Reconstruction of M31 Velocity Dispersion & Neutral Hydrogen Column Density

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(Dated: June 9, 2021)

Radio astronomy provides an extremely powerful lens into the depths of the cosmos: whether one probes the Sun, the Galactic Center, pulsars, clusters of galaxies, super-massive black holes (anything that produces radio emission, you name it), radio telescopes allow for the reconstruction of crucial aspects of cosmic entities. In this paper, we will observe scans of the hydrogen hyper-fine line for a distinct swathe of our galaxy (58.8°, -2.6°) and quantify the neutral hydrogen column density thereby. We implement a Gauss-Newton least squares algorithm to subtract background from our raw observations of amplitude turned brightness temperature. Upon fitting a Gaussian to our Doppler-broadened velocity dispersion, we find that $\sigma = 13.79, \bar{v} = -1.54$, with $\chi^2 = 1.026$. Integrating over velocity space, our data resolves the galactic hydrogen column density to be $2.198 \times 10^{20}\ cm^{-2}$, which differs by roughly an order of magnitude from NASA data [3][4][1].

I. INTRODUCTION

Radio telescopes are used to process emission signals emanated by Bremsstrahlung radiative processes, SNR, synchrotron radiation, line emission from low energy transitions, as well as blackbody radiation to a high precision. Sources of radio span across all walks of the cosmos: our own Sun, AGN, jets, the Galactic Center, puslars, supernova remnants, HII regions, star formation (molecular lines from cold gas). HI observations even allow us to probe the spiral structure of the Milky Way and rotation curves of distant galaxies!

While providing a stellar method of exploring the outer reaches of space, there are limitations: the radio window stretches over several decades in frequency (5 MHz to 300 GHz), but is limited by ionospheric reflection at the low end and water/carbon-dioxide absorption at the high end. Thus, we can only probe such a span of wavelengths from the surface of the Earth.

Atmospheric noise proves to be a worthy problem with water attenuating radio, oxygen causing the sky to become opaque around its rotational transition frequency. The atmosphere itself also emits radio noise dependent on local temperature and opacity, while cosmic microwave background (CMB) yield a very large source of noise in its limited range [5]. Worst of all are man-made radio interference effects on astronomical observations.

In this paper, we are to detect the hydrogen hyper-fine line, representing a distinct latitude of the galaxy in the neighborhood of the galactic longitude that we chose.

A. Hydrogen 21-cm Line

While typical electron transitions in hydrogen give photons in UV (n=1), optical (n=2) and infrared (n=3), spin coupling of the proton and electron yields a hyperfine line at 21 cm or 1.4 GHz [2]:

$$hf = \frac{8}{3}\alpha^4(2.79)\frac{m_e}{m_p}m_ec^2 = 5.90 \times 10^{-6}eV \tag{1}$$

As a temperature, this energy corresponds to 0.068 K, making higher energy states easily excited by collisions. In reality, the rate of spontaneous transitions is 10^7 years, making for a good assumption that half of our observed hydrogen atoms are in this excited state.

Antenna diameter	1.8 meters
Antenna focal length	0.684 meters
Antenna solid angle	0.0110 sr
LNA Gain	37 dB
LNA Noise Figure	0.32 dB
Cable type	LMR 400
Cable attenuation	3.0 dB

Table I. Component specifications.

Central frequency	1420.4 MHz
Resolution Band Width	30 KHz
Span	2 MHz
Dwell time per sweep	1 second
Attenuation	0 dB
Display reference level	-100 dBm
Display sensitivity	1 dB/division
L_{avg}	300 sweeps

Table II. Data acquisition parameters.

B. Error & Statistical Methods

Our radio telescope is, by no means, perfect. Using a radio dish on the roof of the Baskin Engineering Building (UCSC), the feed looks like a glorified coffee can and the amplifiers are delicate. Despite this, we are still able to

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retrieve valuable data relating to the cosmos, to our host galaxy.

In radio astronomy, noise sources are typically given in terms of temperature. The noise power is compared to a resistor at some temperature T, whose thermal noise would equate to the power per unit bandwidth of the source (Nyquist formula):

$$\begin{aligned} P_\nu &= k_B T \\ T_N &= \frac{P_\nu}{k_B} \end{aligned} \tag{2}$$

The system noise temperature is the total noise power from all possible sources. Receiver temperature and associated noise can be minimized by cooling the receiver to cryogenic temperatures: unfortunately, we do not have access to this type of lab equipment so we instead continue with error analysis.

We assume the background distribution of counts in our data roughly follows a Poisson distribution such that we can obtain fit statistics with $\sigma \approx \sqrt{N}$, where N is the number of counts.

When presented with the radio .csv data, we quickly transform amplitudes to temperatures, frequencies to velocities. More relevant to this section, we employ a Gauss-Newton least squares fit to subtract background noise and subsequently isolate the peak. It is crucial to note that because of this step (as well as a multitude of other contributing errors), we unintentionally cut off portions of the Gaussian distribution modeled in Fig. 2. Chi-square test values are quoted in Sec. III.

In total, we will discuss the underlying concepts behind the radio astronomy we've conducted in Sec. I, describe our analysis process and provide specifications for the lab equipment utilized in Sec. II, disclose our results in Sec. III, as well as provide concluding remarks in Sec. IV.

II. APPARATUS AND PROCEDURE

Radio waves are detected by their alternating EM field which excited an AC field inside the detector; thus, we characterize them based on amplitude, frequency, and (most important for interferometry) phase.

A. Brightness Temperature Conversion

The spectrum analyzer detects the power present for a given configuration in the confines of each Resolution Bandwidth (RBW) interval. Note that during our experiment, we had an RBW value of 30,000 Hz. Since we wish to convert the spectrum analyzer's power to a brightness temperature, we must trace back the signal to its original source, accounting for all possible sources of noise:

1. **Conversion to dBm to milliwatts per RBW:** our spectrum analyzer yields power/RBW for a given input in units of dBm. We utilize $P = 10^{(dBm/10)}$, where P is in milliwatts.

2. **Conversion from milliwatts per RBW to Watts per RBW:** multiply by a factor of 10^{-3}.

3. **Conversion to unit Hz bandwidth:** Watts per Hz = $(1/RBW)\times$(Watts per RBW).

4. **Cable attenuation:** Knowing that $dB = 10 \log P_{in}/P_{out}$, we correct for attenuation in the 60 foot cable with specifications defined in Tab. I.

5. **Input power to pre-amplifier:** Trace signal strength to the input of the low noise amplifier by dividing LNA gain (given in Tab. I).

6. **Correction for polarization:** Our feed-horn is only sensitive to one of two polarizations of EM waves.

7. **Conversion to brightness distribution:** Now we have dP/df! Let's make the approximation that our observed hydrogen cloud is diffuse enough such that it is roughly uniform over the angular spread of the antenna's diffraction cone. Here, $B(f, \mathbf{n}) = (1/\beta\lambda^2)(dP/df)$, where $\beta = 0.5$ assuming optimum impedance matching.

8. **Conversion to brightness temperature:** The low frequency approximation of the Planck function states $T_B(f, \mathbf{n}) = \lambda^2 B(f, \mathbf{n})/2k_B = (dP/df)/2\beta k_B$. This will yield a brightness temperature in Kelvins at each frequency point.

B. Spectrum Fitting

It is necessary to fit the background and get an accurate reading on the Hydrogen 21-cm line.

At this point, we have converted our spectrum to brightness temperatures: Using .csv data taken from the Agilent Spectrum Analyzer, we analyze and implement a Gauss-Newton algorithm to subtract all unwanted noise from the peak (Fig. 1).

Next, we should model the neutral hydrogen line with a Gaussian function, as it encompasses its behavior quite well. In Python, we use the scipy.optimize library to efficiently discover parameters describing the standard deviation, mean, as well as norm of our data spread and subsequent function fit.

Before we can calculate the hydrogen column density, we need to ensure that our frequencies are converted to a velocity distribution. To convert frequency to proper velocity, we translate values according to the Doppler formula:

$$
\begin{aligned}
f &= f_0 \frac{\sqrt{1-\frac{v}{c}}}{\sqrt{1+\frac{v}{c}}} \approx f_0 \left(1 - \frac{v}{c}\right) \\
&\Rightarrow \frac{f-f_0}{f_0} = \frac{\Delta f}{f_0} = -\frac{v}{c} \\
&\Rightarrow v = -\lambda \Delta f
\end{aligned} \tag{3}
$$

By convention, red-shifted (receding) matter is conventionally defined as having *positive* values. The width of the fitted Gaussian in velocity space indicates the velocity dispersion of the neutral gas along our line of sight.

We are now able to calculate the hydrogen column density $N(\mathbf{n})$, units of cm^{-2}, by numerically integrating the following:

$$
\begin{aligned}
N(\mathbf{n}) &= 1.8224 \times 10^{18} \int T_B(v; \mathbf{n}) dv \\
&\approx 1.8224 \times 10^{18} \sum T_B(v; \mathbf{n}) \Delta v
\end{aligned} \tag{4}
$$

where T_B is in Kelvins and Δv is step size in km/s. We note that a code library such as sympy greatly streamlines the integration process.

To compare our results with NASA data, we recruit the help of measured and tabulated galactic hydrogen column densities from earlier surveys [3][4][1]. First, we obtain the RA of our local meridian:

$$
\begin{aligned}
RA_{Sun} &= 24h\,(N-80)\,/365.25 \\
LST &= RA_{Sun} + \alpha
\end{aligned} \tag{5}
$$

Note that α is the local time of observation. In our case, we observed from 12pm to 1pm (May 12, 2021), roughly speaking. This range of times provides a subsequent range in RA of the meridian (51.3° - 66.3°).

Plugging this into NASA's online resource [6], we can easily obtain an expected hydrogen column density. Later comparison in Sec. III will allow for identification of systematic error and exact calibration.

III. RESULTS AND DISCUSSION

Upon conducting data analysis in Python with our radio telescope's observed values, we obtain the parameters for our Gaussian in velocity space (χ^2=1.026): $\sigma = 13.79, \bar{v} = -1.54, A = 0.0083$, where σ is our standard deviation, $\bar{v}$ is our mean velocity, and A represents the normalization constant of our Gaussian fit (Fig. 2).

This directly indicates the velocity dispersion of neutral gas along our line of sight in the Galaxy!

Now, invoking Eq. (4), we calculate the associated hydrogen column density $N(\mathbf{n})$ by integrating our Gaussian model over all velocity space (T_B in Kelvins, $dv = \Delta v$ in km/sec) and are left with a value of 2.198×10^{20} cm^{-2}.

This seems reasonable, but let's confirm with NASA data. Assuming an observation time of 12:30pm (May 12, 2021) and looking at Eq. (5), one can calculate our right ascension (RA) to be 58.8° with known declination (Dec) of -2.6°.

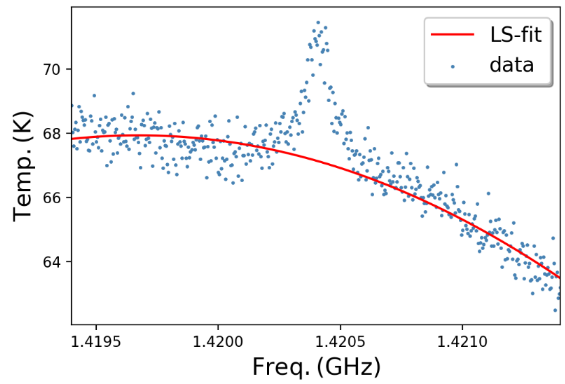

Figure 1. Raw data converted to brightness temperature versus frequency of binned radio signal. LS-fit depicts the Newton-Gauss Least Squares fitting implemented.

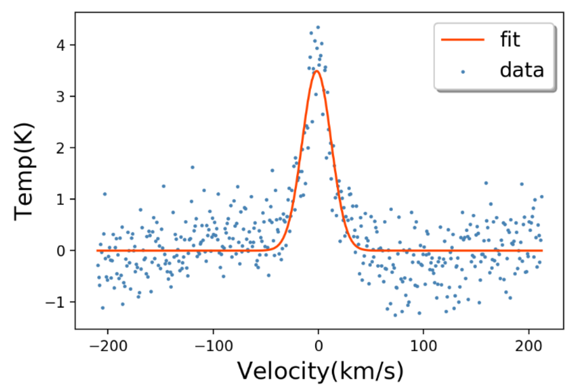

Figure 2. Brightness temperature (noise-reduced) in Kelvins versus neutral hydrogen, relative velocity in km/s. The red fit line highlights the Gaussian model established for the background-subtracted data.

Within a 0.1 degree cone search radius, [6] yields an average nH (cm^{-2}) of 1.8×10^{21}. Comparing to our own rounded, hydrogen column density of 2.2×10^{20} (cm^{-2}), we note that our column density is systematically low by slightly over an order of magnitude. This can be attributed to unavoidable losses in the system that we cannot possibly isolate with the equipment at hand.

IV. CONCLUSIONS

We have successfully recovered a line-of-sight, neutral hydrogen column density for coordinates (58.8°, -2.6°) observed on May 12, 2021 (12:30pm). Furthermore, we reconstructed a velocity dispersion plot illustrating the Doppler broadening of the 21-cm line (Fig. 2). The width of this line gives us an indication as to the speeds range, motion and dispersion of gas within our radio telescope's view.

As of now, we can only say that the 21-cm line was observed to have $\bar{v} = -1.54$, implying that our column of cold gas was blue-shifted relative to our motion. Further research must be conducted to infer detailed information as to the global distribution of neutral hydrogen within M31, as well as calculations to describe the motion of the gas in its entirety.

ACKNOWLEDGMENTS

SE is a part of the ASTR 135, Advanced Laboratory course. None of this information is presented for journal publication, only for writing improvement.

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