Mapping the Magellanic Stream

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Abstract

The Magellanic Stream is composed of high velocity gas and is located between the Large and Small Magellanic Clouds. We observed the 21cm line, which corresponds to HI, the hyperfine transition, with a frequency of $1420.4MHz$. The goal was to map the velocities of the HI particles in the Magellanic Stream in galactic coordinates. The coordinates of the Magellenic Stream were sampled at $\Delta b = 2^o$ in latitude and $\Delta l = \frac{2^o}{cosb}$ in longitude. We determined that the Magellanic Stream was observable from our location in Berkeley, CA, from about 7am to 3pm everyday during our observation dates (end of April and beginning of May 2014). The data was calibrated by observing at two LO frequencies, $1269.6MHz$ and $1273.6MHz$, corresponding to off the HI line and on the HI line, respectively, then calculating the system temperature in order to generate a temperature of the sky spectrum with respect to frequencies. Our signal was too weak to generate a reliable signal, so instead I created an image mapping the column densities at each observed point. The image was generated by convolving with a 2D Gaussian and normalized with weights.

1 Introduction

The Magellanic Stream is found between the Large and Small Magellanic Clouds and is composed of high velocity gas clouds. The Magellanic Stream is believed to have formed as a result of tidal disruptions between the Large and Small Magellanic Clouds and with our Milky Way Galaxy. The Large and Small Magellanic Clouds are small galaxies orbiting around our Milky Way Galaxy. Since Hydrogen is the most abundant element in the Universe, and is what makes up most of the matter between stars, it is useful to study neutral Hydrogen. By studying HI, we gain insight about the velocity and motion of celestial objects by studying their Doppler velocity profiles. By studying the emission and absorption spectra of an object, we can learn about both the bulk flow velocity and rotational velocity, the density and size of the object, its temperature, composition, and excitation of the object's particles.The 21cm line corresponds to the Hyperfine transition. It is the wavelength of the photon emitted when a transition from parallel to anti-parallel spin occurs.

The goal of this project is to create an informational color image of HI velocity distribution in the Magellanic Stream based on location in galactic coordinates. However, as will be discussed later, our signal was very weak, which made it hard to create an image for the velocities, and instead I will discuss column densities. The 12-foot (3.66 meters) radio dish located at Leuschner Observatory in Lafayette, California, was used for our observations. The telescope operates at frequencies between 1320MHz and 1740MHz with a bandwidth of 12MHz, a spectrometer of 8192 elements, and thus has a spectral resolution of 1.46kHz.

2 Methods

2.1 Coordinates and Observing

The first step in observing the Magellanic Stream was to determine its location in the sky relative to our position as observers on Earth. The Magellanic Stream is located roughly within the bounds of -90^o to -60^o in galactic latitude and -90^o to 90^o in galactic longitude. I converted these galactic coordinates to equatorial coordinates in terms of right ascension and declination. Then these were converted to horizontal coordinates (azimuth and altitude) which are dependent on the observer's location as well as date and time. We determined that the Magellanic Stream was observable to us between roughly 7am and 3pm (local Berkeley time) over the course of our observation weeks. Since the Half-Power Beam Width is 4^o, we sampled the area of interest every $\Delta b = 2^o$ in latitude and every $\Delta l = \frac{2^o}{cosb}$ in longitude in order to account for the angular distance between two points.

2.2 Data Collection

The data collected is a power spectrum measured by counts over a range of frequencies. We wrote observing scripts which store the data in .npz files. The following information can be loaded from each data file: measured power count stored as 'spec', galactic longitude 'l', galactic latitude 'b', number of individual spectra averaged 'N', frequency the lo was set to as 'LO', whether noise was turned on or off as 'noise', and any comments as 'notes'.

Each time a point was observed, we generated four data files. We observed at two different LO frequencies, one being on the spectral line and one being off the spectral line. And for each, we measured with the noise turned on and with the noise turned off. We chose our LO frequencies to be $1269.6MHz$ and $1273.6MHz$, off the HI line and on the HI line, respectively. These values were chosen using the range of expected velocities of HI in the Magellanic Stream ($-400km/s$ to $-100km/s$) and the frequency of the HI line ($1420.40575177MHz$). We can thus calculate the range of expected frequencies in which we should see our signal corresponding to these velocities by using Doppler shift calculations.

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

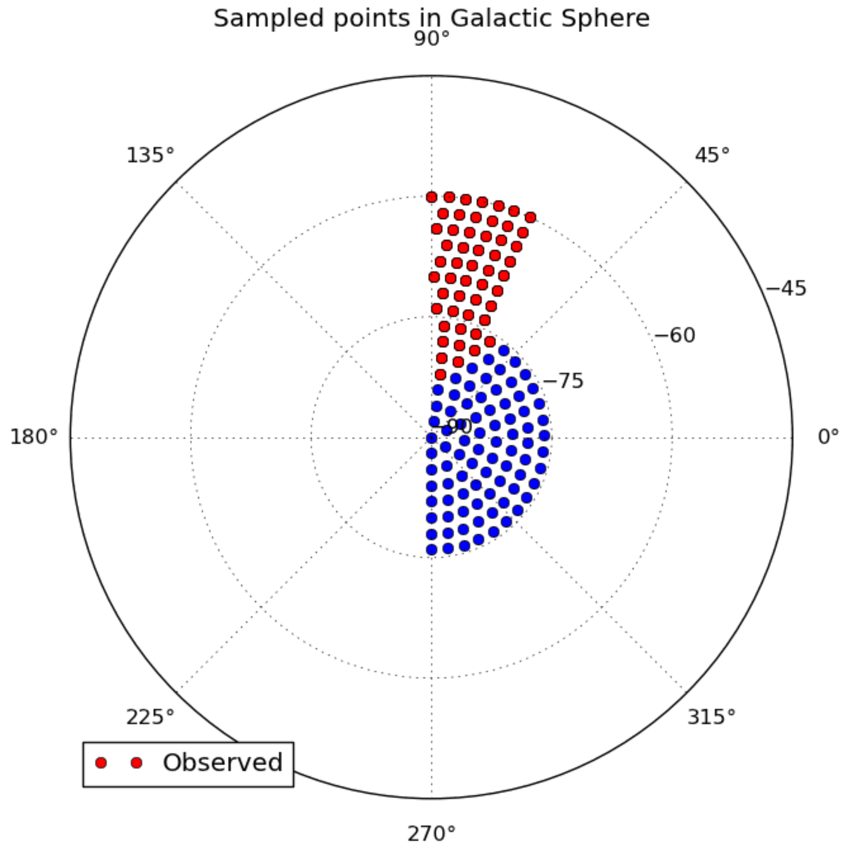

Figure 1: This figure shows the area of the sky covered by the sampled points where the Magellanic Stream is located in galactic coordinates. The area was sampled every 2^o in latitude and every $\frac{2^o}{cosb}$ in longitude. The red points are the points we have observed, which are also all of the points we can observe. The points too close to the South Pole are beyond the limits of observation of our telescope. The circles are the latitudes while the radial lines are the longitudes, all in degrees.

So,

$$\nu_{max} = \nu_0 \; (1 - \frac{v_{min}}{c}) = 1422.3MHz \quad , \quad \nu_{min} = \nu_0 \; (1 - \frac{v_{max}}{c}) = 1420.88MHz \tag{2}$$

So the middle of this range of frequencies is $\nu_{mid} = 1421.6MHz$. From this we get the LO frequencies:

$$LO_{on} = \nu_{mid} - 150 + 2 = 1273.6MHz \quad , \quad LO_{off} = LO_{on} - 4 = 1269.6MHz \tag{3}$$

Each signal corresponding to the second bandwidth is affected by aliasing, so the signal corresponding to the $12MHz$ to $24MHz$ range is reflected. The bandwidth ranges are all multiples of $12MHz$ and thus choosing the range of $144MHz$ to $156MHz$, we want our ν_{mid} to correspond to the center of this channel, so $150MHz$ is the center of the IF mixer. $2MHz$ are cut off on the edge because the two sets of frequency ranges, one centered on the line (LO_{on}) and one off the line (LO_{off}), do not overlap.

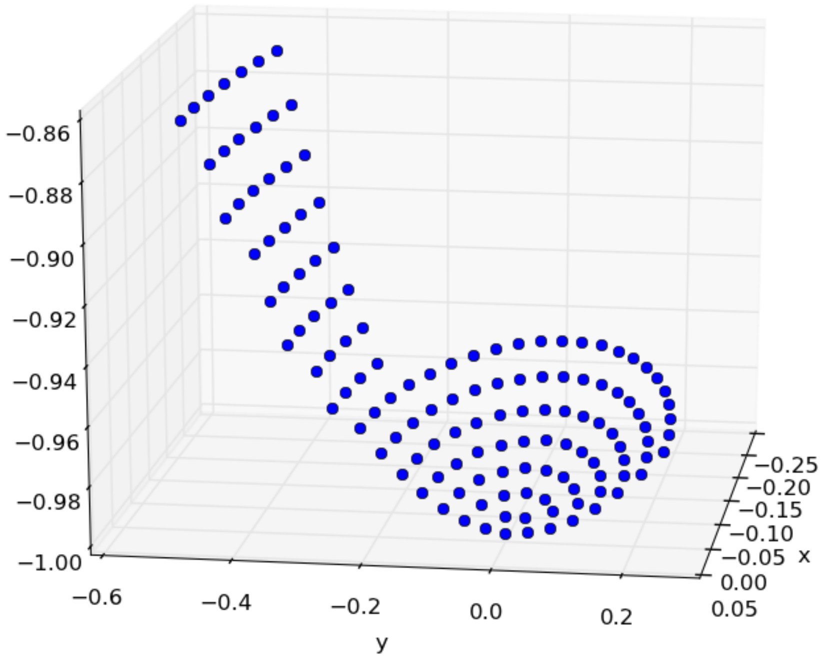

Figure 2: The 3-dimensional plot of the sampled points in Cartesian coordinates covering the area where the Magellanic Stream is located represented on the unit sphere. Please note, the point at x = 0, y = 0 , and z = -1 represents the South Pole and the x and y values are not to scale because this is done on the unit sphere.

We observed each point for two minutes, meaning that we observed with the LO_{on} frequency for two minutes, then with the LO_{off} frequency for two minutes. We expect our signal to be very weak so we need to observe each point for a long period of time. Although we don't expect an integration time of two minutes to be long enough, we chose it so that we could observe a maximum number of points and cover the whole area. Since we were able to cover all of the observable points multiple times, after calibration, we can combine the spectra corresponding to the same points, and thus, as if we had observed each point for longer times because their integration times add up. The total integration time (in seconds) for each point can be calculated by loading 'N' from our data and multiplying by $120sec$.

2.3 Data Calibration

For each point observed, we measure four spectra: on the line with noise turned off (S_{on}), on the line with noise turned on ($S_{on,noise}$), off the line with noise turned off (S_{off}), and off the line with noise turned on ($S_{off,noise}$).

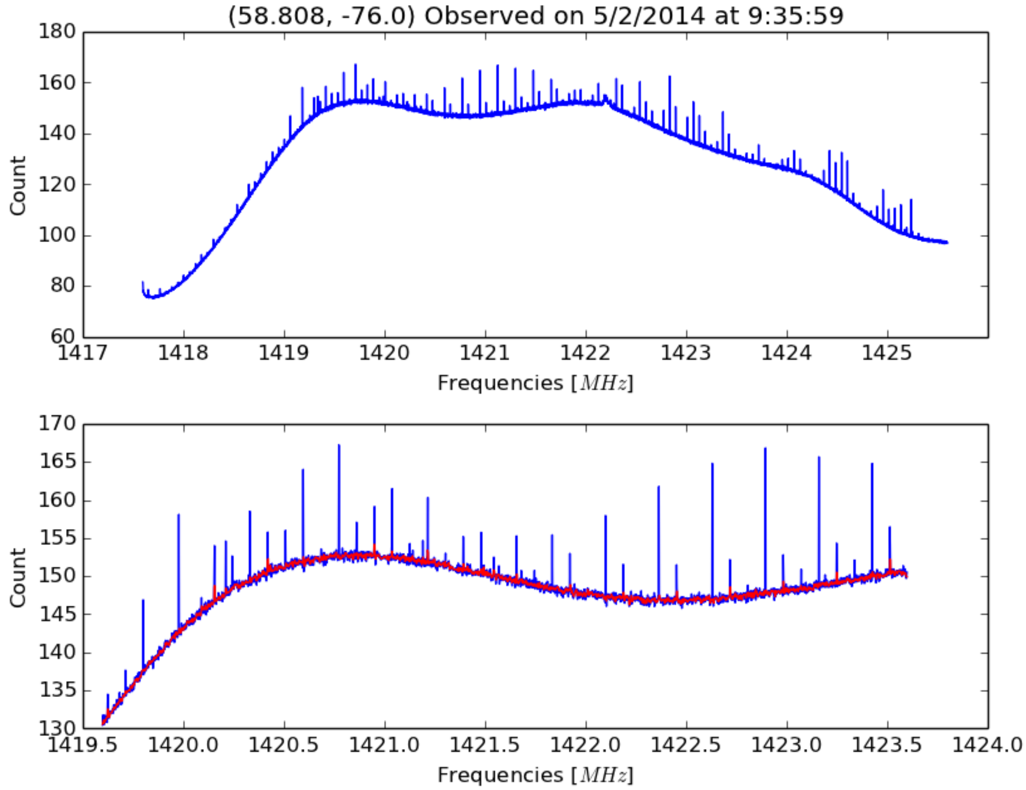

Figure 3: The raw data collected is presented as the y-axis, which is a power spectrum represented by an arbitrary count and the x-axis is shown in units of frequency. The top plot represents the raw full data on the line and with the noise turned off. The bottom plot presents the same raw data cut over the range of frequencies which include the galactic H1 line and the range in which we expect the Magellanic Stream's H1 line to be located. And also shows the smoothed signal with the interference spikes removed.

The first step in calibrating data is to remove the interference spikes in each spectra that appear due to interfering radio emissions on Earth. This is done by applying a median or boxcar filter, meaning that each point's intensity is averaged with its neighboring points and thus the spikes are removed and the signal is smoothed out. This can be seen in the bottom plot of Figure 3.

Next, the temperature of the system needs to be calculated in order to determine the temperature spectra of the sky as a function of frequency and look for the HI line signal coming from the Magellanic Stream. The detected spectra can be expressed as:

$$S_{on} = g_{on}\ B(\nu_{IF})\ (T_{sys,on} + T_{sky}(\nu_{RF})) \tag{4}$$

$$S_{on,noise} = g_{on}\ B(\nu_{IF})\ (T_{sys,on} + T_{sky}(\nu_{RF}) + T_{noise}) \tag{5}$$

$$S_{off} = g_{off}\ B(\nu_{IF})\ T_{sys,off} \tag{6}$$

$$S_{off,noise} = g_{off}\ B(\nu_{IF})\ (T_{sys,off} + T_{noise}) \tag{7}$$

where g is the gain and $B(\nu_{IF})$ is the intensity of the spectrum. By combining Equations (5) & (4) and (7) & (6) we obtain the frequency independent system temperature $T_{sys,on}$ and $T_{sys,off}$, respectively:

$$T_{sys,on} = T_{noise}[\frac{\Sigma S_{on,noise}}{\Sigma S_{on}} - 1]^{-1} \qquad T_{sys,off} = T_{noise}[\frac{\Sigma S_{off,noise}}{\Sigma S_{off}} - 1]^{-1} \tag{8}$$

By combining Equations (4) and (6) along with the ratio of the gains we can write an expression for the sky temperature. Since the system temperatures differ for the on and off measurements, we have two expressions for T_{sky}:

$$T_{sky,on} = (\frac{S_{on}}{g\ S_{off}} - 1)\ T_{sys,on} \qquad T_{sky,off} = (\frac{S_{on}}{g\ S_{off}} - 1)\ T_{sys,off} \tag{9}$$

The ratio of S_{on} to S_{off} is what determines the shape of the calibrated spectra, while T_{sys} is its scaling factor. We then fitted each T_{sky} to a polynomial of degree three because of the shape of the band-pass filter, as seen in the top plot of Figure 3. The goal is to use a fit of the lowest possible degree, so as to have a minimum number of dependent variables but enough to fit the cubic shape of the data. We then averaged the two fitted expressions for the sky temperature measurements. The final step in data calibrating was to combine the spectra of the points we had observed more than once.

Figure 4 shows the final calibrated data of various points we observed. This is a temperature spectrum as a function of frequency. The big peak is the HI line from the galaxy. We would expect our signal from the Magellanic Stream to be located to the right of the HI line, at frequencies within the range of ν_{min} to ν_{max}, from Equation 2. But there is no visible peak in this range of frequencies. The main issue was probably the time spent observing, if we had been able to observe for longer, we would have been able to detect stronger signals, which would be visible above the noise in the spectrum.

3 Results and Analysis

Our goal is present an image of the Magellanic Stream, which gives information about its spatial location as well as the velocities of the HI particles at each of these locations and thus create a map of the distribution of velocities. This helps us better understand the motion of the particles in the Magellanic Stream.

3.1 Velocity Measurements and Column Density

Our signal was so weak, that we were not able to clearly detect it. If we had been able to detect peaks corresponding to various frequencies, we could have calculated the corresponding velocities, using similar equations to those discussed with Doppler shift above

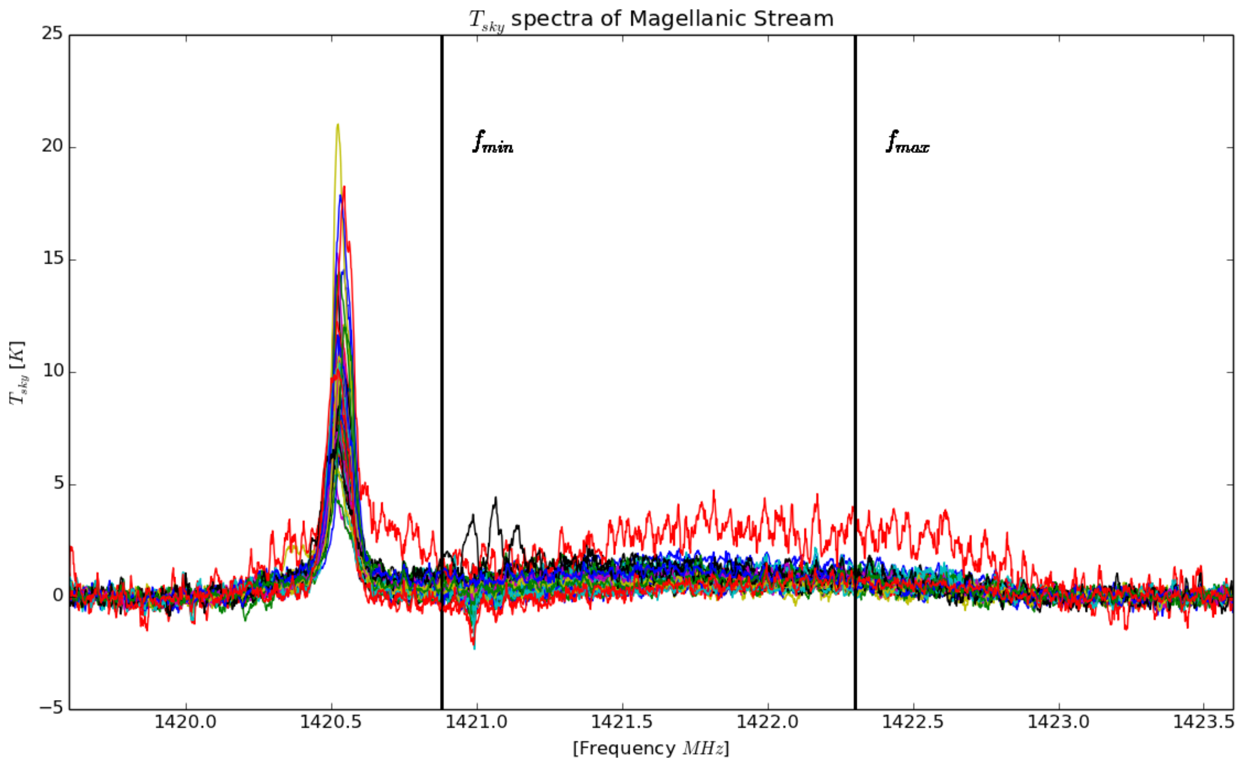

Figure 4: All of the observable points, after being calibrated are plotted as temperature spectra over frequency. The big spike around 1420.5MHz corresponds to the HI line in the galaxy. We expected our signal to be to the right of that, within the range shown in the plot. But there is no apparent clear signal detected within this range.

(Equation 1). We would then have various velocities, each corresponding to an observed point. Another option would have been to calculate the average velocity from the average frequency within our signal, instead of the peak.

Instead, I calculated the column density of HI in the galaxy corresponding to each point observed. The column density is given by:

$$N_{HI} = 1.8{\cdot}10^8 \int T_B(v) dv \tag{10}$$

where the brightness temperature is a function of velocity. I converted our range of frequencies to a range of velocities and summed T_{sky} as a function of velocity. The different column densities values corresponding to each point observed are the values I used to generate my image.

3.2 Image

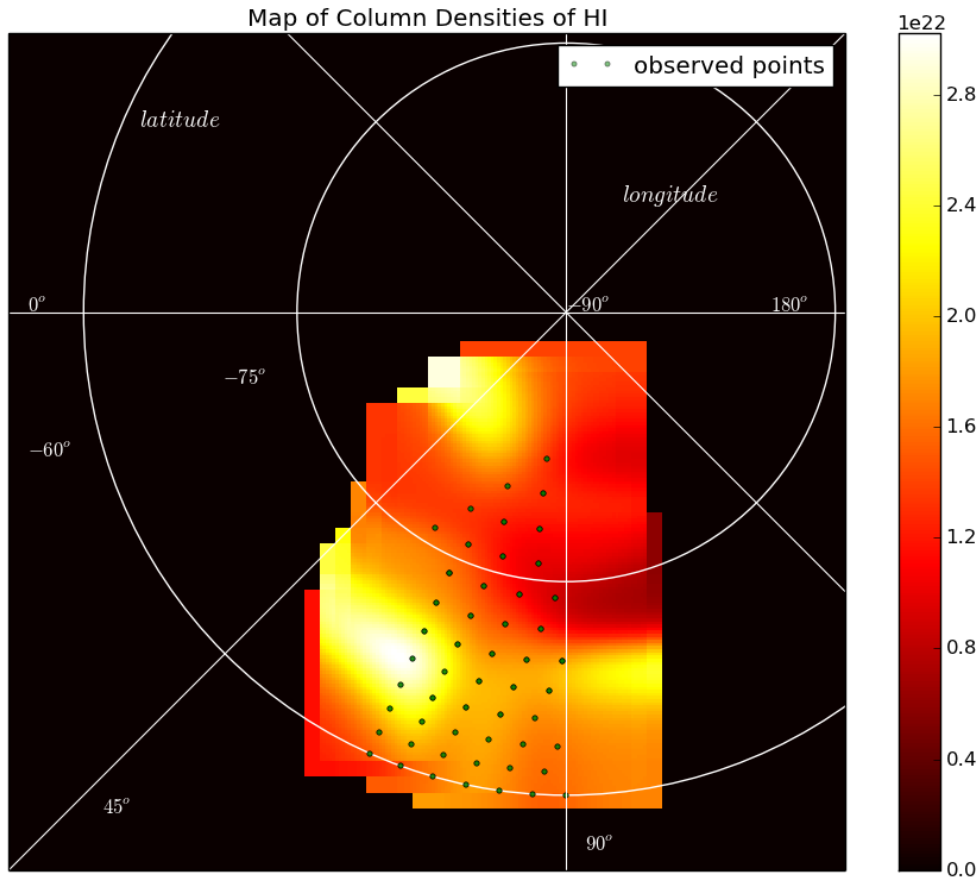

Figure 5: This image maps the column densities of HI at each point on the detectable Magellanic Stream. The points are plotted on a projection of the Galactic Sphere. The color bar represents the range of values of the HI column density.

To generate information as an image, the first step was to create a grid of the pixels corresponding to our coordinates in the form of a 2D matrix. I converted our l,b coordinates to x,y coordinates. Then converting these x,y values of the observed points to their corresponding pixel indices. Two matrices were created, an image matrix and a weights matrix. The value of the column density was inserted at that coordinate location in the image matrix. At the corresponding coordinate location in the weights matrix, a weight was assigned. This weight was defined by the number of times a point had been observed, or in other words, the points that had longer integration times were given greater weights. The points in the matrix that did not correspond to an observed point were set to zero. Each matrix was convolved with a 2D Gaussian and the resulting convolved image matrix was divided by the convolved weights matrix. This produced a smoothed out image, which interpolated between the points corresponding to the data by using the weight of each point. I set the FWHM of the 2D Gaussian to 20 pixels, because the resolution of the telescope is 4^o and I set the resolution of the grid to be 1 pixel $= 0.2^o$, so $4^o/0.2^o = 20$ pixels. I then set the size of the side of the 2D Gaussian to be three times the value of the FWHM, so 60 pixels. Also, when the value of the resulting convolved image was less than 1/1000, I set it to zero and then, set the corresponding weight to 1, so as to not divide by zero.

4 Conclusion

We determined the coordinates of the Magellanic Stream and from those, chose to sample the area at small enough separations in order to create a good image, but also not too small so as to not have redundant information and waste observing time. We determined when we could observe the Magellanic Stream and where to point the telescope. Then the data collected was calibrated to create a temperature spectrum as a function of frequency. Our signal was too weak to be detected so instead of generating a map of the velocity distributions, I mapped the column densities of HI. The main problem was not having been able to observe for long enough integration times to generate a strong enough signal to be detected above the noise. Maps are great way to relay information both about the spacial location of an object as well as an other factor, such as velocity, intensity, or column density in relation to its location in the sky.

5 Acknowledgments

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