Milky Way HI Spectroscopy

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(Data collected with Kevin Schindler)
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Abstract

In this lab, we use the previously studied 3.8 meter parabolic Josephine Hopkins Radio Telescope to obtain spectra centered on 1420 MHz with a 10 MHz band at several galactic longitudes between l = 0° and l = 90°. After performing a thorough analysis of these data, which takes into account the local standard of rest (LSR) corrections among other intricacies, I use the results to determine the respective minima and maxima Doppler velocities at three different longitudes. From these results and assuming a flat rotation curve, it is possible to find the approximate radius (R_0) of HI gas in the galaxy, which is determined to be ~16 kpc, and the value of the flat rotational velocity (V_0), which is found to be ~280 km/s. Finally, these results are compared to previous results from the literature.

Introduction

The 21 cm (1420.40 MHz) hyperfine HI line is the result of a spin-flip of a neutral Hydrogen atom. The HI line is the perfect candidate to study systematic (in this case rotational) motion. Even taking into account some degree of widening from random, thermal motion, the HI line is incredibly thin. It's also at a low enough frequency that it can pass through nebulae unhindered. Finally, Hydrogen is the most common element in the universe, so the HI line can be observed in virtually any direction one looks.

Procedure

Data were collected on the afternoon of November 21, 2014 on the previously studied radio telescope. All spectra were taken using the provided "do_lb_scan_rspec" command with an integration time of 60 seconds. We performed two measurements at three different galactic longitudes (l = 20, 35, & 50°) at zero galactic latitude. Since we started fairly late in the afternoon, we were limited to about these longitudes.

Sample Number	Galactic longitude (l°)	Galactic latitude (b°)
1	20	0
2	20	0
3	35	0
4	35	0
5	50	0
6	50	0

Data Analysis

The data were all analyzed in Matlab. I used the raw data files simply for completeness, but the majority of the actual study was restricted to a small band around the HI line. A plot of the raw data for sample 1 can be seen in figure 1. The data were truncated to a region of width 8 MHz centered at 1420 MHz. After experimenting with several different processes for fitting different order polynomials, I determined that the best fit was obtained by fitting an eighth order polynomial to only every fourth value. By using distinct x-values the fit is less likely to be contaminated by erroneous, large higher order terms, and there's the added benefit that radio-frequency interference (RFI) is less likely to disturb the fit. I then calibrated out the bandpass shape as described in the handout to plot (T / T_{sys}). This process, which can be seen visually in figure 1, was repeated for each of the six measurements independently.

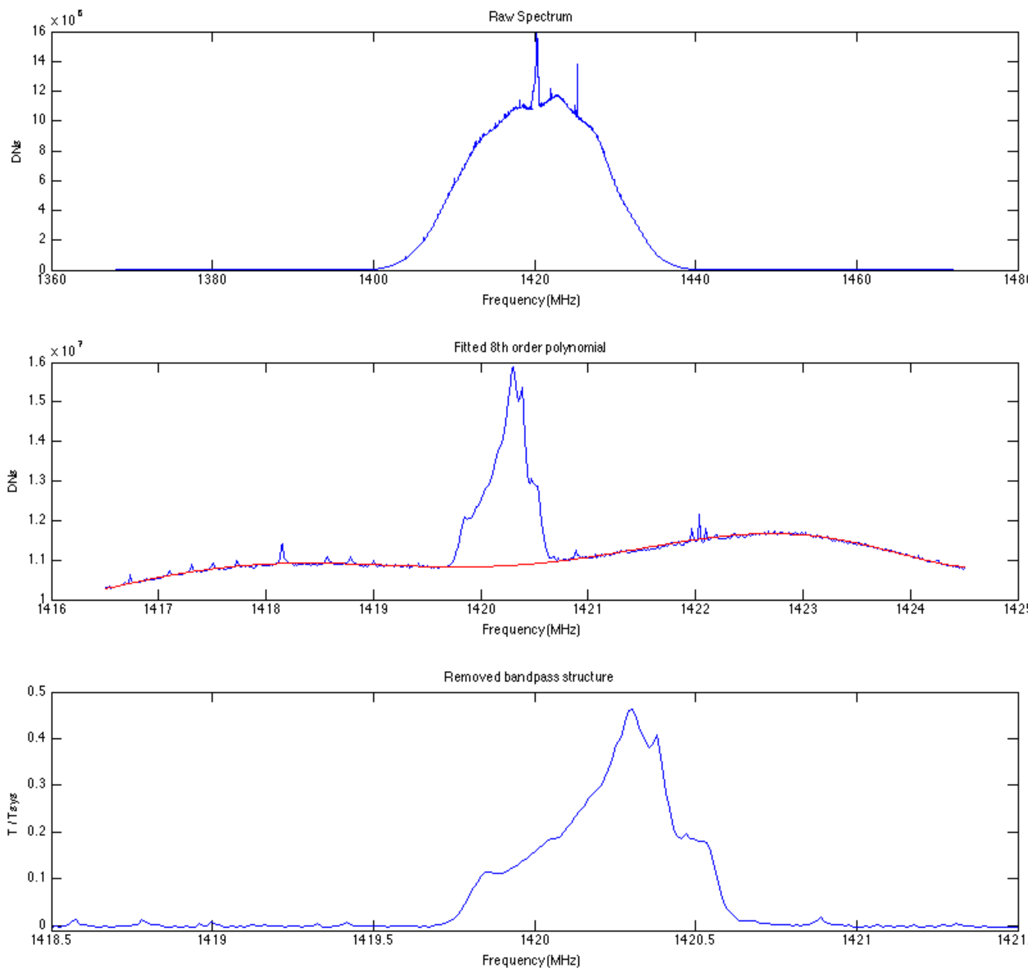

Figure 1

To further reduce the influence of random error, I averaged the data for each longitude, e.g. samples 1 and 2 were averaged to get a final plot at l = 20°. Using my experimentally determined value of T_{sys} (165 ± 7.1° K) from the previous lab, I calibrated the results.

I used the following equation for the non-relativistic Doppler effect to plot the measured temperatures with respect to radial velocity: $V = C*(\nu_0 - \nu)/\nu_0$, where ν_0=1420.40 MHz.

From these plots, one may determine the minimum and maximum radial velocities within a certain degree of random error. Using the provided python script, I found the radial velocity corrections, which take into account the Earth's rotation and orbital velocity and the motion of the sun relative to the LSR, at each longitude and applied these corrections to my minimum and maximum velocities ($V_{r,min}$ & $V_{r,max}$).

Samples	Galactic longitude (l °)	Radial velocity correction (km/s)
1 & 2	20	3.45
3 & 4	35	2.90
5 & 6	50	2.10

Finally, using the following equations it is possible to determine the radius of HI gas in the disk of the Milky Way (R_0) and the rotational velocity (V_0):

$V_0 = V_{r,max} / (1 - \sin(l))$
$R_0 = R_{sun} / [1 + V_{r,min} / (V_0 * \sin(l))]$, where $R_{sun} = 8.5$ kpc.

Results

Figures I through III in the appendix summarize the results in a visual format for the three different longitudes. The following tables provide the approximate peak temperatures for the three different longitudes and the standard deviations.

Galactic longitude (l °)	Approximate peak temperature (° K)
20	75
35	70
50	90

Galactic longitude (l °)	Standard deviation / noise (° K)
20	0.7
35	0.4
50	0.4

At l = 20°, there's significant RFI at around 1422 MHz that peaks at ~7.2 ° K. This RFI, while still present at other longitudes, is not nearly as dramatic. The most obvious explanation is that there was some source of interference in that general direction. This also probably caused the unusually high standard deviation at that longitude.

The structure in the spectral lines is a result of separate parcels of gas having their own unique radial velocities. If the concentration of gas were constant along the line of sight, i.e. if there were no spiral arm structure, then the spectral lines would look more like the ideal—a convolution of a step function with a Gaussian.

Galactic longitude (l °)	$V_{r,min}$ (km/s)	$V_{r,max}$ (km/s)
20	-50 ± 5	148 ± 10
35	-65 ± 8	120 ± 8
50	-80 ± 8	78 ± 10
Taking into account corrections	Corrected V_{min}	Corrected V_{max}
20	-54 ± 10	144 ± 10
35	-68 ± 8	117 ± 8
50	-82 ± 8	76 ± 10

Using these corrected minima and maxima velocities, one can find V_0 and R_0 using the equations given in the data analysis section. The following values of R_0 use a value of V_0 = 280 ± 25 km/s, which is the average calculated from V_0 at the first two galactic longitudes. The value at l = 50 ° is excluded because of its large error and because for larger values of l, the error becomes even more inflated.

Galactic longitude (l °)	R_0 (kpc)	V_0 (km/s)
20	20 ± 4	288 ± 16
35	15 ± 3	274 ± 19
50	14 ± 3	325 ± 43
Average	16.5 ± 6	280 ± 25

According to the results in Ruiz-Granados et al., most luminous matter lies within a radius less than ~15 kpc. This is close to my result of ~16 kpc. In the same publication, the rotation curve hovers between 200 and 200 km/s. This again is close, although slightly less than, my value of ~280 km/s.

Summary and Conclusions

The purpose of this lab was to determine the radius and rotational velocity of the Milky Way. The values I attained are both slightly larger than values from the literature. It is possible that my inaccuracy was in determining the minima and maxima velocities. A greater degree of precision, and possibly accuracy, may be attained by a careful study of the convolutions of various step functions with the appropriate Gaussian functions.

Reference

Ruiz-Granados et al. 2012, ApJLetters, 755, L23. Dark Matter, Magnetic Fields, and the Rotation Curve of the Milky Way. Web. <http://www.astro.cornell.edu/~cordes/A4410/ruiz_granados_mw_rotation_curve_apjl_755_2_23.pdf>.