Krittika Summer Projects 2024

Radio Astronomy

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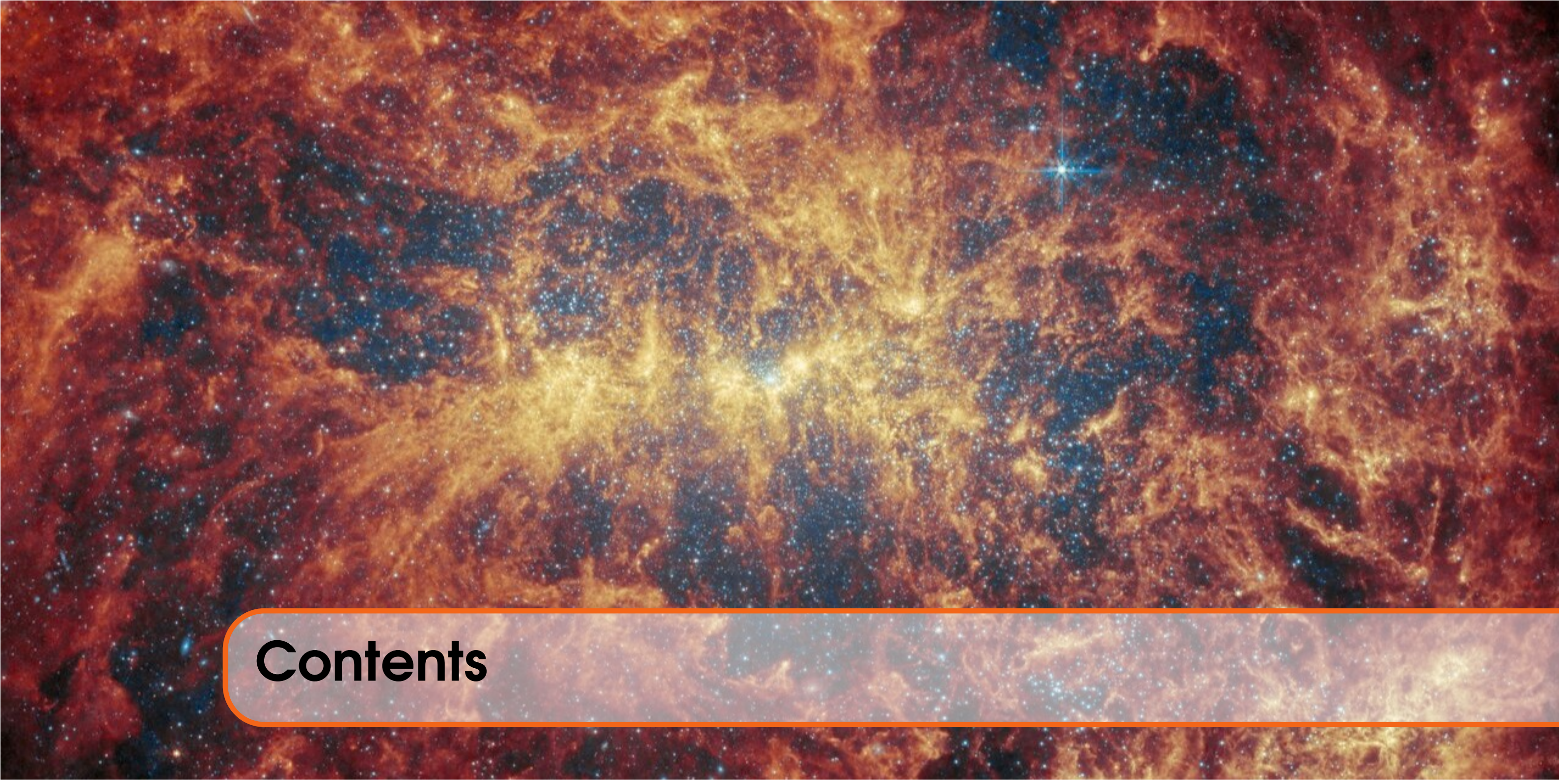
Abstract

Radio astronomy, with its unique ability to pierce through dust clouds due to the long wavelengths of radio waves, unveils a hidden universe invisible to optical telescopes. These waves can travel enormous cosmological distances, offering insights into the universe's earliest epochs like the cosmic dawn and re-ionization era. This project will explore the wonders of radio telescopes, some of the most remarkable feats of engineering. We will delve into the analysis of data from these world-class instruments, focusing on pulsars and neutron star mergers. Lastly, we will learn about the Pulsar Timing Array, used in the detection of gravitational wave background.



Contents

Part One

1. Foundations of Radio Astronomy

Week 1 included Introduction to Radio Astronomy, FITS imaging, curve fitting. Reading Assignment was to complete the first chapter of the textbook. The tasks given included plotting FITS images of different galaxies, some theoretical questions and plotting the Jet Afterglow Light-curve of the GW170817.

1.1 Theory

1.1.1 Fundamentals of Radio Waves

Radio Waves are part of the electromagnetic spectrum like visible wavelength but at a much lower frequency than which our eyes can detect. Speed of light waves in vacuum is $c = 3 \times 10^8 ms^{-1}$. One peculiar behaviour of light is its dual nature. It acts as both a wave and a particle. The smallest unit of light is a **photon**. A **Photon** has no mass but it still has energy.

Few important equations and constants to keep in mind with light waves:

$$\lambda \nu = c \quad \text{where } \lambda \text{ is the wavelength and } \nu \text{ is the frequency of light wave} \tag{1.1}$$

$$E = h\nu = \frac{hc}{\lambda} \quad \text{where } h \text{ is the Planck's Constant} \tag{1.2}$$

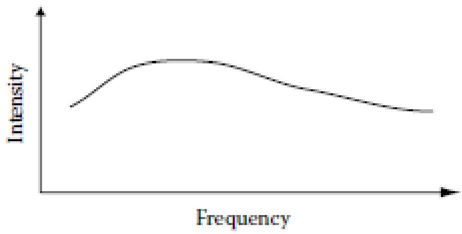
$$h = 6.626 \times 10^{-34} J \cdot Hz^{-1} \tag{1.3}$$

$$c = 3 \times 10^8 m \cdot s^{-1} \tag{1.4}$$

1.1.2 Types of Spectrum

Three types of Spectrum observed:

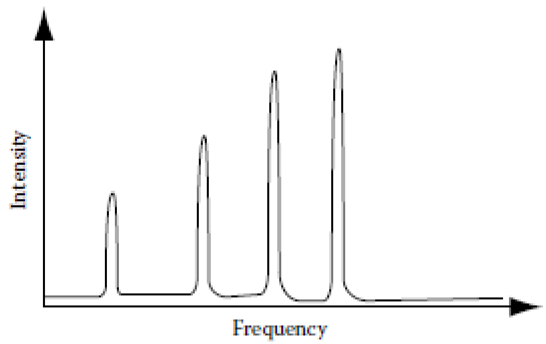
1. Continuous Spectrum: This is seen when a source emits all frequencies over a range without any breaks. The emitting object is called a continuum source.



Graphical representation of a continuous spectrum.

Figure 1.1: Continuous Spectrum(1, page 8)

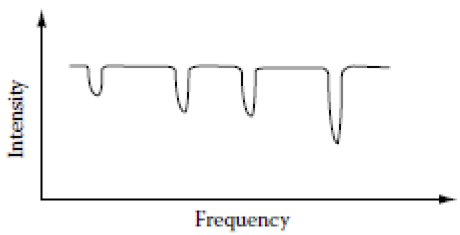
2. Bright Line or Emission Line Spectra: This is seen when a radiating object emits radiation only at some very specific frequencies, or wavelengths. The spectrum consists a set of discrete bright lines, called emission lines.



Graphical representation of an emission-line spectrum.

Figure 1.2: Emission Line Spectrum(1, page 9)

3. Dark Line or Absorption Line Spectra: This is seen when some discrete values of frequency is absorbed by some gas, hence removing those frequencies from the continuum. These dark lines are called absorption lines.



Graphical representation of an absorption-line spectrum.

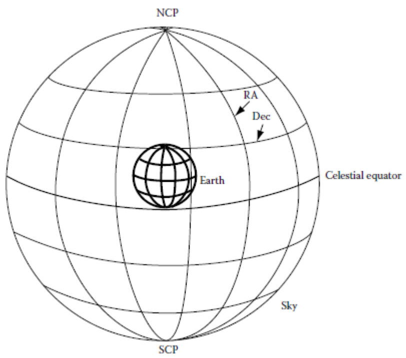
Figure 1.3: Absorption Line Spectrum(1, page 9)

1.1.3 Sky Coordinate System

Just like we have Latitudes and Longitudes to pinpoint locations on Earth, we have a coordinate system to map the sky. To get our sky coordinate system, we take the earth as the center and project the lines of latitudes and longitudes on to the sky.

The extensions of the lines of longitudes are called **Right Ascension(RA)**, often represented by α.

The extensions of the lines of latitudes are called **Declination(Dec)**, often represented by δ.



Celestial sphere, containing lines of RA and Dec, with Earth at the center.

Figure 1.4: Sky Coordinate System(1, page 11)

As the earth rotates, the coordinate system becomes a bit complex. Due to earths rotation we have to fix our RA lines relative to stars. Position of 0 degree longitude on noon of first day of spring is taken to be the time when $0°$ longitude coincides with $0°$ RA.

One thing to note is that while **Declination** has units of **degrees** just like latitudes and longitudes, **RA** has the units of **time** which makes many calculations easier. RA also increases to the left, which seems counter intuitive but isn't. Another thing to keep in mind is that $1s$ of RA $\neq 1s$ of arc.

$$1s \text{ of RA} = 15s \text{ of arc at the equator} \tag{1.5}$$

$$\text{Seconds of arc} = 15\cos\delta \times \text{seconds of RA} \quad \text{where } \delta \text{ is the Declination} \tag{1.6}$$

1.1.4 Observer Centered Terms

1. **Horizon**: Defines the limit of what part of the sky you can see at any point of time.
2. **Zenith**: Point in the sky that is directly overhead
3. **Altitude or Elevation**: Angular height of an object above the horizon at any given moment
4. **Azimuth**: Angular position perpendicular to the altitude. Defined as the angular position of an object along the horizon relative to due north
5. **Meridian**: It is the line of RA that runs through your zenith.
6. **Transit**: (verb) means to pass through the meridian. "When something transits?" means what is the best time to view an object.

7. **Hour Angle(HA)**: Amount of time since the object transited. + means transit completed, - means transit to occur.
8. **Local Sidereal Time(LST)**: Defined as RA of the meridian. Runs faster than normal time. Its measured with respect to rise and set of stars other than the sun.

$$HA = LST - RA \tag{1.7}$$

9. **Universal Time(UT)**: This refers to the solar time.

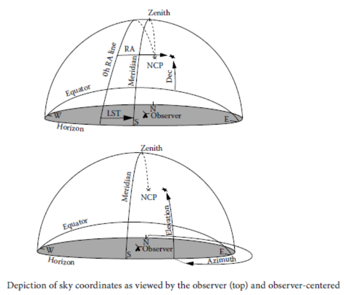


Figure 1.5: Observer Terms in Sky (1, page 16)

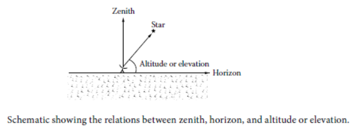


Figure 1.6: Zenith, Horizon and Altitude (1, page 13)

1.1.5 Apparent Size

We perceive the sizes of distant objects in terms of their **angular size**, which is related to objects linear size and distance. The unit to measure angle is **radian**. The ratio of arc length to the radius of the circle, give the angle in units of radians. A radian is dimensionless.

$$\theta = \frac{s}{r} \quad \text{where } s \text{ is the arc length and r is the radius} \tag{1.8}$$

For small angles, the angular size can be approximated using l.

$$\theta \approx \frac{l}{r} \quad \text{where l is the straight line distance between endpoints of the arc} \tag{1.9}$$

Angle is only a 1D measurement so for the objects in the sky we have another measurement called **Solid Angle** denoted by the symbol Ω.

$$\Omega = \pi \left(\frac{\theta}{2}\right)^2 = \left(\frac{\pi}{4}\right)\theta^2 \tag{1.10}$$

$$\Omega = \frac{A}{d^2} \quad \text{where A is cross sectional area, d is the distance to the object} \tag{1.11}$$

1.2 Task

1.2.1 Multi-Wavelength Astronomy

The purpose of this task was to compare the images from different telescopes to see how astrophysical objects differ in their emission at different wavelengths. All images were obtained from the CIRADA image cutout web service. `http://cutouts.cirada.ca/get_cutout/` The three galaxies I chose were

1. **HydraA**

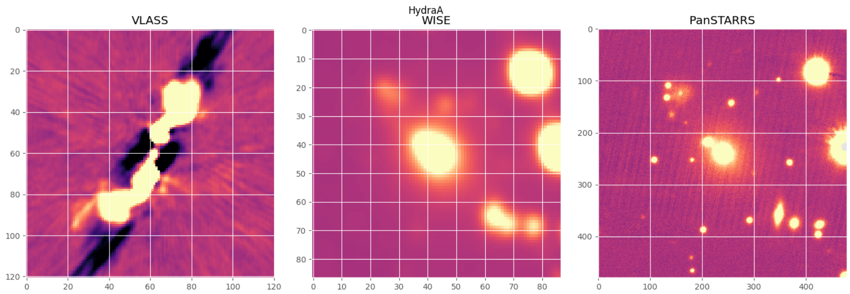


Figure 1.7: The **VLASS** image shows that there is elongated radio emission source in the image with **jet** like features. **WISE** image shows **infrared** emission, from star forming regions. The **PanSTARRS** optical observation shows numerous distinct point sources, galaxies and stars, with **HydraA** being one of the bright objects.

2. **NGC2484**

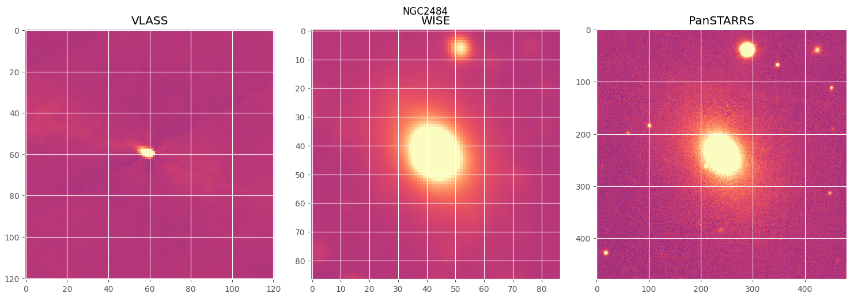


Figure 1.8: VLASS image shows a point, compact radio source in the center of the galaxy. WISE image shows a very bright infra red source in the center with a smaller bright spot, indicating significant emission. PanSTARRS image shows two prominent "lobe" structures and many small point sources of visible light.

3. **NGC6466**

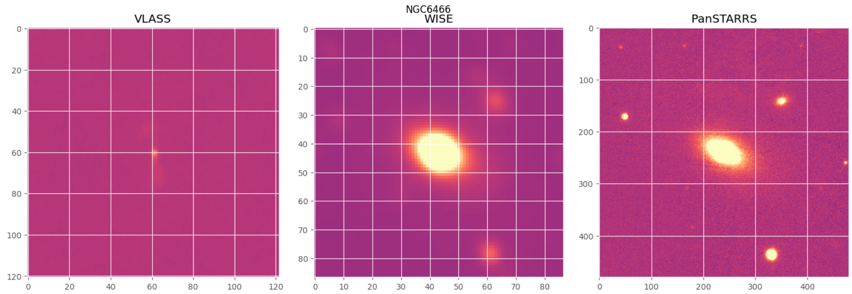


Figure 1.9: VLASS image shows a very faint radio source in the center of the image, indicating a very weak radio source. WISE image shows a prominent bright infra red source in the centre with 2-3 faint sources nearby. PanSTARRS image shows a prominent lobe in the centre and 3 smaller lobes and many faint point sources of visible light.

1.2.2 Plotting The Jet Afterglow Light-curve Of GW170817

GW170817 was a merger of two neutron stars that was accompanied by both gravitational waves and electromagnetic radiation. For this task, I used the data for the non-thermal emission from this source that spans across all frequency bands following a single spectral index of $F_\nu \propto \nu^{-0.584}$. The dataset in the ascii format is present at `http://www.tauceti.caltech.edu/kunal/gw170817/gw170817_afterglow_data_full.txt` which was compiled by Makhathini etal. 2021. (2).

Using the data, and the astropy and matplotlib, I plotted the lightcurve for all the VLA 3GHz data points.

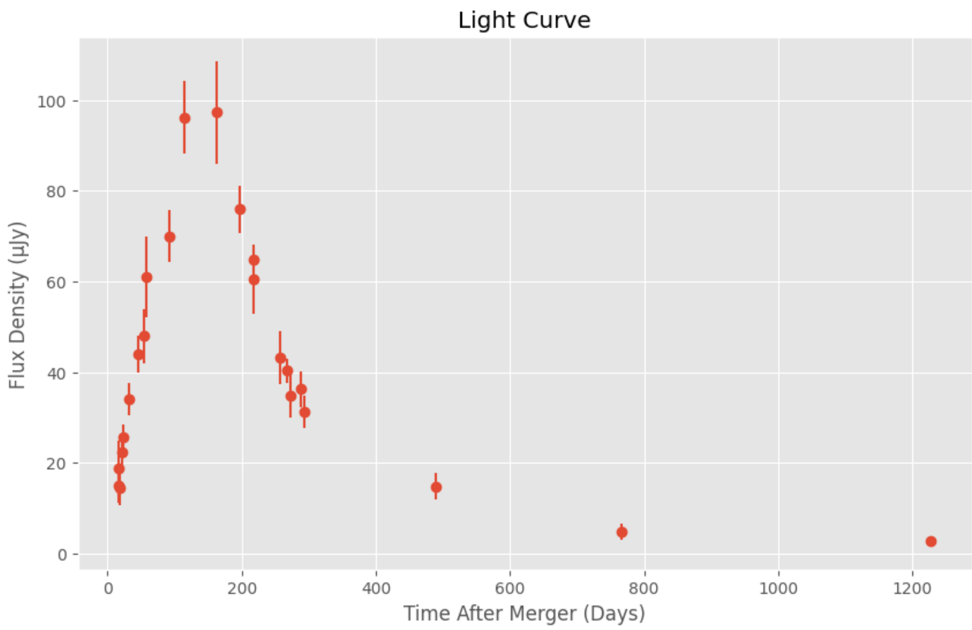


Figure 1.10: VLA 3GHz data points with error bars

Then I scaled the Chandra $2.41 \times 10^{17} Hz$ data points using the spectral index relation and plotted them over the VLA 3GHz data points.

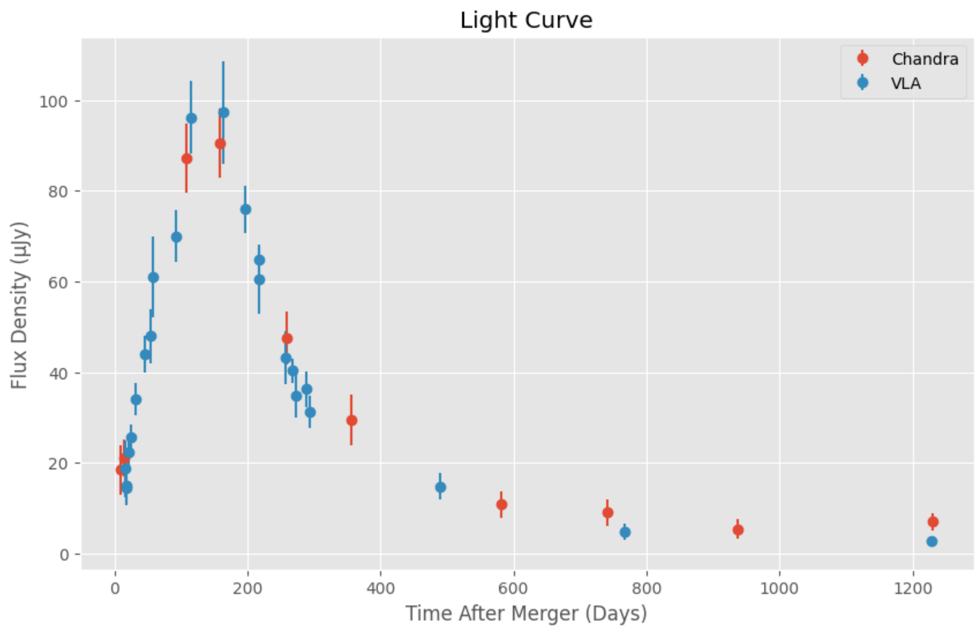


Figure 1.11: Chandra $2.41 \times 10^{17} Hz$ data points over VLA 3Ghz data points

2. Radiation Physics and Its Application

Having a brief introduction to radio astronomy and its importance, this week was an exploration into the different radiative processes. Reading assignment for this week was to read few sections of Chapter 2 of the textbook (1). This week covered the topics Blackbody radiation, planck function, Rayleigh Jeans Approximation and Brightness Temperature. The task included fitting a Planck Function to given data and using the Hydrogen 21 cm line to plot the galaxy rotation curve.

2.1 Theory

2.1.1 Measures of the Amount of Radiation

(1)

1. **Total Energy Emitted:** Light output of a source in terms of total energy emitted over a source's lifespan, at all frequencies, in all directions.
2. **Luminosity:** Rate at which Energy is emitted. SI units are Js^{-1} or watts $(1W = 1Js^{-1})$ and $erg \cdot s^{-1}$ in cgs.

$$L = \frac{\text{energy emitted}}{\text{time over which energy was emitted}} \tag{2.1}$$

3. **Flux:** Amount of Light energy per unit time per unit area. Units are $Js^{-1}m^{-2}$ or Wm^{-2} (SI) or $ergs \cdot s^{-1}cm^{-2}$ P is the power detected on our telescope.

$$P = L\frac{A_{eff}}{4\pi d^2} \tag{2.2}$$

The radiation flux, that is, the detected power divided by the area of the telescope (for an isotropic source), then, is related to the luminosity of the source by

$$F = \frac{L}{4\pi d^2} \tag{2.3}$$

Flux is a measure of the rate that energy crosses a unit cross sectional area at a given distance from the source..

4. **Flux Density:** Flux per unit frequency in the observed spectral region, and it equals the detected flux divided by the width in frequency of the observation.

$$S_\nu = F_\nu = \frac{F}{\Delta\nu} \tag{2.4}$$

$\Delta\nu$ is the bandwidth of detected EM waves. When working with visible wavelengths astronomers tend to measure flux density in terms of wavelength rather than frequency.

$$F_\lambda = \frac{F}{\Delta\lambda} \tag{2.5}$$

Relation between Flux and flux density,

$$F = \int F_\nu d\nu \tag{2.6}$$

The flux density is the characteristic of the source that we want to infer from these data. The amount of power a telescope collects from a source of given flux density is given by

$$P = F_\nu A_{eff} \Delta\nu \tag{2.7}$$

SI units: 1 jansky(Jy) $= 10^{-26} W m^{-2} Hz^{-1} = 10^{-23} ergs \cdot s^{-1} m^{-2} Hz^{-1}$

5. **Intensity**$(I_\nu$ **or** $I_\lambda)$ Intensity, specific Intensity or surface brightness, brightness is the Flux density per unit solid angle. It has units $WHz^{-1}m^{-2}sr^{-1}$ for I_ν or $Wnm^{-1}Hz^{-1}m^{-2}sr^{-1}$ for I_λ.

$$I_\nu = \frac{F_\nu}{\Omega} \tag{2.8}$$

Where,

$$F_\nu \approx \frac{L}{4\pi d^2 \Delta\nu} \tag{2.9}$$

Some important points:

1. Flux density, F_ν, does not distinguish between the directions that the photons come from or travel to, whereas I_ν does.
2. Intensity is independent of distance.
3. Intensity is direct measure of the objects surface brightness, that is, the amount of energy radiated per second per unit area of the surface per unit solid angle right at the surface.

2.1.2 Blackbody Radiation

A body that absorbs all light that hits it, reflecting nothing, and preventing transmission of light is called **opaque** and is considered **black**.

The radiation that is emitted by a body that **absorbs all light incident** on it is called **Blackbody radiation**.

Planck Function

The Planck function provides a mathematical description of the spectrum of the light emitted by black-bodies. In terms of the emitted flux per unit frequency interval per unit steradian, the Planck function is given by

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\left(\frac{h\nu}{kT}\right)} - 1} \tag{2.10}$$

Where

$h = 6.626 \times 10^{-34} J \cdot s$ is the Planck's Constant
$k = 1.38 \times 10^{-23} J \cdot K^{-1}$ is the Boltzmann Constant
c is the speed of light
ν is the frequency of observation
T is the temperature of radiating body in Kelvin

This intensity can also be represented as flux per unit wavelength per steradian, which is denoted as $B_\lambda(T)$.

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\left(\frac{hc}{\lambda kT}\right)} - 1} \tag{2.11}$$

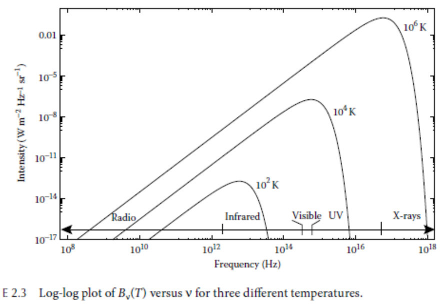


Figure 2.1: B_ν vs ν (1, page 43)

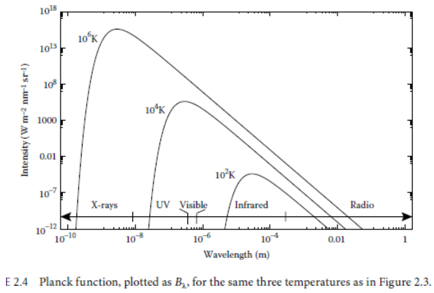


Figure 2.2: B_λ vs λ (1, page 44)

B_ν and B_λ represent the same concept they are not the same numerical quantity nor the same function.

Relation between the two is as follows:

$$B_\lambda = \frac{c}{\lambda^2} B_\nu \tag{2.12}$$

Stefan Boltzmann Law

Total Flux of radiation emitted by a body can be obtained by integration of Planck Function over frequency and solid angle. This shows that the total Flux is proportional to the fourth power of the temperature of the body.

$$F = \sigma T^4 \tag{2.13}$$

This is known as **Stefan-Boltzmann Law** and the constant σ is known as the **Stefan-Boltzmann Constant**. $\sigma = 5.67 \times 10^{-8} W m^{-2} K^{-4}$

2.1.3 Rayleigh Jeans Approximation

Makes use of the fact that at radio wavelengths frequency is very small, and thus the Planck Function can be approximated to a much simpler equation. As frequency is so small, $\frac{h\nu}{kT} << 1$, So we use Taylor expansion of the exponential term and get the simplified equation.

$$\frac{1}{e^{\frac{h\nu}{kT}} - 1} \approx \frac{kT}{h\nu} \tag{2.14}$$

$$B_\nu(T) \approx \left(\frac{2k\nu^2}{c^2}\right) T = \frac{2kT}{\lambda^2} \tag{2.15}$$

2.1.4 Brightness Temperature

It is the property of radiation and not the emitting object. It is the direct measure of the radiation intensity, only equals the temperature of the radio source when its both thermal and opaque. We convert intensity to temperature terms as its easier to then compare.

$$T_B = \left(\frac{\lambda^2}{2k}\right) I_\nu \tag{2.16}$$

This equation is obtained by using Rayleigh Jeans Approximation.

2.2 Task

2.2.1 A Near- Perfect Black Body

I was tasked to fit a blackbody curve to the data obtained of the Cosmic Microwave Background(CMB) which is a blackbody, a relic of the Big Bang omnipresent in every direction. This task makes use of a very key feature of black body radiation. As temperature increases the value of $B_\nu(T)$ increases at every frequency, meaning any particular value of intensity only corresponds to only one given temperature. So even if we know the intensity of an opaque object at only a single frequency, and we know the object is a blackbody then we can find its temperature.

Using matplotlib and numpy libraries and the far infrared data adapted from the COBE satellite (3) of the CMB I plotted the brightness(Intensity as function of frequency.

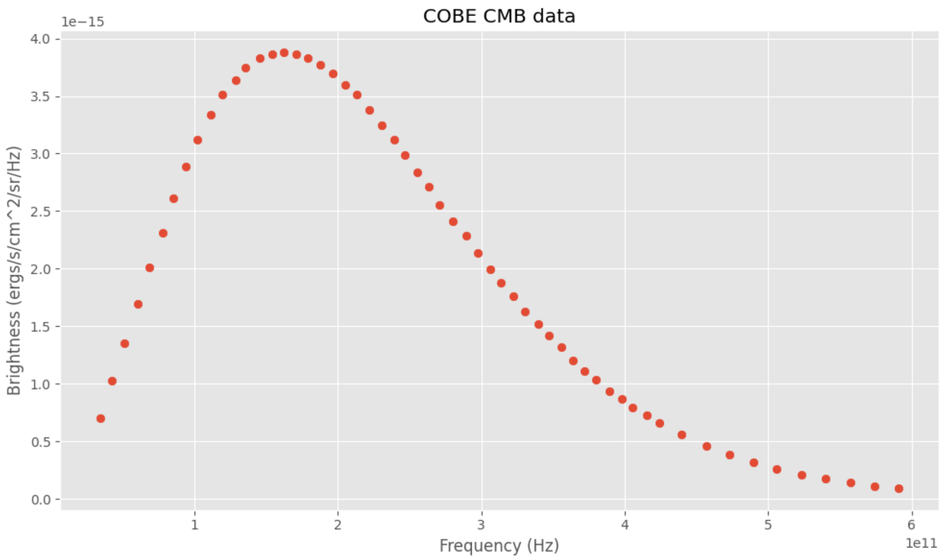


Figure 2.3: Brightness vs Frequency

then using the scipy library I fit a blackbody curve to the CMB, obtaining the temperature of the CMB in the process to be $T_{CMB} = 2.73915K$.

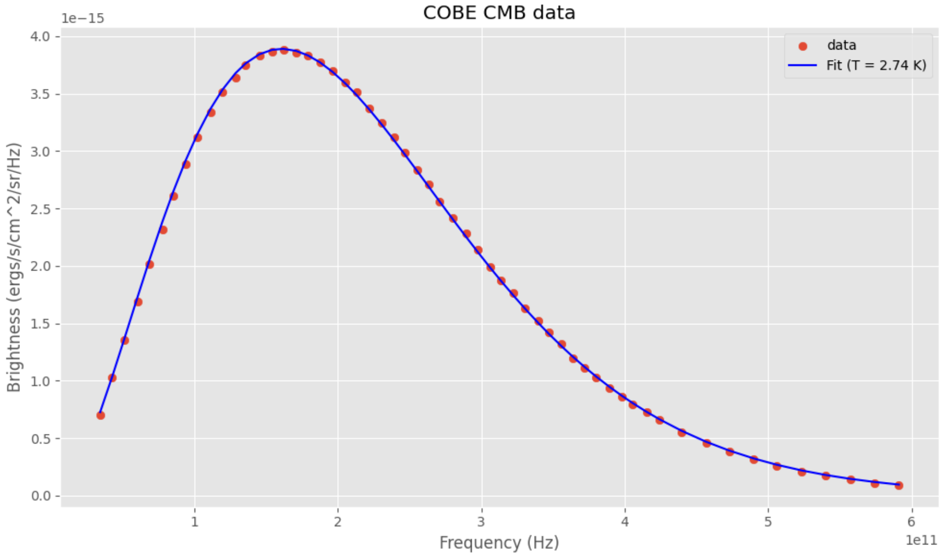


Figure 2.4: Brightness vs Frequency with fitted blackbody function(T = 2.74K)

2.2.2 Plotting the Galaxy Rotation Curve

In this task using the synthetic spectra available within galaxy21cm spectrum.tar.xz, which has each file labelled as spectrum d XX kpc.txt where XX denotes the distance from galactic center, I fitted for the Doppler Velocity of the 21cm line for each distance.

To do this I fitted a Gaussian to the spectral line and determined the central wavelength for each case.

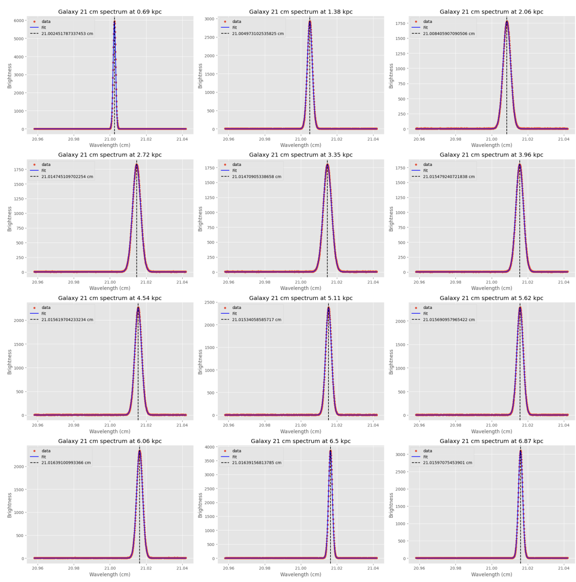


Figure 2.5: Gaussian fit for each distance

Then applying the Doppler formula, I obtained the velocity values for different distances and plotted those values against distance to get the galactic rotation curve.

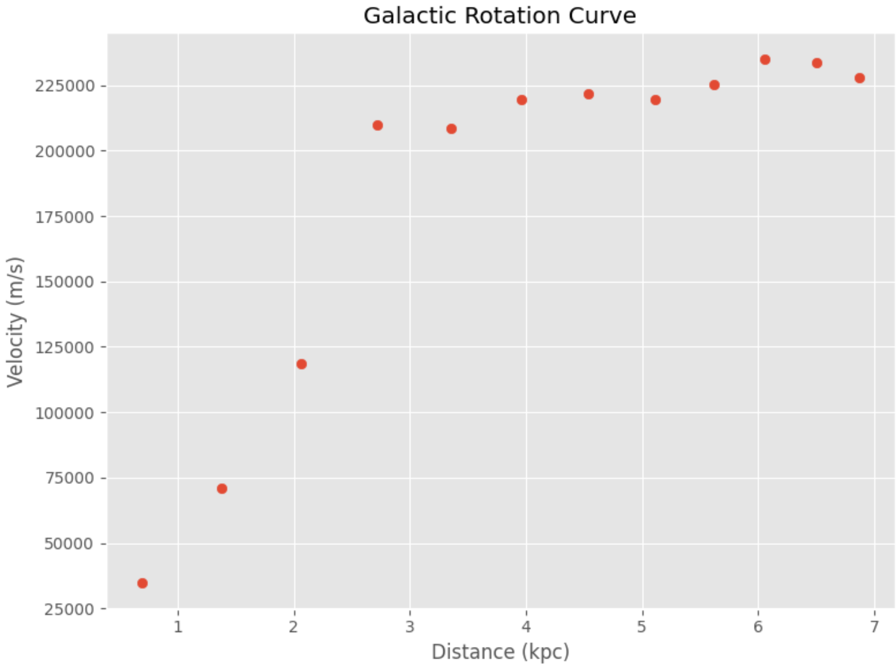


Figure 2.6: Galactic Rotation Curve

We can observe in the Rotation Curve, The velocities of objects (stars or gas) orbiting the center of the galaxy, rather than decreasing as a function of the distance from the galactic centers as had been expected, remain constant out to very large radii. This flattening of the rotation curve played a crucial role in the discovery of dark matter.

We know from the formula,

$$v^2 = \frac{GM}{R} \tag{2.17}$$

that velocity should decrease if distance increases but here that is not the case. To justify this, **Dark Matter** was introduced as a concept. The reasoning was that as the velocity flattens on increasing distance, the mass term in equation (2.17) must be larger than what we currently assume it to be so that it can counter the effects of increasing distance. Astronomers earlier worked under the assumption that only the visible matter had mass, which was a fairly sensible assumption. But to explain this flattening, it was assumed that there is more mass in a galaxy which we cannot see. Hence it was called "**Dark Matter**".

3. Radio Telescopes

This week was a purely theoretical week where I covered the 3.1 and 3.3 sections of Chapter 3 from the textbook(1). It covered topics including different parts of a radio telescope, noise, noise temperature, antenna temperature, etc.

3.1 Theory

Radio Telescopes comprise of the following parts:

- **Primary Reflector or dish**
- **Feed**
- **Transmission Lines**
- **Receiver**

And most of them are fully steerable, and can point to any direction in the sky.

At shorter wavelengths, we detect to **particle nature** of light, meaning the individual photons. This can be done because the **energy of the photon** at shorter wavelengths is *sufficient* to excite a valence electron to a conduction band or to produce electron hole pairs in a semiconductor.

Radio photons have *very low energies*, thus we make use of the **wave nature** of light to detect them.

3.1.1 Radio Telescope Reflectors, Antennas, and Feeds

Antenna - device that couples electromagnetic waves in free space to confined waves in a transmission line

Reflectors - Parabolic in shape, collect and concentrate the radiation.

Primary Reflectors

Parabolic in shape causes all waves approaching it from direction perpendicular to its entrance plane to converge at a point on the focal plane of the dish.

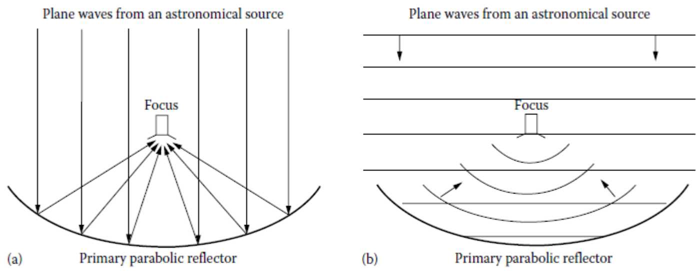


FIGURE 3.1 Two depictions demonstrating the focusing of light to a single point due to reflection of a parabolic surface. The left panel (a) shows rays of light coming from a distant astronomical source and converging to a single focus, while the right panel (b) depicts a wave-front representation, showing how a parabolic reflector converts plane waves from a distant astronomical source to spherical waves that converge at the focus.

Figure 3.1: Prime Focus Configuration (1, page 77)

At the focal plane are feed horns, which convert EM waves from free space into transmission lines, through which signal travels to receivers.

The figure above is Prime Focus Configuration of a telescope, in this the feed and receiver are in an awkward position, located high above the primary reflector and hence not accessible easily when the telescope is aimed at the sky.

Thus to avoid this another design is used called **Cassegrain Design**. It makes use of a secondary reflector before the focal plane of the primary reflector and redirects the converging waves to converge at another focal point at or behind the vertex of the primary reflector.

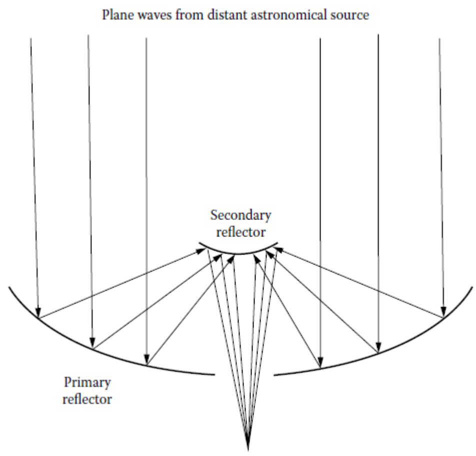


FIGURE 3.2 Optical layout of a Cassegrain radio telescope. Ray tracing illustrates how plane parallel light rays are brought to a common focus, in this case, at a point behind the primary reflector.

Figure 3.2: Cassegrain Design(1, page 78)

Beam Pattern
Measure of the sensitivity of the telescope to incoming radio signals as a function of angle on the sky. The term derives from the idea of a beam of radio waves leaving a transmitting antenna. As the sensitivity pattern is the same whether the antenna receives or transmits - **reciprocity theorem** - we can describe the pattern either way. (1)

Feeds
At the focus of a radio telescope we have antennas to couple to EM waves in free space into transmission lines. Each feed is connected to one receiver, each of which produces a single measure of detected power.

Feeds are usually Horn Antennas. Often Flared with the radiation entering the larger end and tapering down to the proper size for a type of transmission line called a *waveguide*.

FIGURE 3.9 Example of a circular feed horn used to couple the radio light to a transmission line. In this case, a waveguide, connected to the rear of the horn, serves as the transmission line.

Figure 3.3: Horn Antenna (1, page 86)

Flared end of the horn has a size at least as large as the wavelength of the light.

The opening size of the feeds restricts the number of feeds we can use thus limiting the positions at which we can measure power for each pointing of the telescope.

Surface Errors
The primary reflector is never a perfect parabola, manufacturing imperfections limit its surface accuracy. This deviation causes the path length to the focus to be slightly different for different parts, and as path difference causes phase differences, less than full constructive interference occurs, reducing the power collected by the telescope.

The **Ruze Equation** describes the effect of surface errors on the collecting area.

$$A_\delta = A_0 e^{-(4\pi\delta z/\lambda)^2} \tag{3.1}$$

where:

A_δ and A_0 are the collecting areas of a telescope with and without surface errors respectively.

δz is the RMS deviation of real surface to the ideal surface of a parabola measure parallel to the optical axis.

$\delta z/\lambda$ denotes the fraction of wave accuracy.

Surface errors less than 1/20th of the wavelength of the light being detected is required to have reasonable performance.

3.1.2 Noise, Noise Temperature, Antenna Temperature

Noise

All components in the receiver, especially amplifiers, generate their own electrical signals that propagate through the receiver and are unrelated to the signal from the astronomical source.(1, page 102) The power measured contains these extra signals, interfering with our ability to measure the power of the radiation.

These extra signals are undesirable but cannot be avoided. Hence called **"Noise"**. (1, page 103)

Antenna Temperature

Antenna temperature is used to describe the power received by a radio telescope from a source. It's a way of quantifying the amount of radiation picked up by an antenna in terms of temperature, making it easier to compare with thermal sources and their emission properties.

It is defined as the temperature at which a resistor with impedance equal to the antenna would emit the same amount of thermal noise power per unit bandwidth.

$$T_A = \frac{P}{k\Delta\nu} \quad \text{where } k \text{ is the Boltzmann constant, } \Delta\nu \text{ is the bandwidth} \tag{3.2}$$

Noise Temperature

Total Noise power is described by the noise temperature T_N.

Equivalent temperature of the final power output isn't simply the sum of the equivalent temperatures of all the sources in the path as there is a gain/loss in each process.

$$P = Gk\Delta\nu T_A$$

It is tricky to handle noise temperature as the noise generated later in the process has not undergone the gains and losses of the previous steps. So we take into account the gain of each step while measure the noise temperature.

If total gains is

$$G = G_1 G_2 G_3 .... \tag{3.3}$$

Then Noise Temperature is

$$T_N = T_{N1} + \frac{T_{N2}}{G1} + \frac{T_{N3}}{G_1 G_2} + \cdots \tag{3.4}$$

Total noise produced by all components in the receiver is called the **receiver noise temperature**, T_N.

3.1.3 Radio Frequency Interference(RFI)

A significant complication at frequencies below 300 MHz is radio frequency interference(RFI). RFI is any radio signal, made by nature or by humans, that interferes with the radio waves we wish to detect.(1, page 123).

This type of interference also occurs at higher frequencies.

Source	Frequency Range
Cell phone, GPS, WiFi	0.8-2.5 GHz
Radar Systems, Telephone Microwave Links	4-8 GHz
Geostationary Satellites	11-15 GHz

Table 3.1: RFI sources, data from textbook(1, page 123)

Above these frequencies the radio spectrum becomes cleaner with relatively low RFI.

The situation gets worse the lower we go in the frequency band. Lower the frequency one wishes to observe, more cluttered the radio environment becomes.

RFI is to low frequency radio astronomer as light is to visible light astronomers. (1, page 123)

There are many different ways to deal with RFI, one is to locate the telescopes as far away from human activity as possible. Another way is to make the observation channels smaller, so instead of one big channel of 20MHz, 2000 channels of 10KHz would help remove the few dozen channels that were affected by RFI, rather than discarding the one big channel due to RFI in limited regions.

Digital Filters, which can automatically detect RFI affected data and remove them are also used to deal with doppler shifted RFI coming from aircrafts or long duration pulses refleccted back from clouds. RFI identification and excision are active areas of research, and will continue to be so, as new forms of RFI continually present themselves.

Part Two

Bibliography

Books

(MSK20) Jonathan M Marr, Ronald L Snell, and Stanley E Kurtz. *Fundamentals of radio astronomy*. en. Series in Astronomy and Astrophysics. London, England: CRC Press, June 2020 (cited on pages 8–10, 15, 17, 23–27).

Articles

(Mak+21) S. Makhathini et al. "The Panchromatic Afterglow of GW170817: The Full Uniform Data Set, Modeling, Comparison with Previous Results, and Implications". In: ApJ 922.2, 154 (Dec. 2021), page 154. DOI: 10.3847/1538-4357/ac1ffc. arXiv: 2006.02382 [astro-ph.HE] (cited on page 12).

(Mat+90) J. C. Mather et al. "A Preliminary Measurement of the Cosmic Microwave Background Spectrum by the Cosmic Background Explorer (COBE) Satellite". In: ApJ 354 (May 1990), page L37. DOI: 10.1086/185717 (cited on page 19).

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