KRITTIKA SUMMER PROJECTS 2024

Radio Astronomy

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Abstract

This report presents an overview of the fundamental principles and methodologies in radio astronomy, as covered in the initial chapters of "Fundamentals of Radio Astronomy: Observational Methods". Chapter 1 introduces the basics of radio astronomy, focusing on the nature of radio waves, their interaction with the interstellar medium, and the electromagnetic spectrum. Chapter 2 delves into radiation physics, detailing the processes that generate radio emissions, including thermal and non-thermal mechanisms. This chapter also emphasizes the significance of spectral line observations, notably the 21 cm line, for probing hydrogen in the galaxy. Chapter 3.1 outlines the design and function of single-dish radio telescopes, exploring their key components, sensitivity, and resolution capabilities. It discusses the role of antenna systems and receivers in capturing and amplifying weak radio signals. Chapter 3.3 addresses the complexities of data collection and processing, highlighting techniques for reducing noise and improving signal clarity through calibration and signal integration methods. The report aims to elucidate the essential concepts and practical aspects of radio astronomy, laying the groundwork for advanced observational techniques and research applications.

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1. Theory

1.1 Introduction to Radio Astronomy and Radio Physics

(1) This report explores key concepts from "Fundamentals of Radio Astronomy: Observational Methods" by Marr, Snell, and Kurtz, focusing on chapters 1, 2, and sections 3.1 and 3.3.

- Chapter 1 introduces the development and impact of radio astronomy. It covers the discovery of cosmic radio waves and the evolution of radio telescopes, emphasizing their role in studying phenomena like the cosmic microwave background and pulsars.
- Chapter 2 delves into radiation physics, explaining electromagnetic radiation, blackbody radiation, and spectral lines. It discusses emission mechanisms such as synchrotron and thermal radiation, which are crucial for interpreting radio signals from astronomical sources.
- Sections 3.1 and 3.3 provide an in-depth look at radio telescopes and observational techniques. They explain the components and operation of radio telescopes, including antennas, receivers, and feed systems, and introduce key concepts like beamwidth, sensitivity, and resolution. These sections also cover single-dish radio telescope observations, detailing methodologies for mapping the sky, measuring radio sources, and calibrating observations. Practical aspects such as noise reduction and correction for atmospheric effects are discussed, highlighting the capabilities and limitations of single-dish observations.

1.2 Fundamentals of Radio Waves

Radio waves are a type of electromagnetic radiation with lower frequencies than visible light. They consist of oscillating electric and magnetic fields perpendicular to their direction of travel, moving at a constant speed c (approximately 3.00 $\times 10^8$m/s). Their wavelength λ and frequency v are related by $\lambda v = c$.

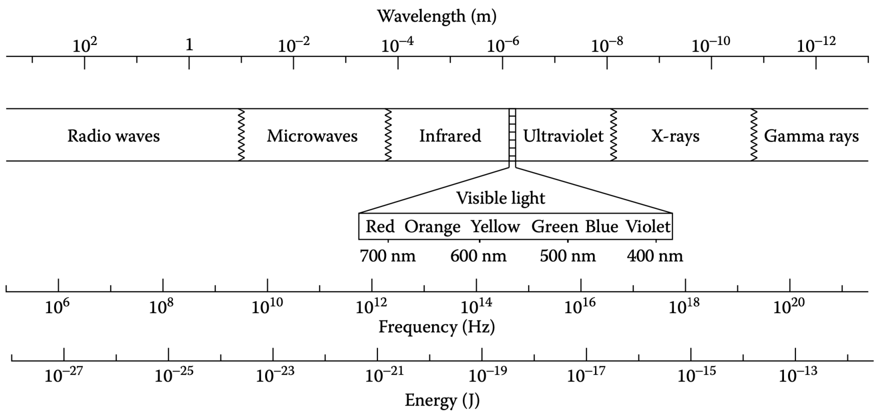


Figure 1.1: Display of all the bands of the entire electromagnetic spectrum, shown in order of energy of the waves, with the lowest energy radiation on the left.

1.2.1 Electromagnetic Spectrum and Radio Waves

Radio waves span from 10 MHz to 300 GHz on the electromagnetic spectrum, known as the "radio window." They penetrate Earth's atmosphere, allowing ground-based radio observations.

1.2.2 Spectroscopy and Applications in Radio Astronomy

Spectroscopy is pivotal in radio astronomy, analyzing spectra—continuous or with emission/absorption lines—to unveil details about celestial sources.
Radio telescopes detect and analyze radio waves from space, enabling studies of cosmic microwave background radiation, pulsars, and molecular clouds. They extend observational capabilities beyond optical telescopes.

1.3 Citation

This statement requires citation (**book_key**); this one is more specific (**article_key**).

1.4 Understanding the Sky Coordinate System and Observer-Centered Definitions

1.4.1 Sky Coordinate System

- **Right Ascension (RA)**: Measured in hours, minutes, and seconds, RA lines are fixed relative to the stars, aligning initially with Earth's longitude on the vernal equinox. RA increases to the east due to Earth's rotation.
- **Declination (Dec)**: Analogous to latitude, Dec is measured in degrees north or south from the celestial equator. It remains constant relative to the stars as Earth rotates.

1.4.2 Observer-Centered Definitions

- **Horizon**: Defines the visible sky from a specific location, obstructed by Earth's surface.

- **Zenith**: Directly overhead point in the sky, continuously changing due to Earth's rotation.
- **Altitude**: Angular height of an object above the horizon, varying from 0° (on horizon) to 90° (zenith).
- **Azimuth**: Angular position of an object along the horizon, referenced from due north (0°), east (90°), south (180°), and west (270°).

1.4.3 Meridian and Transit

- **Meridian**: Line in the sky passing through zenith and celestial poles.
- **Transit**: Occurs when an object passes through the observer's meridian, indicating its highest point in the sky.
- **Hour Angle (HA)**: Time since an object's transit, useful for scheduling observations.
- **Local Sidereal Time (LST)**: RA of the meridian, aiding in tracking when objects transit based on their RA.

1.4.4 Apparent Sizes and Solid Angles

- **Angular Size**: Describes how large an object appears in the sky, measured in radians.
- **Solid Angle**: Extension of angular size to a three-dimensional space, critical for understanding an object's visibility.
- **Steradians (sr)**: Unit measuring solid angles, with the entire sky covering 4 steradians.

1.5 Basic Structure of a Traditional Radio Telescope

Radio astronomy involves observing celestial objects at radio wavelengths using specialized instruments known as radio telescopes. Unlike visible light telescopes, radio telescopes detect electromagnetic radiation at much longer wavelengths, which requires different technological approaches and observing conditions. This section provides an overview of the basic components and operational principles of a traditional radio telescope based on the text provided.

1.5.1 Basic Structure

1. Parabolic Reflector (Dish):

1. The primary component of a radio telescope is the parabolic reflector or dish, which collects and focuses radio waves. Unlike visible light telescopes that use lenses, radio telescopes rely on reflecting surfaces due to the properties of radio waves.
2. The size of the dish determines the sensitivity of the telescope, directly affecting its ability to capture faint radio signals from celestial sources.
3. At longer radio wavelengths, the dish can even be a mesh structure rather than a solid surface, provided the mesh holes are smaller than the wavelength being observed.

Mount:

mount is the physical structure that supports and moves the dish. Most modern radio telescopes use an Altitude-Azimuth (Alt-Az) mount, which allows movement in altitude (up-down) and azimuth (side-to-side).Older equatorial mounts are also used, tilted to align with the Earth's rotational axis, translating movement into Right Ascension (RA) and Declination (Dec) coordinates.

Feed, Receivers, and Computers:

1. Radio waves collected by the dish are directed to a feed antenna, which converts the waves into electrical signals.
2. These signals are then processed by a receiver front-end located near the feed, amplifying and converting the signal to a manageable frequency range.
3. The processed signal is transmitted via coaxial cable to the receiver back-end, which further detects and digitizes the signal for analysis by a computer.
4. Each feed-receiver assembly typically corresponds to a single detector, akin to a pixel in imaging systems.

Observational Considerations

1.5.2 Atmospheric Transparency

: Unlike visible light, radio waves are not significantly scattered by Earth's atmosphere. This allows radio observations to be conducted during both day and night, as well as under cloudy conditions at longer wavelengths.

1.5.3 Resolution and Sensitivity

: The resolution of a radio telescope is determined by diffraction rather than atmospheric turbulence, with larger dishes providing better angular resolution.

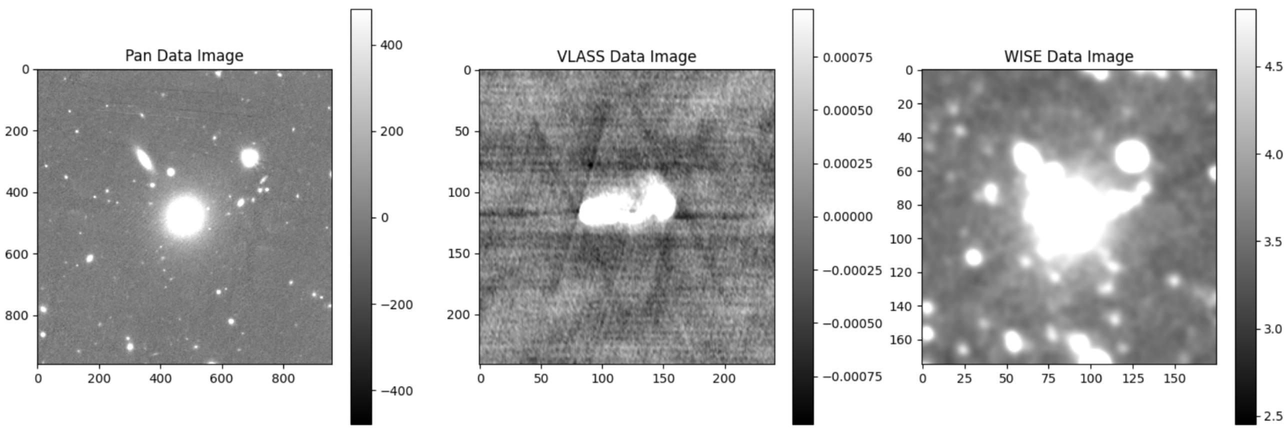
1.5.4 Data Handling

: Radio astronomy data differs from visible light observations in that it typically results in fewer discrete measurements per observation, emphasizing precision over spatial coverage.

2. Work

2.1 Multi-Wavelength Astronomy

we will choose interesting portions of the sky and compare the images from different telescopes to see how astrophysical objects differ in their emission at different wavelengths.



(7) (5)

Figure 2.1: Figure obtained upon pre-processing and removing outliers from the image data

2.2 Plotting The Jet Afterglow Lightcurve Of GW170817

We get the data from VLA telescope with frequency of 3GHz and the data of Chandra telescope with frequency of 2.41 $\times 10^{17}$ Hz, and converting the 2.41 $\times 10^{17}$ Hz data to 3 GHz data, with the relation $F_\nu \propto \nu^{-0.584}$. (6)

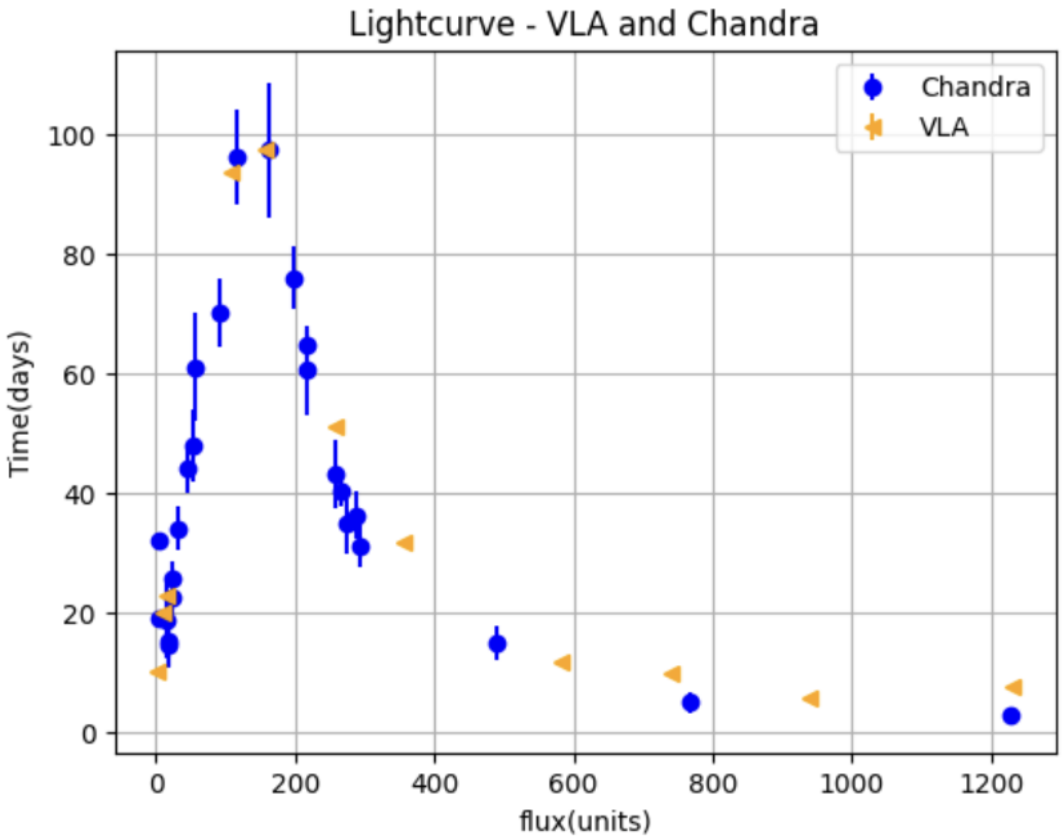


Figure 2.2: Plotting the data points of Chandra and VLA

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1. Theory

1.1 Blackbody Radiation and its Physical Characteristics

(2)
Blackbody radiation refers to the thermal radiation emitted by an idealized object that absorbs all incident light and reflects none. This theoretical concept helps in understanding how objects emit and absorb radiation based on their temperature. The intensity of blackbody radiation across different frequencies is described by the Planck function, which depends solely on the body's temperature and the frequency of the emitted radiation.

1.2 Planck Function

The Planck function, $B_\nu(T)$, characterizes the spectral intensity of blackbody radiation per unit frequency interval per unit solid angle. It is expressed as:

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

where:

- h is Planck's constant,
- ν is the frequency of the radiation,
- k is Boltzmann's constant,
- T is the temperature of the radiating body,
- c is the speed of light.

1.2.1 Stefan–Boltzmann Law

The total flux of radiation emitted by a blackbody is proportional to the fourth power of its temperature, as described by the Stefan–Boltzmann law:

$$F = \sigma T^4$$

where σ is the Stefan–Boltzmann constant.

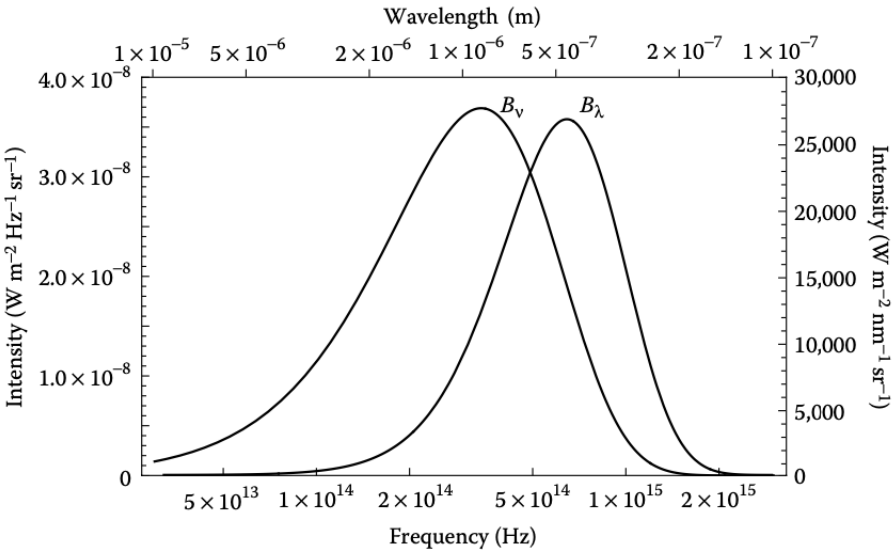


Figure 1.1: Curves of the Planck function for a 5800 K blackbody shown as both Bλ and Bν. Even though both of these curves represent the intensity emitted by the same blackbody, they peak in different parts of the electromagnetic spectrum.

1.2.2 Wien's Displacement Law

Wien's displacement law states that the wavelength at which the emission spectrum of a blackbody peaks is inversely proportional to its temperature:

$$\lambda_{\text{peak}} T = b$$

where b is a constant.

1.2.3 Rayleigh–Jeans Approximation

At lower frequencies or longer wavelengths (e.g., in the radio region), the Planck function simplifies to the Rayleigh–Jeans approximation:

$$B_\nu(T) \approx \frac{2kT\nu^2}{c^2}$$

This approximation is valid when $h\nu \ll kT$.

1.2.4 Brightness Temperature

Brightness temperature (T_B) is a parameter used in radio astronomy to describe the intensity of radiation from a source. It represents the temperature of a hypothetical blackbody that would emit radiation at the same intensity observed:

$$T_B = \frac{c^2}{2k\nu^2} I_\nu$$

where I_ν is the intensity of the radiation.

1.3 Coherent and Incoherent Radiation

The concept of coherence in electromagnetic radiation plays a crucial role in understanding its properties and applications, especially in fields like radio astronomy. Coherent radiation refers to waves that maintain a constant phase relationship over time and space, whereas incoherent radiation consists of waves with random phases.

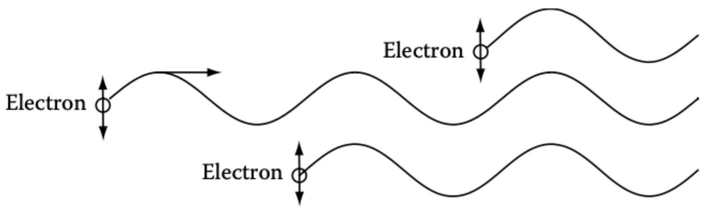


Figure 1.2: Schematic of the creation of coherent radiation. An oscillating electron emits a chain of sine waves, which is joined by another identical chain of sine waves with exactly the same phase, and then another wave is added, in phase with the first two.

1. Coherent Radiation:
   Definition : Radiation where all wave components have a fixed phase relationship.
   Properties : Results in constructive interference, amplifying the intensity significantly. Examples include lasers and some astronomical sources.
   Mathematical Representation : The addition of coherent waves leads to an intensity that can be several times higher than the sum of individual wave intensities, depending on the phase relationship.
2. Incoherent Radiation:
   Definition : Radiation from sources where wave components have random phases.
   Properties : Results in overall intensity proportional to the sum of individual intensities. Typical examples include thermal sources like incandescent bulbs and most astronomical sources.

1.4 Interference

1.4.1 Interference Patterns

: Illustrated by the double-slit experiment, where coherent light sources produce distinct interference patterns due to phase differences.

1.4.2 Applications

: Understanding interference patterns helps in designing radio telescopes and interferometers. Even partially coherent sources can produce interference patterns, impacting observational techniques in radio astronomy.

1.5 Polarization of Radiation

Electromagnetic waves propagate with mutually perpendicular electric and magnetic fields perpendicular to the direction of propagation. Polarization refers to the orientation of the electric field vector of these waves. In the context of radio astronomy, understanding polarization helps discern physical properties of astronomical sources.

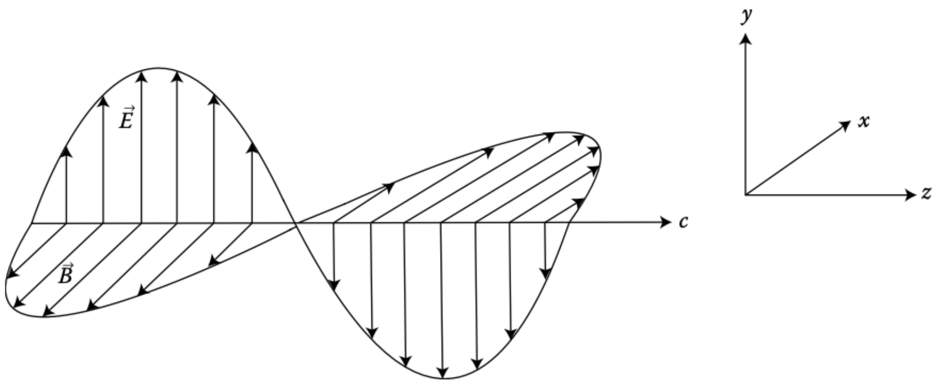


Figure 1.3: Propagation of plane electromagnetic waves along the z-axis with the electric field oscillating along the y-axis.

1.5.1 Types of Polarization

(a) Linear Polarization: The electric field oscillates in a single plane.
(b) Circular Polarization: The electric field vector rotates either clockwise or counterclockwise as the wave propagates.
(c) Elliptical Polarization: The electric field vector traces out an elliptical path due to varying magnitudes and phases of its components.

1.5.2 Measurement of Polarization

Polarization is quantitatively described using Stokes parameters, which provide a comprehensive framework to measure both linear and circular polarization simultaneously.

Stokes Parameters

Stokes I (Total Intensity) : Sum of intensities of orthogonal polarizations.

Stokes Q and U (Linear Polarization) : Measure the difference and correlation between two orthogonal linear polarization states.

Stokes V (Circular Polarization) : Measures the difference between intensities of left and right circular polarization.

2. Work

2.1 Finding the Temperature of the Cosmic Microwave Background(CMB)

The Cosmic Microwave Background (CMB) is a relic of the Big Bang that allows astronomers to probe the universe at an age as young as 400,000 years. When measured at different frequencies, we can know more about the nature of this radiation. In this activity, we used far infrared data adapted from the COBE satellite to fit a blackbody curve to the CMB.

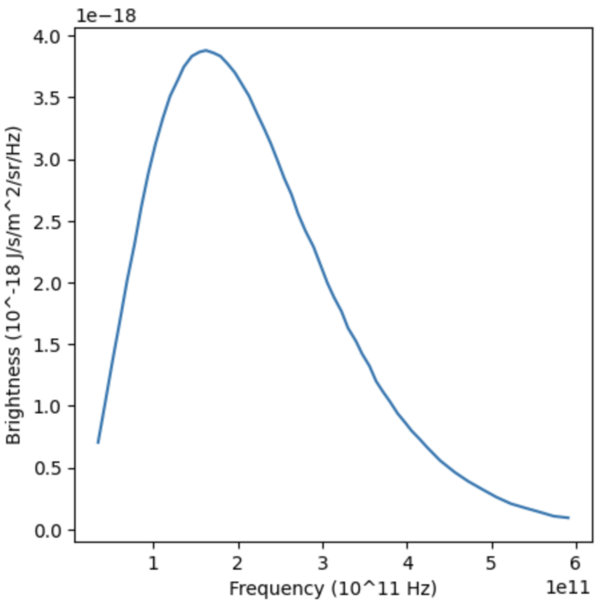


Figure 2.1: Plotting the Frequency vs Brightness

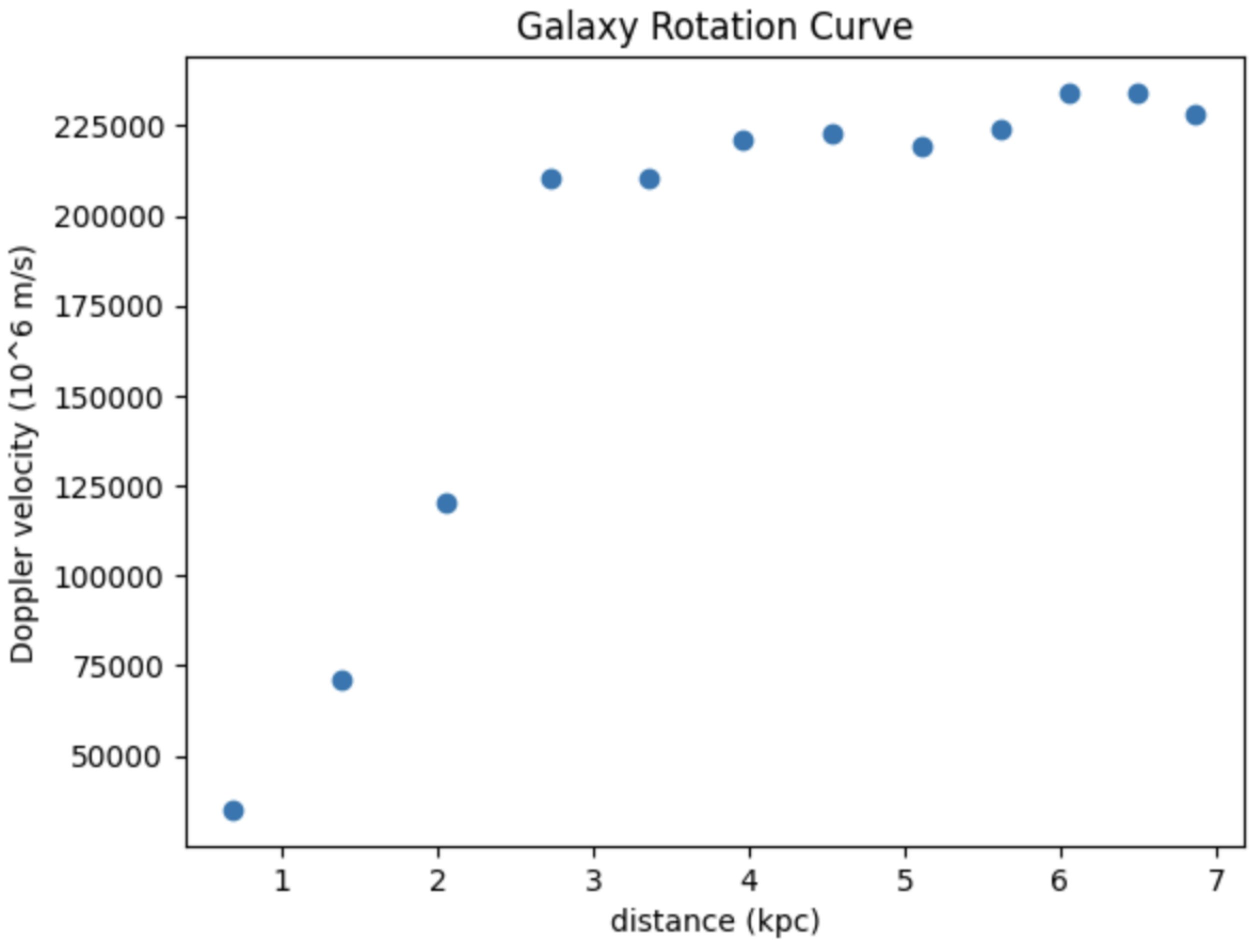
Knowing that it is a blackbody spectrum, we fit the blackbody function to the data with temperature as the free parameter. We end up getting

$$T_{CMB} = 2.740289273966668K$$

The expansion of the Universe has stretched out the CMB radiation by around 1000 times, which makes it look much cooler. So instead of seeing the afterglow at around 3000 degrees, we see it at just 3o above absolute zero, or 3 Kelvin (-270^{o}C).

2.2 Plotting the Galaxy Rotation Curve

Fit for the Doppler velocity of the 21 cm line for each distance. To do so, we fit a gaussian to the spectral line and determine the central frequency, we plot the velocities as a function of distance from the centre of our galaxy.



When studying other galaxies it is invariably found that the stellar rotational velocity remains constant, or "flat", with increasing distance away from the galactic center. This result is highly counter-intuitive since, based on Newton's law of gravity, the rotational velocity would steadily decrease for stars further away from the galactic center. Analogously, inner planets within the Solar System travel more quickly about the Sun than do the outer planets (e.g. the Earth travels around the sun at about 100,000 km/hr while Saturn, which is further out, travels at only one third this speed). One way to speed up the outer planets would be to add more mass to the solar system, between the planets. By the same argument the flat galactic rotation curves seem to suggest that each galaxy is surrounded by significant amounts of dark matter. It has been postulated,and generally accepted, that the dark matter would have to be located in a massive, roughly spherical halo enshrouding each galaxy.

Week3

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1.6 Noise, Noise Temperature, and Antenna Temperature

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1. Theory

1.1 Radio Telescope Reflectors, Antennas, and Feeds

(3)
In radio telescopes, the terms "antenna" and "reflector" are often used interchangeably but they have distinct meanings. An *antenna* is a device that couples electromagnetic (EM) waves from free space into a transmission line. A *reflector*, typically parabolic, collects and concentrates radiation. Large radio telescopes use a reflector as the initial element, directing EM waves to an antenna that then transmits these waves to the receiver. For long radio wavelengths, simple dipole antennas can act as the primary element.
Dish refers to the reflector, while *feed* denotes the device that couples concentrated radiation into a transmission line.

1.2 Primary Reflectors

Parabolic Reflectors : Most radio telescope dishes are parabolic, ensuring that incoming plane waves (from astronomical objects) are focused to a single point, called the focus. When the source is off the central axis, waves converge to a point near this focus, forming a focal plane. In radio telescopes, the feed horns placed at this focal plane convert EM waves from free space into transmission lines.

Prime Focus Telescopes : In these telescopes, the feed and receivers are at the primary reflector's focus. Multiple feeds may collect power from different directions simultaneously. This setup can be inconvenient due to the awkward placement of feeds and receivers.

Cassegrain Telescopes : A secondary reflector is used to redirect waves to another focal point, often behind the primary reflector. This design is more practical as the feed and receiver are more accessible.

The Green Bank 20-m telescope is an example of a Cassegrain telescope.

Functions of Primary Reflector :

(a) Collecting and Focusing Radiation: This enhances the detection of faint sources. The collected power depends on the telescope's effective area (A_eff), which is smaller than its geometrical area due to several factors.

(b) Providing Directivity: This enables the telescope to differentiate emissions from objects at different sky positions. The directivity is described by the beam pattern, which is influenced by diffraction.

1.2.1 Diffraction and Beam Pattern

: The beam pattern measures the telescope's sensitivity to incoming signals at various angles, similar to the point-spread function in optical astronomy. The $Huygens\check{}Fresnel principle$ illustrates how waves diffract and interfere, forming a beam pattern. The $Airy pattern$ is a typical sensitivity pattern of a parabolic reflector, with a central peak and sidelobes, determining the telescope's resolution and ability to distinguish closely spaced sources.

1.2.2 Resolution and Directivity

: The resolution angle, defined as the full width at half maximum (FWHM) of the main lobe, indicates the telescope's ability to discern fine details. This angle is inversely proportional to the reflector's diameter, meaning larger telescopes offer better resolution and power collection.

1.3 Feeds and Primary Reflector Illumination

Feeds : At the focal point, antennas (usually horn antennas) couple EM waves into transmission lines leading to receivers. Horn antennas, which may have rectangular or circular cross-sections, are designed to collect and direct waves effectively. The feed horn's beam pattern, determining the illumination on the primary reflector, is crucial for telescope performance.

Illumination Pattern : The illumination pattern affects the telescope's angular resolution, sidelobe sensitivity, and effective collecting area. The ideal pattern maximizes the use of the reflector's area while minimizing background noise.

Edge Taper : This describes the sensitivity ratio between the center and edge of the reflector, influenced by the feed horn's beam width. A large edge taper reduces sensitivity to the reflector's edges, improving sidelobe levels but reducing effective area. A small edge taper improves resolution but increases sidelobes.

1.4 Surface Errors

The primary reflector of a radio telescope is crucial for gathering incoming radio waves. Ideally, it should be a perfect parabola to focus waves precisely. However, manufacturing imperfections lead to deviations from this ideal shape, characterized by root mean square (rms) deviations (dz). These deviations cause phase errors, which reduce the telescope's sensitivity. The Ruze equation quantifies this reduction in collecting area due to surface errors:

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

where A_δ and A_0 are the collecting areas with and without surface errors, respectively. Surface errors should ideally be less than 1/20th of the wavelength of light to minimize performance loss.

1.5 Beam Pattern

The beam pattern of a radio telescope is determined by its aperture and is crucial for understanding its resolution and sensitivity. The pattern is derived using Fourier transforms, relating the electric field distribution across the aperture to its angular distribution in the far-field. For example, a uniformly illuminated aperture yields a beam pattern characterized by a sinc function, with the angular resolution $\theta_{FWHM} = 0.89\lambda/a$ radians.

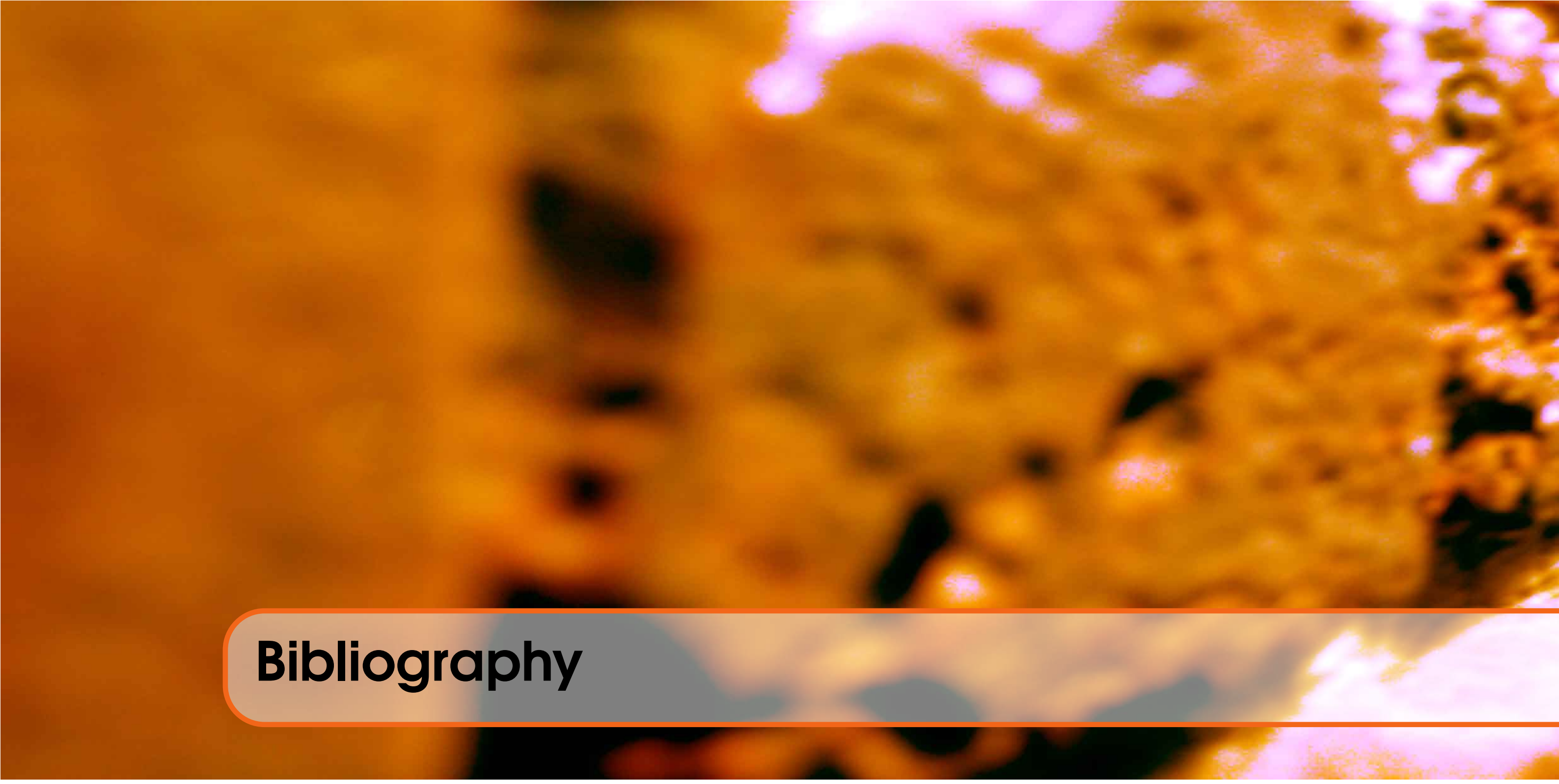
1.6 Noise, Noise Temperature, and Antenna Temperature

(4)
Noise in radio telescopes originates from internal electronic components and degrades signal detection. The noise temperature (TN) quantifies this noise power in terms of an equivalent temperature. It is critical to minimize TN to enhance sensitivity. The total noise temperature of a receiver chain is the sum of individual noise temperatures weighted by their gains. The total noise temperature TN is given by:

$$TN = \frac{TN_1}{G_1} + \frac{TN_2}{G_1 G_2} + \frac{TN_3}{G_1 G_2 G_3} + \ldots$$

1.6.1 Impact on Telescope Performance

Surface errors reduce the effective collecting area, while noise limits the telescope's ability to detect faint astronomical signals. Techniques such as switched power measurements mitigate noise influence but do not eliminate it entirely, emphasizing the need for low-noise components and careful system design.



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