Instructor Notes: Live Observations with the Allen Telescope Array

Objective

The goal of this lab is to provide students with a hands-on experience in conducting live radio astronomy observations and analyzing real astronomical data from the Allen Telescope Array (ATA). Students will use software-defined radio (SDR) tools within GNU Radio to process and interpret signals, focusing on the 21 cm hydrogen line emission in the Milky Way. Through this lab, students will gain practical skills in data collection, signal processing, and troubleshooting SDR-based observations.

Learning Outcomes

Upon completion of this lab, students should be able to:

- Understand the operational basics of a radio telescope and its key components, with a focus on the ATA.
- Use custom GNU Radio flowgraphs to receive, filter, and visualize real-time signals from the ATA.
- Perform data integration and analysis on observed signals, including Doppler shift calculations.
- Collaborate effectively in troubleshooting and problem-solving during live observations.

Pre-lab Preparation

Instructor Responsibilities

To ensure a smooth lab experience, instructors should:

- Verify that each group has access to a computer with GNU Radio installed and properly configured. Instruction for installing GNU Radio can be found here: `https://wiki.gnuradio.org/index.php/InstallingGR`
- Confirm that the ATA is operational and accessible for live observations.
- Prepare printed plots of recorded hydrogen line data and a Milky Way diagram for reference.
- Review the following GNU Radio flowgraphs: `ATA_HI_Live.grc`, `ATA_HI_Integrated.grc`, and `ATA_HI_File_View.grc`.

Lab Procedures

Part 1: Analysis of Recorded Hydrogen Line Data

Objective: Analyze recorded 21cm hydrogen line data to infer information about the hydrogen line, Doppler shifts, and the structure of the Milky Way.

Procedure:

- Distribute printed plots and diagrams of the Milky Way to students.
- Instruct students to analyze spectral peaks, identifying frequency shifts that suggest gas movement toward or away from the observer.
- Instruct students to calculate Doppler velocities for each identified peak, recording redshift or blueshift values.
- Have students use claim-evidence reasoning to show that we live in a rotating spiral galaxy. Compare this with the scenario that we live in an elliptical galaxy where spiral arms are not present.
  - **Proving rotation:** The rotation of the Milky Way can be shown by the distribution of redshifted and blueshifted data. Explain how a rotating galaxy will give rise to a redshifted hydrogen line for one half of the galaxy, and a blueshifted hydrogen line for the other half.

    Draw a diagram on the board, Figure 1, with the Sun at the center and labeled galactic longitudes. Have students draw arrows on the board, at the galactic longitude of their plots, indicating whether their hydrogen line data is redshifted or blueshifted. Redshifted data should be indicated by an arrow pointing away from the center, while blueshifted data should be indicated by an arrow pointing towards the center. Have students explain why the distribution of redshifted and blueshifted data at different galactic longitudes indicates that we live in a rotating galaxy, and which direction (e.g. clockwise or counter-clockwise) the galaxy is rotating.
  - **Proving spiral arms:** The presence of spiral arms in the Milky Way can be shown by the multiple peaks present in the hydrogen line data. Each peak corresponds to emission from distinct spiral arms moving at a different velocity. This can be contrasted with the scenario that we live in an elliptical galaxy, where the distribution of stars and hydrogen gas is more diffuse and does not form spiral arms.

    Draw a diagram on the board, Figure 2, comparing these two scenarios. Have students explain why the presence of multiple distinct peaks indicates the existence of spiral arms in the Milky Way. Ask students what they would expect the hydrogen line profiles to look like if we did live in an elliptical galaxy. Have students compare their data with the image of the Milky Way in the lab manual, and match the number of peaks in their data with the number of spirals arms along the line of sight of their pointing.

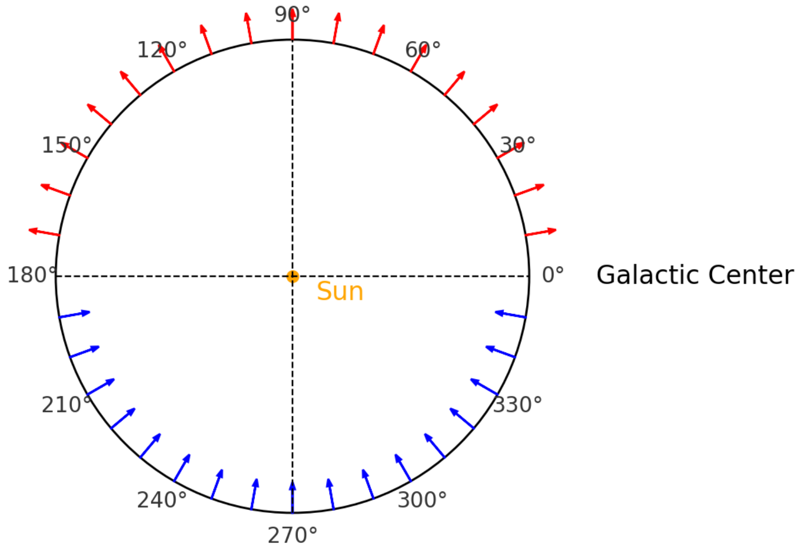

Figure 1: Example diagram to illustrate the relationship between telescope pointing along the Milky Way plane and the Doppler shift of the hydrogen line. This visualization helps demonstrate the Milky Way's rotational motion: red arrows indicate hydrogen gas moving away from the Sun, creating a redshift, while blue arrows show gas moving toward the Sun, resulting in a blueshift.

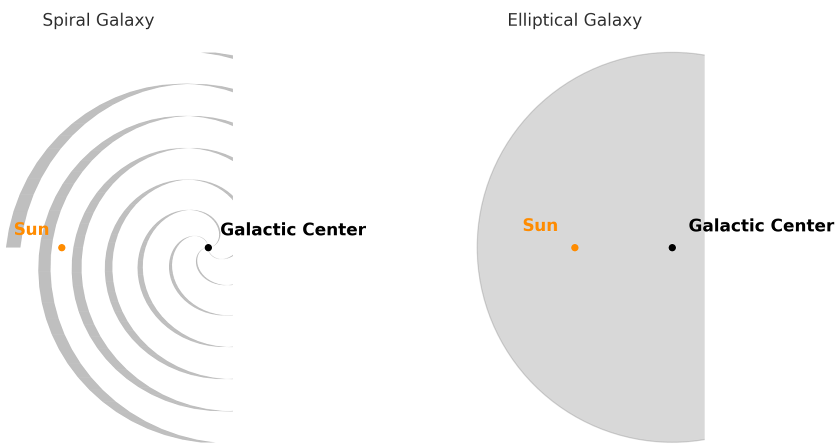

Figure 2: Diagram to contrast a spiral galaxy (left) with distinct spiral arms, and an elliptical galaxy (right) with a more uniform structure. Prompt students to investigate which structure aligns with their observed hydrogen line data, allowing them to identify the Milky Way's spiral structure.

Part 2: Live Observations with the ATA

Objectives

Guide students through conducting live observations of the 21cm hydrogen line using the Allen Telescope Array. The goal is to use real-time data to identify hydrogen clouds at various galactic longitudes and connect these observations with the Milky Way's structure.

Preparation for Live Observations

- **Assign Galactic Longitudes**: Each group should be given specific galactic longitudes to observe. Assign longitudes spanning a range to illustrate variations across the galaxy. Before starting the lab, ensure that the desired galactic longitudes are more that 20° above the local horizon at the ATA during the lab time. This can be done directly in the Easy ATA GUI, which will display the current observable galactic longitudes with the `Show Available Targets` button, or by using a planetarium app such as Stellarium. If using the latter method, ensure that you're using the correct latitude and longitude for the ATA (`40.8171° N, 121.4690° W`).
- **Demonstrate Telescope Calibration**: Lead students through initializing and calibrating the ATA with the Easy ATA GUI. Highlight the importance of accurate calibration for signal clarity. If you're running this lab without the assistance of someone from the AGISETI team, contact us in advance so we can setup the proper VPN and VNC settings on your computer so that you can operate the ATA directly. Note that we can only grant access to the ATA systems for instructors and not students, so the telescope control will have to be done on your computer. If you are teaching with the assistance of someone from the AGISETI team, we will provide a computer with the proper setup for operating the ATA.
- **Target Selection**: Guide students to use the "Show Available Targets" feature. Confirm visibility of each group's assigned longitude and emphasize the effect of Earth's rotation on observable regions.
- **Tracking and Slewing**: Ensure students input coordinates correctly and monitor the telescope's alignment with their target coordinates. Use the `Show Antenna Status` button and the camera feed as a confirmation tool.

GNU Radio Companion Flowgraph Instructions

1. ATA_HI_Live

Purpose: The `ATA_HI_Live` flowgraph is designed for real-time observation of the 21 cm hydrogen line. This setup provides immediate, live data from the ATA, allowing students to monitor the hydrogen line frequency as it appears.

Instructions:

1. Launch the `ATA_HI_Live.grc` file in GNU Radio.
2. Ensure that the `ZMQ SUB Source` block is connected to the correct network address, which streams data from the ATA.
3. Run the flowgraph. The `QT GUI Vector Sink` displays power density across frequencies, with the X-axis centered around the hydrogen line frequency (1.420.405 GHz).
4. Observe the real-time spectrum, noting any peaks or patterns corresponding to hydrogen emissions.

Troubleshooting:

- If no data appears, verify network connectivity and ensure the `ZMQ SUB Source` address is correctly configured(`tcp://10.1.50.11:5555`).
- Adjust the sample rate if the display appears unstable, or change the integration time to improve clarity.

2. ATA_HI_Integrated

Purpose: The `ATA_HI_Integrated` flowgraph performs data integration over a set period, which helps in enhancing signal clarity and reducing noise. This approach is ideal for obtaining a clearer view of the hydrogen line signal over time.

Instructions:

1. Open the `ATA_HI_Integrated.grc` file in GNU Radio.
2. Set the parameters for `integration_time` according to the desired integration length, this should be set between 20-60 seconds.
3. Run the flowgraph. The `QT GUI Vector Sink` will display an averaged spectrum with enhanced signal clarity.
4. To save data, enable the `File Sink` block (select the block and type e to enable, d to disable) and specify a save location. Ensure students use clear file names that include the observation details.

Troubleshooting:

- If data appears noisy, increase `integration_time` for improved noise reduction.
- Confirm that the `File Sink` is active if data saving is required, and ensure file paths are correctly set.

3. ATA_HI_File_View

Purpose: The `ATA_HI_File_View` flowgraph allows students to analyze recorded data files. This flowgraph is used for plotting saved observations and interpreting them in the frequency domain.

Instructions:

1. Load the `ATA_HI_File_View.grc` file in GNU Radio.
2. Set the file path in the `File Source` block to the desired recorded data file.
3. Run the flowgraph. The `QT GUI Vector Sink` displays the frequency spectrum, with the X-axis centered on the hydrogen line frequency.
4. For velocity-based analysis, enable the second `QT GUI Vector Sink` to view data in terms of Doppler shifts.

Troubleshooting:

- If the file doesn't load, check the path and format compatibility.
- If the file is displaying incorrectly, ensure that the `QT GUI Vector Sink` block parameters, match those in the `ATA_HI_Live.grc` and `ATA_HI_Integrated.grc` files.

General Troubleshooting Tips

- **Network Issues:** Verify network configurations if data from the ATA does not appear in the live flowgraphs.
- **Data Saving and File Access:** Remind students to enable the `File Sink` when saving data, and check permissions and paths to avoid storage issues.
- **Integration and Averaging:** In `ATA_HI_Integrated`, adjust integration settings to balance noise reduction with observation time.

Guidance During Observations

- Circulate among groups to ensure they follow the flowgraph procedures correctly and understand each parameter adjustment.
- Address common issues, such as signal drops, by recalibrating the telescope or adjusting integration time. For proper recalibration, select the `Shut Down Antenna` button, wait for the text box to say the antenna is parked (this may take a few minutes), close down the Easy ATA GUI and restart it, and recalibrate the telescope with the `Activate Antenna` button.
- Encourage students to check their real-time spectra for identifiable peaks and notate these for analysis.

Data Analysis and Interpretation

Peak Identification and Comparative Analysis

- **Identifying Spectral Peaks**: Guide students to examine spectra, identifying and marking prominent peaks. They should compare the number and position of peaks with their initial predictions based on galactic longitude.
- **Doppler Shift Calculation**:
  - Instruct students to apply the Doppler shift equation for each peak to determine velocity, noting whether the shift indicates movement towards (blueshift) or away from (redshift) the observer.
  - Discuss how these calculated velocities reveal the relative movement of hydrogen clouds within the Milky Way's arms.

Comparing Live Data with Recorded Data

- Instruct students to overlay live data with recorded data from Part 1, looking for similarities or variations in spectral peaks. Guide them in discussing the reasons for any differences, such as equipment limitations or observational angles.
- Encourage students to hypothesize how their findings reflect the rotational dynamics of the Milky Way.

Visualization and Interpretation of Galactic Structure

- **Add to the Milky Way Model**: Based on Doppler shifts and peak positions, students should add arrows to a class-wide Milky Way diagram, indicating hydrogen clouds' movement. Use blue and red arrows to distinguish between blueshifted and redshifted regions.

- **Rotation Curve Discussion**: Facilitate a discussion on how the observed Doppler shifts suggest a spiral structure. Briefly touch on the concept of a galactic rotation curve and its implications, such as supporting evidence for dark matter in the galaxy.