New SRT: Mapping the Galactic Rotation Curve

1 Objective

The 21cm line produced by neutral hydrogen in interstellar space provides radio astronomers with a very useful probe for studying the differential rotation of spiral galaxies. By observing hydrogen lines at different points along the Galactic plane one can show that the angular velocity increases as you look at points closer to the Galactic center. The purpose of this experiment is to create a rotational curve for the Milky Way Galaxy using 21-cm spectral lines observed with a small radio telescope. The sample observations for this experiment will be made using the small radio telescope located at the Haystack Observatory. The rotational curve will be created by plotting the maximum velocity observed along each line of sight versus the distance of this point from the Galactic center. [Stefanis and Kimball,]

2 Introduction

Hydrogen is the most abundant element in the cosmos; it makes up 80% of the universe's mass. Therefore, it is no surprise that one of the most significant spectral lines in radio astronomy is the 21-cm hydrogen line. In interstellar space, gas is extremely cold. Therefore, hydrogen atoms in the interstellar medium are at such low temperatures (100 K) that they are in the ground electronic state. This means that the electron is as close to the nucleus as it can get, and it has the lowest allowed energy. Radio spectral lines arise from changes between one energy level to another.

A neutral hydrogen atom consists of one proton and one electron, in orbit around the nucleus. Both the proton and the electron spin about their individual axes, but they do not spin in just one direction. They can spin in the same direction (parallel) or in opposite directions (anti-parallel). The energy carried by the atom in the parallel spin is greater than the energy it has in the anti-parallel spin. Therefore, when the spin state flips from parallel to anti parallel, energy (in the form of a low energy photon) is emitted at a radio wavelength of 21-cm. This 21-cm radio spectral line corresponds to a frequency of 1.420 GHz.

The first person to predict this 21-cm line for neutral hydrogen was H. C. van de Hulst in 1944. However, it was not until 1951 that a Harvard team created the necessary equipment, and the first detection of this spectral line was made.

One reason this discovery is so significant is because hydrogen radiation is not impeded by interstellar dust. Optical observations of the Galaxy are limited due to the interstellar dust, which does not allow the penetration of light waves. However, this problem does not arise when making radio measurements of the HI region. Radiation from this region can be detected anywhere in our Galaxy.

Measurements of the HI region of the Galaxy can be used in various calculations. For example, observations of the 21-cm line can be used to create the rotation curve for our Milky Way Galaxy. If hydrogen atoms are distributed uniformly throughout the Galaxy, a 21-cm line will be detected from all points along the line of sight of our telescope. The only difference will be that all of these spectra will have different Doppler shifts. Once the rotation curve for the Galaxy is known, it can be used to find the distances to various objects. By knowing the Doppler shift of a body, its angular velocity can be calculated. Combining this angular velocity and the plot of the rotation curve, the distance to a certain object can be inferred. Using measurements of the HI region, the mass of the Galaxy can also be determined.[Stefanis and Kimball,]

3 Procedure

1. A command file that will collect the data relevant for this lab can be found in the cmdfiles directory under the title galactic.cmd. Upload this or a command file with a similar routine to the SRT dash interface, which will tell the SRT to take data at successive galactic longitudes $0° \leq l \leq 90°$ along the galactic equator $b = 0°$.

2. Once the observations have been completed, open up the Galactic Rotation Curve file in Jupyter Notebooks and enter the file path containing the output data.

3. Using the notebook, plot integrated power spectra for each galactic longitude.

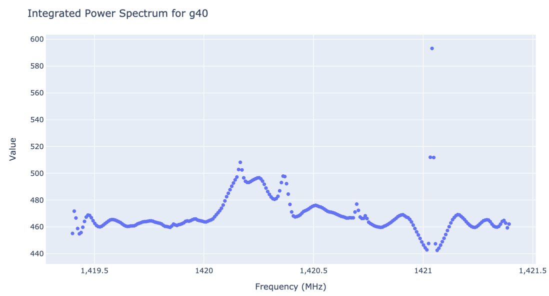

Figure 1: Example integrated power spectrum for G40

4. The relative velocity V of a frequency channel is given by $V = \frac{(1420.406 - f)V_c}{1420.406} - V_{lsr}$, where V_c is the speed of light ($V_c = 299790 km/s$), V_{lsr} is the velocity of the observer relative to local standard of rest, and f is the frequency of the channel. Use the notebook to calculate the observed relative velocities for every frequency channel at each galactic longitude.

5. Using the notebook, plot raw power vs relative velocity and create a corrected plot by subtracting the average power at each frequency bin.

Figure 2: Example corrected power spectrum for G40

6. Use the corrected power vs velocity graphs for each observed galactic longitude to find the velocity corresponding to the maximum redshifted frequency. This can be done by locating the maximum nonzero (above noise level) velocity on each graph (hovering over the points on the graph to see the exact values proves useful here).

7. Repeating the previous step for each galactic longitude, enter these values at the specified point in the notebook to plot the galactic rotation curve corresponding to your data.

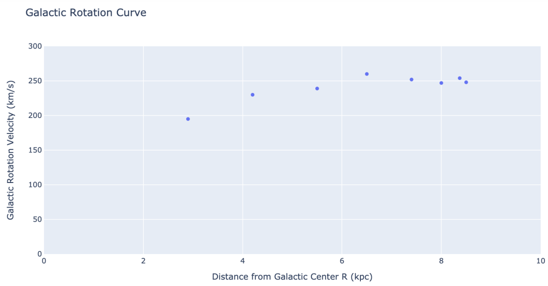

Figure 3: Example galactic rotation curve result

4 Theory

Galactic motion can be modeled as circular motion with monotonically decreasing angular rate as distance from the center increases. For example, if the mass of the galaxy is completely concentrated at the center, the angular velocity at distance R is given by

$$w = M^{\frac{1}{2}} G^{\frac{1}{2}} R^{\frac{3}{2}} \tag{1}$$

where M is the central mass in kg, G is the gravitational constant $6.67 * 10^{-11} Nm^2 kg^{-2}$, and R is the distance from the central mass M. If we are looking through the Galaxy at an angle g from the center, the velocity of the gas at radius R projected along the line of sight minus the velocity of the sun projected along the same line is:

$$V = wR \sin\delta - w_0 R_0 \sin\gamma \tag{2}$$

as illustrated in fig.2.

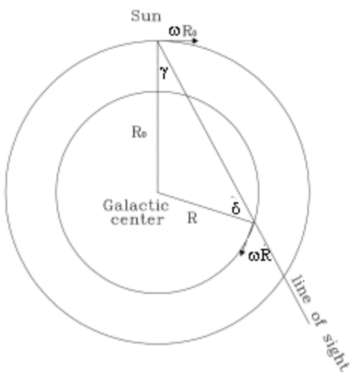

Figure 4: Geometry of model galactic motion. w is angular velocity at distance R, w_0 is angular velocity at distance R_0, R_0 is the distance from the sun to the galactic center, and $\gamma = l$, the galactic longitude. [Stefanis and Kimball,]

By law of sines:

$$\sin\delta = \frac{R_0 \sin\gamma}{R} \tag{3}$$

Substituting this into equation 2 yields:

$$V = (w - w_0) R_0 \sin\gamma \tag{4}$$

The maximum velocity occurs where the line of sight is tangential to circular motion, in which case:

$$R = R_0 \sin\gamma \tag{5}$$

Therefore, we obtain

$$V_{max-observed} = wR = V_{max-observed}(R) + w_0 R \tag{6}$$

The sun's rotational velocity $w_0 R_0$ and distance to the Galactic center can be taken from other measurements to have the following values:

$$w_0 R_0 = 220km/sR_0 = 8.5kpc = 2.6x10^{17}km \tag{7}$$

5 Analysis

1. Compare your plot of the angular response function of the antenna obtained in the scans of the sun with the theoretical diffraction pattern of a circular aperture.
2. Derive an estimate of the brightness temperature of the sun at 21 cm from your measurements.
3. Why are you only able to plot the velocity curve of the galaxy as a function of radius for locations interior the radial position of our solar system?
4. optional: Using the galactic data, construct some features of spiral-arm structure of the Milky Way.

References

[Stefanis and Kimball,] Stefanis, M. and Kimball, L. Measurement of galactic rotation curve. https://www.haystack.mit.edu/edu/undergrad/srt/SRT%20Projects/rotation.html.