Using HI Emission to Map the Magellanic Stream

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Abstract

The Magellanic Stream is a stream of gas clouds located between the Milky Way and the surrounding Magellanic Clouds. The gravitational force exerted by our galaxy on the larger Magellanic Clouds has caused gas to spill from these clouds and form a stream about half-way around our rotating galaxy. To understand the velocity and density distributions of these clouds, we observed spectra from the stream focused particularly at the 21-cm line, where we expected to see a signal associated with the emission of atomic hydrogen at approximately 1420.41 MHz.

We discovered that the average peak of our signal was about 1321.29 MHz, though the median was closer to 1420.67 MHz. This implied that there were clouds within the Magellanic Stream experiencing a significant level of Doppler red shift. Accordingly, we measured an average Doppler shift in velocity of -84.09 km/s, indicating that the clouds in the stream were receding as expected. Using this information, we were able to estimate the column densities of atomic hydrogen in the clouds and discovered that the two most dense portions of the stream were those with Doppler shifts of -50 km/s and -150 km/s.

1 Introduction

This report concerns itself with the methods taken by our lab group to determine various characteristics of the Magellanic Stream. Though our mapping of the stream is incomplete, we observed enough data to estimate the distributions of column densities and cloud velocities to our expectations.

Section two of the report covers the pointing of the telescope. It includes an overview of the scripts used to both operate the Leuschner telescope and format our data. Also in this section, is a plot exemplifying one of our many observed spectra. Section three covers the the analysis of our data. This includes the work required to determine our final cloud velocities and column densities. Section four concludes the paper and provides necessary acknowledgements.

2 Pointing the Telescope

2.1 Scripts

We used three different scripts in observing the Magellanic Stream. The purpose of the first script was to point the telescope and collect the data. This proved rather difficult considering that we had to use larger exposure times to really capture our signal. Furthermore, the Leuschner telescope was only able to observe the stream for roughly 6 hours a day, making our data significantly smaller with larger exposure times. To allow for enough data collection, we in turn limited our exposure time to 2 minutes rather than the recommended 10 minutes. This allowed us to capture 24 hours of data as opposed to 52 hours, but with the signal still very much present. To prevent duplicate sets of data, we titled our data-files according to their galactic coordinates and implemented a function in our script that verified whether or not a data-file had already been collected. As recommended, we followed galactic coordinates $\ell = 60° \rightarrow 110°$ and $b = -90° \rightarrow -30°$ with pointings spaced at $2°$, allowing us to capture a total of 806 pointings.

The second and third scripts were used to manipulate the data collected by the first. With the Leuschner telescope programmed to capture data every 0.7 seconds, this amounted to about 170 spectra per 2 minutes of exposure time. Script two was a data reduction function that summed the polarization of each of these spectra in the pointing, compiling them into a single spectra per pointing. The third script used these compiled spectra to find the peak frequencies which would later be used to determine the Doppler velocities.

3 Analysis

3.1 Measuring the Baseline

Determining a baseline for our data was only the first step in measuring the various characteristics of the stream. To do so, we applied a Savitzky-Golay Filter to each of our spectra and assumed a third-degree polynomial - this was to account for the galactic coordinates and our third measured value. Figure 1 below illustrates the power spectra of our first successful pointing. The signal was measured at 1420.67 MHz, a +0.26 MHz deviation from the expected HI emission line and one of the few associated with a Doppler blue-shift. The calibrated power spectrum yielded a brightness temperature of approximately 0.003 K after removing the baseline, which is significantly low but indicative of the faintness of the Magellanic Stream. It is important to note that this temperature could be affected by factors such as ISM when considering the large 160,000 light year distance from Earth to the Magellanic clouds.

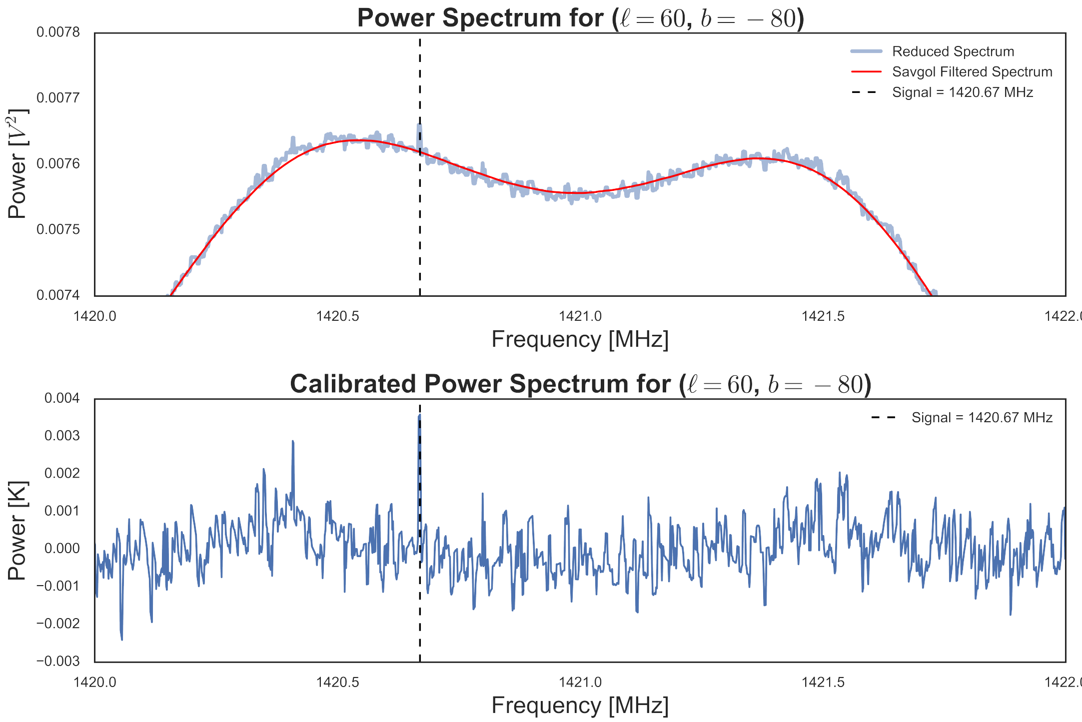

Figure 1: This figure illustrates two plots: the above showing the power spectrum as a function of frequency, and the lower showing its calibrated spectrum as a function of frequency. The dashed line in both plots indicate where the signal was measured, at 1420.67 MHz. The fitted line in the above plot represents the baseline for our spectrum, modeled using the Savgol Filter. The calibrated plot below is the power spectrum plotted with the baseline removed.

Averaging over all spectra, we found the approximate brightness temperature to be somewhere about 0.002 K, not far from the peak shown in the plot above. Additionally, we measured the mean and median of our peak frequencies to be 1321.29 MHz and 1420.67 MHz respectively, hinting that our signal shown above was not reflective of the heavy red-shift occurring throughout the stream.

3.2 Cloud Velocities

Mapping the clouds of the Magellanic Stream with their corresponding Doppler velocities helped us understand how fast they were moving and in what direction. By designing a 31x26 matrix filled with our pointings, were able to assign to each index of that matrix a Doppler velocity that corresponded to a particular shade in a blue-to-red color scale. The positive values were associated with the color blue, whereas the negative values were associated with the color red - both indicative of their relative Doppler velocity calculated using Equation 1.

$$\nu_{Dopp} = \frac{\nu_0 - \nu}{\nu_0} c \tag{1}$$

Setting ν_0 to be the expected 1420.41 MHz, we calculated an array of Doppler velocities that ranged from -527.94 km/s to 255.66 km/s. The average Doppler velocity was measured at -84.09 km/s, just outside our expected range of -400 km/s to -100 km/s. This deviation from the expected range can be attributed to a few different factors, some of which include our incomplete observation of the entire stream and the influence of ISM in the distance between us and the Magellanic Clouds. Figure 2 below shows a contour plot of the measured Doppler velocities in relation to their location on the galactic sphere.

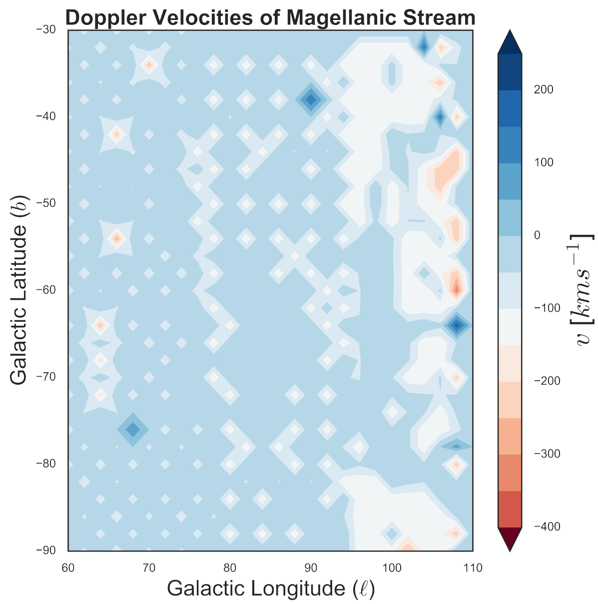

Figure 2: This figure illustrates the distribution of cloud Doppler velocities across the Magellanic Stream. The most abundant velocities range from 200 km/s to just under 400 km/s. Most of the fluctuations occur around $\ell = 60°$ and $\ell = 110°$, one possibly an indication of the stream's tail.

We were able to infer from this plot that the vast majority of the clouds in the Magellanic Stream experienced a Doppler red-shift. It was also evident that fluctuations in velocity increased around the perimeter of the stream. This should make sense assuming that the more dense clouds are located near the center, as they are expected to gravitationally attract more gas.

3.3 Column Densities

Measuring the column density of the clouds, we were able to deduce the direction of material flow throughout the Magellanic Stream. What we discovered was that the most dense portions of the stream were red-shifted by either -50 km/s or -150 km/s as shown in Figure 3. This implied that the bulks of the clouds were moving away from the Milky Way, while the less dense clouds were responsible for the few measured blue-shifts. We expect this to be true provided that the universe is expanding rather than contracting. The blue-shifts associated with the relatively less dense clouds could be explained by the Milky Way's gravitational acceleration exerted on the material that is subsequently incapable of remaining gravitationally bounded.

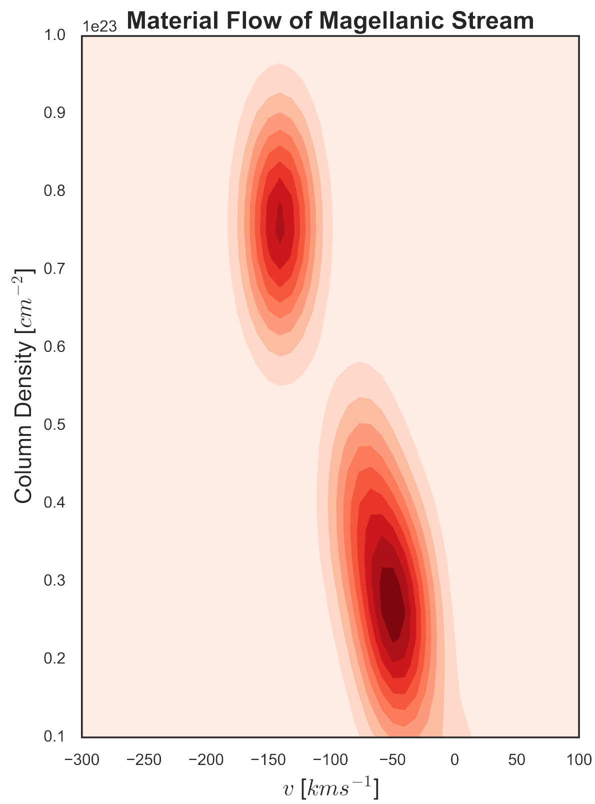

Figure 3: This figure illustrates the correlation between the directional flow of atomic hydrogen in the Magellanic Stream and its corresponding column densities. The darker regions indicate a higher degree of correlation, meaning most of the clouds in the stream are characterized by these values. Altogether, the plot tells us that the most dense portions of the stream are receding so as to create a Doppler red-shift. The vast majority of the cloud seems to be characterized by a column density of about $0.3 \times 10^{23} cm^{-2}$ that is red-shifted by -50 km/s.

Equation 2 was used to calculate the various column densities of the cloud.

$$N_{HI} = 1.8 \times 10^{18} \int T_B(\nu) \Delta\nu cm^{-2} \tag{2}$$

T_B represents the average brightness temperature, and $\Delta\nu$ represents the measured Doppler shift as a function of peak frequency. By assuming that the area of the beam was filled entirely by the source, we used Equation 3 to reason that the temperature of the antenna was equivalent to that of our measured brightness temperature.

$$T_A \approx T_B \frac{\Omega_s}{\Omega_s + \Omega_b} \tag{3}$$

Ω_s and Ω_b represent the solid angle of the source and beam respectively. When Ω_s is significantly larger than Ω_b, as was in our case, the fraction can be reduced to 1 thus equating our two temperatures. Our resulting column densities ranged from $16.11 \times 10^{19} cm^{-2}$ to $22.51 \times 10^{22} cm^{-2}$, with the vast majority in the upper range as shown in Figure 3.

4 Conclusion

Of a total 806 pointings, we were able to successfully measure data from 465. This was a big shortcoming in our research but still a difficult task to tackle. With so little time to observe and so much data to capture, we were limited in the analysis of our data. The issues concerning the functionality of the Leuschner telescope only made our problems worse. Nevertheless, we were able to correctly identify a signal for the 21-cm line and worked with our spectra to develop a series of color-maps that achieved the goal of this lab. In the future, we may consider taking much more time to measure as well as reverting back to the recommended 10 minute exposure times.

4.1 Acknowledgements

Much of this lab revolved around our data acquisition. Arthur was responsible for the pointing script, while we combined efforts to design scripts two and three for data analysis. Oscar was responsible for matrix structuring and preliminary mapping, while Romain focused on the Savgol filtering method outlined above as well as a few edits in the scripts. My role in the group was to calculate Doppler velocities and design an appropriate mapping to Oscar's coordinate matrix.