Galactic HI Observations

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1 Introduction

Radio Astronomy involves the detection of extremely weak radio signals originating from astronomical sources. In order to obtain information about the source, these signals must be amplified, processed and recorded with high sensitivity and stability. This experiment focuses on the observation of Galactic neutral hydrogen (HI) emission near 1420.405 MHz using a compact radio astronomy setup. The aim was to gain experience with detection of weak astronomical radio signals and to understand the practical steps involved in radio astronomical observations. A radio antenna system was used to collect radio signals and the received data were recorded in the form of power spectra around the hydrogen line frequency. Observations were made for different antenna pointings, along with reference measurements. The reference measurements were performed to characterize the system response and enable calibration of the recorded data. The data was processed to study the variations in received signal and to identify spectra features and provide various information on the structure of galaxies, galactic rotation, velocity fields.

2 Theory

2.1 Neutral Hydrogen (HI) and the 21 cm Line

Hydrogen is the most abundant element in the universe and plays a key role in astrophysics. In its neutral atomic form, hydrogen (denoted H I) consists of a single proton and a single electron bound in the ground electronic state. Along with the well known electronic transitions that produce optical and ultraviolet radiation, neutral hydrogen also shows a much weaker transition known as the hyperfine transition. This transition happens because of the interaction between the magnetic moments of the proton and the electron. The spins of the proton and electron can be aligned in two ways, parallel, which leads to a slightly higher energy state, or anti parallel, which leads to a lower energy state. When an atom shifts from the higher energy parallel state to the lower energy anti parallel state, it emits a photon with a wavelength of 21.1 cm. This corresponds to a frequency of 1420.405 MHz. The chance of this transition happening for a single hydrogen atom is very small, with a spontaneous emission timescale of about about 10^7 years . However, since neutral hydrogen exists in huge amounts throughout the interstellar medium, the combined emissions from many atoms create a detectable radio signal. This radiation is known as the 21 cm hydrogen line and serves as the foundation for HI radio astronomy.

2.2 Galactic HI and the Interstellar Medium

The Interstellar Medium (ISM) consists of gas and dust spread throughout the milky way galaxy. Neutral hydrogen is a key part of the ISM and is especially plentiful in the galactic disk and spiral arms. HI usually exists in diffuse clouds with temperatures from a few tens to several hundred kelvin and low particle densities. One major benefit of observing the 21 cm line is that radio waves at this wavelength are mostly affected by interstellar dust. This means HI emission helps astronomers explore areas of galaxy that are not visible at optical wavelengths. Observations of galactic HI have been crucial for mapping the spiral structure of the milky way, studying large scale gas distribution, and understanding galactic dynamics.H.C van de Hulst first predicted the 21 cm line in 1944. It was experimentally detected in 1951 by Ewen and Purcell, followed soon after by observations from Jan Oort and his team. These findings marked the start of modern Galactic radio astronomy and greatly improved our understanding of the milky way's structure.

2.3 Doppler Shift and Galactic Kinematics

The observed frequency of the HI line often shifts from its rest frequency because of the Doppler effect. This effect occurs due to the movement between the emitting hydrogen gas and observer. The radial velocity v of the hydrogen gas along the line of sight relates to the observed frequency f through the non relativistic Doppler formula:

$$v = c\left(1 - \frac{f}{f_0}\right),$$

where c is the speed of light and $f_0 = 1420$ MHz is the rest frequency of the hydrogen line.
By measuring the Doppler shifted frequencies of HI emission in various directions, we can study the velocity distribution of neutral hydrogen in the galaxy. These velocity measurements provide direct evidence of the milky way's differential rotation and help Galactic rotation curves.
To interpret these results accurately, we must adjust the measured velocities for the Earth's motion, both from its rotation and its orbit around the sun. We also need to consider the unusual movement of the sun relative to the Local Standard of Rest (LSR).

2.4 Brightness Temperature and Calibration

The intensity of a received signal is commonly expressed in terms of brightness temperature rather than power. In the Rayleigh Jeans limit, which is valid at radio frequencies near 1.4 GHz, the power received by a matched antenna system is directly proportional to temperature:

$$P = kT$$

where k is Boltzmann's constant and T is the effective temperature of the source.
The measured signal from the receiver includes contributions from the astronomical source, the sky background, and the receiver system noise, known as the receiver temperature. To convert the measured power spectrum into a calibrated temperature spectrum, observations are made using reference sources with known temperatures, typically the ground (approx 300 K) and a region of cold sky away from the Galactic plane (about 5 K).
This calibration process changes raw power measurements into calibrated brightness temperature spectra. We can then interpret these in terms of H I emission.

2.5 Principle of the Galactic HI Observation

The goal of this experiment is to detect and study the 21 cm emission from neutral hydrogen in the milky way using a compact and low cost radio telescope system. The system includes a horn antenna, low noise amplifier, a band pass filter, and a software defined radio (SDR) receiver.
The horn antenna gathers radio waves from the sky and provides directional sensitivity. The low noise amplifiers boost the weak signal and the band pass filter isolates the frequency range around the hydrogen line. The SDR converts the signal into digital form and records the power spectrum over a narrow bandwidth centered on 1420.405 MHz.
By directing the antenna toward different areas of the Galactic plane and integrating the signal over time, we obtain characteristic HI spectral line profiles. After calibrating for temperature and making Doppler corrections, these spectra show the presence of neutral hydrogen and its velocity distribution along the line

of sight. Even with its simple design, this setup illustrates the basic principles of radio astronomy and mimics key observational techniques used in professional HI surveys.

2.6 Scientific Significance

The Galactic H I experiment provides a direct connection between atomic scale quantum processes and large scale Galactic structure. It demonstrates how a weak hyperfine transition in neutral hydrogen enables the study of the distribution and motion of gas across the Milky Way. In addition, the experiment introduces fundamental concepts such as antenna response, receiver calibration, spectral analysis, and velocity measurements, making it a valuable educational tool in observational astrophysics.

3 Experimental Setup

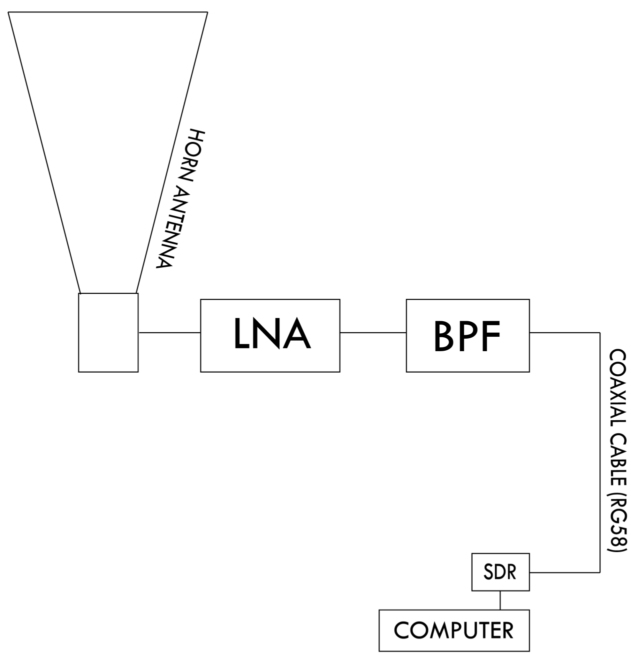


Figure 1: Experiment Setup

Where :

LNA : Low Noise Amplifier
BPF : Band Pass Filter
SDR : Software Defined Radio

4 Observations and Calculations

4.1 Data Acquisiton

Download HI datafile

4.2 Plotting the Observed spectra

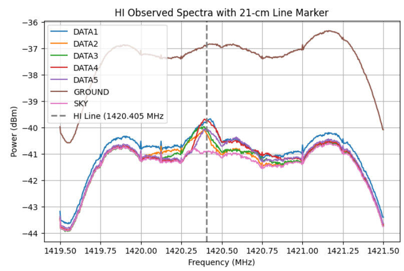


Figure 2: HI Observed Spectra with HI marker

4.3 Temperature Calibration

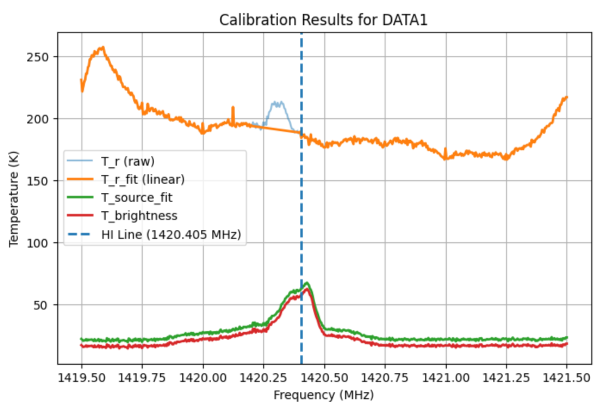


Figure 3: Temperature calibration for DATA 1

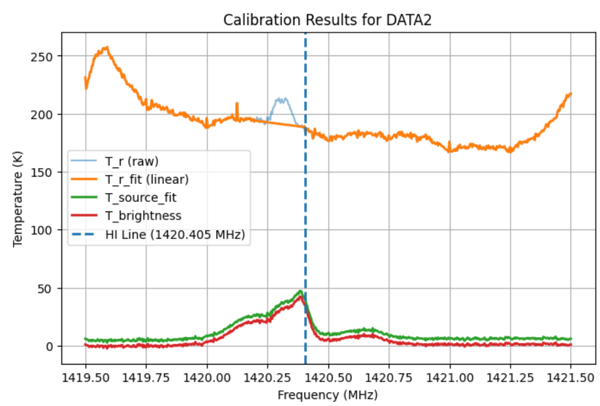


Figure 4: Temperature calibration for DATA 2

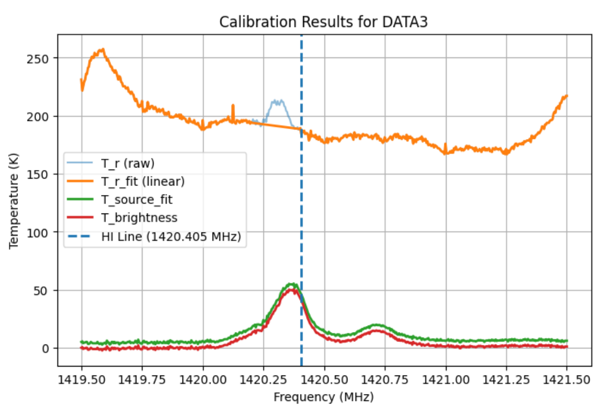


Figure 5: Temperature calibration for DATA 3

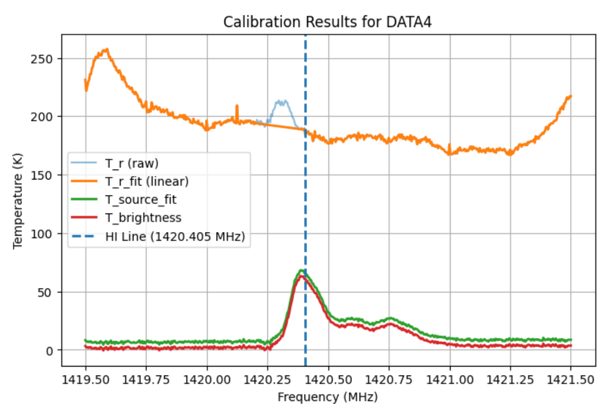


Figure 6: Temperature calibration for DATA 4

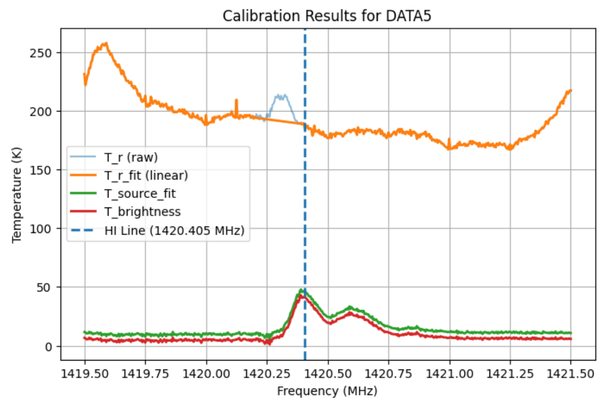


Figure 7: Temperature calibration for DATA 5

4.4 Measuring locations

Table 1: Observation Date, Time, and Pointing Coordinates

Dataset	Date & Time (IST)	Altitude (deg)	Azimuth (deg)
DATA 1	2025-12-11 17:50:00	25	257.0
DATA 2	2025-12-11 17:53:00	39	265.0
DATA 3	2025-12-11 17:57:00	49	285.0
DATA 4	2025-12-11 18:01:00	56	324.0
DATA 5	2025-12-11 18:04:00	49	2.48

4.5 Converting Alt Az values to RA-Dec values

Table 2: Right Ascension (RA) and Declination (DEC) of Observed Sources

Source	RA (h m s)	DEC (d m s)
D1	18h 27m 01.36570115s	$-3°23'02.58619726''$
D2	19h 13m 22.47904626s	$7°46'38.22334657''$
D3	19h 48m 01.05690216s	$23°35'10.83583376''$
D4	20h 58m 50.56239423s	$43°44'35.94610135''$
D5	23h 01m 11.22855886s	$41°17'29.49655245''$

4.6 Velocity Calibration

item Positive value → receding source (redshift) and Negative value → approaching source (blueshift)

Dataset	LSR Correction (km s^{-1})
DATA 1	−8.572
DATA 2	−4.393
DATA 3	−2.820
DATA 4	0.392
DATA 5	2.971

Table 3: LSR velocity correction applied to each dataset.

4.7 Plotting brightness temperature vs velocity

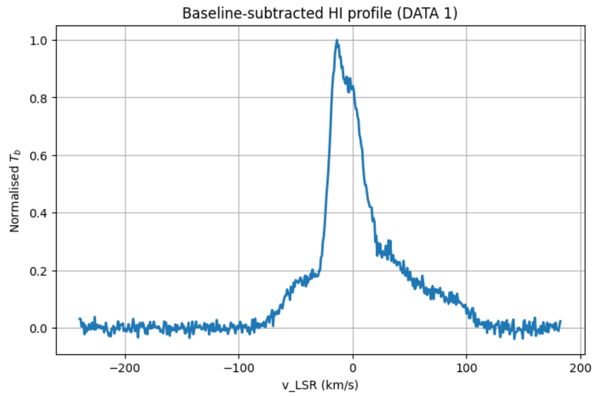


Figure 8: Brightness temperature vs velocity (DATA 1)

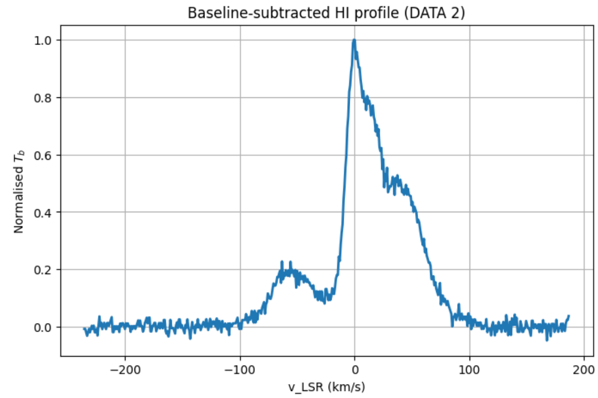


Figure 9: Brightness temperature vs velocity (DATA 2)

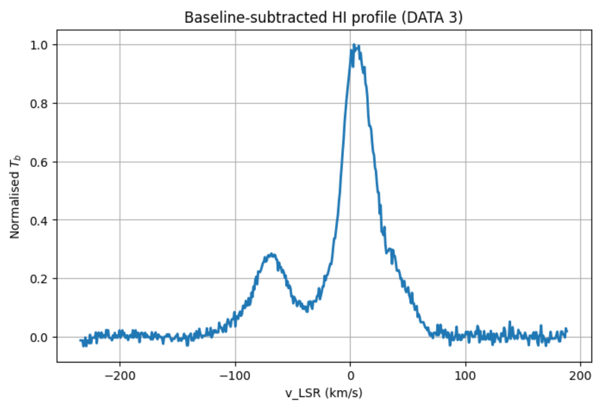


Figure 10: Brightness temperature vs velocity (DATA 3)

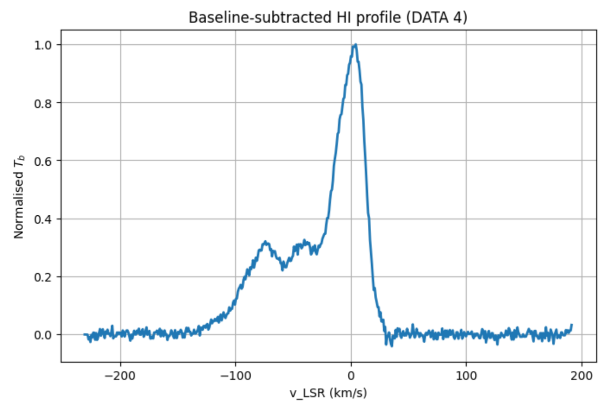


Figure 11: Brightness temperature vs velocity (DATA 4)

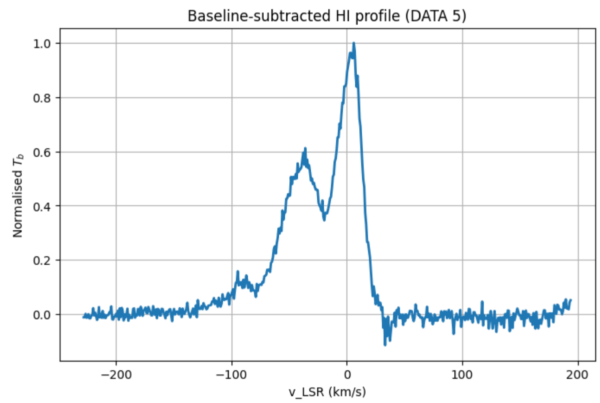


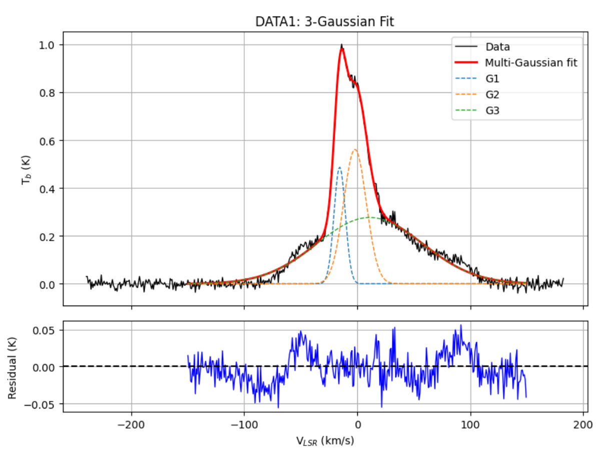
Figure 12: Brightness temperature vs velocity (DATA 5)

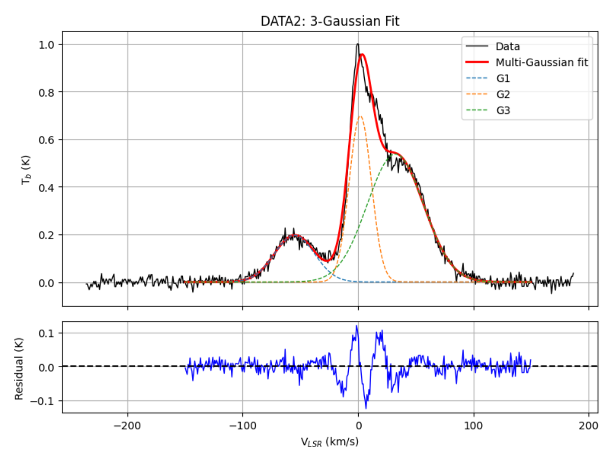
4.8 V LSR

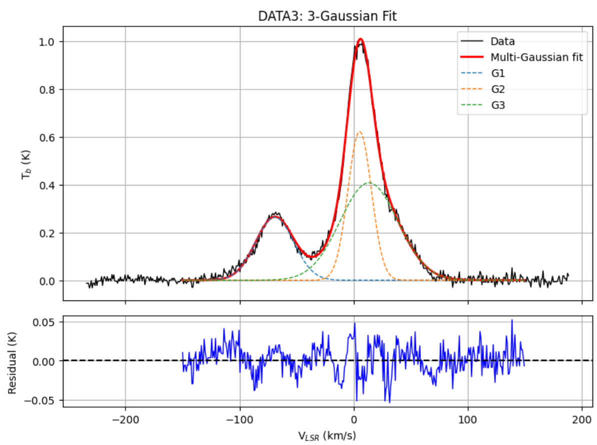
Dataset	Peak v_{LSR} (km s^{-1})
DATA 1	-13.78
DATA 2	-0.53
DATA 3	3.51
DATA 4	4.25
DATA 5	6.00

Table 3: Peak line-of-sight velocities (v_{LSR}) for the observed datasets.

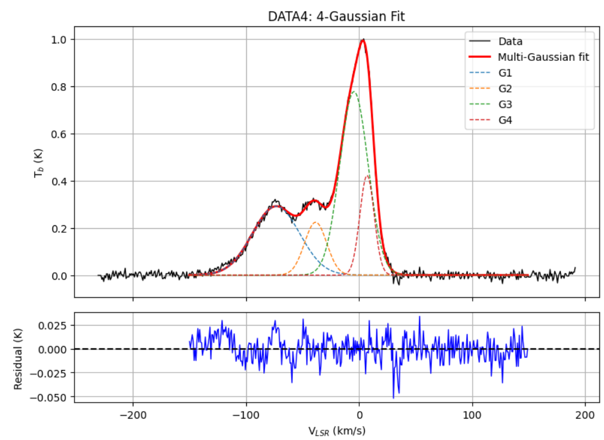
4.9 Gaussian Fit







Gaussian fit for DATA 3



Gaussian fit for DATA 4

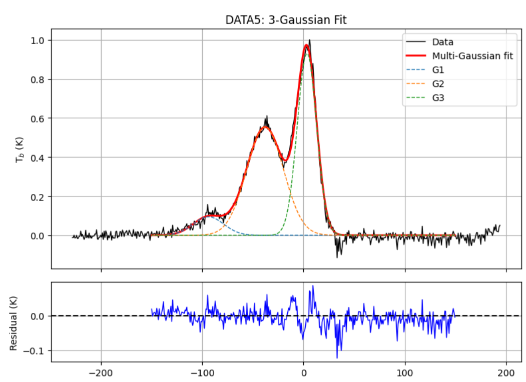


Figure 13: Gaussian fits to the HI line profiles for DATA 3, DATA 4, and DATA 5

4.10 Galactic Rotation Curve

This will be a zoomed of the general galactic rotation curves we see, as we go from around 3.5 to 8 kpc

- Galactic longitude, l (deg):
$$[27.13,\ 42.35,\ 60.21,\ 85.06,\ 101.62]$$
- Galactic latitude, b (deg):
$$[3.87,\ -1.29,\ -0.97,\ -1.38,\ -16.97]$$

Peak Line-of-Sight Velocities:

Dataset	v_{LSR} **(km s^{-1})**
DATA 1	-13.78
DATA 2	-0.53
DATA 3	3.51
DATA 4	4.25
DATA 5	6.00

Table 4: Peak line-of-sight velocities with respect to the Local Standard of Rest.

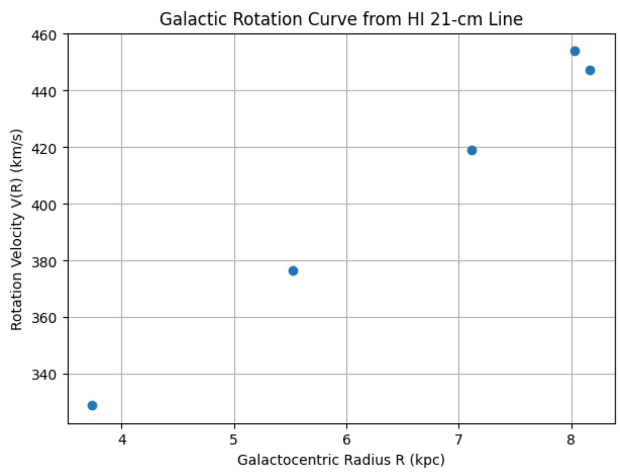


Figure 14: Derived Galactic rotation curve from HI observations

5 Results

Observations were carried out using a horn antenna radio telescope tuned to the neutral hydrogen hyperfine transition at a rest frequency of 1420.4057 MHz. Power spectra were recorded for different antenna pointings, including the ground, sky near zenith, and directions along the Galactic plane.
A prominent spectral feature corresponding to the H I 21 cm line was detected when the antenna was pointed towards the Galactic plane. No such feature was observed in the ground or off-plane sky measurements, confirming the astronomical origin of the signal.

5.1 Temperature Calibration

Using ground and sky observations for calibration, the measured power spectra were converted to brightness temperature following the radiometric calibration procedure. After baseline subtraction and removal of the receiver contribution, the calibrated H I line exhibited a peak brightness temperature of approximately 40–70 K, depending on the pointing direction.

5.2 Velocity Calibration

The frequency axis was converted to radial velocity with respect to the Local Standard of Rest (LSR) using the Doppler relation,

$$v = c\left(1 - \frac{f}{f_0}\right),$$

where $f_0 = 1420.4057$ MHz is the rest frequency of the hydrogen line. Corrections for Earth's rotation, orbital motion, and the Sun's peculiar motion were applied.
The resulting velocity profile revealed multiple peaks spanning velocities of approximately -200 to $+200$ km s^{-1}. These components correspond to emission from neutral hydrogen clouds at different galactocentric radii along the line of sight.

5.3 Gaussian Fitting

The velocity-calibrated brightness temperature profile was fitted using multiple Gaussian components. A minimum of three Gaussians was required to adequately model the observed line shape. The residuals after subtraction of the fitted model were consistent with random noise, indicating a satisfactory fit.
The presence of multiple velocity components reflects the differential rotation of the Milky Way and the complex distribution of neutral hydrogen in the Galactic disk.

6 Interpretations

In this experiment, the H1 line of neutral hydrogen spin flip transition was probed and the doppler shifts due to the rotational velocities of the galaxy at different galactic longitudes (and hence galactic radii) were calculated which translate to the line of sight velocities when the tangent to the galaxy at the given galactic radius becomes the line of sight, which is possible when the most redshifted H1 line is taken.

By plotting the redshifts (translated to the tangential velocities) against the galactic radii, the Galactic Rotation Curve is obtained.

By Keplerian orbital laws, the tangential velocities should start decreasing after a certain radius if only the luminous matter was taken. Howver, the deviation suggests the presence of 'non-luminous' matter in the galaxy which results in a deviation of the mass distribution. However, in thsi experiment the number of data points are too few to calculate quantitatively the mass of the dark matter present and other parameters.

7 Acknowledgements

We would like to express our sincere gratitude to Mr. Jameer Manur, Dr. Prakash Arumugaswamy and Dr. Avinash Deshpande for helping us get valuable insights in this particular experiment. We also thank IUCAA and the entire organizing committee of RAWS 2025 for their support and providing us with the opportunity to perform this experiment.

8 Contributions

Introduction - Ambika S[1]
Theory - Bhargava Ganesh Bhat[3]
Data Analysis, Plotting and Observations - Anaya Atul Dixit[2] and Dhairya Kotecha[4]
Results - Saanvi Pande[6]
Interpretation - Pranjal Sengupta[5]

9 References

Manual, HI in the Galaxy, Chatgpt, Hydrogen 21 cm line