Mapping the Magellanic Stream

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Abstract

The Magellanic Stream is a stream of high-velocity clouds of gas visible near the southern pole of our galaxy, with LSR velocities ranging from around -400 to +300 km/s. This hydrogen gas comes from the small and Large Magellanic Clouds, nearby dwarf galaxies that are part of the Local Group. These clouds emit radio waves which are weak but detectable using our radio antenna at Leuschner. In this paper we attempt to image a portion of the Magellanic Stream using the radio dish at Leuschner Observatory, measuring gas velocities via Doppler shifting of the hydrogen 21cm line.

1 Introduction

In this paper we aim to measure the LSR (Local Standard of Rest) velocities and masses of the hydrogen clouds that make up the Magellanic Stream. The gas stretches for at least 180 degrees across the sky. This corresponds to 180 kpc at an approximate distance of 55 kpc. The gas is polar with respect to the Milky Way. The velocity range is huge (from 400 to 400 km s1 in reference to Local Standard of Rest) and velocity patterns do not follow the rest of the Milky Way. Hence, it was determined to be a classic high-velocity cloud. Section 1 outlines our methods for observation. In Section 2 we go over the specifics of our survey area and our observing setup. Section 3 details our data reduction and analysis methods, while Section 4 goes over our results. In Section 5 we discuss our results and conclusion.

2 Observing

Our survey area focuses primarily on the blue-shifted portion of the Magellanic Stream, covering a pizza shaped region of the sky ranging from -90 °to -30 °in Galactic latitude b and 60 °to 110 °in Galactic longitude l. To sample this section of sky, we follow the usual criterion of two samples per HPBW (half power beam width). For the radio dish at Leuschner, the HPBW is approximately four degrees. Accordingly, we selected our observing points to be on a square grid (in equatorial coordinates), with a uniform spacing of two degrees between adjacent points.

The specifics of our observing setup are listed in Figure 5. The Leuschner dish is a 30-inch radio dish supported by an alt/az mount, and is able to measure both horizontal and vertical polarization's of incoming RF signal. Each polarization is passed through a separate sequence of components, consisting of amplifiers/alternators (to boost the signal and cut transmission line noise) and band-pass filters. Each polarization is then mixed up to optical frequency and transported across fiber optic cable to the rest of the observatory, where the signals are mixed back down to radio frequency, mixed again with a variable LO of 1270 to 1272MHz, integrated for 0.7 seconds, and then Fourier Transformed via a ROACH board. The great thing about the ROACH board is that we can read power spectra directly from it, which saved us a huge headache.

To achieve integration times longer than 0.7 seconds, we simply track the desired point in the sky and take multiple individual power spectra, which we then sum up over all spectra for that point. Tracking while taking data might seem simple, but we will outline our difficulties of this in section 2.2. For our observations we chose to sum up two minutes of observing spectra, which generated enough signal to use for our analysis. We confirmed this while comparing the signal strength to the signal produced by the center of our galaxy.

2.1 Determining Pointing Targets

We followed the recommended galactic coordinate area of $l \approx 60° \rightarrow 110°$ and $b \approx -90° \rightarrow -30°$. The original recommended observations included 310 profiles at a 10 minute exposure time, which was a whopping 52 hours of observing. There was a discrepancy between how the lab manual calculated their number of pointing's and how we calculated ours. With our source only being visible for about 6 hours a day, we needed to cut down on observational points. In order to reduce the time needed for observation, we decreased our profiles to 2 minutes of exposure per point, and a spacing of 2 degrees in Right Ascension and Declination space, leading to about 800 total points. This let to about 24 hours of observing split into three days of observations. Overall many groups had troubles pointing the telescope, but we reported only a single issue over our 20+ hours of observing. This can be attributed to the help of Professor parsons in going over our observing script as well as Frank's help dealing with technical issues.

2.2 Data Collection

Data collection was done by using three separate scripts; pointing and collection, data reduction, and data filtering. For pointing of the telescope we converted galactic coordinates into RA, DEC and then to Alt, Az using astropy's built in function SkyCoord. The rotation matrices used were outlined in "Spherical/Astronomical Coordinate Transformation" by Carl Heiles and Depthi Gorthi. Now we initially planned observations spanning 10 minutes which required re pointing the telescope while taking data. This was an issue which required multiple threads within our script. We consulted with Professor Parsons who walked us through the process of Threads and multi threading. We chose not to implement this in our final script due to reliability issues. We also confirmed that our signal was observable with two minute exposures which didn't necessitate the use of threading. The Data reduction script opens each fits file and sums up the two polarization's and returns the associated spectra. Data filtering goes one step further and finds the peaks of each spectra. This will be used later on to calculate velocities.

3 Analysis

3.1 Accounting for the Baseline Shape

After taking sample spectra from our radio dish, we employed more complex methods to smooth out the baseline of our signal, due to what we assume to be noise in our observing equipment, or objects which are reflecting the signal back onto our dish, according to Professor Parson's. We implement scipy's Savgol Filter to create a smoothed version of our frequency data, and then subtracted our original data from the smoothed version. We wish this method was shown to us during lecture since it wasn't an intuitive assumption to make but necessary for our calculations. Shown in Figure 1, the savgol.filter smooths data by fitting a second order polynomial per specified frequency window. This method makes local peaks much more apparent and drastically minimizes the semi-sinusoidal frequency-space noise/baseline shape we see in our raw data.

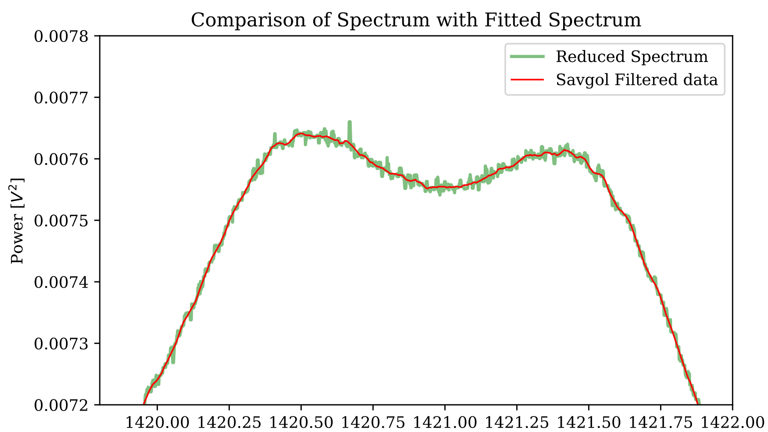

Figure 1: An example spectrum of the Magellanic cloud. Using the savgol.filter function. Additionally, signal strength varies greatly from spectrum to spectrum, so it is often difficult to tell by eye where exactly the Cloud lies

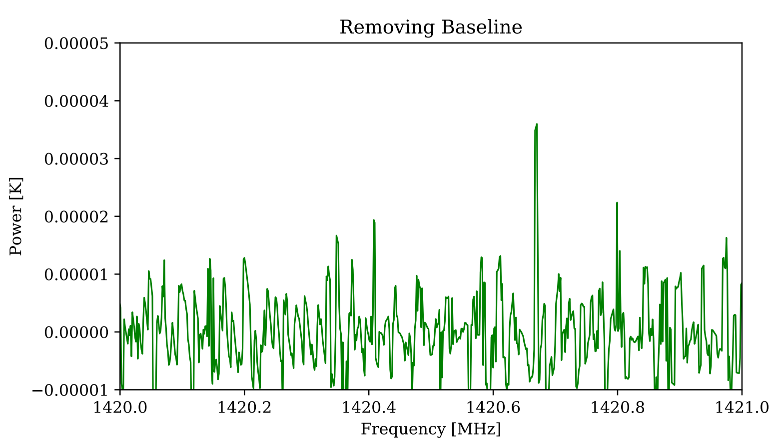

Figure 2: An example spectrum brought down using our baseline we found with our savgol filter. We are more clearly able to make out the Doppler shifted absorption line from the Magellanic stream, although the signal is still weak.

3.2 Determining Cloud Velocity

For our final mapping of the Magellanic Stream, the main objective was to create an array consisting of a galactic longitude and latitude, as well as a LSR velocity to associate with that patch of sky, ultimately giving us a velocity map of the gas cloud. Recall that the equation to find Doppler Velocity,

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

where c is the speed of light, ν_0 is the frequency of our un-shifted HI line, and ν is our observed frequency. In order to find the Doppler velocity of the Magellanic stream, we found the largest peak in the noise-subtracted data at a further blue-shift than the Intergalactic line. The strongest consistent peak, outside of the Intergalactic red-shifted line, was around 1421MHz, corresponding to a Doppler velocity of about -100km/s. This could be an indication of the overall velocity of the Magellanic Cloud, as opposed to the higher velocity regions of the Stream. There are some larger peaks, particularly around -400km/s. This could possibly indicate a tail of the Magellanic Stream.

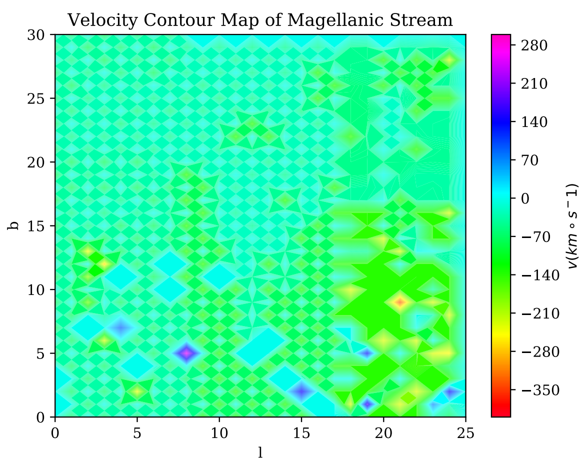

Figure 3: A contour plot of velocity in the Magellanic Cloud in (RA,Dec) space. There seems to be a noticeably high-velocity patch at about v=-180km/s, possible indicating part of the Stream

3.3 Brightness Temperature

To measure the physical properties of the cloud we can also calculate the brighness temperature T_B for each pointing. To calculate the brightness temperature we use these equations:

$$F(\nu) = g(\nu)T_B(\nu) \tag{2}$$

$$F^*(\nu) = g(\nu)(T_B(\nu) + T_{noise}) \tag{3}$$

The variable g represents a term that encompasses all forms of gain from our setup, which we calculated to be roughly 89.6, T_{noise} is the effective noise temperature of our noise generator (a constant 140K in the y polarization and 70K in the x polarization for the Leuschner radio dish).

F and F^* are our observed power spectra with and without our noise generator, respectively. Combining the two equations we get:

$$g(\nu) = \frac{F^*(\nu) - F(\nu)}{T_{noise}} \tag{4}$$

We can use this to solve for brightness temperature,

$$T_B(\nu) = \frac{F(\nu)}{g(\nu)} \tag{5}$$

Our resulting brightness temperature function has a surprisingly reliance on ν (possibly due to the nature/imperfections of the noise generator) and gradually increases from 2.7K to 4.3K. This means the signal we are attempting to see is likely on the order of magnitude of the cosmic background radiation in terms of strength. Figure **??** shows a noticeable bump in brightness temperature at the intergalactic HI line, and a very tiny bump corresponding to the Magellanic Cloud.

We can also convert the brightness temperature into a specific intensity using the equation,

$$I_\nu = \frac{2kT_B\nu^2}{c^2} \tag{6}$$

Unfortunately we didn't have sufficient time to produce a map of Brightness temp mapped onto our portion of the galactic plane.

3.4 Finding Hydrogen Density

To find the column density, we use the approximation,

$$N_{HI} = 1.8x10^{18} \int T_B(\nu)\Delta\ \nu \quad cm^{-2} \tag{7}$$

where $\Delta\nu$ is the appropriate FWHM velocity dispersion of our Doppler-shifted HI line. We approximate $T_B(\nu)$ as a constant over our small dispersion in order to remove the need for an integral in approximating N_{HI}. The resulting column densities follow a very similar pattern to that of the velocity dispersion.

We can also solve for the total mass of hydrogen inside the solid angle covered by our beam, M_{HI}, by using:

$$M_{HI}(\nu) = 1.8x10^{18}\Delta\nu d^2 m_H T_A \Omega_b \quad grams \tag{8}$$

where Ω_b is the solid angle covered by our beam, m_H is the molecular mass of hydrogen, and d is the distance to the source. Since our source is extended over a long angular range, from the equation,

$$T_A \approx T_B \frac{\Omega_s}{\Omega_s + \Omega_b} \tag{9}$$

where Ω_s is the solid angle filled by the source, we can approximate $T_{AB}(\nu)$. In our calculations, since d is not particularly well known, we assume it to be the approximate distance to the Large Megallanic Cloud, 160 light years. Given that the angular diameter of our beam area of our telescope is $4°$, the total beam area is 4π square degrees, or $\pi^3/1800$ steradians. After making our approximations, we can easily see that many of these terms are constant, and that $M_H I$ is in fact equal to $N_H I$, multiplied by a conversion factor of

$$d^2 m_H \Omega_b \approx 6.6086x10^{14} cm^2 g \tag{10}$$

4 Results and Mapping

We chose our color map to highlight the characteristics of the cloud. Meaning we chose to display the red and blue-shifts using the corresponding velocities calculated per pointing. In the future we would also like to produce a contour map of the Hydrogen density which we hypothesis should correspond to the Doppler shift contour map as well.

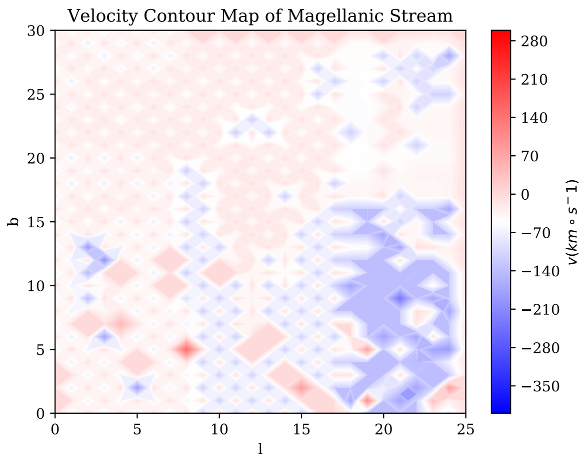

Figure 4: A contour plot of the calculated column density of hydrogen $N_H I$. The color corresponds to the Doppler shift of the gas chunk, meaning blue portions are moving towards us and red portions are moving away from us

5 Conclusion

In this lab we measured the LSR (Local Standard of Rest) velocities and masses of the hydrogen clouds that make up the Magellanic Stream. Section 1 outlined our methods for observation and section 2 outlined the specifics of our survey area and our observing setup. Section 3 detailed our data reduction and analysis methods, while Section 4 discussed our findings, presenting us with our final mapping of the Magellanic Stream. Initially we were confused by the observations, since both the Large and Small Magellanic clouds are not visible in the northern Hemisphere, but with the help of Jonathan, as well as Frank and Professor Parsons, we were able to get through this lab.

This lab combined all of the previous topics into a very applicable topic that is still a very active area of research especially with the EHT and other telescopes such as ALMA and the Sub millimeter array. While we weren't able to correctly identify the boundaries of the Magellanic Stream, we were able to identify some likely candidates, and this lab was crucial in introducing us to real-world applications of radio astronomy.

Distribution of Effort

This lab heavily relied on computational work which all of us did individually. I was responsible for writing the telescope pointing script and gathering all the data, while Oscar did preliminary work on structuring the large amounts of data we would have to process. Roman worked on calculating a baseline using the savgol method outlined above and Matthew worked on velocity calculations. Our appropriate code can be viewed under our corresponding branches:

$$http://github.com/arthurm101/radiolab/blob/Arthur/Lab4 \tag{11}$$

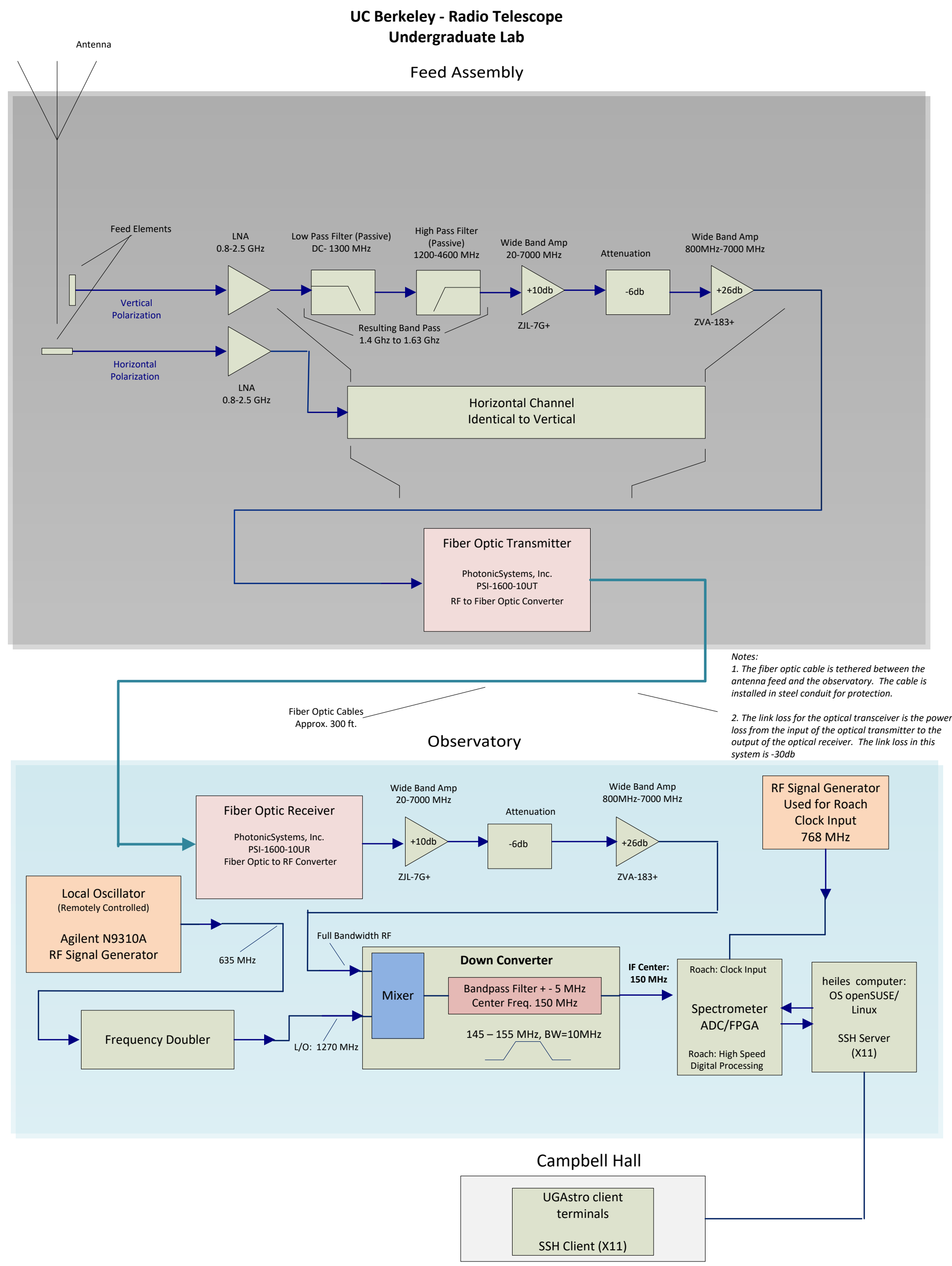

Figure 5: Fringe