Krittika Summer Projects 2023

Exploring the Radio Sky

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Part One

1. The Basics

1.1 Why Radio Astronomy

- The sky at radio wavelengths is very different from the sky at visible wavelengths. Objects bright at visible wavelengths, such as stars, are not what dominate the emission in the radio sky.
- Using radio waves, we can detect the thermal continuum and spectral-line emission from objects too cold to produce visible light, permitting studies of the cold interstellar medium of our Galaxy and others, as well as the cosmic microwave background, the relic radiation from the early universe.

Figure 1.1: NGC1004 as observed by the WISE telescope in micrometer wavelengths

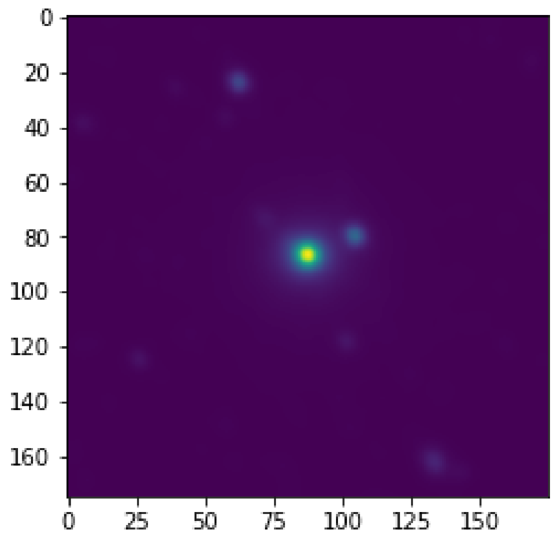
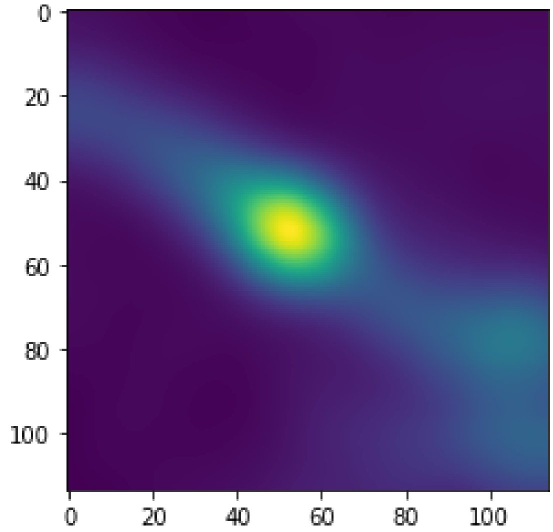


Figure 1.2: NGC1004 as observed by the NVSS survey in GHZ frequency



1.2 A Brief History of Radio Astronomy

For a long time we could not do radio astronomy due to the extremely weak nature of the astronomical radio waves reaching us. Radio astronomy was able to begin once we were able to aplify radio signals entering the antenna.
After this, radio astronomy made big leaps during the war due to the need of similar technology involved in radars
Over all this time, many astronomical radio sources were discovered like the galaxy centre, supernovae, sunspots, lightning and meteor showers.
The realization of a major avenue for study of large pieces of the universe using radio observations was initiated in 1944 when Jan Oort suggested to Hendrik van de Hulst that he calculate the wavelength of the emission line of hydrogen due to the spin flip of the electron. The calculations by van de Hulst predicted that this transition should emit radiation at 21 cm wavelength.
The first step in development of high resolution radio astronomy was taken when Sir Martin Ryle and D. D. Vonberg made the first astronomical observation using a pair of radio antennas as an interferometer.
Radio astronomy yielded discoveries of quasars, pulsars, and the cosmic microwave background, and continued advancing with the use of radio interferometers.
Nowadays, radio astronomy has reached the same level of operation as visible wavelength astronomy

1.3 Structure of a Traditional Radio Telescope

Radio Astronomy is very different from Visible Wavelength astronomy in a few ways:

- The Sun does not light up the whole sky at radio wavelengths
- At radio wavelengths, there is no scattering by the atmosphere
- At long radio wavelengths, observations can occur even with a cloud-covered sky

The Telescope design takes into account these unique situations

A Radio Telescope has 3 main parts

1.3.1 The Reflector

Most Radio Telescopes have a parabolic reflector, also known as the dish to collect and focus the radio light. As Radio waves are much easier to reflect than to refract, radio telescopes are not made using a refractor model
The radiation that reflects off the reflector can be collected at the focus, or be reflected again at the focus and collected behind the dish.
Some important aspects of the reflector are:

- The collecting area, which affects the sensitivity .
- The deviations in the surface of the reflector. The deviations must be much smaller than the wavelength of the light being collected
- The size of the reflector, which affects the resolution due to diffraction.

1.3.2 The Mount

This is the physical structure which holds and moves the dish with the help of motors. For the telescope to be able to point in any direction, the mount must have 2 degrees of freedom.
There are 2 types of mounts

1. Alt-Az mount
2. Equatorial mount

1.3.3 The Feed, Receiver and Computer

The dish focuses light from the sky to specially designed antennae called feeds. These antennae convert the EM radiation in free space to currents in a wire.
Each feed is connected to a receiver, which has 2 parts.

1. The front end, connected as close to the feed as possible, provides amplification and frequency conversion. The signal can then be sent a significant distance away using a coaxial cable.
2. The back end receives the signal from the cable. It contains a detector which measures the amount of power and converts it to a radio signal, which is then stored in a computer for future analysis.

A feed-receiver assembly is called a detector and is equivalent to a pixel in visible wavelength astronomy. Usually the number of detectors in a telescope is quite small. This is again in contrast to visible wavelength astronomy, where a single observation can give millions of pixels.

1.4 Exercise: Plotting the Jet Afterglow of the GW170817 event

GW170817 was a merger of two neutron stars, accompanied by gravitational and electromagnetic waves. For this activity, I considered the radiation to be having a non thermal emission, following the spectral index:

$$F_\nu = \nu^{-0.584}$$

at all frequencies. The lightcurve, which is the flux density (F_ν) as a function of time was calculated by me using two different sets of measurements.

Figure 1.3: 3GHz data points from the VLA telescope

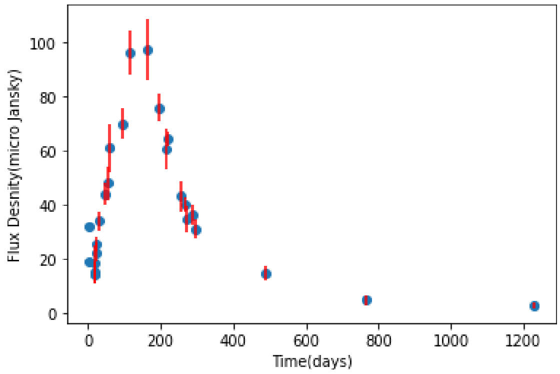
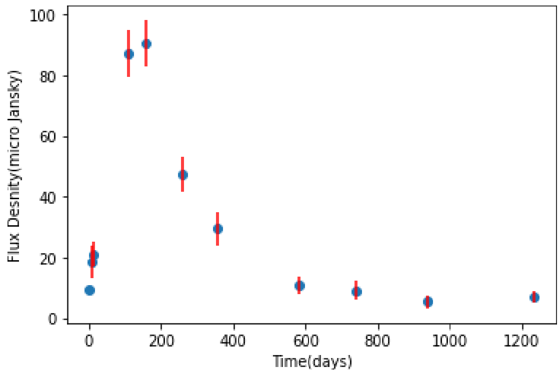


Figure 1.4: Data points from the Chandra telescope, normalized to 3GHz



2. Radiative Processes in Astronomy

2.1 Quantifying radiation

2.1.1 Total Energy

Not very useful. Not very easy to measure.

2.1.2 Luminosity

Same is power. Rate of emitting power. Not easy to measure as we do not receive all the power.

2.1.3 Flux

$$F = \frac{L}{4\pi d^2} = \frac{P}{A_{eff}}$$

Where P is the power measured by the telescope

2.1.4 Flux density (wrt bandwidth)

$$F_\nu = \frac{F}{\Delta\nu}$$
$$F_\lambda = \frac{F}{\Delta\lambda}$$

$$P = F_\nu A_{eff} \Delta\nu$$

2.1.5 Intensity

The most fundamental, independent of distance from source

$$I_\nu = \frac{F_\nu}{\Omega}$$

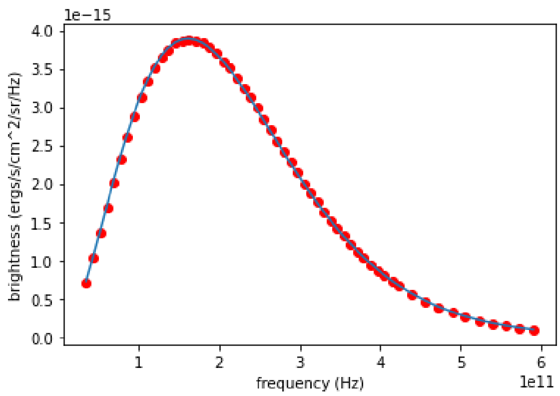
where Ω is the angular size of the source. Intensity is, in fact, the correct description of the quantity that your eye measures and your brain interprets.

2.2 Black Body Radiation

2.3 The Universe, an almost perfect black body

The Cosmic Microwave Background is a remnants of the big bang that allows us to probe the early stages of the universe. It is radiation that comes to us from every direction and is almost uniform.
Here, in Figure 2.1 I tried to fit a black body curve to this radiation and find the effective temperature.

Figure 2.1: Intensities of the CMB at different frequencies, fit to a black body curve at 2.74K

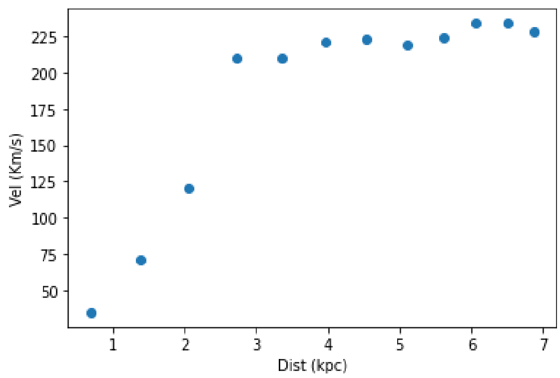


2.4 The 21cm line

2.4.1 Using the 21cm line to find the rotation curve of a galaxy

The 21cm line will be red-shifted when viewed from a frame in which the source has a radial component to its velocity.
Using this red-shift value, and the extremely thin nature of the 21cm line, we can calculate the speed of the source to a high accuracy.
I did the same in Figure 2.2

Figure 2.2: Rotation curve of a galaxy calculated using the 21cm line



3. Radio Telescopes

Unlike telescopes with deal with high frequency light, Radio Telescopes can not exploit the particle nature of light for their detectors, as the photons have insufficient energy to produce any effect on a semiconductor device. Instead, they detect radiation using large ensembles of photons and make use of the wave nature of light.

3.1 Reflectors

The dishes of most radio telescopes are parabolic reflectors. The parabolic shape causes all waves approaching the dish from the direction perpendicular to the entrance plane to come to a single point, known as the focus of the telescope.
If the waves are not exactly perpendicular, they still converge at a point, slightly offset from the focus (on the focal plane).
Having a receiver at this focus is usually inconvenient, so most telescopes have a secondary reflector which redirects the radiation to a point behind the primary reflector.
The primary reflector serves two important functions.

1. It collects and focuses the radiation from astronomical sources, making faint sources more detectable.
   The amount of radiation collected depends on the telescope's effective area (Aeff), which is closely related to the physical area of the primary reflector
2. It provides directivity, which is a telescope's ability to differentiate the emission from objects at different angular positions on the sky.

3.2 Beam Pattern

The beam pattern is a measure of the sensitivity of the telescope to incoming radio signals as a function of angle on the sky.

Because the sensitivity pattern is the same, whether the antenna receives or transmits—a principle known as the **reciprocity theorem** we are free to describe the pattern either way.
Ideally we would want the beam pattern to be extremely sharp, pointing only in 1 direction. But this is not possible due to diffraction.
Light coming from different parts of the sky interfere when they reach the receiver, and mix with each other. This pattern of constructive and destructive interference give rise to the beam pattern.
(i didnt include much of the maths)
For a telescope with a uniformly illuminated circular aperture, the total collected power is zero when the source is $1.22(\lambda/D)$ radians from the central axis.
As the off-axis angle increases further, the response goes through of peaks and valleys caused by partial constructive and destructive interference. These off-axis responses are called sidelobes and are undesirable as they can add confusion to observations.
The width of the central peak of the pattern is used to define the angular resolution of a single-dish telescope. By custom, we define this angular resolution as the full width at half maximum (FWHM) of the main beam of the telescope. This occurs (for a uniformly illuminated circular aperture) at $1.02(\lambda/D)$
Usually a small angular resolution is desirable, as it means that astronomical sources close together in angle on the sky can be distinguished

3.3 Feeds

Feeds are present at the centre of the dish and convert the EM waves into voltages. The feeds and receiver work well only for specific frequency ranges dictated by their design. Once again, Diffraction, determines the amount of power the feed collects and passes onto the receiver.
Ideally, we would like a feed-horn beam that had as close to uniform sensitivity out to the edge of the dish as possible, as this would yield a maximum response to the radiation from the source. However, we do not want the feed horn to detect contaminating back- ground radiation coming from beyond the edge of the dish
A quantity that describes how the feed horn's beam is distributed on the primary reflector is called the edge taper, which is defined as the ratio of the sensitivity at the center of the reflector to that at the edge.

3.4 Surface Errors

There are always manufacturing imperfections that limit its surface accuracy. We can characterize an imperfect reflector by the root mean square (rms) deviations, δ z
Such deviations will cause the path length to the focus to be slightly different for various parts of the reflector, and hence incomplete interference
The effect of surface errors on the collecting area is described by the Ruze equation, which is given by

$$A_\delta = A_0 e^{-(4\pi\delta z/\lambda)^2}$$

The rms error should be much smaller than the wevalength for the telescope to have a reasonable preformance

3.5 Noise and Temperature

All components in a radio telecope generate their own (unwanted) electrical signals. This interferes with our ability to observe radiation from an astronomical source.

3.5.1 Charachterising Noise

Nyquist in 1928, found that a resistor in the circuit will add electrical noise with a power per Hz that depends solely on the resistor's temperature. For this reason, the electronic power in a circuit, in general, can be described in terms of an equivalent temperature, T_{equiv} , which is equal to the temperature of a resistor that would produce the same amount of power as the resistor.
Following this convention, power is described using an equivalent temperature given by

$$T_{equiv} = \frac{P}{k\Delta\nu}$$

The equivalent temperature from the astronomical source is called the antenna temperature. The temperature due to noise from system components is called the noise temperature.

3.5.2 Gain

At each stage in a reciever, the signal is either amplified or reduced. We quantify this as the gain of that component. Each of these components also add some noise to the system.
An amplifier's noise temperature is defined by the equivalent temperature of the noise power as if it was introduced at the input to the amplifier, and hence it is amplified along with the astronomical signal.
So, if we have multiple amplifiers in succession, the net noise temperature is given by

$$T_N = T_{N1} + \frac{T_{N2}}{G_1} + \frac{T_{N3}}{G_1 G_2} \ldots.$$

This makes it very easy to compare the effects of different components on the noise.
Note that that first device the radiation enters into immediately after the feed, therefore, is the most critical in determining the total noise temperature. So this first amplifier should be a stateof-the-art device, and not a device that is mass-produced for commercial use.

3.5.3 Switched Measurements

For most sources, $T_A << T_N$, so even if we look at the blank sky, the power received is significant. Because of this, we cant make direct measurements of the sky.
We must make switched power measurements in which we measure the difference in voltage between when the telescope is aimed at the astronomical source (called an on-source observation) and when it is aimed at blank sky (called an off-source observation)
This removes the offset in measured power caused by noise, but it does not remove the fluctuations in noise. It is the fluctuations of the noise power that limits the ability to detect a weak astronomical source.

The variance in this noise(for low frequencies radiation like radio waves) is proportional to the number of photons per mode.

$$\sigma_P = \frac{P_N}{\sqrt{\Delta t \Delta \nu}}$$

3.6 Radio Frequency Interference

3.6.1 Sources

RFI is any radio signal, made by nature or by humans, that interferes with the radio waves we wish to detect. There are different sources of RFI at different frequencies. for example:

- GPS, WiFi at 0.8 - 2.5GHz
- satellites at 10-25GHz
- lightning at lower frequencies

3.6.2 Avoiding RFI

- locate the telescope as far away from human activity as is reasonably possible and to install filters to keep interfering signals out of the receiver path.
- divide the observed passband into many spectral channels, and remove the channels which have RFI