Instructor Notes: Live Observations with the Allen Telescope Array

Objective

The primary goal of this lab is to provide students with hands-on experience in analyzing real astronomical data and conducting live radio astronomy observations using the Allen Telescope Array (ATA). By the end of the lab, students will have an understanding of how radio telescopes are used to observe astrophysical signals from neutral hydrogen gas in the Milky Way. Students will also gain practical experience using software-defined radio (SDR) tools and Python for signal processing and data analysis.

Learning Outcomes

1. Explain the function of a radio telescope and its key components, including how the ATA is designed to capture and process radio signals.
2. Operate the ATA through the provided tools to conduct a live observation.
3. Build and modify GNU Radio flowgraphs to receive, filter, and visualize real-time signals from the ATA.
4. Use GNU Radio and Python to perform signal analysis, including techniques such as Fourier transforms and time-domain analysis.
5. Interpret the signals received from hydrogen in the Milky Way to understand the relationship between frequency and wavelength, Doppler shifts, and the spiral structure of the Milky Way.
6. Collaborate in a group setting to troubleshoot and solve problems, improving the ability to analyze observational data and ensure successful signal acquisition.

Lecture Tools

7. Digitization and Nyquist Sampling
8. Fourier Transforms and the Frequency Domain
9. Interferometry and Beamforming

Pre-lab Preparation

Instructor Responsibilities

1. **Equipment Check:**

- Verify that each group has access to a computer with GNU Radio installed and properly configured.

- Ensure that the ATA is operational and accessible for live observations.
- Prepare printed plots of recorded hydrogen line data for Part 1.
- Have access to the Milky Way diagram (as referenced in the lab manual) for visualization activities.

2. **Software and Tools Familiarization:**

- Review the GNU Radio flowgraphs mentioned in the lab manual:
  - `ATA_HI_Live.grc`
  - `ATA_HI_Integrated.grc`
  - `ATA_HI_File_View.grc`
- Ensure Easy ATA GUI (`EAG.py`) is functioning correctly and that all students know how to navigate it.

3. **Review Lab Procedures:**

- Familiarize yourself with both parts of the lab to effectively guide students through the processes.
- Prepare any additional explanations or demonstrations that may help clarify complex concepts.

4. **Prepare Supplementary Materials:**

- Gather diagrams, example calculations, and reference materials to support student understanding during the lab.

5. **Set Up Observation Stations:**

- Organize computer stations with necessary software pre-installed.
- Ensure network connectivity between computers and the ATA is stable.

Observing Tools

Telescope Control

The Allen Telescope Array (ATA) is accessed through a VNC (Virtual Network Computing) remote desktop, which requires a VPN (Virtual Private Network) connection for secure access. As the instructor, you will need to ensure that the VPN and VNC are properly configured before running the lab. In some cases, a representative from the AGISETI project will be present to assist with the setup, providing a computer that already has the necessary VPN and VNC configurations. If an AGISETI representative is not available, please contact us well in advance so that we can assist you in setting up everything needed for successful access.

During the lab, students will use the control computer to operate the telescope with the Easy ATA GUI. Once observations begin, the data will be streamed to the students' computers, where they can use GNU Radio to receive, process, and analyze the information collected. Students should have GNU Radio installed and working properly before beginning the lab, instructions for installation can be found here: `https://wiki.gnuradio.org/index.php/InstallingGR`

1. **Easy ATA GUI (`EAG.py`):**

- Functionality: Provides a user-friendly interface for calibrating and operating ATA antennas via VNC with proper settings.
- Operations:
  - Calibration: Initiate the calibration process by selecting the `Active Antenna` button. Monitor the status until "Calibration Complete!" appears.
  - Target Selection: Use the `Show Available Targets` button to display observable galactic longitudes.
  - Tracking Sources: Input the desired galactic longitude and select `Track Source` to slew the telescope to the target.
  - Ending the Observation: Select `Shut Down Antenna` and wait for the telescope to park and release.
- Troubleshooting:
  - Verify that the correct galactic longitude is entered and is within the observable range.
  - If calibration does not complete within 90 seconds, select `Shut Down Antenna`, wait until the antenna parks and releases. Close the program and restart it using the terminal command *python EAG.py*.

2. **VNC Connection:**

- Purpose: Allows remote control of the ATA interface.
- Access: Ensure that VNC clients are installed on all computers and that network settings permit VNC traffic.
- Usage Tips:
  - Provide students with the necessary VNC credentials.
  - Demonstrate how to establish and disconnect VNC sessions.

Data Reception

1. **GNU Radio Companion (GRC):**

- Functionality: Open-source toolkit for building and simulating software-defined radio (SDR) systems.
- Flowgraphs:
  - `ATA_HI_Live.grc`: Displays live data streaming from the ATA.
  - `ATA_HI_Integrated.grc`: Integrates live data over a set duration to enhance signal clarity.
  - `ATA_HI_File_View.grc`: Plots saved data files for further analysis.
- Operations:
  - Running Flowgraphs: Guide students on how to open and execute the flowgraphs.
  - Adjusting Parameters: Explain how to modify variables such as integration time to optimize data quality.

- Troubleshooting:
  - Ensure that all necessary blocks in the flowgraph are enabled before running.
  - Verify that the ATA is correctly transmitting data by checking the `Calibration Complete!` status.

2. **Data Saving and Viewing:**

- File Sink Configuration:
  - Instruct students to enable the `File Sink` block by selecting it and pressing `e`.
  - Configure the `File Sink` to save data with appropriate naming conventions, including group identifiers and observation details.
- Viewing Saved Data:
  - Guide students to use the `ATA_HI_File_View.grc` flowgraph to plot and analyze their saved data files.
  - Demonstrate how to locate and open saved files within the flowgraph.
- Data Management:
  - Emphasize the importance of organizing saved data in designated folders for easy retrieval.
  - Encourage consistent naming conventions to facilitate data comparison and analysis.

Lab Procedure

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

- 21cm Hydrogen Line: Emission resulting from the spin-flip transition in neutral hydrogen atoms, crucial for mapping hydrogen distribution in the galaxy.
- Doppler Shifts: Changes in frequency due to the motion of hydrogen gas relative to the observer, used to calculate radial velocities.
- Galactic Structure: Understanding how Doppler velocities inform the spiral structure and rotation dynamics of the Milky Way.

Procedure

1. **Plot Analysis:**

- Distribute printed plots of the hydrogen line at different galactic longitudes to each group.
- Instruct students to examine the plots, identify the number of distinct peaks, and estimate the observed frequency for each peak.

- Instructor Tip: Highlight that multiple peaks may indicate the presence of multiple hydrogen clouds or spiral arms along the line of sight.

2. **Calculate the Doppler Velocity for Each Peak:**

- Provide the Doppler shift equation:

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

- Guide students through an example calculation:

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

- Instruct students to apply the equation to each identified peak and record whether the gas is redshifted (moving away) or blueshifted (moving toward).

3. **Wavelength Calculation from Frequency:**

- Present the relationship between wavelength and frequency:

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

- Ensure students convert frequencies from MHz to Hz:

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

- Guide students through calculating the wavelength:

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

4. **Compare the Strength of Each Plot:**

- Have students compare the peak heights across different galactic longitudes.
- Discuss how positions closer to the galactic center or plane typically exhibit stronger signals due to higher hydrogen density.
- Instructor Tip: Encourage students to consider observational angles and their impact on signal strength.

5. **Visualize the Galaxy:**

- Provide each group with a large Milky Way diagram.
- Instruct students to draw arrows representing the motion of hydrogen gas based on their Doppler velocity calculations:
  - Blue Arrows: Indicate gas moving toward the Sun (blueshifted).
  - Red Arrows: Indicate gas moving away from the Sun (redshifted).
- Differentiate between strong and weak signals by using varying arrow lengths or colors.
- Instructor Tip: Use the included figure (1) to demonstrate how to plot arrows accurately.

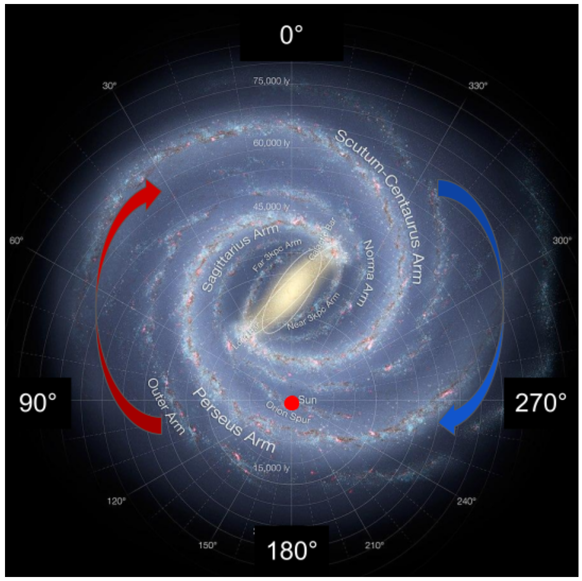

Figure 1: An artist's impression of the Milky Way from above with labeled galactic longitudes. The red dot marks the location of the Sun in the Orion spur, and the arrows indicate the direction the spiral arms are moving.

Data Analysis and Interpretation

1. **Critical Evaluation:**

- Encourage students to consider the accuracy of their peak identification and Doppler velocity calculations.
- Discuss potential sources of error, such as measurement inaccuracies or overlapping signals.

2. **Galactic Dynamics:**

- Facilitate discussions on how the observed Doppler velocities inform our understanding of the Milky Way's rotation curve.
- Highlight the evidence for dark matter based on flat rotation curves in outer galaxy regions.

3. **Report Compilation:**

- Instruct students to compile their findings into a structured report, including:
  - Introduction and objectives
  - Methods and procedures
  - Results with calculated velocities and plotted maps
  - Discussion on implications and potential errors

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, students will gain hands-on experience with radio telescope operations and data collection, enhancing their understanding of astronomical observation techniques.

Procedure

1. **Assign Galactic Longitudes:**

- Assign each group one or more specific galactic longitudes for live observation.
- Instruct students to use the Milky Way diagram to predict the number of spectral peaks they expect to observe at their assigned longitude.
- Instructor Tip: Ensure that assigned longitudes cover a range of positions to demonstrate different aspects of galactic structure.

2. **Initiate Telescope Calibration:**

- Have students select the `Active Antenna` button in the Easy ATA GUI.
- Instruct them to wait approximately 75 seconds for the calibration process to complete, indicated by the message "Calibration Complete!"
- Instructor Tip: Monitor the calibration process and assist any groups experiencing delays or issues.

3. **Select Available Targets:**

- Guide students to click the `Show Available Targets` button in the Easy ATA GUI.
- Explain that this displays galactic longitudes currently observable (more than 20° above the local horizon).
- Confirm that each group's assigned longitude is within the observable range.
- Instructor Tip: Provide a brief demonstration of selecting a target and interpreting the overlaid lines on the Milky Way diagram.

4. **Track the Source:**

- Instruct students to enter their assigned galactic longitude into the prompt and select the `Track Source` button.
- Explain that the telescope will slew to the chosen location and begin tracking as the Earth rotates.
- Encourage students to monitor the live camera feed to ensure proper alignment.

- Instructor Tip: Assist groups in verifying that the telescope has successfully reached the target by checking for the "Arrived at galactic coordinate (l,b)" message.

5. **Run GNU Radio Flowgraphs:**

- Have students open GNU Radio Companion and load the `ATA_HI_Live.grc` flowgraph to start streaming live data.
- For clearer visualization, instruct them to run the `ATA_HI_Integrated.grc` flowgraph and set the integration time between 20-60 seconds.
- Explain the concept of integration time as analogous to shutter speed on a camera, where data is accumulated over the set duration.
- Instructor Tip: Demonstrate how to adjust integration time and discuss its impact on data clarity and signal-to-noise ratio.

6. **Save and View Data:**

- Ensure students enable the `File Sink` block in the flowgraph by selecting the block and pressing `e`, and disable if necessary by pressing `d`.
- Instruct them to double-click the `File Sink` block and set the file path to a designated folder, naming the file to include:
  - Group number or name
  - Galactic coordinates of the pointing
  - Integration time
- Have students run the `ATA_HI_File_View.grc` flowgraph to plot and analyze their saved data.
- Instructor Tip: Remind students to save their data before disabling the `File Sink` to prevent data loss.

Data Analysis and Interpretation

1. **Peak Identification and Comparison:**

- Instruct students to examine their live observation plots to identify all significant spectral peaks.
- Have them count the number of peaks and note their corresponding observed frequencies.
- Compare these peaks with predictions and recorded data from Part 1.
- Instructor Tip: Facilitate discussions on why certain peaks may be stronger or weaker and the presence of unexpected peaks.

2. **Doppler Velocity Calculation:**

- Guide students to calculate the Doppler velocity for each identified peak using the Doppler shift equation:

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

- Instruct them to determine whether each velocity indicates a redshift (negative velocity, moving away) or blueshift (positive velocity, moving toward).
- Have students record their calculated velocities in a data table alongside the corresponding frequencies.

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

- Instruct students to overlay their live observation plots with the recorded data plots from Part 1.
- Have them identify corresponding peaks between the two datasets and note any differences in positions or velocities.
- Discuss possible reasons for inconsistencies, such as observational timing, equipment calibration, or inherent variability in gas motion.

4. **Visualization and Mapping:**

- Direct students to update the Milky Way diagram they contributed to in Part 1 with additional data from 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

- Challenges Encountered:
  - Encourage students to reflect on any technical or analytical challenges they faced during the lab.
  - Discuss how these challenges were overcome and what could be improved in future observations.
- Insights Gained:
  - Facilitate discussions on how their findings contribute to the broader understanding of the Milky Way's structure and dynamics.
  - Explore the implications of their work for future astronomical research and the search for extraterrestrial intelligence (SETI).
- Collaborative Learning:
  - Highlight the importance of teamwork in troubleshooting and problem-solving during live observations.
  - Encourage groups to share their experiences and insights with the class.

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.

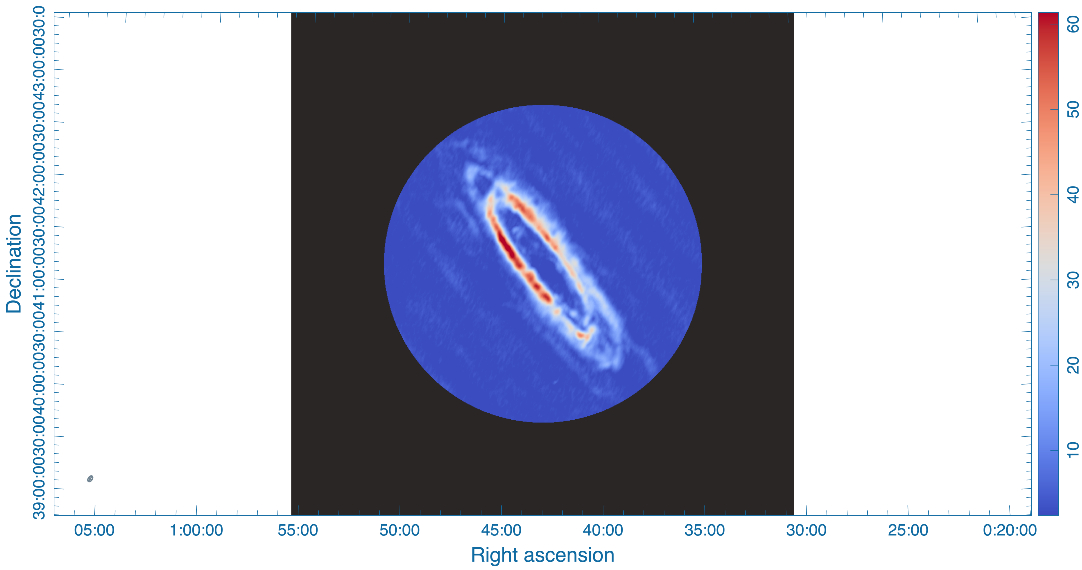

Figure 2: Intensity field of M31 (Andromeda Galaxy) observed at the 21cm hydrogen line. This image reveals the distribution of neutral hydrogen gas, highlighting the galaxy's spiral structure and overall morphology.

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.

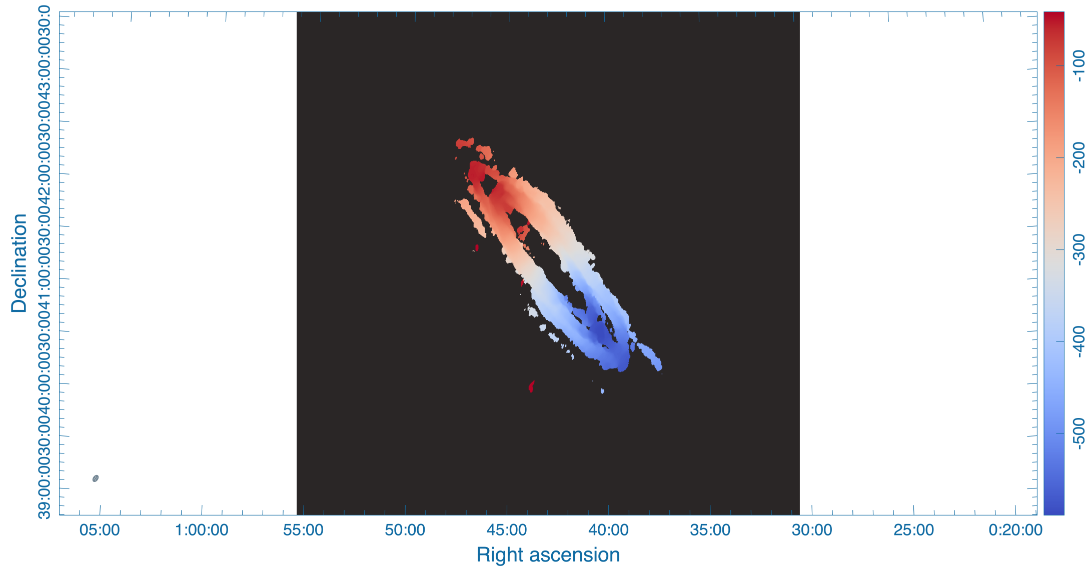

Figure 3: Velocity field of M31 (Andromeda Galaxy) observed at the 21cm hydrogen line. This image displays the Doppler-shifted velocities of the hydrogen gas, clearly illustrating the rotational redshift and blueshift across the galaxy.

Troubleshooting Tips

GNU Radio Issues

1. **Flowgraph Errors:**

- Ensure all necessary blocks are connected correctly.
- Verify that no blocks are disabled unless intentionally done.
- Check for missing dependencies or libraries required by GNU Radio.

2. **Data Stream Interruptions:**

- Confirm that the ATA is actively transmitting data.
- Restart the GNU Radio flowgraphs if data does not appear.
- Recalibrate the ATA if persistent data issues occur.

3. **Integration Time Settings:**

- Advise students to set integration time between 20-60 seconds for optimal data quality.
- Explain the impact of shorter vs. longer integration times on signal clarity and noise levels.

ATA Calibration Problems

1. **Calibration Incomplete:**

- Check network connections between the computer and ATA.
- Ensure that the ATA antennas are powered on and functioning.

- Restart the Easy ATA GUI and attempt calibration again.

2. **Incorrect Target Slewing:**

- Verify that the correct galactic longitude is entered.
- Ensure that the target is within the currently observable range.
- Recalibrate if the telescope fails to slew to the correct location.

Data Saving Errors

1. **File Sink Not Enabled:**

- Remind students to enable the `File Sink` block before running the flowgraph.
- Show how to enable and disable blocks using keyboard shortcuts (`e` to enable, `d` to disable).

2. **Incorrect File Path:**

- Ensure that students have write permissions to the designated save folder.
- Guide them in correctly navigating the file browser to select the save location.

3. **Naming Conventions:**

- Stress the importance of descriptive file names for easy identification and retrieval.
- Provide examples of effective naming conventions.

Enhancing the Learning Experience

Interactive Demonstrations

1. Conduct a live demonstration of running a GNU Radio flowgraph to showcase real-time data processing.
2. Walk through an example Doppler velocity calculation to reinforce the mathematical concepts.
3. Show how to overlay live observation data with recorded data plots for comparative analysis.

Encourage Collaboration

1. Promote teamwork by having groups discuss their findings and compare results.
2. Facilitate inter-group discussions to share insights and address differing observations.
3. Assign roles within groups (e.g., data analyst, flowgraph operator, report writer) to ensure active participation.

Provide Additional Resources

1. Offer supplementary readings or tutorials on advanced topics like interferometry, signal processing, or galactic dynamics for interested students.

2. Share links to GNU Radio tutorials and documentation to help students build and modify flow-graphs.

3. Provide access to online forums or support groups for troubleshooting and peer assistance.

Assessment and Feedback

Monitor Progress

1. Circulate among groups to observe their workflow, provide assistance, and ensure they are on track with each step.

2. Use formative assessment techniques by asking probing questions to gauge understanding.

Evaluate Understanding

1. Review students' calculations, data plots, and galactic maps for accuracy and comprehension.

2. Use the reflection and discussion section to assess their ability to synthesize information and apply theoretical concepts.

3. Provide constructive feedback on their reports and presentations.

Provide Constructive Feedback

1. Highlight successful strategies and correct any errors in data analysis or interpretation.

2. Encourage students to reflect on their observational techniques and suggest improvements for future labs.

3. Acknowledge innovative approaches or insightful analyses to motivate continued learning.

Post-Lab Activities

Data Compilation

1. Collect all groups' data tables, rotation curves, and galactic maps for comprehensive analysis.

2. Create a master dataset to compare and contrast different observations and findings.

Report Writing

1. Instruct students to compile their findings into a structured lab report, including:

- Introduction: Objectives and background theory.
- Methods: Detailed description of procedures followed.
- Results: Data tables, calculated velocities, and plotted maps.
- Discussion: Interpretation of results, comparison with predictions, and implications.
- Conclusion: Summary of findings and their significance.

2. Provide a template or guidelines to help students structure their reports effectively.

Presentation

1. Consider having groups present their observations and analyses to the class.

2. Encourage the use of visual aids such as plots, diagrams, and the Milky Way map.

3. Facilitate a Q&A session to allow other students to engage with the presented material.

Safety and Best Practices

Equipment Handling

1. Ensure that students handle all equipment, including computers and any connected hardware, with care to prevent damage.

2. Instruct students on proper shutdown procedures for the ATA and related software to avoid data corruption.

Data Privacy

1. Emphasize the importance of properly saving and labeling data to maintain confidentiality and accuracy.

2. Instruct students not to share data files outside their groups without permission.

Software Usage

1. Remind students to follow software usage guidelines to prevent data loss or system malfunctions.

2. Encourage regular saving of work and backing up important data files.

Conclusion

By following these instructor notes, you will be well-equipped to facilitate a successful and educational lab session on observing the 21cm hydrogen line with the Allen Telescope Array. Encourage active participation, foster a supportive learning environment, and utilize the provided resources to enhance students' understanding of radio astronomy and galactic dynamics.