on the horizon upwards through the zenith and then downward to the south point on the horizon is known as the *Meridian*.

Azimuth and Altitude: Azimuth is the angle around the horizontal from due north and running clockwise. It corresponds to the compass directions with 0 degrees representing due North, 90 degrees due East, 180 degrees due South, and 270 due West. Altitude is the height of the object, in degrees above the horizon. Altitude can range from 0 degrees (on the horizon) to 90 degrees (directly overhead). A good approximation of these to use at night is your hand at arm's length. Your whole hand (thumb through pinky) is about 10 degrees and each finger is about 2 degrees.

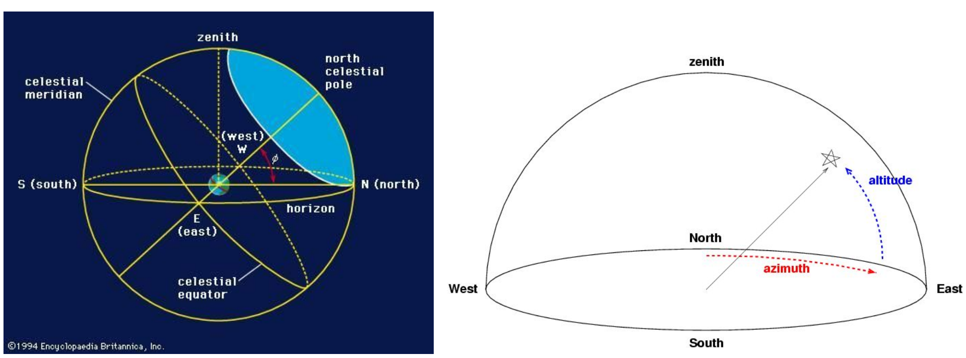

Figure 4: Celestial Coordinate System

In the same way that we use Longitude and Latitude to find a point on the surface of the earth, we use the Celestial Coordinates, *Right Ascension (RA)* and *Declination (DEC),* to find objects on the celestial sphere. The longitude lines on a celestial sphere are called Right Ascension and are measured in an easterly direction, in hours, minutes, and seconds. A full rotation corresponds to 24 hours, roughly the time it takes for the sphere to rotate once around. Each hour of right ascension is about 15 degrees on the celestial sphere (that is, 1/24 of a circle, or 15°). The Right Ascension of 0 hours occurs on the Vernal Equinox (first day of spring – equal day and night – 12 hours each). The benefit of this numbering system is that as the Earth rotates, you see the sky turn by about 1 hour of right ascension for each hour of time. This makes it easy to figure out when celestial objects will come in and out of view. Declination corresponds to latitude and is measured in degrees above or below the celestial equator. The celestial equator is at 0° declination. An object above the celestial equator has a positive declination whereas an object below the celestial equator has a negative declination. Since this coordinate system is relative to fixed objects in the celestial sphere, the Right Ascension and Declination do not change.

Arcminutes and Arcseconds: Since ancient Babylonia, people have divided both degrees and hours into finer units by means of base-60 arithmetic. In 1° there are 60 arcminutes, written 60'. One arcminute contains 60 arcseconds, written 60". A good telescope in good sky conditions can resolve details about as fine as 1" on the surface of the celestial sphere. By comparison, 1" of latitude on Earth is about 101 feet. Hours of right ascension are divided into minutes and seconds of *time,* not of arc. One hour of RA is 60 minutes and one minute of RA is 60 seconds.

How are pulsars observed with radio telescopes?

The sensitivity of pulsar observations can benefit from the *availability of a large collecting area*. Due to the compact nature of the source of radiation (typically a few hundred kilometers across), single dish observations are enough for pulsar work. Since pulsars are relatively weaker sources (typical average flux densities < 100 mJy), large collecting areas are very useful. Pulsar observations can be carried out in two different ways: (1) incoherent phased array observations and (2) coherent phased array observations. In the incoherent phased array mode, the signal from each antenna is put through a detector and the output from these is added to obtain the net signal. In the coherent phased array mode, the voltage signal from each antenna is added and the summed output is put through a detector to obtain the final power signal. The coherent phased array mode is ideally suited for observations of known pulsars while the incoherent phased array mode is most useful for large-scale pulsar search observations, where the aim is to cover a maximum area of the sky in a given time, at a given level of sensitivity.

The pulsar observations also benefit from *large bandwidths of observation*, although one cannot combine the data from across a large bandwidth in a single detector. This is mainly because of the smearing of the pulses produced by differential dispersion delay of frequencies across the band, due to propagation of the pulsar signal through the interstellar medium. In the simplest technique for reducing the effect of dispersion delay smearing, the pulsar signal is processed in a multichannel receiver where the observing band is broken up into narrower frequency channels. The signal in each channel is detected and acquired separately.

The pulsar signals are intrinsically periodic signals, with pulse periods ranging from a few seconds for the slowest pulsars to about a millisecond for the fastest pulsars known. The pulsar is actually "off" most of the time and the pulse is "on" for only a small fraction of the pulse period. This means that the pulses have a very small duty cycle (the ratio of pulse width to the period of repetition of the pulse or in other words, the fraction of the pulse period in which the pulse is actually on), with typical pulse widths of the order of 5 – 10% of the period. Sometimes, there may also be a small pulse somewhere in the middle of the cycle, which is called an interpulse. Less than 1% of the pulsars have an interpulse. Study of such pulsar signals requires the final data to have time resolutions ranging from ~milliseconds to ~microseconds and *require very fast sampling times for the data*. This leads to a substantial increase in the speed and complexity of the back-end designed for pulsar. The value of the sampling interval also should be known accurately to preserve the pulse phase coherence over a long stretch of pulsar data spanning many periods.

The other property of the time variation of pulsar signals is that the rotation rate of pulsars is very accurate. This means that if the time of arrival of the Nth and (N+1)th pulses is known, the arrival time for the (N+M)th pulse can be predicted very accurately. Slow variations of the pulsar period can be studied if the absolute time of arrival of the pulses can be measured sufficiently accurately, which requires the *availability of a very precise clock at the observatory* such as that provided by a GPS receiver.

The intensity of individual pulses varies randomly over various time scales. On the shortest time scale, pulse-to-pulse intensity fluctuations are thought to be due to intrinsic processes in the pulsar magnetosphere. The propagation processes in the ionized plasma of the interstellar medium (ISM) produces longer time scale fluctuations in the mean pulsar flux. Some of these intensity fluctuations can be uncorrelated over large frequency intervals. Thus, for estimating the pulsar flux (including estimates of the spectral index) and studying the variations in the pulsar flux (to understand the ISM properties), *pulsar observations need to be calibrated with known sources of power*. Using either calibrated noise sources that can be switched into the signal path or by known calibration sources in the sky can do this.

Explanation of different parts of pulsar search plots/Pulsar certification tips and tricks

Use a 20 Meter radio telescope at Green Bank to investigate objects

Pulsar P-Pdot diagram and ATNF catalog

Single pulse search plots

Reduced chi-squared value:

The quantity called **"reduced chi-squared"** is a measurement of how well your data fit a particular model. If the data and the model are exactly the same, reduced chi-squared will be exactly 1. The more the data deviate from the model, the larger the reduced chi-squared gets. In the case of the pulsar prepfold plots, the model that is used is random noise and we do not want to find random noise! We want to find pulsars. So, for us, **a large reduced chi-squared is good** because it means that our data do not look like noise. The closer reduced chi-squared is to 1, the more likely that the signal is a noise, and the less likely it is to be a pulsar.

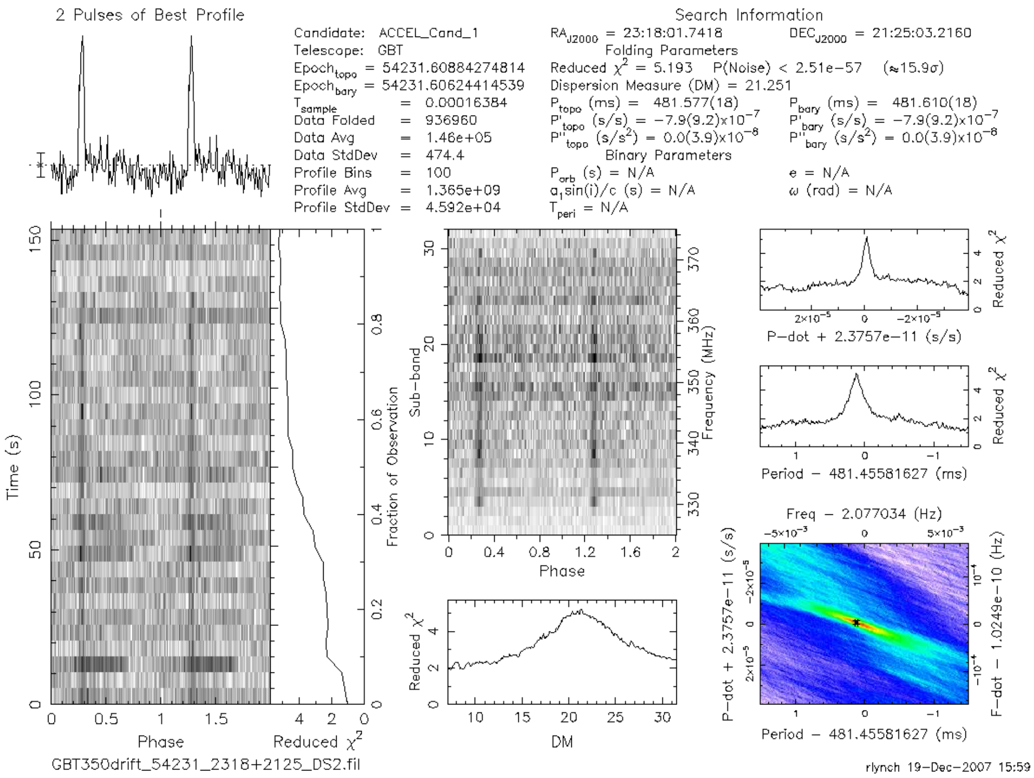

Figure 5: Prepfold plot of a pulsar.

In figure 5, the subplot next to the time domain subplot shows “reduced chi-squared” plotted against “fraction of observation.” As you go from left to right along the “fraction of observation” axis, you are looking at more and more of the data (remember, from above, that the observations have been “folded,” or added together at the guessed period). The more data that have been added together, the more you would expect the signal to look like a pulsar, if it does, in fact, contain a pulsar. So if your plot is showing a pulsar, you would expect reduced chi-squared to get higher and higher as you look at more and more of the data (or go from left to right along the “fraction of observation” axis), because it looks less and less like the model: noise.

If your plot does not contain a pulsar signal, you would expect reduced chi-squared to stay close to one, because folding more and more data does not make a signal pop out, and the data resembles noise, resulting in a reduced chi-squared close to 1.

References: