Lab #3: Radio Receivers and HI Detection

Lab report is due Wednesday, Mar 20, 2019, before 11:59 pm EST

1. Overview

This handout provides a description of the activities that we will explore in this lab. In this lab, you will construct a radio receiver to detect 21cm emission from atomic hydrogen (HI) within our galaxy. If time permits, you will measure the kinematic signature of HI within the galaxy and determine the existence of dark matter.

1.1 Schedule

This is a two and a half-week lab. By end of week of March 4th, you should have designed and constructed your pyramidal horn. By the end of the week of the 11th, you should have obtained preliminary on-sky data with your radio telescope. Your lab report is due electronically on Mar 20, 2019 before 11:59 pm EST.

1.2 Goals

Explore the nature of coherent detection of radio waves by constructing a pyramidal horn receiver for 21cm emission, which is coupled with a software defined radio (SDR). Learn how to calibrate a radio receiver. Detect doppler shifted HI emission within our Milky Way and infer the existence of dark matter.

1.3 Key steps

You will execute eight key steps in this lab:

1. Familiarize yourself with the AirSpy SDR by installing the necessary software to operate it. Resources on how to set it up and run it can be found at these links:
    - http://thor.dunlap.utoronto.ca/~suresh/ast2050/lab3/SoftwareInstallation.pdf
    - http://thor.dunlap.utoronto.ca/~suresh/ast2050/lab3/AirSpyInstructions.pdf
2. Design the dimensions of your pyramidal horn. You are limited by the maximum size of one of the petals to be 32"x40". The length (a) and width (b) of the waveguide are 6.5"x4" (a metal solvent can). After calculating the dimensions, please send me a sketch of the horn so I can double-check the dimensions. The full details on how to calculate the necessary dimensions can be found in the following write-up:
    - http://www.ece.mcmaster.ca/faculty/nikolova/antenna_dload/current_lectures/L18_Horns.pdf
3. Build your feed horn. You will cut the petals of the feedhorn from foam board and aluminize its inside surface by gluing sheets of aluminum foil. I will make the necessary modifications to the waveguide based on your calculations and install the antenna. You will coordinate the construction phase with me, and I will provide the supplies.
4. Check the bandpass of your feedhorn using a Vector Network Analyzer. The vector network analyzer can measure reflection losses by feeding a range of frequencies to your antenna and thereby determine its bandpass. Build your signal chain which requires low noise amplifiers and bandpass filters.
5. Measure the Sun with your newly built feed horn. Characterize its beam width in both directions and measure the antenna gain. You will need to estimate the brightness of the Sun within your band.

6. After aligning your mount using the Sun, observe HI at a range of galactic longitudes so you can probe different regions of the galaxy. Use the tangent method to estimate the radial velocity of the HI gas within the galaxy at different galactocentric distances.
7. (If time permits) Infer the existence of dark matter from the galactic rotation curve.
8. Write your lab report.

2. Background

2.1 21-cm Line Emission

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 in hydrogen results in the absorption or emission of a photon with the following properties:

$$\Delta \mathbf{E} = \mathbf{5.974}\ \boldsymbol{\mu}\mathbf{eV};\ \boldsymbol{\lambda} = \mathbf{21.106\ cm};\ \mathbf{f} = \mathbf{1420.413\ GHz}$$

Unfortunately, such a transition is quantum mechanically forbidden and is extremely rare. The excited state has a half-life of about 10 million years! This means the line is extremely faint. Fortunately, galaxies have large reservoirs of atomic gas, which compensates for this fact and makes this line detectable with reasonable ease. Moreover, the rarity of this transition when combined with the Heisenberg uncertainty principle means that this line is extremely narrow. Any offset or dispersion in this emission line's frequency can be attributed to kinematic Doppler shifts in the gas.

An example of this spectrum of our Milky Way measured at a galactic longitude (*l*) of 90° and latitude (*b*) of 0° is shown in Figure 1. The velocities are measured with respect to our Local Standard of Rest (LSR). The LSR follows the mean motion of the Milky Way in the neighbourhood of the Sun.

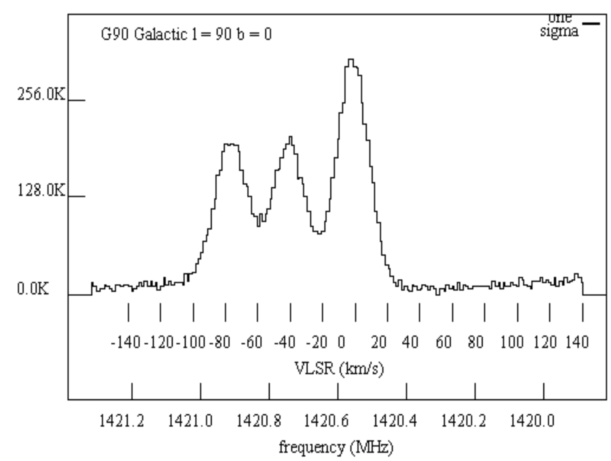

Figure 1: 21-cm spectrum along a line-of-sight within the Milky Way. Three distinct kinematic signals are present: -80, -40, +10 km/s. These are likely associated with gas clouds in different spiral arms within the galaxy. The width indicates internal motion in these clouds. Taken from: https://sat-sh.lernnetz.de/milchstrasseE.html.

As a refresher, Doppler shifts due to radial motion along a line-of-sight can be calculated using the following approximation when $v \ll c$:

$$\frac{v}{c} = \frac{f_0 - f}{f_0} = \frac{\lambda - \lambda_0}{\lambda_0} = z$$

where v is the velocity of the object, f_0 and λ_0 are the rest-frame frequency and wavelength of a given line, respectively, f and λ are its observed frequency and wavelength, and z is the redshift.

2.2 Coordinate System

When studying the Milky Way, it is best to use the galactic coordinate system as it describes when one is looking within the plane of the galaxy or toward/away from its center. There are two angles that describe the coordinate system, galactic longitude (l) and latitude (b) both of which are measured from the location of the Sun. A depiction of the galactic coordinate system is shown in Figure 2.

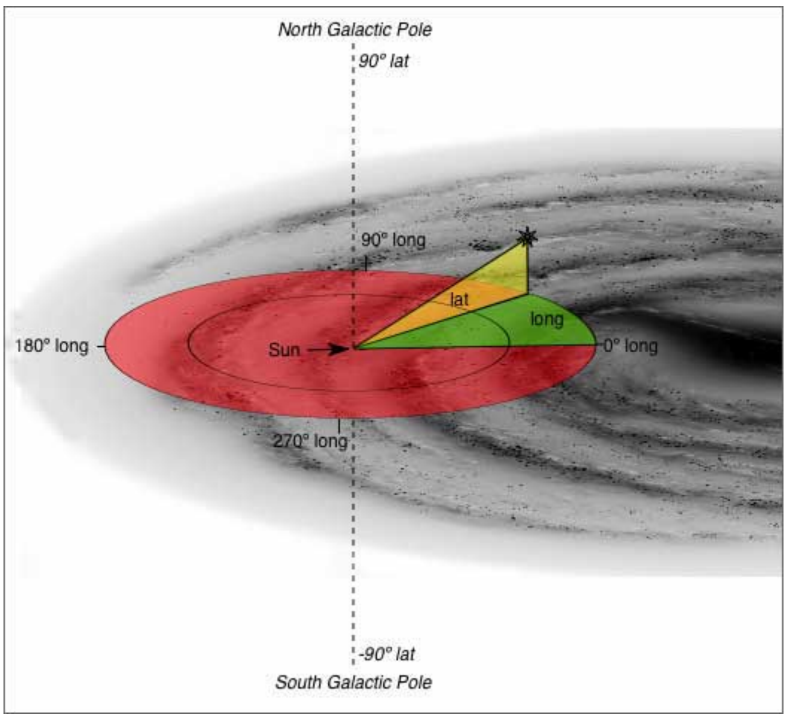

Figure 2: Galactic coordinate system. The plane of the galaxy is defined to have a $b=0$ while the center of the galaxy is at $l=0$.

To carry out coordinate transformations from celestial (right ascension and declination) to galactic coordinates, one can use *astropy's* handy *coordinates* class to perform the calculation. In fact, you could also the specify the location you are observing from and the time to obtain the altitude and azimuth that you would need to point in order to observe a certain l and b.

2.3 Galactic Rotation

We can use the tangent-point method to measure the radial velocity at a given radius from the galactic centre along a given line-of-sight. This method works very well for the inner galaxy where the galactocentric radius, R < R_{Sun}, because you can unambiguously identify the velocity of a gas cloud at given distance R. The primary assumption is that orbits are circular. See Figure 3 for a depiction of the geometry. The maximum line of sight velocity, v_{los}, is observed at position T.

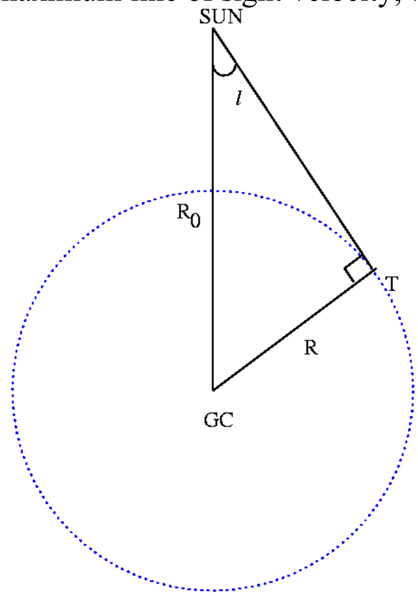

Figure 3: Simple model of galactic rotation. The Sun is located at a distance R

We can relate the distance of T from the Galactic Center (GC) and its associated velocity using simple geometry:

$$R_T = R_0 \sin(l)$$
$$v_{los} = R_0 \sin(l)(v_T/R_T - v_0/R_0) = v_T - v_0 \sin(l)$$
$$v_T = v_0 \sin(l) + v_{los}$$

where R_0, R_T are the galactocentric radii of the Sun and Point T, respectively, and similarly v_0 and v_T are the velocities at the location of the Sun (LSR) and Point T, respectively. By plotting v_T at different radii, one is able to extract the rotation curve of the galaxy out to the distance of our Sun.

3. Key Considerations

3.1 Signal Chain

We will be using low noise amplifiers (LNAs) and bandpass filters (BFs) within our signal chain to amplify and filter our signal before being digitized by the AirSpy. BFs are critical for filtering radio frequency interference (RFI) outside our band of interest. The LNAs and BFs are from Mini-Circuits (www.minicircuits.com). I have provided the part numbers below:

LNAs:
ZX60-P33ULN+

BFs:
VBF-1445+
VBFZ-1400+

You can look up the datasheets for these at the Mini-Circuits website to understand what their properties are. I recommend using two LNAs and each of the BFs. The LNAs have an input and an output. Make sure they are wired in order. They are also driven by **3V** DC power. I will provide the necessary assistance to wire them up. The BFs are passive components, so do not require additional power. You may need to play around with the right order of LNAs and BFs to get an optimal output. Remember that BFs are not lossless, so if you put them in front of your LNA you will lose precious signal from the antenna. Also, LNAs are also not noiseless, and they degrade your signal-to-noise ratio (SNR). They simply amplify the signal so that it is within the range of input for the SDR. I have tried to pick the best available LNA with the highest gain and lowest noise figure for this experiment.

3.2 Solar Data Acquisition

Unfortunately, the Sun is a minimum in radio activity at the moment, so you may need to integrate for a few seconds to get a good signal. The Sun is quite faint at radio wavelengths! Try to center the Sun on your feed and take measurements at few degree intervals in azimuth and elevation to characterize the beam profile. You can look at the summed continuum flux at each position to construct the overall beam profile. Remember to take an off-source measurement as your baseline.

You can estimate the solar radio flux at 1.42GHz by visiting the NOAA/NRC website that reports the daily 2.8GHz (10.7cm) flux from the Sun:
ftp://ftp.geolab.nrcan.gc.ca/data/solar_flux/daily_flux_values/fluxtable.txt

The flux value at 2.8GHz is within 10-20% of the 1.42GHz flux because the spectrum is relatively flat. You can use the 2.8GHz value as an approximation. The flux table provides the flux in solar flux units (sfu), which corresponds to 10^4 Jy. Since the Sun does not fill the entire beam, the measured antenna temperature needs to be corrected for the differences in beam size and the Sun's size (0.5°).

3.3 HI Data Acquisition

I expect that you will require several tens of seconds of data acquisition before you can obtain a firm HI detection. I recommend pointing at dense regions of the galaxy where you expect a strong signal. I anticipate the beam width of your telescope to be ~10 – 20° so you do not need to be pointed very accurately.

I took 1-minute long datasets for my HI observations. I suspect you will need less time due to your larger telescope. Data quantity can become quite onerous. You will end up a few GB file for a minute-long dataset. To process the data, you need to first channelize it, i.e. turn it into a spectrum. I broke the datafile up into small chunks, and I took an FFT of each chunk to obtain the spectrum. I then co-added all of the spectra to obtain a single high SNR spectrum. In order to determine the correct frequency range, you need to pay special attention to the intermediate frequency (IF) and the sampling rate you choose. This sets your overall bandwidth ($f_{sample}/2$) and spectral range. You can also choose to bin the spectrum to improve your SNR. Once the frequency scale is determined, you can convert the measured spectrum into a velocity scale.

Remember that you should take an off-galaxy pointing to obtain a baseline measurement, which you then subtract from your on-galaxy measurements. This removes thermal power (T_{sys}) from the various noise sources across your bandpass.