Lab #6: Mapping the Milky Way

Lab report is due Monday, April 5th, 2019, before 11:59 pm EDT

1. Overview

This handout provides a description of the 6th and final lab of AST326, which builds on your experiences from previous labs to observe and map the spiral arms of the Milky Way. You will be able to produce a rotation curve, and by contrasting it to a standard potential, infer in presence of the Milky Way's Dark Matter Halo.

> *IMPORTANT: The three labs this term will give you more latitude to explore than the first three, and hence include fewer explicit instructions on how to proceed. If you are lost or need help, attend tutorials, lectures, or office hours, ask your classmates, google around for tips, and by all means ask questions.*

1.1 Schedule

This is a four-week lab, with lectures and sessions the weeks of March 11th, 18th, 25nd, and April 1st. The first step is to plan your observations: you should get started on those asap, then schedule time to observe with Michael Williams. The telescope appears to be working, but you should assume **something will go wrong**, and leave yourselves time to re-observe.

You should aim to complete through section 4.1 during the 1st and 2nd week, section 4.2 during the 2nd and 3rd to allow time for additional observations if needed. You should be sure your data looks reasonable for 4.3 by the end of the 3rd lab week, and complete the analyses and write-up during the 4th.

This may sound a bit repetitive at this stage, but **do not underestimate the time the analysis and write-up will take!** Since you'll be doing this on your own data, and that data may have problems with it, you'll need to start the analysis early, to give yourself time to re-observe.

The lab report should to be submitted electronically, on or before April 5th at 11:59pm EDT. Because final course grades are due shortly after that, **we cannot accept late submissions** unless there are extenuating circumstances!

1.2 Goals

Understand galactic coordinates, plan an observation. Use a radio spectrometer to make real-world observations of the Milky Way. Study Doppler-shifted emission and infer structures and rotation velocities. Discover the Milky Way's massive halo, and infer the presence of Dark Matter.

1.3 Reading assignments

- Astronomical Coordinates: Equatorial, Horizon, and Galactic

  - Wikipedia's surprisingly good summary, and links therein, https://en.wikipedia.org/wiki/Celestial_coordinate_system
- The 21cm Line and Galactic HI emission
  - Essential Radio Astronomy (Condon & Ransom, 2016) Ch 7.8. Available online, https://www.cv.nrao.edu/~sransom/web/Ch7.html#S8
- Python: arrays, functions, and advanced plotting

1.4 Key Steps
This lab is broken down into several stages.

1. Planning your observations: choose a series of positions in the galaxy which can be seen from Toronto during your scheduled observing time.
2. Gathering data: Use the small radio telescope on the top of MP to make measurements of the galactic HI 21cm signal.
3. Analysis: Process your data to build a map of HI recession velocity throughout the Galaxy.

2. Background

2.1 The 21cm Line
Quantum physicists worked out almost a century ago that a spin-orbit coupling in the hydrogen atom would give rise to an extremely fine energy splitting in its ground state. The so-called "singlet" state, where the spin of the electron and proton are counter-aligned, has a very slightly lower energy than the "triplet" state, where they are aligned.

This Hyperfine splitting is ≈ 6 μeV in Hydrogen. An atom transitioning from one state to the other emits (or absorbs) a photon of wavelength and frequency:

$$\boldsymbol{\lambda \approx 21.1\text{cm}}$$

$$\boldsymbol{\nu \approx 1420.4\text{MHz}}$$

Such a transition, however, is quantum mechanically forbidden: the excited state has a half-life of ≈$3\text{x}10^{15}$ s, or about 10 My. This means that the resulting signal is extremely faint, unless it results from a particularly large reservoir of HI gas – thankfully, galaxies like ours are full of just such reservoirs!

The long lifetime has another effect: the intrinsic width of any spectral line is limited by the Uncertainty Principle, since $\Delta E \Delta t \geq \hbar/2$. Short-lived states naturally produce wide spectral lines, while long-lived rare transitions like the Hyperfine transition are naturally extremely narrow. This makes the 21cm line from HI first an excellent clock (Hydrogen Masers excite this line to form a basis for modern high-precision clocks), and more importantly for our purposes, HI is an extremely sensitive probe of other spectral perturbations such as kinetic Doppler shifts.

In this lab, you will be observing Doppler-shifted HI 21cm emission from within the Milky Way, using the spectral properties observed to infer structure. A high-resolution spectrum around 1420MHz is shown in Figure 1. (What causes the residual broadening of these three lines?)

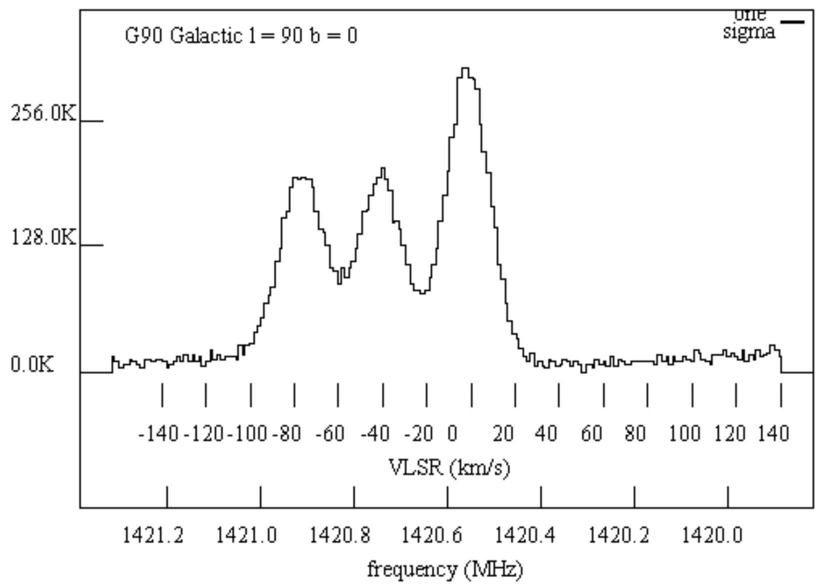

Figure 1 – Sample spectrum of Doppler-shifted 21cm radiation from the Milky Way. Three distinct signals are visible, two approaching the earth at ≈ 40km/s and ≈ 80km/s and one receding at ≈ 10km/s. These arise from three spiral arms along the line of sight. Taken from http://sat-sh.lernnetz.de/milchstrasseE.html

2.1.1 Doppler Shifting of Lines

You should be familiar by now with the effect of relative velocities between sources and observers: a spectral shift results from any relative radial motion. Though more commonly known today in reference to sound, Doppler first proposed the idea as leading to colour variability in binary stars. A proper relativistic treatment leads to the relationship

$$\frac{v}{c} = \frac{f_0^2 - f^2}{f_0^2 + f^2}$$

This a slightly painful equation to work with, but at low velocities $v \ll c$, a linear expansion simplifies the equation. Historically, two definitions existed, the "optical" approximation takes $f_0 \to 0$ in the denominator and has become the IAU-approved standard.

$$\frac{v}{c} = \frac{f_0 - f}{f} = z$$

You may also come across the "radio" approximation, which yields a linear relation between velocity and frequency shift, but is now considered deprecated,

$$\frac{v}{c} = \frac{f_0 - f}{f_0} = \frac{z}{1+z}$$

2.2 Coordinates

Because we live on a rock spinning about its own axis, orbiting a star that's bobbing around a galaxy, we have to be careful in defining our coordinate systems when describing events or locations. "Up" isn't a terribly useful direction to an astronomer!

Depending on the context, a variety of different coordinate systems are in wide use. You're already familiar with a few of these from previous labs, but to quickly review the key ones for here:

2.2.1 Equatorial

Equatorial coordinates are probably most familiar astronomical system, and describe positions on the celestial sphere in terms of a Right Ascension (or Hour Angle), and a Declination. Equatorial coordinates uniquely specify a position on the sky, independent of the observer on earth.

2.2.2 Horizontal

Also known as alt-az (or az-el) coordinates, these are the earth-based system you saw in Lab #4. These coordinates are specified with two quantities,

- Azimuth, which describes an angle clockwise from North
- Elevation, which describes an angle from the horizon up toward zenith.

They are commonly used to describe the state of a telescope, which are most easily mounted so they can rotate in azimuth (about a vertical axis) and elevation (about a horizontal). Importantly, these are not celestial coordinates, they are descriptions of directions relative to a point on the ground. Where exactly they point in e.g. (RA,Dec) will depend on the location of the telescope, and will vary in time as the earth rotates.

2.2.3 Galactic

When studying features within the Milky Way galaxy, it is often helpful to use a coordinate system more suited to that study, which compactly allows someone to see what is in the plane of the galaxy vs out of the plane, and what is toward the center vs away from it.

The Galactic coordinate system describes directions in terms of a galactic latitude (b), describing how far above ($b>0$) or below ($b<0$) the galactic plane it is; and a galactic longitude (ℓ) describing whether it is toward or away from the center of the Milky Way. The system is shown schematically in Figure 2.

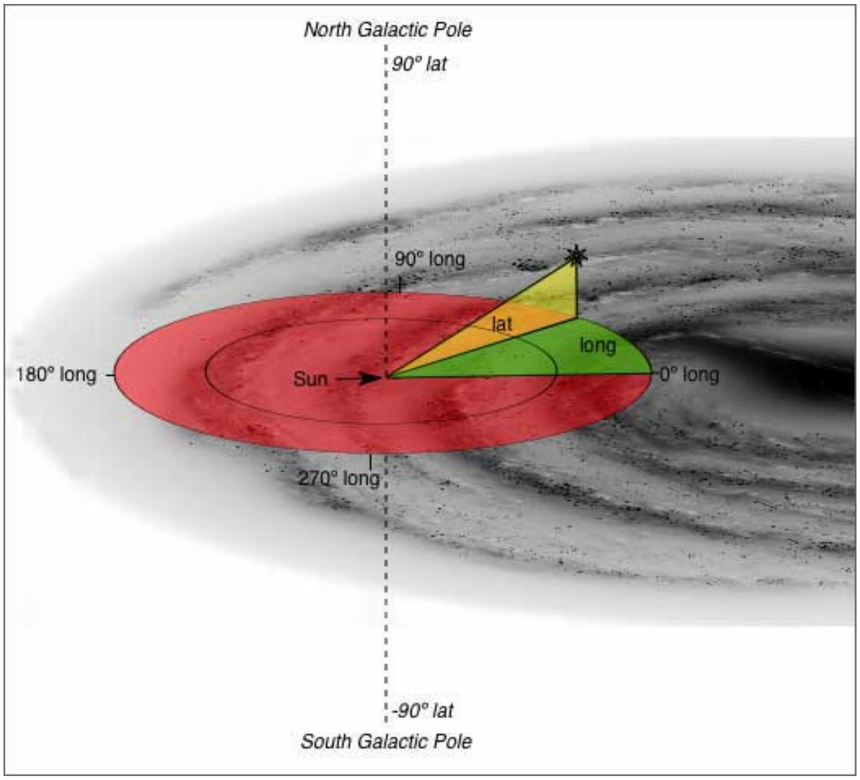

Figure 2 – The Galactic coordinate system.

Since you'll be studying the structure of the galaxy, most of your observations should be close to galactic latitude of *b*=0, with varying galactic longitude.

2.3 The MP Small Radio Telescope

This portion of the lab will require you to take new data using the dish on top of the McLennan Physical Laboratories.

The dish on the roof is from the Small Radio Telescope (SRT) kit, you can look up its properties at https://www.haystack.mit.edu/edu/undergrad/srt/oldsrt.html. Record its size, focal ratio, latitude / longitude. The feed is at prime focus; what sort of beamwidth do you anticipate?

> *Note that the dish on the roof is still in pretty rough shape at the moment. You may have to defer to the telescope operator in targeting sources. We're working on refurbishing it, but realize that part of experimental science is dealing with equipment breaking.*

The telescope receiver uses an AirSpy (as you saw in Lab #2) to record data. The airspy has one particularly unfortunate feature: an internally-generated emission line at exactly 1420MHz. Don't let that distract you from the actual 1420.4 ± 1 MHz signal of the galaxy.

3. Observations

In this lab you will be gathering your own data using the small telescope on the roof of MP. required to schedule time with the telescope operator Michael Williams when you can go to the 16th floor of MP.

3.1 Planning your survey

The Milky Way is a big place, and you'll want to decide how you want to study it. You'll be recording spectra of radio light around 1420MHz to produce spectra (and hence radial velocity measurements) at a variety of Galactic longitudes, only some of which are visible from Toronto at any given time. The existing telescope control software requires pre-programming all targets, so we have programmed it to be able to point along galactic plane, every 10 degrees in galactic longitude.

The receiver on MP is sensitive enough to see the 21cm in real-time, but you should plan on short (≥15s) recordings at each pointing. Choose a series of points along the galactic plane and find out when they will be visible (elevation > 20 degrees) from Toronto. Given constraints on your time and the availability of the telescope, revise and finalize a plan. Please include this schedule in your lab report!

As you saw in labs #2 and #4, radio receivers have response and noise performance that can vary considerably with operating frequency. It's hard to interpret a radio spectrum without comparing it some sort of baseline! As you plan your observations, you should schedule a few "baseline" measurements, looking somewhere well off the galactic plane. It's best if these are close to your targets, since the RFI environment can shift dramatically as the telescope is turned.

3.2 Observing

The SRT uses an AirSpy to record data, but we won't be recording individual samples with the `airspy_rx` program anymore. As you saw with the data from lab #4, a full set of raw voltages is simply too large to save, so we'll have to employ some in-situ signal processing. To record data from the MP telescope, you will need to use a special piece of software called `kotekan` which will gather data, convert it into a spectrum, and average the spectral power estimates over longer timescales.

3.2.1 Powering up the Receiver Chain

The Low Noise Amplifiers out at the focus of the telescope require power from inside. Ask the telescope operator to help you turn that on, there is a power supply present for this task. **Unplug** the BNC connection **before** powering on the supply, just in case the last user set it to some dangerously high voltage.

Power on the supply, turn the voltage down to 0V, and reconnect the BNC. Now you can safely power the LNAs, gently turn the voltage back up to ≈7.5V. **DO NOT GO PAST 8V.** If you're uncomfortable with operating this, ask the operator to help you. It should draw 0.2 – 0.3A when operational.

3.2.2 *Using the Receiver*

A desktop computer running Ubuntu 16.04 Linux will serve as your frontend for examining and recording from the telescope. It should be set up and ready to go when you arrive, but if not, ask the telescope operator to help get it set up and booted.

> The username is `ast326` and the password is `ast326student`

From the desktop, open a terminal and run the acquisition process.

```
cd ch_gpu/build/kotekan
sudo ./kotekan -c ../../config/airspy.yaml
```

This will ask for the password (above), and should spit out a number of comments, then finish with some messages about AirSpy. The computer is now gathering raw voltages from the AirSpy, running Fourier Transforms on them, then squaring the resulting spectra and averaging it over longer time periods. The program will process the data continuously, and also listen for client programs who request a copy of the integrated spectra.

We'll be using python to view and record the data from `kotekan`. Open a second terminal (you can minimize the first), and start a python viewer to show you a waterfall of the data.

```
cd Desktop
ipython -i pyPeekTCP_1pol.py
```

This will open an interactive python session, and a window should appear, showing data from the telescope streaming past. You can use the python session to alter parameters of the viewer, but all interactions you need should be available via the Graphical User Interface (GUI). You should expand this window to fill at least half the screen. (This can be quickly done by dragging the window to the far left of the screen, which will highlight the left half of the screen. An example screenshot is shown in Figure 3. (Make sure the python terminal is still visible as well.)

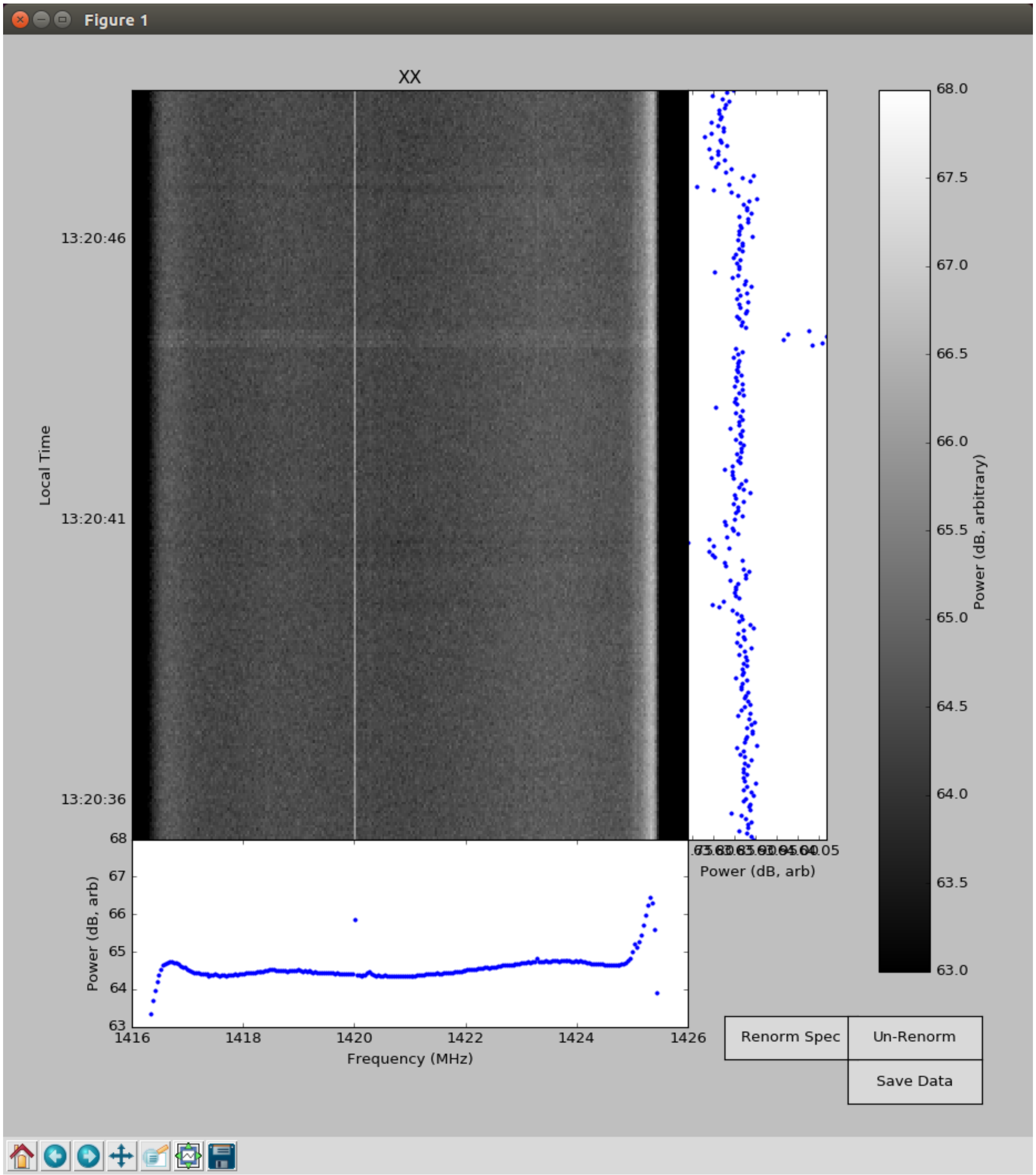

Figure 3 – The viewer interface for the MP telescope. The greyscale color map shows an intensity waterfall, representing the power at each frequency over time, and the time axis should slowly scroll by as new data arrives. The bottom plot shows a time-averaged spectrum of the visible waterfall; the side plot shows a frequency-averaged power timestream, a light curve.

3.2.3 *Saving Data for Offline Analyses*

If you click the "**Save Data**" button in the GUI, the current waterfall array will be saved to a pickle file. (Pickle is a convenient python-native way of saving and transferring data in python.)

The file will be named according to the current time, and the filename should be printed to the python terminal.

> Make sure you record the filename and a description of any data you save!

You'll have to copy these files onto a USB memory stick to get it off the receiver computer and available for offline analyses. You are responsible for your own data! Once you have copied it onto your USB stick, please delete it from the desktop or place it into a subfolder to distinguish it from others groups'.

You can restore the data in these files easily in python, for example

```
In [1]: import pickle
In [2]: d = pickle.load(open('MP_20180306-133147.pkl','rb'))
```

In this example, `d` is now a dictionary, containing 3 entries, `"data"`, `"times"`, and `"freqs"`. You can confirm with `d.keys()`, or access them via e.g., `d["data"]`.

> The only data recorded to pkl files is the raw data used to make the waterfall, along with the axis values. If you have already had the GUI remove a baseline, that is not captured in the recorded data set! You need to record the baseline independently and will have to reconstruct the corrected spectra as part of your analysis.

3.2.4 Removing a Baseline
As described above, you will need to calibrate the receiver's bandpass by recording some data off the galactic plane. Based on the beamwidth of the telescope, how far should you steer away from the galactic plane to take a baseline measurement? (Two full beamwidths is a good rule of thumb.)

To make it easier to see what's going on live, you can tell the viewer to use the current spectrum as a baseline, subtracting it from all future spectra. Click the "**Renorm**" button to turn this on using the current waterfall buffer, or the "**Un-Renorm**" to turn it off. We recommend you take a baseline and turn it on, then take a new baseline if the spectrum drifts substantially from zero.

4. Key Lab Activities
This section outlines the key measurements you should be making throughout the lab, and which should be discussed in your lab report.

4.1 *Observing*
Following the instructions set out above, plan your observations and record spectra from a variety of galactic longitudes, along with off-galaxy calibrations. After pointing the telescope,

you should wait ≥15s for the waterfall to fill with data from the new location, then save your data and move on.

4.1.1 Interpreting 21cm Detections

A sample detection of the Milky Way HI is shown in Figure 4. The two bumps just above 1420MHz show two bundles of HI gas, moving at different speeds relative to earth. Do not attempt to analyze the data during your observations; the interpretation should take place offline.

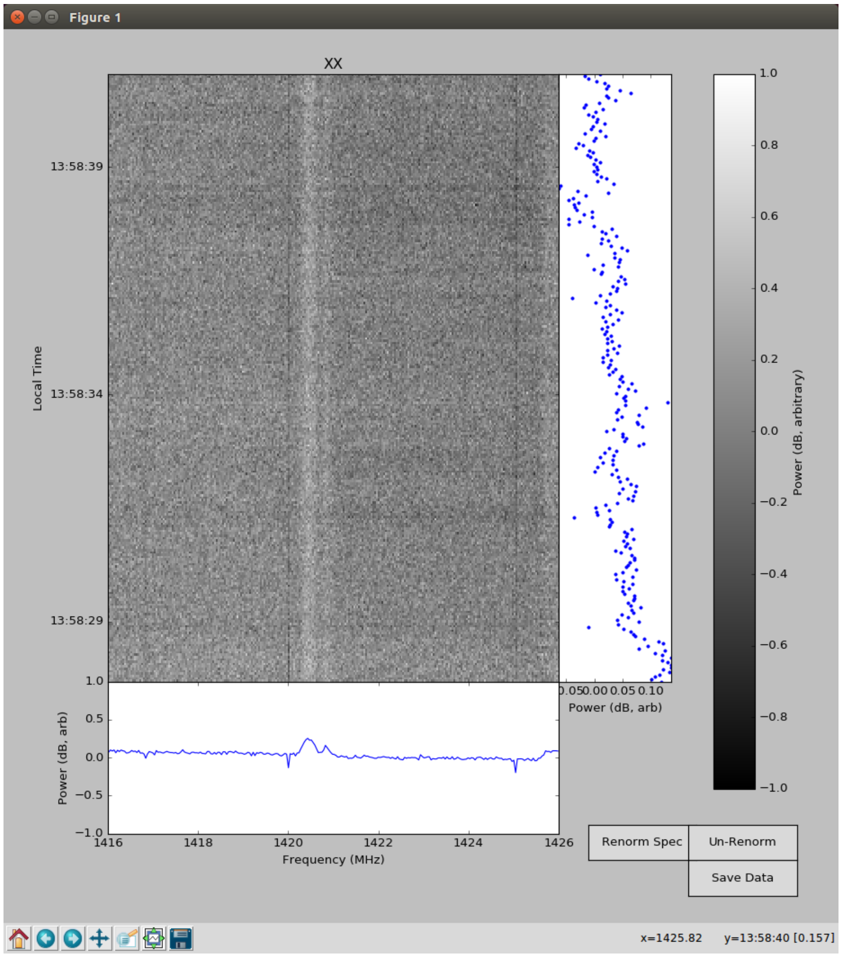

Figure 4 – A detection of 21cm HI emission from the Milky Way. The double-peak structure indicates two distinct and large sources of HI emission, usually interpreted as two distinct spiral arms in our galaxy.

4.2 Radial Velocities

For each pointing at which you recorded data, make a spectrum, and remove your calibration baseline. You may see a single- or multi-peaked 21cm detection. Assuming that all line broadening and shifting comes from Doppler shifting of narrow intrinsic lines, translate your frequency axis into a radial velocity axis. Consider helpful ways to view this data and try plotting it up. (If you have enough points along the galactic plane, an image of flux as a function of Doppler velocity and galactic latitude is an interesting one.)

For each peak in your spectra, record the radial velocity and galactic coordinates. As above, examine these data for hints of underlying structure. These derived data will form the basis of your further analyses.

4.3 Galactic Rotation Curve

A schematic of what you've observed is shown in Figure 5. Recall the Tangent-point method for estimating rotation speed. For each peak in your spectra, at each pointing through the galaxy, estimate the rotation speed of the cloud, and its location relative to the galactic center. You'll need to look up our position within the galaxy!

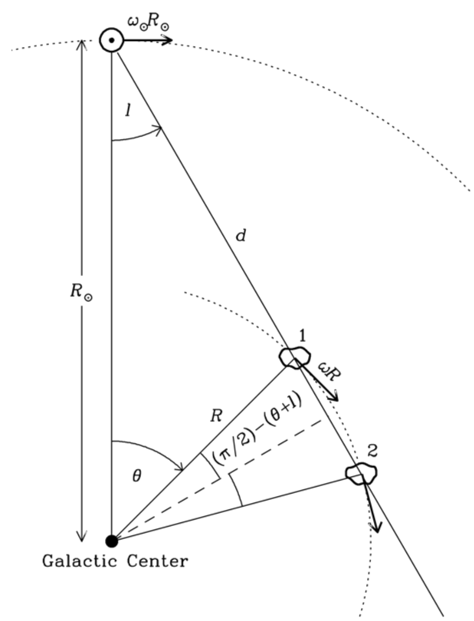

Figure 5 – The geometry of your observations. From Ransom & Condon, Essential Radio Astronomy.

Compare the rotation curve you calculate to one you would expect for a system with centrally-located mass. What can you infer about the gravitational potential of the Milky Way? About its mass distribution?

Most of the luminosity of the Milky Way comes from the central bulge. Is your rotation curve consistent with this? What alternate explanation can you provide?