Lab Manual: 21cm Hydrogen in the Milky Way - Live Observations with the ATA

Introduction

In this lab, you will learn how to analyze 21cm hydrogen line data and conduct live observations using the Allen Telescope Array (ATA). By studying the 21cm hydrogen line, astronomers can map the distribution and motion of neutral hydrogen in the galaxy, leading to important insights about the structure and dynamics of the Milky Way.

This lab is divided into two parts. First, you will work with recorded 21cm hydrogen line data taken along the galactic plane to calculate the Doppler velocity and explore the spiral structure of the Milky Way. In the second part, you will use the ATA to conduct live observations of the hydrogen line at various galactic longitudes.

Each group must have at least one computer with GNU Radio installed and properly configured. GNU Radio is essential for processing and analyzing the radio frequency data received during live observations. Ensure that your GNU Radio setup is operational before commencing the lab to facilitate seamless data reception and analysis. Instructions for installing GNU Radio can be found at the following link: `https://wiki.gnuradio.org/index.php/InstallingGR`

Part 1: Analysis of Recorded HI Data from the ATA

Objective

Analyze recorded hydrogen line data and infer information about the motion of gas in the Milky Way, including Doppler shift, velocity, and the structure of spiral arms.

Background Theory

The 21cm hydrogen line is a crucial tool in radio astronomy for mapping neutral hydrogen gas in the galaxy. This emission line arises from a specific quantum mechanical transition known as the **spin flip** transition in neutral hydrogen atoms. In this transition, the spin of the electron flips from being parallel to the proton's spin to antiparallel, resulting in the emission of a photon with a wavelength of approximately 21 centimeters (1420.40575 MHz in frequency).

Spin Flip Transition: Neutral hydrogen atoms consist of one proton and one electron. The electron can occupy two spin states relative to the proton:

- **Parallel Spin**: The electron and proton spins are aligned in the same direction.
- **Antiparallel Spin**: The electron and proton spins are aligned in opposite directions.

When the electron transitions from the parallel to the antiparallel spin state, it releases energy in the form of a photon, producing the 21cm hydrogen line. This transition is highly improbable but occurs frequently enough in the vast expanses of space to be a reliable tool for mapping hydrogen gas.

Doppler Shifts in Astronomy: The Doppler effect describes the change in frequency or wavelength of a wave in relation to an observer moving relative to the wave source. In astronomy, Doppler shifts are used to determine the radial velocity of astronomical objects:

- **Blueshift** ($v < 0$): Occurs when the source is moving toward the observer, causing the observed frequency (f_{observed}) to be higher than the rest frequency (f_{rest}).
- **Redshift** ($v > 0$): Occurs when the source is moving away from the observer, causing the observed frequency (f_{observed}) to be lower than the rest frequency (f_{rest}).

By measuring the Doppler shifts of the 21cm hydrogen line at various galactic longitudes, astronomers can determine the velocities of hydrogen gas clouds. These velocities provide insights into the rotational dynamics of the Milky Way and help in mapping the galaxy's spiral structure. Regions with multiple Doppler-shifted peaks indicate the presence of multiple spiral arms or varying velocities within the same arm.

The Doppler velocity can be calculated using the following equation:

$$v = c \times \frac{f_{\text{rest}} - f_{\text{observed}}}{f_{\text{rest}}} \tag{1}$$

Where:

- v is the radial velocity of the hydrogen gas,
- c is the speed of light, approximately 300,000 km/s,
- f_{observed} is the observed frequency,
- f_{rest} is the rest frequency of the 21cm line, 1420.40575 MHz.

Steps

1. **Plot Analysis:** Each group will be provided with printed plots of the hydrogen line from different galactic longitudes. These plots often show multiple peaks representing hydrogen gas moving at varying speeds in different spiral arms. Examine the provided plots and identify the number of distinct peaks. Label the peaks in each plot and estimate the observed frequency for each peak.

2. **Calculate the Doppler velocity for each peak:** Using the observed frequency for each peak, calculate the Doppler velocity using the Doppler shift equation above. Write down the calculated velocities for each peak, and indicate whether the gas is redshifted (moving away) or blueshifted (moving towards us). **Example Calculation:**

$$v = 300,000 \times \frac{1420.40575 - 1420.100}{1420.40575} \approx +64 \text{ km/s}$$

   (This indicates a redshift, meaning the gas is moving away from us.)

3. **Wavelength Calculation from Frequency** The wavelength (λ) of an electromagnetic wave is related to its frequency (f) by the equation:

$$\lambda = \frac{c}{f}$$

   Where:

- λ is the wavelength in meters (m).

- c is the speed of light ($\approx 3 \times 10^8$ m/s).
- f is the frequency in hertz (Hz).

  (a) **Convert Frequencies to Hertz:** Ensure all observed frequencies (f_{observed}) are in hertz (Hz). If the frequencies are given in megahertz (MHz), convert them by multiplying by 10^6.

  (b) **Calculate Wavelengths:** For the observed frequency with the largest peak in each plot, use the equation above to calculate the corresponding wavelength. **Example Calculation:**

- Given an observed frequency of 1420.100 MHz:

$$f = 1420.100 \times 10^6 \text{ Hz} = 1.420100 \times 10^9 \text{ Hz}$$

$$\lambda = \frac{3 \times 10^8 \text{ m/s}}{1.420100 \times 10^9 \text{ Hz}} \approx 0.211\text{m} \approx 21.1\text{cm}$$

4. **Compare the strength of each plot:** Compare the peak heights in the plot. Pointings closer to the galactic plane will typically be stronger, while those further away may be weaker. Discuss with your group how the number of peaks and their strength vary with the galactic longitude and latitude.

5. **Visualize the galaxy:** Your instructor will draw a large circle representing the Milky Way, with galactic longitude marked around the perimeter. Each group will draw on the diagram and use arrows to represent the motion of the gas based on their data. Arrows pointing towards the Sun's location indicate gas moving towards us (blueshifted, positive Doppler velocity). Arrows pointing away from the Sun's location indicate gas moving away from us (redshifted, negative Doppler velocity). Add arrows for each scan, distinguishing between strong signals (on the galactic plane) and weak signals (off the galactic plane).

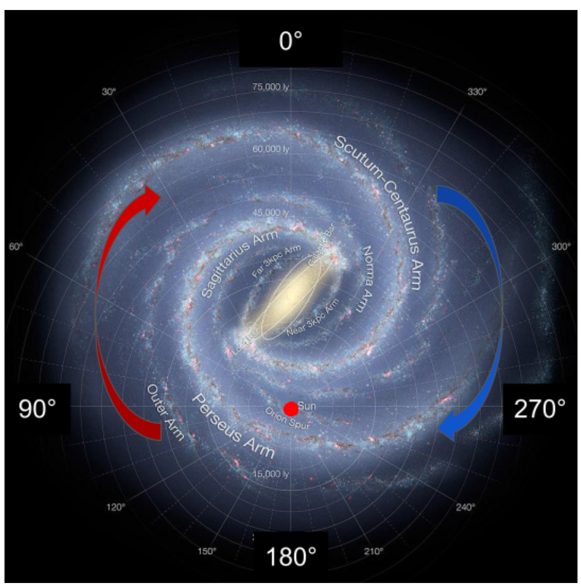

Figure 1: An artist's impression of the Milky Way from above with labeled galactic longitudes. The red dot marks the location of the Sun in the Orion spur, and the arrows indicate the direction the spiral arms are moving.

Part 2: Live Observations with the ATA

Objectives

Conduct live observations of the 21cm hydrogen line using the Allen Telescope Array. Use the live data to identify multiple peaks (spiral arms) and confirm the predictions made in part 1.

Background Theory

Live observations allow astronomers to collect real-time data, providing immediate insights into the behavior and properties of celestial objects. By operating the ATA, you'll gain hands-on experience with radio telescope operations and data collection, enhancing your understanding of astronomical observation techniques.

Conducting the Live Observation

1. Your group will be assigned one or more galactic longitudes for live observation. Based on your assigned longitude, use the diagram of the Milky Way above to predict how many peaks you will see in the live observation. Based on what you've seen from the recorded data, and what you know of the Milky Way's rotation, do you expect the signal to be redshifted or blueshifted? Record your prediction below.

2. Steps 2-4 will be done on the control computer. Select the `Active Antenna` button. Nothing may appear on the screen at first, wait for about 75 seconds for the process to finish. This will run multiple operations in the background, calibrating the telescope and tuning to the hydrogen line frequency. Live data will start streaming into the GNU Radio flowgraphs once this step is complete; the text box will display `Calibration Complete!` once it's finished.

3. Select the `Show Available Targets` button. This will automatically compute the galactic longitudes, in 10° increments, that are currently observable (more than 20° above the local horizon). Lines will be overlaid on the diagram of the Milky Way showing the range of pointings that are currently available. Ensure that the galactic longitude you were assigned is currently observable.

4. Enter your galactic longitude into the prompt and select the `Track Source` button. The telescope will slew to your chosen location and continue to track the source as the Earth rotates. A red line will be overlaid on the Milky Way diagram showing the pointing of the telescope. Monitor the live camera feed to ensure the telescope arrives on target without issue. The text box will display `Arrived at galactic coordinate (l,b)` once the telescope is finished slewing.

5. Run the `ATA_HI_Live.grc` flowgraph in GNU Radio Companion. This will display the live data streaming in from the telescope. For a cleaner plot, run the `ATA_HI_Integrated.grc` flowgraph, which will integrate the live data over a duration set by the `integration time` variable. Integration time can be thought of like the shutter speed on a camera; all the incoming data will be "added up" over the duration of the integration time. This variable should be set between about 20-60 seconds.

6. To save the generated plot, ensure that the `File Sink` block is enabled (select the block and press e

to enable, and d to disable); this must be done before the flowgraph is run. Double click the block and point it to the folder you'd like to save the data to using the three dots next the `File` entry. Give the file a name that includes at least: your group number or name, the galactic coordinates of your pointing, and the integration time.

7. Run the `ATA_HI_File_View.grc` flowgraph to plot your saved file. Double click the `File Source` block and point it to the location you saved the file.

Analyze the Data

After conducting your live observations, it's time to analyze the data you've collected. This analysis will help you interpret the Doppler-shifted signals and understand the underlying galactic dynamics. Follow the steps below to thoroughly examine your live data.

1. **Peak Identification and Comparison:**

- Carefully examine your live observation plots to identify all significant spectral peaks.
- Count the number of peaks and note their corresponding observed frequencies.
- Compare these peaks with your predictions and the recorded data from Part 1. Are there more or fewer peaks than expected? Discuss possible reasons for any discrepancies.

2. **Doppler Velocity Calculation:**

- For each identified peak in your live data, calculate the Doppler velocity using the Doppler shift equation from part 1.
- Determine whether each velocity indicates a redshift (negative velocity, moving away) or a blueshift (positive velocity, moving toward).
- Record your calculated velocities in a data table alongside the corresponding frequencies.

3. **Comparative Analysis with Recorded Data:**

- Overlay your live observation plots with the recorded data plots from Part 1.
- Identify which peaks correspond between the two datasets and note any differences in their positions or velocities.
- Explore possible reasons for any inconsistencies, considering factors like observational timing, equipment calibration, or inherent variability in gas motion.

4. **Visualization and Mapping:**

- Update the Milky Way diagram you contributed to in Part 1 with the additional data from your live observations.
- Use color-coding or different arrow styles to distinguish between data from recorded and live observations.
- Analyze the combined data to identify patterns that illustrate the spiral arms and rotational motion of the galaxy.

Reflection and Discussion

- Reflect on the entire observation and analysis process. What challenges did you encounter, and how did you overcome them?
- Discuss how your findings contribute to the broader understanding of the Milky Way's structure and dynamics.
- Consider the implications of your work for future astronomical research and the search for extraterrestrial intelligence (SETI).

Appendix: 21cm Observations of M31 (Andromeda Galaxy)

While the Milky Way provides a wealth of information about galactic structure and dynamics, 21cm astronomy extends its reach to other galaxies, offering comparative insights that enhance our understanding of the universe. M31, also known as the Andromeda Galaxy, is a prime example of how 21cm observations can unveil the intricate details of other galaxies. The following images captured by the Allen Telescope Array (ATA) demonstrate the power of 21cm hydrogen line studies in mapping both the distribution and motion of neutral hydrogen gas in galaxies beyond our own.

These images were created using the spectral line correlator at the Allen Telescope Array (ATA), which combines data from 28 of the upgraded antennas to produce high-resolution maps of neutral hydrogen gas in M31. By analyzing Doppler shifts in the 21cm hydrogen line, the correlator distinguishes gas motion towards and away from the observer, enabling detailed intensity and velocity fields that reveal the galaxy's structure and rotational dynamics.

Intensity Field

The intensity field image maps the concentration of neutral hydrogen (HI) gas within M31. Bright regions indicate areas with higher hydrogen density, allowing astronomers to trace the spiral arms and other structural features of the galaxy. This distribution is crucial for understanding the mass distribution and star-forming regions within M31.

Velocity Field

The velocity field image showcases the radial velocities of neutral hydrogen gas in M31 through Doppler shifts. Areas appearing red indicate gas moving away from the observer (redshift), while blue regions signify gas moving toward the observer (blueshift). This alternating pattern is a direct consequence of the galaxy's rotation, providing evidence for its rotational dynamics and the distribution of angular momentum within the spiral arms.

Combined Insights: Together, the intensity and velocity field images offer a comprehensive view of M31's structure and motion at radio wavelengths. While the intensity field outlines the spatial distribution of hydrogen gas, the velocity field reveals the underlying kinematic processes driving the galaxy's rotation. These observations underscore the importance of 21cm hydrogen line studies in unraveling the complexities of spiral galaxies.

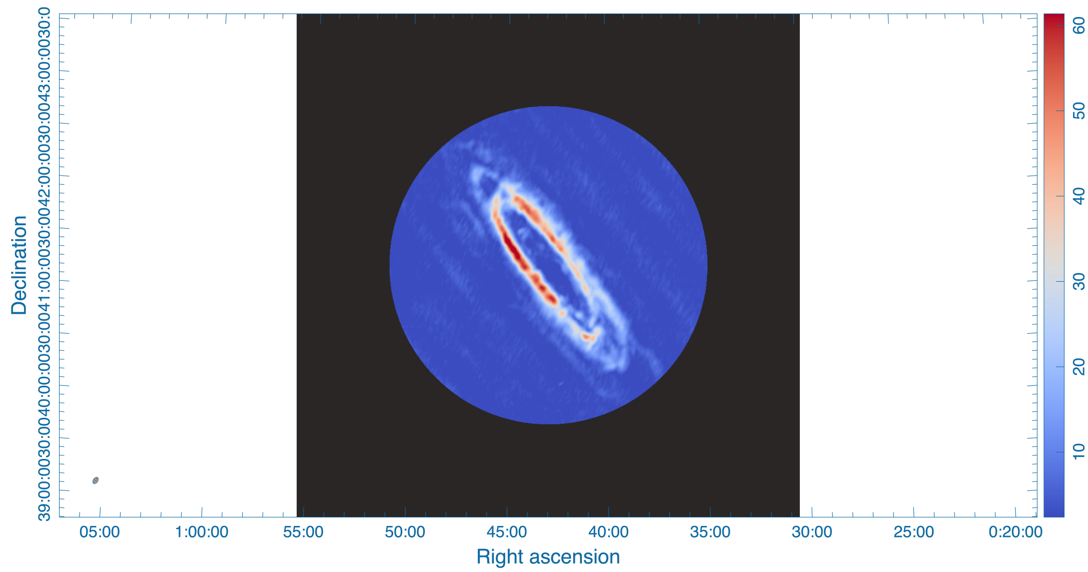

Figure 2: Intensity field of M31 (Andromeda Galaxy) observed at the 21cm hydrogen line. This image reveals the distribution of neutral hydrogen gas, highlighting the galaxy's spiral structure and overall morphology.

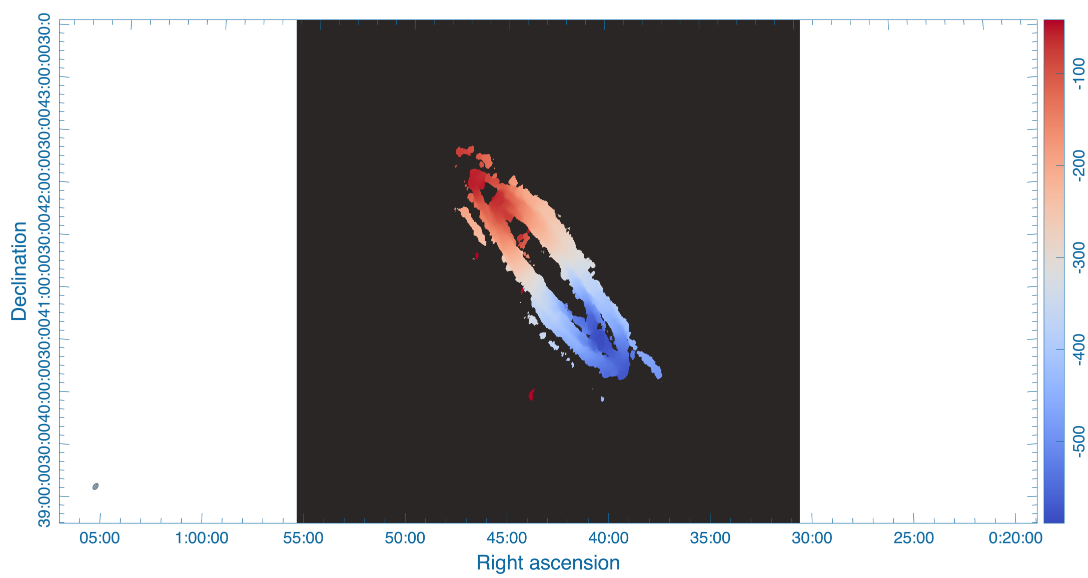

Figure 3: Velocity field of M31 (Andromeda Galaxy) observed at the 21cm hydrogen line. This image displays the Doppler-shifted velocities of the hydrogen gas, clearly illustrating the rotational redshift and blueshift across the galaxy.