Observing the 21 cm Spectral Line using a Radio Telescope

Aaron Dubois*

Swarthmore College

(Dated: March 19, 2025)

Abstract

We explored using Swarthmore's new radio frequency telescope in the Peter van de Camp Observatory. The telescope is still in the process of being calibrated and had not detected the Sun before this lab. The goal of this lab was to verify that we could detect the desired H1 line with our radio telescope and to detect this emission from the Sun. We successfully detected our own dipole antenna in the desired frequency range, before pointing our telescope at the Sun. We then measured the emission spectrum of the Sun and analyzed the resulting data to validate that we had seen the H1 line from the Sun. The resulting peak was more than 8 standard deviations away from the average noise, and the FWHM of the peak indicated Doppler-shifted speeds that correspond to the rotation of the Sun.

* adubois1@swarthmore.edu

I. INTRODUCTION

This lab was focused on detecting the H1 (also known as neutral hydrogen) spectrum of the Sun using Swarthmore's new radio frequency telescope in the Peter van de Camp Observatory. The telescope is still in the testing phase. The results we obtained will aid in the telescope becoming fully operational. Detecting the H1 line of the Sun is important because we can determine the distribution of hydrogen in distant galaxies and celestial bodies. Once we are confident that we can detect the Sun, we can begin to use the telescope for other such observations. In this lab, we confirmed that we could detect radiation around the H1 line using our own signal generator and antenna before detecting the H1 emission of the Sun. The methods and analysis confirming our detection of the Sun are discussed in detail.

II. THEORY

A. H1 Emission

The H1 line or 21 cm line is a spectral line that is produced by the spin-flip transition of the electron of a hydrogen atom [1]. A wavelength of 21 cm corresponds to a frequency of 1.42 GHz. This frequency can easily pass through the Earth's atmosphere and be observed. From measuring the H1 line, we can predict the distribution of hydrogen in distant celestial objects.

B. Angular Size of an Object

The angular size of an object is the amount of the angular space that the object takes up relative to our 2π radians of possible angular space. In this estimation, we are finding the angular size as the diameter of the object. Thus, we use the one-dimensional radians instead of solid angles and steradians. The angular size θ_{size} is given by equation 1.

$$\theta_{size}[radians] = \frac{diameter}{distance} \tag{1}$$

We can use equation 1 to find the angular size of the Sun given that the distance to the Sun is $\approx 149.6 \times 10^9$m and the diameter of the Sun is $\approx 1.39 \times 10^9$m. This gives us that the angular size of the Sun is 0.93×10^{-3} radians.

C. Resolution of a Telescope

The ability to resolve a telescope depends on the wavelength of light and the diameter of the aperture. Equation 2 gives the smallest angular size that we can resolve with a telescope [2]. By resolution, we mean the smallest angle where we can distinguish two point sources of light. The Rayleigh criterion defines this limit as stating that two sources are resolvable once the center of one diffraction pattern aligns with the first minimum of the other. This limit gives us the following equation,

$$\theta_{res}[radians] = 1.22 \times \frac{\lambda_{obs}}{d} \tag{2}$$

where λ_{obs} is the observed wavelength of light, and d is the diameter of the aperture of the telescope.

Swarthmore College's radio telescope has a dish diameter of 3.2 meters, and we are investigating the wavelength of 21 cm, so our angular resolution is $1.22 \times \frac{0.21}{3.2} = 0.08$ radians or 4.58 degrees which is notably larger than the angular size of the Sun indicating that we will not be able to distinguish between different parts of the Sun without sophisticated methods.

III. EXPERIMENTAL METHODS

A. Finding Power against Angle of the Dish

We first used a Siglent SSG3032X Signal Generator and a 6cm dipole antenna (shown in Figure 1) to generate electromagnetic radiation at 1.4 GHz approximately 3 meters from the radio telescope. We then pointed our dish directly at the dipole antenna. We turned the dipole antenna so that its highest intensity of radiation was pointed at the dish. We then used a Siglent SSA3032X Plus Spectrum Analyzer to measure the maximum power in dBm seen by the radio telescope. We used coaxial cables, a band-pass filter, an amplifier, and 10 second time average to detect a readable signal for power on the spectrum analyzer. We then repeatedly changed the angle of the radio telescope by 5 degrees and remeasured the

FIG. 1. Image of Siglent SSG3032X Signal Generator, Siglent SSA3032X Plus Spectrum Analyzer, Swarthmore's Radio Telescope, and other electronic equipment.

maximum time-averaged power for every 5 degrees from 45 to 135 degrees where 90 degrees indicated directly at the antenna.

B. Finding Power against Frequency

We used a nearly identical setup as when we found the power with respect to the angle of the dish, but this time, we generated signals from 1.1 to 1.9 GHz with 0.1 GHz intervals. However, because the telescope was equipped with a narrow band pass filter, we could not observe significantly interesting data.

C. Finding the H1 Line of the Sun

We used the shadow of the telescope's feedhorn to align the telescope towards the Sun. When the shadow was minimized in size, we reasoned that the telescope was pointing in our desired direction. We used SDRangel software (displayed in Figure 2) to record the data from the telescope as we pointed it at the Sun.

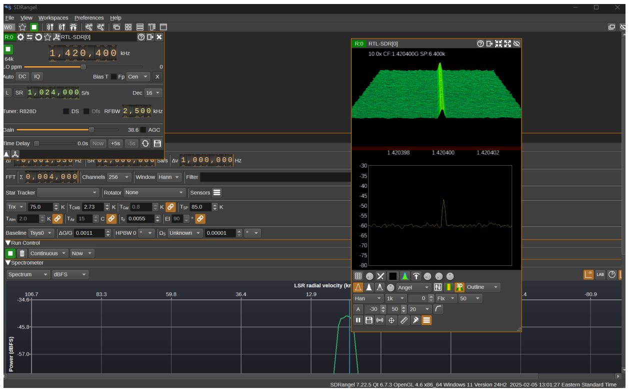

FIG. 2. Screenshot of the SDRangel software used to collect the data that shows the H1 line of the Sun. In the upper right, it can be seen that the H1 peak was clearly visible in a plot of time-averaged power at each frequency.

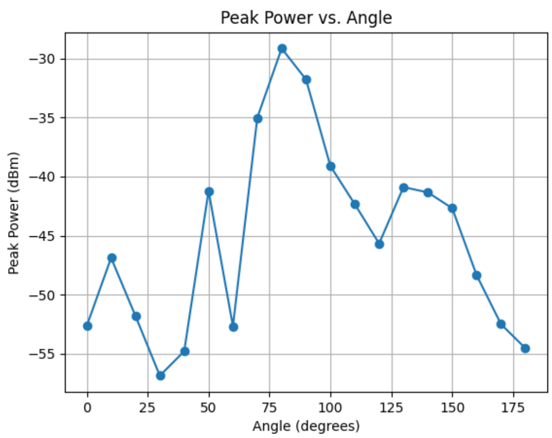

FIG. 3. The peak time-averaged power measured at each angle of the dish is plotted in dBm. This data results from our 6 cm dipole antenna that was placed around 3 m from the dish.

IV. RESULTS AND ANALYSIS

A. Finding Power against Angle of the Dish

Figure 3 shows the peak time-averaged power from our 6 cm dipole antenna that emits 1.4 GHz EM radiation. Although there is significant noise, the general trend appears to be that as the dish is pointed further away from 90 degrees, the intensity decreases. This makes sense as the effective cross-sectional area of the dish decreases as it turns away.

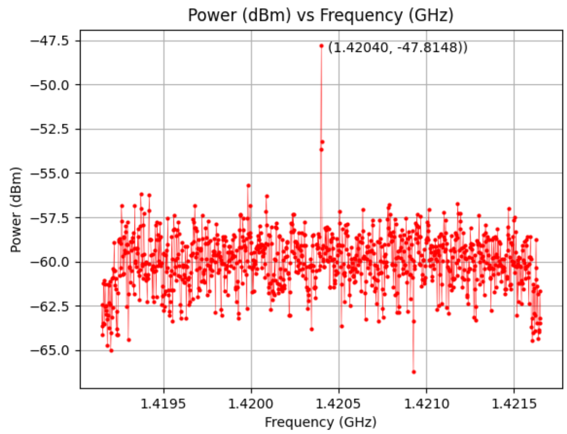

FIG. 4. The power at each frequency is plotted as the telescope is directed at the Sun. The H1 emission line is observed as a peak relative to noise.

B. Finding Power against Frequencies emitted by the Sun

Figure 4 shows the time-averaged power over 10 seconds at each frequency between 1.41915–1.42165 with a bin size of approximately 2.5 KHz. A peak can clearly be seen at 1.42040 GHz. This is precisely where we would expect the H1 emission line to be which is strong evidence by itself that this is the H1 line.

C. Validating our detection of the H1 Line

To validate that our observation is actually the H1 Line, we performed a statistical analysis to see if we can be confident that the peak is not random noise, and we calculated the rotation speed of the Sun using the width of the peak and Doppler techniques.

First, by removing the 24 bins closest to the peak, the remaining emission-free frequencies have an average noise of -60.0337 dBm with a standard deviation of 1.5139 dBm. The peak, -47.8148 dBm, is thus 8.07 standard deviations away from the average noise. This is significantly different and very unlikely to be noise. This is very strong evidence that the peak is not random noise.

Now to calculate the rotational speed of the Sun, we found the full width half max (FWHM) of the peak shown in Figure 4. As seen in Figure 5, the FWHM of the peak is approximately 5.3 KHz. This was calculated by linear interpolating between the points

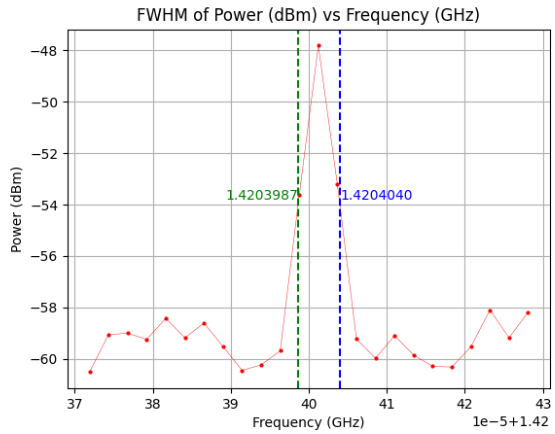

FIG. 5. Power plotted against frequency for 24 closest bins to the peak frequency for power. The vertical lines indicate the frequencies for an estimated FWHM where the lines connecting the points have been linear interpolated.

closest to the peak. From the relativistic Doppler equation in terms of frequency, we can calculate the rotation speed of the Sun. In the following calculation, we calculate the blue Doppler shift of the Sun spinning towards us. We assume that we can take the distance between the earth and Sun as fixed.

$$\frac{f_{shifted}}{f_{source}} = \frac{\sqrt{1+\beta}}{\sqrt{1-\beta}} \tag{3}$$

where $f_{shifted} = 1.42040624\,\mathrm{GHz}$ is the observed frequency of light (the approximate frequency where there is zero intensity from the H1 emission in Figure 5), $f_{source} = 1.42040122\,\mathrm{GHz}$ is the observed peak frequency, and $\beta = \frac{v}{c}$.

Solving for v, we find a speed of roughly $1060\,\frac{m}{s}$. Now, estimating the Sun's period around its axis as 35 days $= 3 \times 10^6\,\mathrm{s}$, and the radius of the Sun to be $700 \times 10^6\,\mathrm{m}$, we can solve for a $v_{expected}$ that corresponds to the Sun's velocity at its surface. Using $T = \frac{2\pi}{w}$, $w \approx 2.1 \times 10^{-6} \frac{[radians]}{s}$. So $v_{expected} = R_{sun} w \approx 1460 \frac{m}{s}$. This is more than our Doppler calculated velocity, but a reasonable order of magnitude for an estimate. The difference in values could be due to us using a period of 35 days whereas the Sun's period changes across its body. This calculation supports our conclusion of H1 line detection from the Sun, but is far from definitive. However, in combination with our other evidence–the peak is statistically significant compared to noise; the peak is precisely where the H1 line has been historically determined–is convincing enough for us to conclude that we detected the Sun.

V. CONCLUSIONS

In conclusion, we demonstrated that we could receive a signal from a 6 cm dipole antenna in the frequency range we desired, found the variation in the power received from the antenna as we changed the dish's azimuthal angle, and performed the first validation of the telescope's ability to detect the Sun's H1 emission line. We also calculated the angular size of the Sun, the resolution of our telescope, the noise in our H1 line detection data, and the Doppler shifted rotational speed of the Sun. Most significantly, we helped establish confidence in the functionality of the telescope.

Our results strongly indicate a successful detection, but repeated measurements could be beneficial to ensure accurate results. Future work could include further observations of the Sun, observations of other celestial bodies, and detections of other spectral lines. Overall, we achieved an important step towards establishing Swarthmore's radio telescope as a reliable research tool.

---

[1] D. J. Griffiths, "Introduction to quantum mechanics," (Pearson Education, 1995) Chap. Hyperfine Splitting.

[2] "College physics," (OpenStax, 1995) Chap. Wave Optics.