Experiment 3:
Mapping the Milky Way at 21 cm

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Abstract
This experiment investigates the Milky Way's rotation curve via measurements of the 21 cm emission line from neutral hydrogen (HI). Using a radio telescope atop Northeastern University's Churchill Building—operated through a custom GNU Radio-based GUI that automated data-collection—spectral data were recorded at nineteen distinct galactic longitudes (0°–90°). After applying Doppler-shift corrections, each frequency spectrum was converted into a velocity profile. Furthermore, calibration steps translated raw power measurements into brightness temperatures, thereby providing a more physically meaningful view of the interstellar medium. By identifying the maximum line-of-sight velocities, the Milky Way's rotation curve was reconstructed. The observed velocities remained flat at large radii, which defies the predicted drop-off that would occur if only visible matter were present. This constitutes as evidence for a substantial, unseen mass component—dark matter.

1 Introduction

In the 21st Century, physics has largely achieved the goal of describing the universe with the utmost precision. One of the major remaining mysteries involves dark matter – matter that does not emit, absorb, or reflect light. Despite these properties, dark matter hides in plain sight, revealing itself through its profound influence on the large-scale structure and dynamics of the universe. The study of galaxy rotation curves—the variation of rotational speed with distance from a galaxy's center—has provided direct evidence for dark matter. These curves deviated from predictions derived from classical mechanics, which can be derived as follows:

Balancing gravitational and centripetal forces describes the motion of an orbiting object.

$$\frac{GMm}{r^2} = \frac{mv}{r} \tag{1}$$

where G is the gravitational constant, M is the mass of the central object, m and v are the mass and velocity of the orbiting object, and r is the distance between them. Solving for v gives ...

$$v_{orbit} = \sqrt{\frac{GM}{r}} \tag{2}$$

... which demonstrates that an orbiting object's velocity depends solely on the mass of the central object and more notably, its distance from the central object. Intuitively, this suggests that as material—planets, stars, nebulae, and interstellar dust and the like—orbit the galactic center, their velocity should *decline* with increasing distance. However, observations of galaxies revealed a different behavior—rotation curves remained nearly flat, defying the expected relationship. If $v(r)$ stays roughly constant ("flat") as r increases, that implies that $M(r)$ is still growing roughly linearly with r. Since visible matter (stars and gas) no longer contributes significant mass beyond the luminous disk, this suggests an extended and massive halo of unseen material—dark matter.

In the mid-20th century, astronomers began using radio telescopes to probe galaxy rotation curves. Unlike optical wavelengths, radio waves can easily penetrate the dust clouds and interstellar gas that would otherwise obscure observations in visible light[2]. This approach is particularly effective for detecting neutral hydrogen (HI)—the universe's most abundant element—which emits a characteristic 1420 MHz (21 cm) signal. Radio telescopes exploit this unique emission line to map and study the structure and dynamics of galaxies. This technique significantly accelerated research in the field. In the 1950s, Harold Ewen and Edward Purcell[1] mapped neutral hydrogen in the Milky Way, providing critical data for charting the galactic rotation curve. Experiments like these contributed to the widespread acceptance of dark matter halos as a fundamental component of galaxies.

The following experiment replicates this foundational work conducted in the 20th century. Emission from neutral hydrogen is collected using a radio telescope atop Northeastern University's Churchill Building. This is then used to map the Milky Way and construct a rotation curve, providing evidence for the presence of dark matter within our own galaxy.

2 Background

The hyperfine structure of neutral hydrogen (HI) results in the emission of photons with wavelengths of 21 cm (or with frequencies of 1420.4 MHz), detectable by radio telescopes. To understand why this occurs, we pay visit to our dear friend quantum mechanics. The hydrogen atom, consisting of a single proton and electron, has discrete energy levels given by:

$$E_n = \frac{-13.6\text{eV}}{n^2} \tag{3}$$

Where n is the quantum number. This description, however, oversimplifies the hydrogen atom's structure, often referred to as the "gross atomic structure." In reality, interactions between the spins of the proton and electron lead to what are known as fine and hyperfine structures – this is known as the spin-flip transition. These interactions cause the ground state ($n = 1$ and $l = [0...n-1] = 0$) energy to split into finer levels based on the spin orientations of both particles. Since both the proton and electron are charged particles with spin $\pm 1/2$, their combined *four* spin orientation combinations (Equation 4) result in slight perturbations of the ground state energy (Equation 5)[4] *.

$$|m_e, m_p\rangle = |\pm\frac{1}{2}, \pm\frac{1}{2}\rangle\ ^{\dagger} \tag{4}$$

$$\Delta E = \frac{g_e g_p e^2}{6\pi a_0^3 m_e m_p} \langle \vec{S_e} \cdot \vec{S_p} \rangle \tag{5}$$

The fine structure energy difference ΔE arises due to the interaction between the magnetic moments ($\vec{\mu}$) of the electron and proton, which depend on their g-factors (g_e and g_p), charges (e), masses (m_e and m_p), and spin:

$$\vec{\mu} = \frac{ge}{2m}\vec{S} \tag{6}$$

To figure out what the term $\langle \vec{S_e} \cdot \vec{S_p} \rangle$ yields, we recall that the the spin operator eigenvalues are given by:

$$S^2 |s, m_s\rangle = s(s+1)\hbar^2 |s, m_s\rangle \tag{7}$$

*Note that in Equation 4, m_e and m_p are the quantum spin values, m, for the electron and proton, respectively. In Equation 5, m_e and m_p are the masses of the electron and proton.

†this yields four total possible states: $|+\frac{1}{2}, +\frac{1}{2}\rangle, |+\frac{1}{2}, -\frac{1}{2}\rangle, |-\frac{1}{2}, +\frac{1}{2}\rangle, |-\frac{1}{2}, -\frac{1}{2}\rangle$

where m_s is the spin quantum number mentioned before, $1/2$ and $-1/2$, and s the total spin, which is $1/2$ for all spin-1/2 particles. Therefore...

$$S_e^2 \left|s, m_s\right\rangle = \frac{1}{2}(\frac{1}{2}+1)\hbar^2 \left|s, m_s\right\rangle = \frac{3}{4}\hbar^2 \left|s, m_s\right\rangle \tag{8}$$

...and the same goes for S_p^2. Now, the total spin S of a two-particle system, such as the electron and proton in hydrogen, can take values of either $S = 1$ or $S = 0$. The corresponding S_z quantum number, which represents the projection of total spin along the chosen axis, can take values $S_z = -1, 0$, or 1. Writing the states in the coupled basis of total spin and spin projection, we obtain the following four possible states. Each of these states determines the expectation value of the spin interaction $\langle \vec{S}_e \cdot \vec{S}_p \rangle$ using Equation 8.

State	Expectation Value
$\|1,1\rangle = \|\uparrow\uparrow\rangle$	$\langle 1,1\|\vec{S}_e \cdot \vec{S}_p\|1,1\rangle = \frac{1}{4}\hbar^2$
$\|1,0\rangle = \frac{1}{\sqrt{2}}(\|\uparrow\downarrow\rangle + \|\downarrow\uparrow\rangle)$	$\langle 1,0\|\vec{S}_e \cdot \vec{S}_p\|1,0\rangle = \frac{1}{4}\hbar^2$
$\|1,-1\rangle = \|\downarrow\downarrow\rangle$	$\langle 1,-1\|\vec{S}_e \cdot \vec{S}_p\|1,-1\rangle = \frac{1}{4}\hbar^2$
$\|0,0\rangle = \frac{1}{\sqrt{2}}(\|\uparrow\downarrow\rangle - \|\downarrow\uparrow\rangle)$	$\langle 0,0\|\vec{S}_e \cdot \vec{S}_p\|0,0\rangle = -\frac{3}{4}\hbar^2$

We observe that three of these states share the same energy, while the fourth state has a distinctly lower energy. These energy differences correspond to what are known as the triplet states ($S = 1$) and the singlet state ($S = 0$). The energy difference between these singlet and triplet states is exactly the ΔE described earlier. Plugging in the singlet and triplet $\langle \vec{S}_e \cdot \vec{S}_p \rangle$ values, $\frac{1}{4}\hbar^2$ and $-\frac{3}{4}\hbar^2$, into Equation 5 yields a ΔE value of roughly $5.88 \times 10^{-6} eV$. This energy difference is illustrated in Figure 1. When the spin orientation of the electron or proton change, a photon with equivalent energy is released. The equation $E = \frac{hc}{\lambda}$ reveals that this photon has a corresponding wavelength of 21 cm, or a frequency of 1420.4 MHz. Although the hyperfine transition is rare (with a spontaneous emission rate of $2.9 \times 10^{-15} s^{-1}$ [3]), the sheer abundance of neutral hydrogen means enough of these transitions are occurring that signal at this frequency is always detectable.

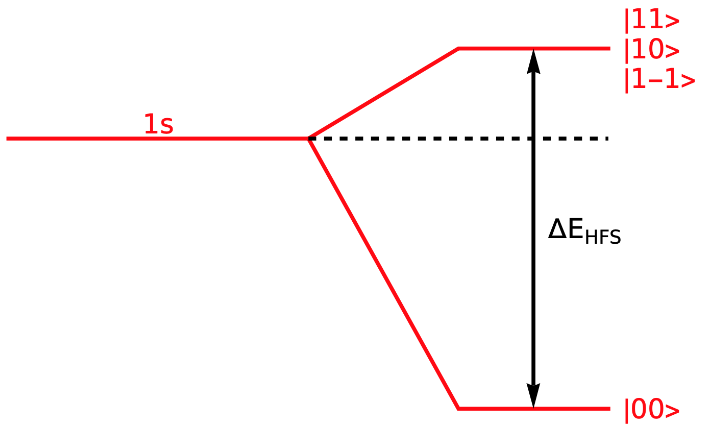

Figure 1: Hyperfine splitting of the hydrogen ground state

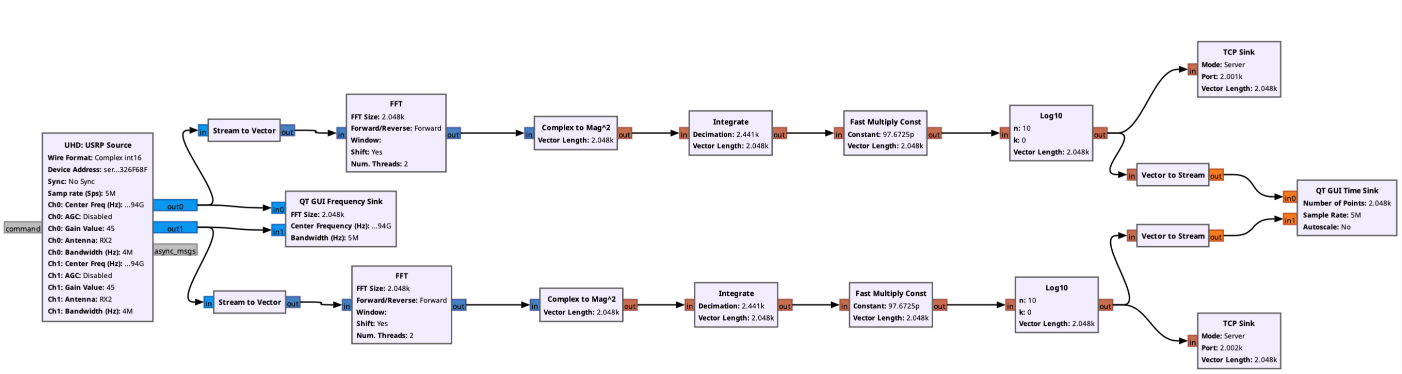

Figure 2: Spectrum GUI

3 Materials and Methods

3.1 Data Collection with a GUI

Data is gathered using the Compact Radio Telescope (CRT) atop Northeaster's Churchill Hall. The GNU Radio-based GUI—depicted in Figure 2 and titled "Spectrum"—sets up real-time radio signal processing, specifically for the 21 cm signal. The process begins with the UHD: USRP Source block capturing raw radio signals at 5 million samples per second with a gain of 45 and a bandwidth of 4MHz. Next, the Stream to Vector block batches samples for the FFT, which converts the time-domain data to the frequency domain. The FFT size is chosen to be 2048. The Complex to Mag Sqaured block then computes the power of each frequency bin, and the Integrate block averages these values, where the decimation is the sample rate divided by the FFT size. Becuase the radio signal is relatively weak, this process helps to reduce noise. Next, the Fast Multiply Const block scales the data using a normalization constant of 97.6725×10^{-12}, and the Log10 block transforms the values to a logarithmic scale (dB). Finally, the QT GUI Frequency Sink and QT GUI Time Sink display the spectrum and time-domain signals in real time, enabling continuous monitoring during the data collection process. After running the Spectrum GUI, the Receiver GUI – shown in Figure 3 – is used to store the data. It retrieves the frequency-domain vectors from two TCP ports at a 32k sample rate, limits each channel to five vectors via Head blocks, and then saves the data into NPZ files for further analysis.

The script `Milky.py` automates CRT observations along the Milky Way by moving the telescope to a series of preset positions and triggering data capture at each stop. On February 14th, 2025, at 7am—when the Milky Way was ideally positioned—the script was called and moved the telescope with the Rotator-Controller library, collecting 19 points defined by galactic longitudes from 0° to 90° in 5° increments (all at galactic latitude 0°). While the Spectrum GUI continuously collects data, `Milky.py` calculates a wait time based on the maximum angular difference between the current and target pointing to ensure data is captured only when the telescope is stationary. The telescope is repositioned using the RotatorController, and at each position, the script calls the Receiver GUI to save the data; once all positions are observed, the telescope is returned to the zenith, or "straight up". The CRT was also manually pointed at Northeaster's Snell Library and data was similarly collected. This is used later for temperature calibrations.

3.2 Data Processing

This process generates a plot of spectral power versus frequency that reveals a prominent peak near 1420 MHz—the hydrogen line. Figure 4 shows Frequency vs. Power outputs for four of the nineteen observed points along the Milky Way. Although the shape of the peak varies slightly between positions—likely due

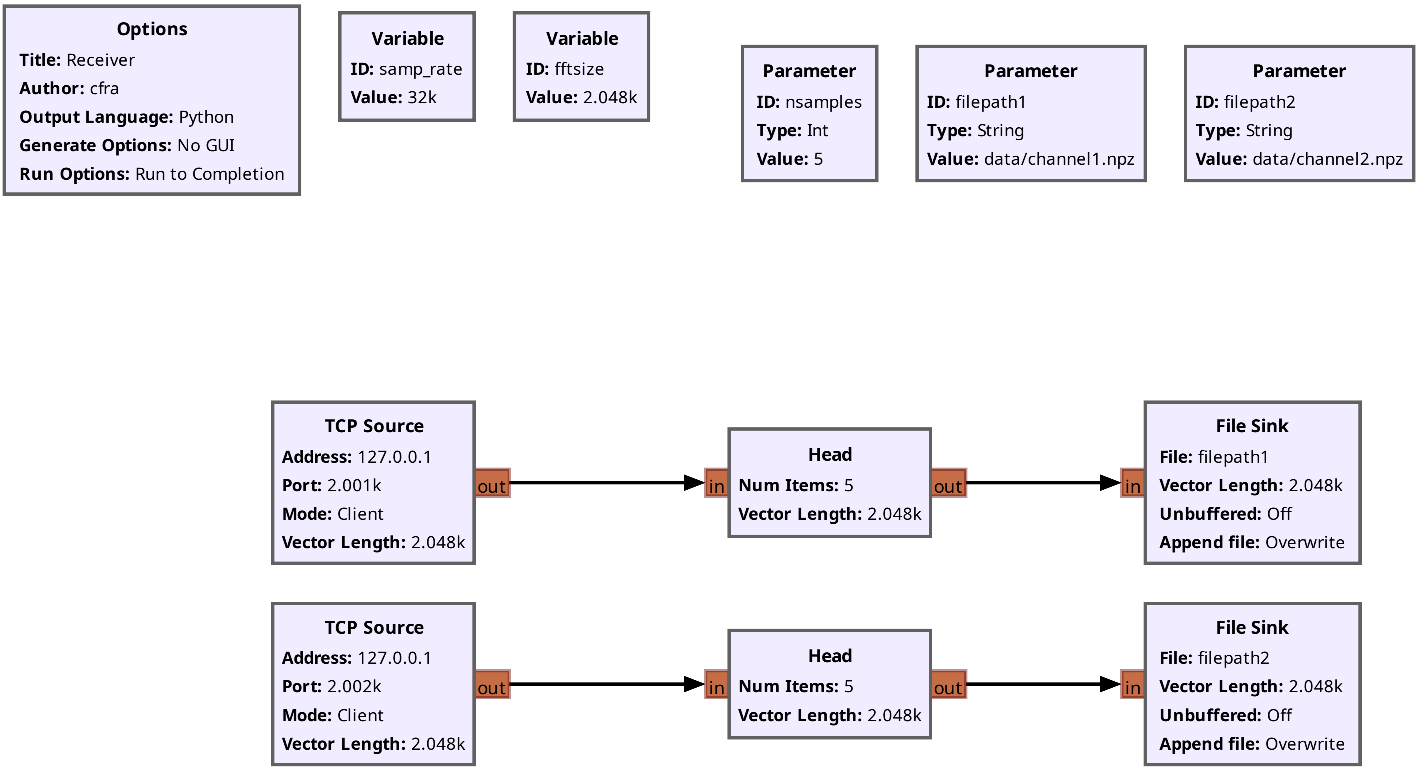

Figure 3: Receiver GUI

to local variations in hydrogen concentration—the central peak consistently appears around 1420 MHz. Additionally, sharp peaks near this central feature are likely due to interference from nearby electronics, such as signals from phone towers. Noise is mitigated using a median filtering function on the data.

The following subsections explain how outputs of Frequency and Power can be used to find velocity as a function of radius.

3.2.1 Frequency to Relative Velocity

The first step is to transform the frequency spectrum into a relative velocity spectrum. Due to the relative motion between the CRT and the hydrogen clouds, the observed frequency undergoes a Doppler shift, which directly reflects the clouds' speed. Equation 9 defines the relationship between frequency and relative velocity with $\beta = v/c$, where ν_0 is the rest frequency of 1420.4 MHz. When rearranged (as shown in Equation 10), this relation clearly isolates velocity, demonstrating that at 1420.4 MHz—where the ratio ν_0/ν equals 1—the relative velocity is zero. Any deviation from this frequency indicates that the hydrogen clouds are moving towards or away from the CRT, with the Doppler shift causing the frequency to increase or decrease accordingly.

$$\frac{\nu_0}{\nu} = \sqrt{\frac{1+\beta}{1-\beta}} \approx 1 + \beta; v << c \tag{9}$$

$$v = \left(\left(\frac{\nu_0}{\nu}\right) - 1\right) c \tag{10}$$

To accurately determine the intrinsic velocities of hydrogen gas in the galaxy, it is necessary to convert the

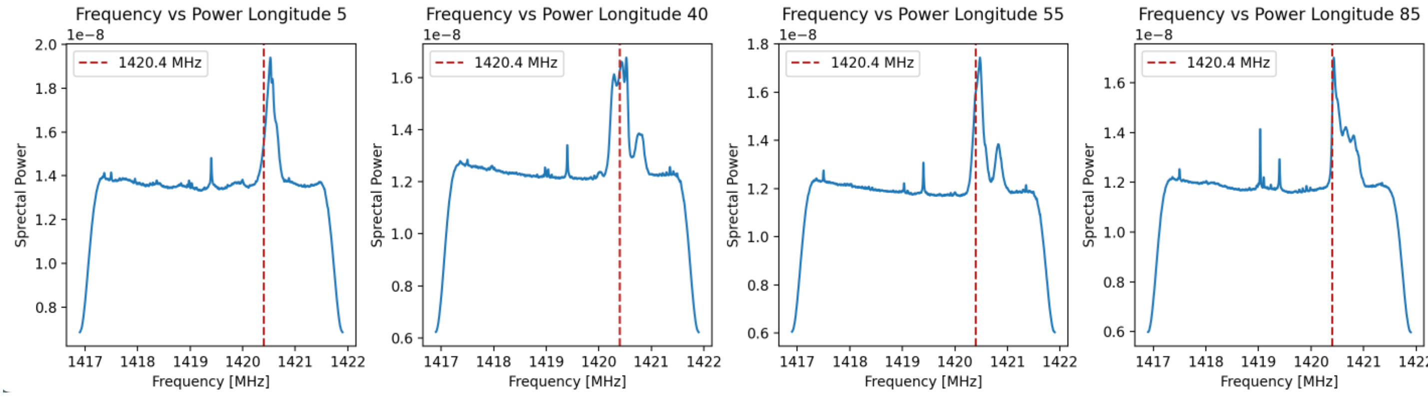

Figure 4: Frequency vs Power at varying Longitudes

measured velocities to the Local Standard of Rest (LSR). This conversion is essential because the observed velocities are influenced by Earth's rotation, its orbital motion around the Sun, and the solar system's movement relative to nearby stars. By converting these measurements to the LSR, these extraneous effects are removed, revealing accurate intrinsic velocities of hydrogen gas across the galaxy. The process, then, involves two corrections: one correction for the Earths motion around the Sun – known as a Barycentric correction – and one correction for the motion of the solar system with respect to the LSR[3]. The function `velcorr` performs the first step by calculating the barycentric radial velocity correction for a given observation time (`obstime`)—a critical parameter since Earth's rotation is time-dependent—and for a target specified in galactic coordinates (`L` and `B`). During the data collection process, a log file was created that logged the exact time at which each position was captured. This function utilizes Astropy's `radial_velocity_correction` method along with the CRT's location, computing the correction needed to account for Earth's motion relative to the barycenter. The values (U, V, W) = (11.1, 12.24, 7.25) km/s represent the solar system's motion relative to the barycenter. By taking the dot product of this velocity vector with the line-of-sight unit vector, the component of the solar system's velocity in that direction is calculated as $11.1\cos(\text{galactic longitude}) + 12.24\sin(\text{galactic longitude})$, which is then used to correct the observed velocities. Running these two corrections for each of the nineteen data collection positions fully transforms the frequency data to V_{LSR}, or the velocity relative to the Local Standard of Rest.

3.2.2 Temperature Calibration

The next processing step converts the measured y-axis power data—originally in arbitrary units—into a physical temperature. The power from the source is given by

$$P_{\text{source}} = G(T_{\text{source}} + T_{\text{sys}}) \tag{11}$$

where T_{sys} accounts for contributions like electronic noise and the CMB. Here, G is the conversion (or amplification) factor that translates temperature into power. G is determined using a two-point calibration::

$$G = \frac{P_{\text{hot}} - P_{\text{cold}}}{T_{\text{hot}} - T_{\text{cold}}} \tag{12}$$

In this calibration, T_{cold} is 10K (representing a cold sky) and T_{hot} is 268.15 K (the ambient sky temperature at the time of data collection). P_{hot} is measured using data from the Snell library wall—approximated as a blackbody—while P_{cold} is taken from a frequency other than 1420 MHz. Once G is determined, it can

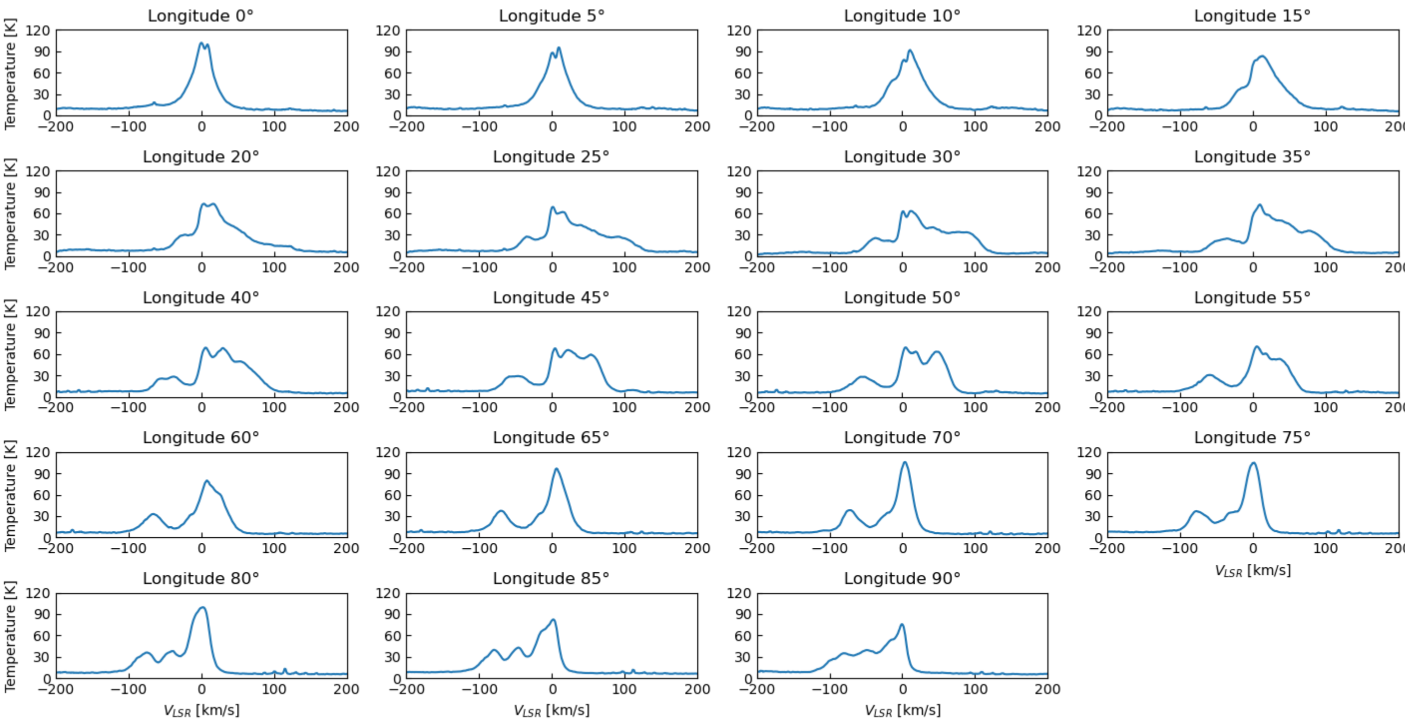

Figure 5: Relative Velocity vs Temperature

be applied to the raw power measurements to convert them into temperature, thereby providing a more meaningful physical interpretation of the data.

Altogether, converting frequency to relative velocity and power to temperature produces nineteen velocity–temperature plots, each peaking around 60–90 K at zero relative velocity, shown in Figure 5. These plots show how the 21 cm (neutral hydrogen) emission varies with radial velocity (relative to the Local Standard of Rest) at different galactic longitudes, providing a snapshot of the distribution and motion of interstellar HI along each line of sight. The distinct brightness-temperature peaks at various velocities indicate multiple gas clouds or spiral-arm components moving toward or away from us. As the galactic longitude shifts from 0° to 90°, the position and strength of these peaks change, reflecting the Galaxy's rotation and the varying column density of neutral hydrogen.

3.3 Rotation Curves

Finally, the data is in a place where it can be used to construct a rotation curve. The goal is to measure the velocity of the hydrogen clouds around the galactic center, noting the fact that the CRT, which resides in the solar system, is also itself rotating around the galactic center. Figure 6 illustrates this set up. Some simple trigonometry reveals that the velocity of a hydrogen cloud is given by:

$$v_r = \omega R \cos\left(\frac{\pi}{2} - (l+\theta)\right) - \omega_\odot R_\odot \cos(\frac{\pi}{2} - l) = R_\odot(\omega - \omega_\odot)\sin(l)^\ddagger \tag{13}$$

Naturally, objects farther from the Galactic center experience weaker gravitational forces and thus orbit more slowly. Because ω (the angular velocity) decreases with increasing radius R, the radial velocity

‡the $\odot$ notation is used to indicate that the variable that of the Sun

increases with R. Consequently, the largest v_r occurs at the smallest radius R, which—according to the schematic—is along the line of sight. Formally:

$$(v_r)_{\max} = R_{\odot}\big(\omega(R_{\min}) - \omega_{\odot}\big)\sin(l). \tag{14}$$

To find the maximum velocity at each longitude, it was visually determined where the HI hyperfine line disappears. Due to persistent radio frequency interference and non-flat baselines, a purely algorithmic approach is currently impractical, so this step relied on manual judgment.

The radius of the Sun is $R_{\odot} = 8.0 \pm 0.5$kPc, the Sun's orbital speed is $v_{\odot} = 220.0 \pm 10$km/s, and $(v_r)_{\max}$ is "eyeballed" for each longitude position. With this information, a radial velocity curve is constructed with proper error propagation, shown in Figure 8.

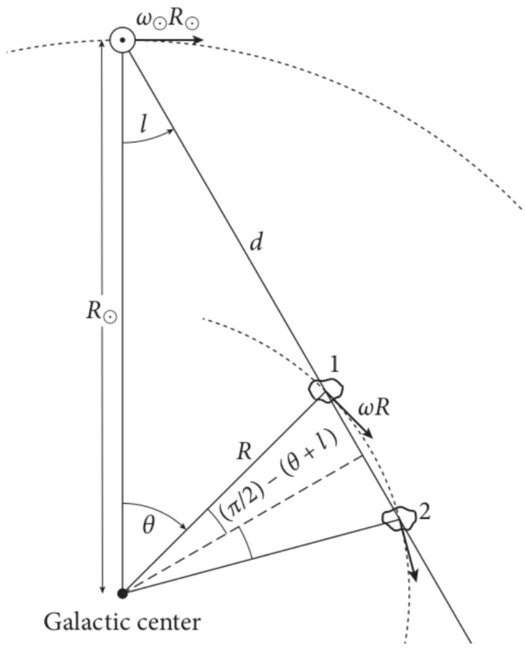

Figure 6: Circular trajectory of HI clouds in the Milky Way

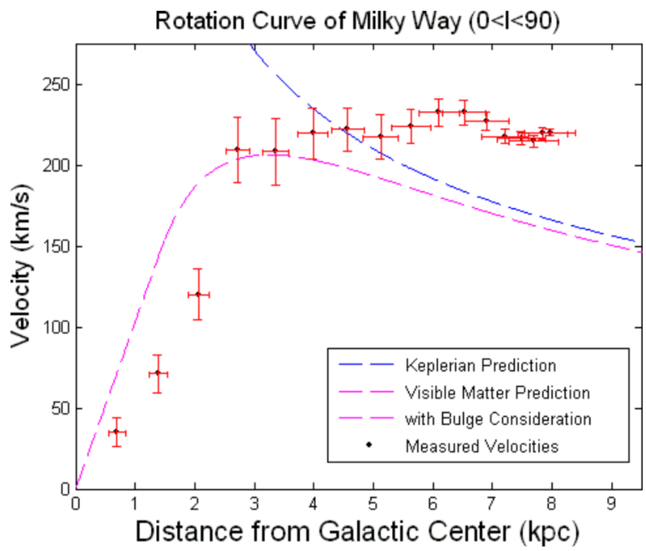

Figure 7: Rotation Curve from MIT study

4 Discussion

The velocity curve obtained in this study exhibits strong agreement with previous experimental findings[2], as illustrated in Figure 7. This consistency reinforces the reliability of these techniques. The most important takeaway from this experiment is that the velocity curve has a notably flat profile. As discussed in the introduction, this persistent flatness is one of the most compelling pieces of direct evidence for the presence of dark matter. The implication is that a substantial unseen mass component is exerting additional gravitational influence, preventing the expected decline in velocity. This phenomenon is not unique to our own Milky Way but has been observed across numerous spiral galaxies. In the 1970's, astronomers Vera Rubin and Kent Ford worked with high-precision optical spectroscopy to demonstrate that galactic rotation curves remained flat in other spiral galaxies aside from our own.

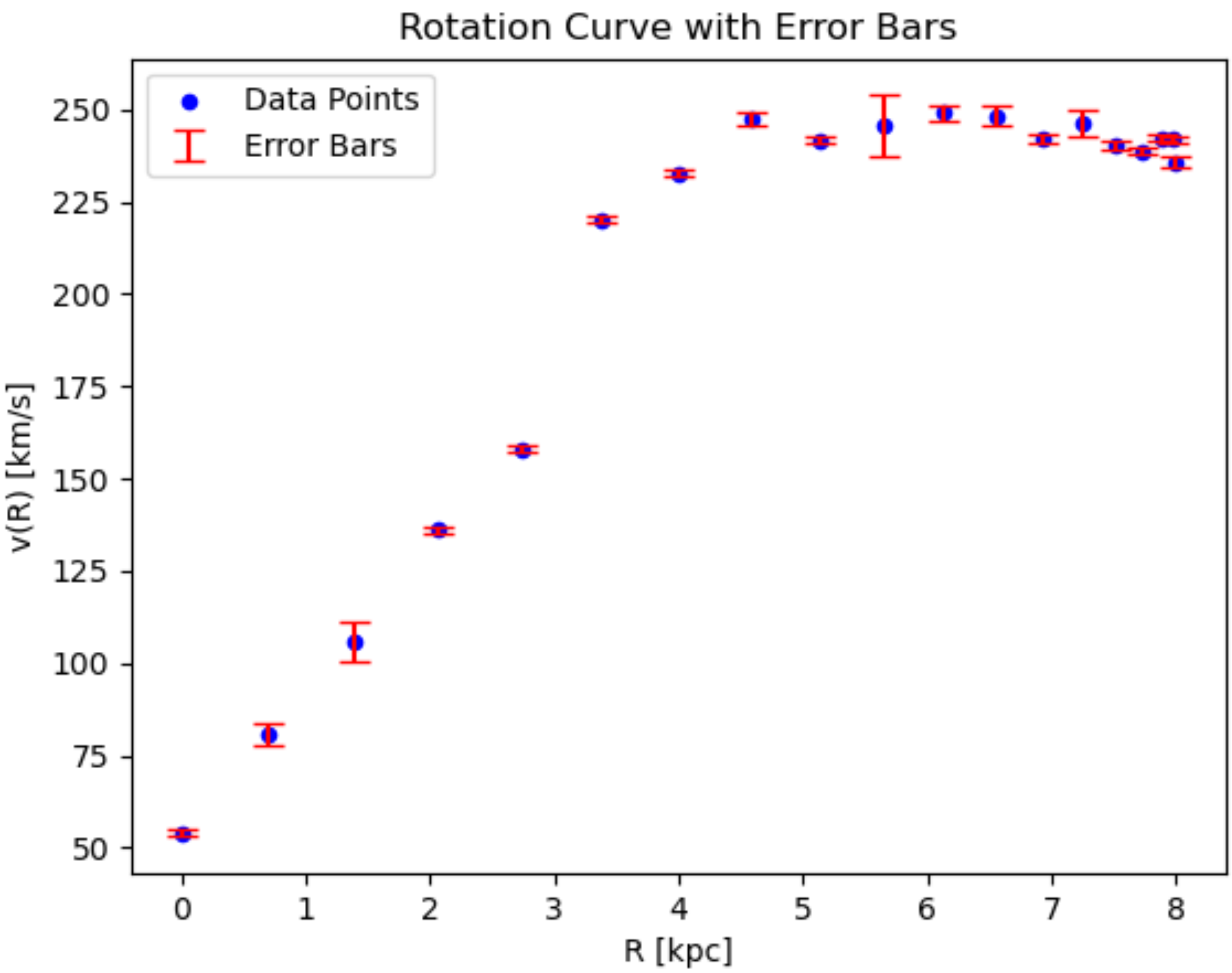

Figure 8: Rotation Curve of the Milky Way

5 Conclusion

This experiment reproduced foundational observations of the 21 cm emission from neutral hydrogen in order to derive the Milky Way's rotation curve. A radio telescope was used to collect the 21 cm emission, which corresponds to a frequency of about 1420 MHz within the radio domain. Two custom GUIs—titled Spectrum and Receiver—facilitated real-time signal processing by automating the radio telescope's rotation and handling data collection. Nineteen distinct points along the Milky Way were observed, all at galactic latitudes of 0° and galactic longitudes between 0°–90°. Acquisition yielded Frequency vs Power data, which was used to determine the velocity of interstellar hydrogen via Doppler shift. Then, two important velocity corrections were applied. First, a Barycentric correction removed the influence of Earth's orbital motion around the Sun. Second, the Solar System's motion relative to the Local Standard of Rest was taken into account, ensuring that all velocity measurements accurately reflected the intrinsic motion of interstellar hydrogen. Additionally, temperature calibration was performed using the Snell Library wall, which served as a blackbody reference to convert raw power values into brightness temperatures.

Index	**max_velocity**	**velocity_error**	**Longitude**	**Radius**	v**(R)**
0	54.029283	0.991773	0	0.000000	54.029283
1	61.548619	2.838297	5	0.697246	80.722883
2	67.556657	5.444904	10	1.389185	105.759256
3	79.279495	0.815385	15	2.070552	136.219685
4	82.802936	1.069402	20	2.736161	158.047368
5	127.239848	0.815663	25	3.380946	220.215866
6	122.750908	0.815649	30	4.000000	232.750908
7	121.240135	2.044034	35	4.588611	247.426951
8	100.233221	0.815551	40	5.142301	241.646495
9	89.873443	8.359741	45	5.656854	245.436935
10	80.584496	2.157541	50	6.128356	249.114273
11	68.055161	2.714228	55	6.553216	248.268611
12	51.482330	0.991909	60	6.928203	242.007919
13	46.771295	3.764716	65	7.250462	246.159008
14	33.730797	1.069234	70	7.517541	240.463173
15	26.204348	0.815259	75	7.727407	238.708030
16	25.556381	0.815273	80	7.878462	242.214087
17	22.839666	0.815276	85	7.969558	242.002499
18	15.706947	1.572407	90	8.000000	235.706947

Table 1: Measured velocities and derived galactic rotation values at various longitudes.

When these calibrated velocity profiles were plotted as a function of radius, the resulting rotation curve revealed velocities that remain nearly flat across large distances. This finding aligns with long-standing observational evidence that suggests the Galaxy is embedded in a massive, non luminous halo. Consistency with historical measurements affirms both the reliability of the 21 cm technique for probing galactic dynamics. However, refinements in interference reduction, as well as velocity peak identification, could enhance measurement precision and extend the scope of similar surveys. Nonetheless, these results underscore the fundamental conclusion: a significant mass component exists well beyond the visible boundary of the Galaxy, shaping its overall rotational behavior.

References

[1] H. I. Ewen and E. M. Purcell. Observation of a line in the galactic radio spectrum: Radiation from galactic hydrogen at 1,420 mc./sec., 1951. Accessed: 2025-02-18.

[2] Lulu Liu. The 21 cm line of neutral hydrogen, Accessed: 2025-02-18. Accessed: 2025-02-18.

[3] Northeastern University. Experiment 15: Mapping the Milky Way at 21cm, 2025. [Accessed: February 20, 2025].

[4] Physics LibreTexts. Hyperfine structure, 2025. Accessed: Feb. 20, 2025.

```python
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from scipy import ndimage

data00 = np.fromfile(open("./Capstone/Data/milkyway_0-2.npz"), dtype=np.float32)
data01 = np.fromfile(open("./Capstone/Data/milkyway_1-2.npz"), dtype=np.float32)
data02 = np.fromfile(open("./Capstone/Data/milkyway_2-2.npz"), dtype=np.float32)
data03 = np.fromfile(open("./Capstone/Data/milkyway_3-2.npz"), dtype=np.float32)
data04 = np.fromfile(open("./Capstone/Data/milkyway_4-2.npz"), dtype=np.float32)
data05 = np.fromfile(open("./Capstone/Data/milkyway_5-2.npz"), dtype=np.float32)
data06 = np.fromfile(open("./Capstone/Data/milkyway_6-2.npz"), dtype=np.float32)
data07 = np.fromfile(open("./Capstone/Data/milkyway_7-2.npz"), dtype=np.float32)
data08 = np.fromfile(open("./Capstone/Data/milkyway_8-2.npz"), dtype=np.float32)
data09 = np.fromfile(open("./Capstone/Data/milkyway_9-2.npz"), dtype=np.float32)
data10 = np.fromfile(open("./Capstone/Data/milkyway_10-2.npz"), dtype=np.float32)
data11 = np.fromfile(open("./Capstone/Data/milkyway_11-2.npz"), dtype=np.float32)
data12 = np.fromfile(open("./Capstone/Data/milkyway_12-2.npz"), dtype=np.float32)
data13 = np.fromfile(open("./Capstone/Data/milkyway_13-2.npz"), dtype=np.float32)
data14 = np.fromfile(open("./Capstone/Data/milkyway_14-2.npz"), dtype=np.float32)
data15 = np.fromfile(open("./Capstone/Data/milkyway_15-2.npz"), dtype=np.float32)
data16 = np.fromfile(open("./Capstone/Data/milkyway_16-2.npz"), dtype=np.float32)
data17 = np.fromfile(open("./Capstone/Data/milkyway_17-2.npz"), dtype=np.float32)
data18 = np.fromfile(open("./Capstone/Data/milkyway_18-2.npz"), dtype=np.float32)
snell = np.fromfile(open("./Capstone/Data/Snell2"), dtype=np.float32)

fft_size = 2048
def refit_data(data):
   data = data.reshape(-1,fft_size)
   data = 10**(data/10)
   data = ndimage.median_filter(data,7)
   data = data.mean(axis=0)
   return data

#files = os.listdir()

# print(files)

snell = np.fromfile(open("./Capstone/Data/Snell2"), dtype=np.float32)

logfile = pd.read_csv('./Capstone/Data/milkyway_obs_log.dat',sep=' ')
```

```
max_velocity = np.array([])
velocity_error = np.array([])

#getting P_hot from wall

fft_size = 2048

snell = snell.reshape(-1,fft_size)
snell = 10**(snell/10)
snell = snell.mean(axis=0)

P_hot = np.mean(snell[400:600])

T_hot = 268.15 #K (was 23 deg F when data taken)
T_cold = 10 #K

freq = np.linspace(1419.4-2.5,1419.4+2.5 , 2048) #defining frequency axis
# print(logfile)

# # print(files)
row = 0
column = 0

fig,ax = plt.subplots(5,4)
ax = ax.flatten()
for i in np.arange(0,19):
   for j in files:
#         print(i)
       if './Capstone/Data/milkyway_{}-2.npz'.format(i) in j:
#             fig,ax = plt.subplots()

           point_utc_time = logfile['utc_date'][i]+' '+logfile['utc_time'][i]
           galactic_lon = logfile['galactic_lon'][i]
           galactic_lat = logfile['galactic_lat'][i]

           data = np.fromfile(open(j), dtype=np.float32)
           fft_size = 2048
           data = data.reshape(-1,fft_size)
           data = 10**(data/10)
           data = ndimage.median_filter(data,7)
           data = data.mean(axis=0)
```

```
#           print(data)

            f0 = 1420.4 #MHz

            c =299792 #km/s
            beta = (f0/freq) - 1
            velocity= beta*c #km/s

            correction1 = velcorr(point_utc_time,galactic_lon,galactic_lat)

            correction2 = 11.1*np.cos(np.deg2rad(galactic_lon)) +
12.24*np.sin(np.deg2rad(galactic_lat))

            corrected_velocity = velocity + correction1 + correction2

            P_cold = np.mean(data[400:600])

            G = (P_hot - P_cold)/(T_hot - T_cold)

            Y = P_hot/P_cold

            Tsys = (T_hot - Y*T_cold) / (Y - 1)

            data_scaled = (data/G) - Tsys

            ax[i].plot(corrected_velocity,data_scaled,label = '{}
Longitude'.format(galactic_lon))
            ax[i].set_xlim(-200,200)
            ax[i].set_ylim(0,125)
            ax[i].set_xlabel('Relative Velocity [km/s]')
            ax[i].set_ylabel('Temperature [K]')
`           #ax[lookup[i][0]][lookup[i][1]].set_title(point_utc_time)
            #adding the two series to a dataframe to make processing a bit easier

            temp = pd.DataFrame()

            temp['Velocity'] = corrected_velocity
            temp['Temperature'] = data_scaled


            #calculating where the max velocity is
```

```
        #restricting to 0 to 150 km/s (just eyeballing where this is)

        temp2 = temp.loc[temp.Velocity > 0]
        temp2 = temp2.loc[temp2.Velocity < 150]


        #take 1st derivative
        temp2['first_deriv'] = temp2.Temperature.diff()
        #clean it a bit
        temp2['first_deriv_rolling'] = temp2.first_deriv.rolling(10).mean()

        temp2 = temp2.loc[temp2.Temperature < 10]

        temp2 = temp2.loc[temp2.first_deriv_rolling < 0.1]
        temp2 = temp2.loc[temp2.first_deriv_rolling > 0.0]

        temp2 = temp2.sort_values(by='Velocity')

        v_max = temp2.Velocity[:5].mean()
        v_err = temp2.Velocity[:5].std()


#           ax[i].scatter(temp2.Velocity[:5],temp2.Temperature[:5],zorder =
100,c='red',label = 'Avg = {}, {}'.format(v_max,v_err))
#           second_deriv = np.diff(first_deriv)

        ax[i].scatter(v_max,temp2.Temperature[:1],c='red',label = 'Avg = {:.2f},
{:.2f}'.format(v_max,2*v_err))


        max_velocity = np.append(max_velocity,v_max)
        velocity_error = np.append(velocity_error,v_err)

        ax[i].legend()
ax[19].axis('off')
df = pd.DataFrame()

Earth_radius = 8.0 #kpc
Earth_radius_error = 0.5 #kpc

Earth_velocity = 220 #km/s
Earth_velocity_error = 10 #km/s
```

```python
df['max_velocity'] = max_velocity
df['velocity_error'] = velocity_error
df['Longitude'] = np.arange(0,95,5)
df['Radius'] = Earth_radius*np.sin(np.deg2rad(df.Longitude)) #kpc
df['v(R)'] = df.max_velocity + Earth_velocity*np.sin(np.deg2rad(df.Longitude)) #km/s
fig,ax = plt.subplots()

ax.scatter(df.Radius,df['v(R)'],s=22)
ax.set_xlabel('R [kpc]')
ax.set_ylabel('v(R) [km/s]')
```