Observations of the 21cm Radiation from Neutral Hydrogen in the Milky Way.

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1 Abstract

Radio observations of the 21cm emission line from neutral hydrogen (HI) are indispensable tools in studying the structure and rotation of the Milky Way galaxy. Measuring the intensity of the 21cm line along a given line of sight makes it possible to determine the amount of HI in that direction, and observing the line's Doppler shift allows for the understanding of the radial motion of that quantity of HI. As such, the measurement and analysis of the 21cm line along different galactic coordinates provide a measure of the quantity of HI as well as the radial motion of HI along those coordinates. In this experiment, we measure the 21cm line with a 1.8m radio dish along several galactic coordinates in the Milky Way galaxy's Quadrants Ib and III. Using our measurements of the 21cm line, we calculate the column density of HI (a measure of the quantity of HI) along each coordinate's line of sight and note the Doppler shifts of the 21cm line for each observation.

2 Introduction

The 21cm emission line from HI is produced from the hyper-fine transition of spin states in the ground state of HI [1]. The energy of HI is higher when the spins of the proton and electron are aligned, so the atom will naturally transition to the lowest energy state where the spins are anti-aligned. This spin flip results in the emission of a photon with a frequency of 1.42 GHz, which is equivalent to a wavelength of 21.1 cm. HI is abundant in the galactic disk of the Milky Way, with a higher density in the galaxy's spiral arms [2]. Therefore, measuring the abundance of HI along various lines of sight is useful in determining the structure of the Milky Way galaxy.

The 21cm line can be used to calculate the column density (N_{H1}) of HI, which is a measurement of the density of HI gas along the line of sight of the observer, using equation (1) [3]

$$N = 1.8224 \times 10^{18} \int T_B(v)dv \tag{1}$$

where $T_B(v)$ is the brightness temperature, a measure of intensity, of the observed 21cm line.

In addition, by measuring the Doppler shift of the 21cm line at different galactic coordinates, we can determine the general direction of the galaxy's rotation by comparing the sections of the galaxy in which the 21cm line is blueshifted (and thereofore, moving radially toward Earth) and the sections of the galaxy in which the 21cm line is redshifted (and therefore, moving radially away from Earth).

In section 3, we describe the observational equipment and set-up used to measure the 21cm line at different galactic coordinates, explain the data processing to calculate the column density of HI at the aforementioned galactic coordinates in section 4, present the results of the data processing in section 5, and discuss the results of the data processing in section 6.

3 Observation

Observations for this experiment were made using a 1.8m radio dish mounted on the roof of the Baskin Engineering building on the campus of the University of California, Santa Cruz. The dish has been set up such that it points toward an hour angle (HA) of 1 with respect to local meridian in Santa Cruz [4]. This set up allows for the observation of targets one hour after they reach culmination (i.e. one hour after they have passed the local meridian). Observations of the Milky Way galaxy were taken in the morning to catch Quadrant Ib of the galaxy, and in the evening to catch Quadrant III of the galaxy. Table 1 provides the times of the morning and evening observations. The radio dish has a focal length of 0.648m, with a feed horn containing a quarter wave antenna placed at the dish's focus [4]. A low noise amplifier (LNA) is attached to the feed horn to amplify the signal from the antenna without causing major degradation to the signal's signal-to-noise ratio. A co-axial cable connects the feed-horn system to a spectrum analyzer. The analyzer sweeps through the signal from the co-axial cable at a rate of 1 sweep per second for frequencies at a resolution bandwidth (RBW) of 30KHz, and registers the power associated with each frequency within the signal. To mitigate the noise associated with each frequency's power reading, 300 scans are averaged together per observational run. For each observational run, the spectrum analyzer provides the averaged power associated with the corresponding frequencies in the signal for 461 frequencies [4]. Different observational runs record data from different galactic coordinates. The timing of each observation is listed in table 1, and the instrument parameters of the equipment used in this experiment is provided in table 2.

Table 1: End times of observation runs. During observations 1-6, we recorded quadrant Ib and during observations 7-15, we recorded quadrant III.

Observation Number	End Time of Observation (PDT)
1	07:14
2	07:25
3	07:32
4	07:37
5	07:43
6	07:49
7	16:40
8	16:54
9	17:00
10	17:06
11	17:11
12	17:17
13	17:23
14	17:29
15	17:35

Table 2: Instrument Parameters

Instrument Parameter	Value
Antenna Diameter	1.8m
Antenna focal length	0.684m
Antenna solid angle	0.110sr
LNA Gain	37dB
LNA Noise Figure	0.32dB
Cable type	LMR 400
Cable attenuation	3.0 dB
Central frequency	1420.4MHz
Resolution Bandwidth	30 KHz

4 Data Processing

In this section, we outline the process of calculating the column density of HI for each observational run.

4.1 Unit Conversions and Corrections

For each observational run, the data is recorded as 461 individual measurements of frequency in megahertz (MHz) and power in decibel-milliwatts (dBm). We used equation 2 to convert from dBm to watts. To convert from RBW to Hz, we divided by 30,000 Hz which is given by the equipment in table 2.

$$W = 10^{\frac{dB}{10}} \tag{2}$$

To estimate the total power reaching Earth we must make corrections due to our equipment. Some signal is lost due to the cable attenuation of 3 dB. We converted this to watts and then multiplied our signal by this to increase the total signal. The LNA gain increases our signal so that we can detect it better, so we must reduce by its value of 0.32 dB converted to watts and then divide our signal by that to reduce it. Finally, our antenna is only sensitive to one polarization of light, so to capture the total power we multiply our signal by 2. Now we have the total power reaching the ground in W/Hz.

4.2 Calculating Column Density

We first calculate the background signal by fitting our data to a Gaussian distribution. Then we remove the baseline from the signal. This is now the power delivered to the amplifier, $\frac{dP}{df}$. We then calculate the brightness distribution (eq 3) [4] and brightness temperature (eq 4) where $\beta = 0.5$ is the absorption coefficient, λ is the 21cm line wavelength, and k_B is Boltzmann's constant.

$$B = \frac{\frac{dP}{df}}{\beta\lambda^2} \tag{3}$$

$$T = \frac{\frac{dP}{df}}{2\beta k_B} \tag{4}$$

Then we calculate the relative velocities of the signals using equation 5 where λ is again the 21cm line and Δf is the difference between the recorded signal and the peak signal.

$$v = -\lambda \Delta f \tag{5}$$

Finally, we are able to calculate column density N with equation 6 where the integral was done numerically as a summation of all 461 data points.

$$N = 1.8224 \times 10^{18} \int T(v)dv \tag{6}$$

4.3 Errors

The background signal error applies equally to all points. This is calculated by taking the residual between the Gaussian fit and the data points for just the background sections of our signals. We defined this and everything 3σ or greater away on either side of the peak. This is $\sigma_{dP/df}$. Then we used equation 4 to calculate σ_T. Finally, we used equation 7 to calculate the total error on column density. All σs are equal, so that is why the formula simplifies to the total points n times σ_T.

$$\begin{gathered} \sigma_N = C\sqrt{\sum_i \sigma_{T,i}^2} = C\sqrt{n\sigma_T^2} \\ C = 1.8224 \times 10^{18} \cdot \Delta v \end{gathered} \tag{7}$$

5 Results and Analysis

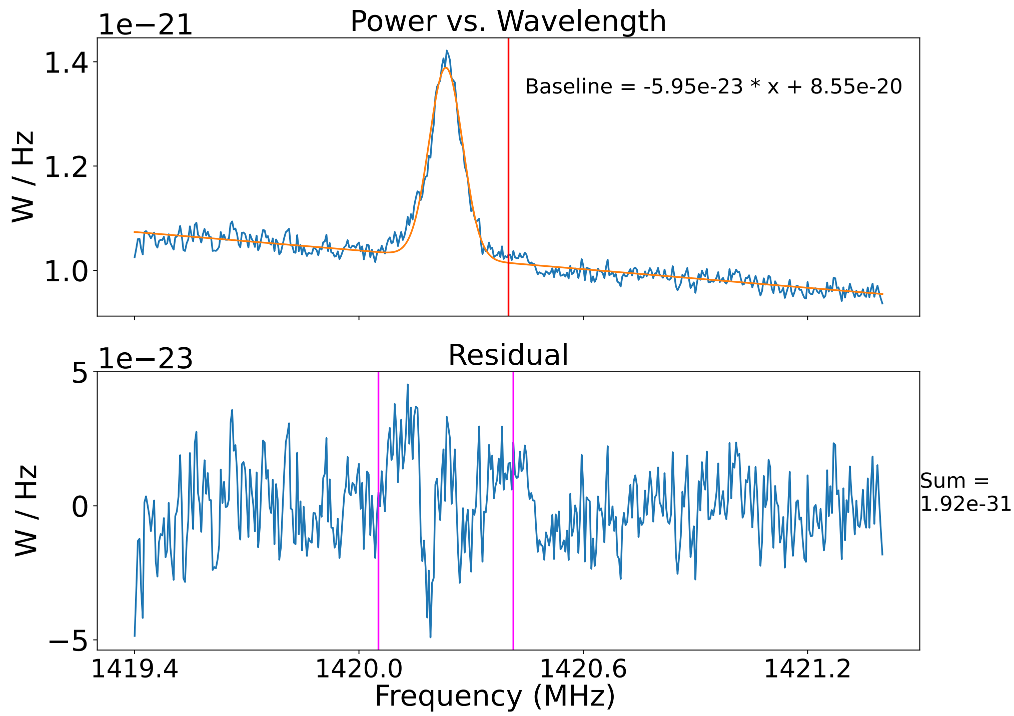
The calculated column densities are given in table 3 for each observation. Figure 2 presents these values in a plot. Figure 1 shows an example of an observation from a) the morning and b) the afternoon. These are runs 4 and 12 respectively. In the upper plot of each the raw data is shown in blue, the Gaussian fit is in orange, and the red line shows where we expect the peak to be. The baseline is from the fitted Gaussian and represents the background signal. In the lower plot is the residual between the data and the fit, with the sum on the right end of the graph. The purple lines mark the 4σ points of the fit. When estimating the background, we only calculated it using points outside of the middle region, ie all points that were more than 4σ away.

Table 3: Calculated galactic coordinates and column density for each observation. Column density is given per cm^2.

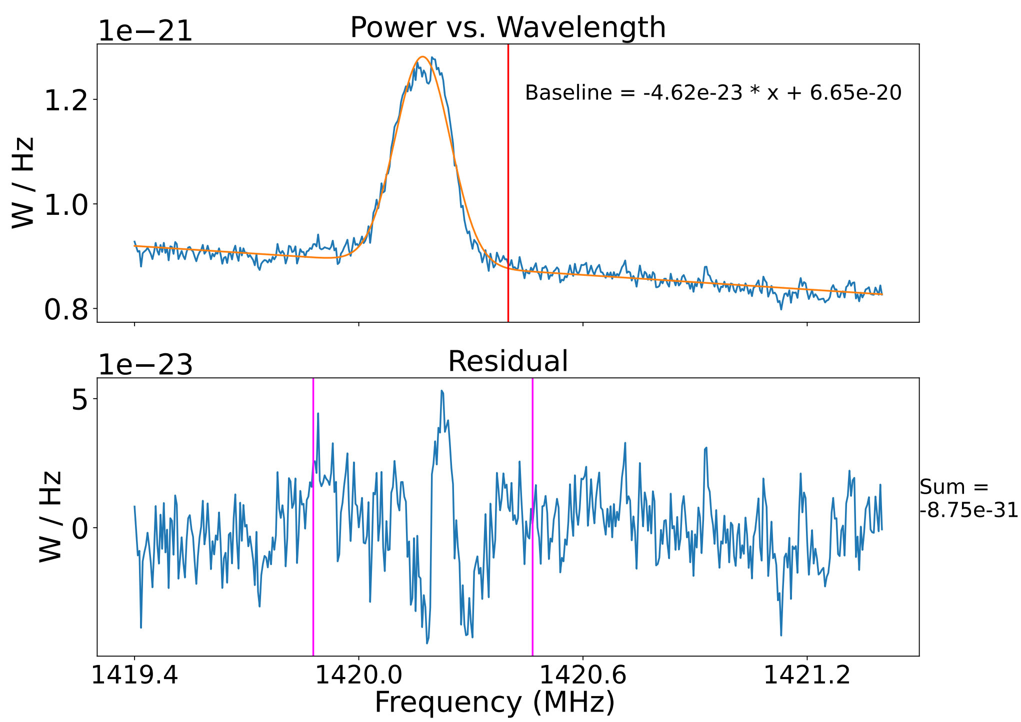
Run	Galactic Coordinates (l,b)	Column Density (cm^2) $\times 10^{20}$
1	74.364, -18.027	8.164 ± 1.814
2	77.734, -21.287	6.696 ± 1.422
3	78.797, -22.229	6.448 ± 2.046
4	79.886, -23.152	7.351 ± 1.583
5	81.002, -24.057	7.527 ± 1.393
6	82.143, -24.942	5.319 ± 2.010
7	208.388, 1.164	11.351 ± 0.443
8	209.972, 4.285	15.238 ± 0.470
9	210.650, 5.623	17.136 ± 0.534
10	211.328, 6.963	18.818 ± 0.603
11	211.894, 8.079	19.796 ± 0.380
12	212.574, 9.419	20.334 ± 0.364
13	213.257, 10.759	19.489 ± 0.439
14	213.943, 12.099	18.544 ± 0.420
15	214.633, 13.439	16.822 ± 0.362

6 Discussion

In table 4, we present the column density values provided by NASA [5] through past radio surveys of the Milky Way galaxy for the coordinates of our observations. In comparing the values of Table 4 to Table 3, we see that the column densities calculated in this experiment for the morning observational runs align well with the column densities provided by NASA for those coordinates. In fact, with the exception of the fourth morning observational run, all of the column density values provided by NASA are within the error range of the corresponding column density values calculated in this experiment. The NASA value for the fourth observational run is just slightly outside the lower bound of the corresponding calculated value's error range, and well within two standard deviations of the calculated value.

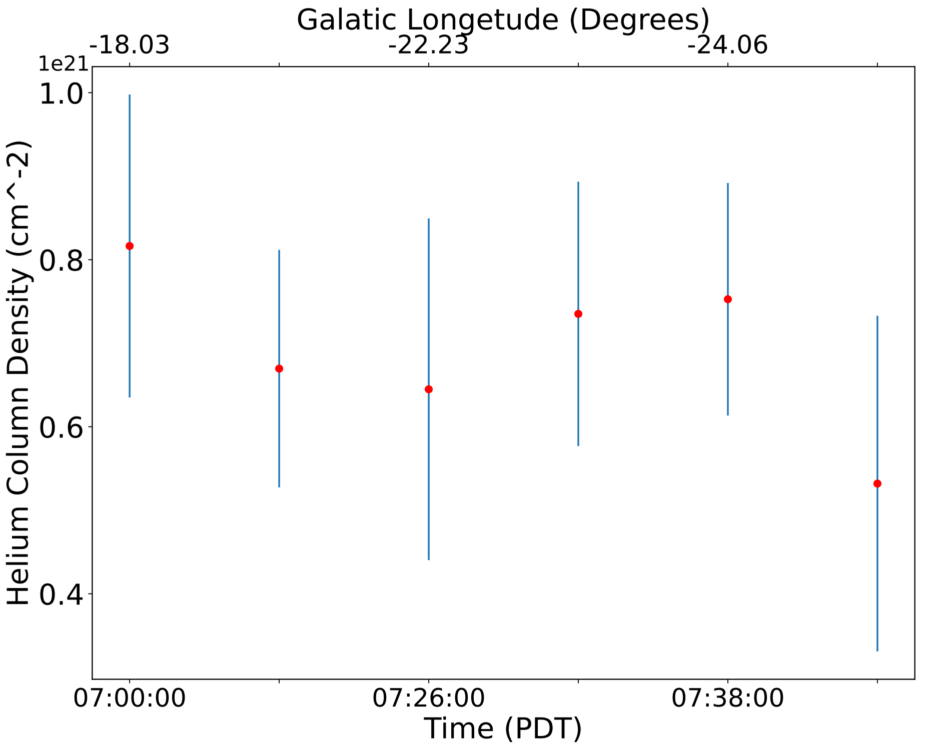


(a) Observation 4 from the morning.

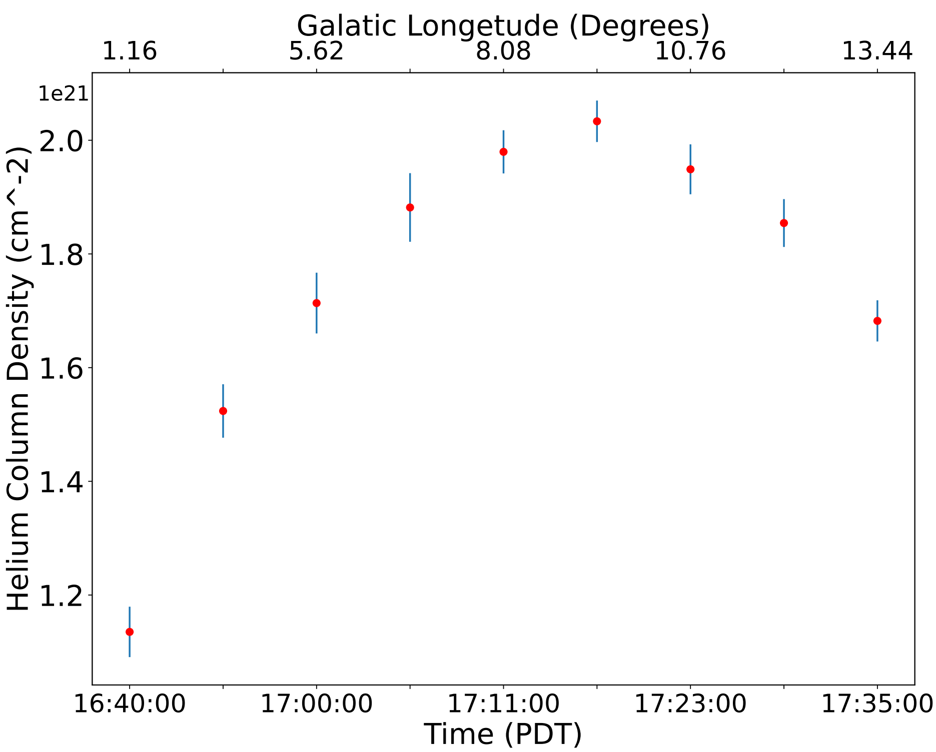


(b) Observation 12 from the afternoon.

Figure 1: Example plots of the data. The upper plot shows the raw data in blue, the fitted Gaussian in orange, the expected position of the peak with a red line, and the baseline linear equation of the Gaussian. The lower plot shows the residual with the 4σ points marked in purple.



(a) Morning Observations.



(b) Afternoon Observations.

Figure 2: Column density progressions for the morning and afternoon.

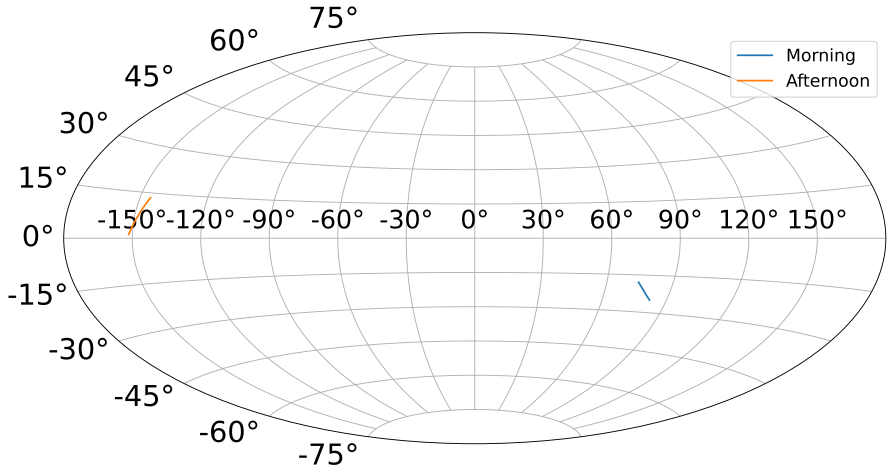


Figure 3: A skymap of where the observations took place. The blue curve shows the span of the morning observations and the orange curve shows the span of the afternoon observations.

However, we notice some stark discrepancies in comparing the calculated column densities of the afternoon observational runs with those of the corresponding NASA values, with the NASA values falling far outside the error bounds of the calculated values. In addition, it is interesting to note that while the calculated column density values increase with each observational run in the afternoon, the corresponding NASA values demonstrate the opposite trend and decrease. Since each subsequent observational run (both in the morning and afternoon) results in measuring data further away from the galactic plane, a trend of decreasing column density should be expected with each subsequent observational run per session. We observe that this trend holds true for the morning observational runs, but not for the afternoon observational runs.

A reason for the discrepancy between our column density and NASA's is that the calculations for galactic coordinates could be wrong. Looking at Figure 2b, we see that the peak density is around 9°, but we should expect it to be around 0°, since that is where the density of HI is greatest in the galaxy. This would also match the rise and fall on either side of the peak as we enter and exit the galactic plane. Therefore, it appears that we are approximately 9° off in our calculation of galactic coordinates. This would also mean we are off in the morning as well, but the effect is smaller there because the dish was already pointed so far from the galactic plane, that the density in that region is lower and less vari-

Table 4: Column density from NASA matching our observation coordinates.

Run	Galactic Coordinates (l,b)	Column Density (cm^{-2}) $\times 10^{20}$
1	74.364, -18.027	7.79
2	77.734, -21.287	5.86
3	78.797, -22.229	5.53
4	79.886, -23.152	5.67
5	81.002, -24.057	6.25
6	82.143, -24.942	6.54
7	208.388, 1.164	53.7
8	209.972, 4.285	32.2
9	210.650, 5.623	24.0
10	211.328, 6.963	17.7
11	211.894, 8.079	14.5
12	212.574, 9.419	12.0
13	213.257, 10.759	9.35
14	213.943, 12.099	7.55
15	214.633, 13.439	5.94

able. For example, from table 4, we see that far from the plane the density changed by around 0.75×10^{20} cm^{-2} in 6°, whereas near the plane the density changed by approximately 50×10^{20} cm^{-2} in 12°. This leads us to believe the galactic coordinate calculations were incorrect and we in fact did pass through the galactic plane in the afternoon observation.

Looking at Figure 1a, we see that the 21cm line is observed at a higher frequency compared with its rest frame frequency for the morning observational runs. Since frequency is inversely proportional to wavelength, the 21cm line is therefore observed at a lower wavelength compared with its rest frame wavelength in the morning runs and is therefore blueshifted. We note that the morning observational runs took measurements from Quadrant Ib of the Milky Way. If the 21cm line from this quadrant of the galaxy is blueshifted, this means that Quadrant Ib is moving radially toward Earth. Further, extending this analysis toward measurements from the afternoon observational runs, we see that the 21cm line is measured at a lower frequency – and therefore a higher wavelength – compared with its rest frame measurements, and is therefore redshifted. Since afternoon observational runs took measurements from Quadrant III of the Milky Way, and the observed 21cm line from this quadrant is redshifted, Quadrant III is moving radially away from Earth. The radial movement of Quadrant

Ib toward Earth and the radial movement of Quadrant III away from Earth is explained by the fact that the Milky Way galaxy is rotating about its center, with the mass in Quadrant Ib rotating toward Earth, and the mass in Quadrant III rotating away from Earth.

7 Acknowledgements

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References

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