Lab 4 Report

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Abstract

In this lab we attempt to map out the spiral structure of the Milky Way using measurements of 21 cm Hydrogen emissions in the plane of the galaxy. Using skills developed in the previous three labs, we conduct a large-scale observation then reduce and analyze the data, finding the mass inside the solar circle to be $M_{grav} \approx 9.55 \times 10^{10} M_{\odot}$. We then explain how we learned to effectively communicate multidimensional scientific results in image form.

1 Introduction

There are several goals in this lab, first, we must conduct a survey, balancing considerations of available time on the telescope, the amount of coverage we need, as well as the deadlines for analysis and report writing. Next, we must consider how to efficiently process the wealth of information we collect, and finally, how we can communicate our results in a way that is informative, clear, and visually appealing.

As we learned previously, The distribution of the diffuse atomic Hydrogen which permeates the Universe reveals the large scale structure of the galaxies. Due to the hyperfine nature of Hydrogen, we can use the 21 cm emissions to map this out. So, for this project we observe the plane of the galaxy on the largest angular scale possible.

We begin by explaining our project logistics and setup in §2, then how we calibrated the data we collected in §3, the process of transforming this into a map in §4, some concluding remarks and acknowledgements in §5 and §6, and finally some code documentation in §7.

2 Operating the Telescope

Our observations were conducted in April 2019 using the 4.5 m radio telescope at the Leuschner Observatory[1]. As mentioned, for our project, we set out to survey as much of the galactic plane as possible using the hydrogen 21 cm emission which, due

[1]Latitude: 37 55.1 North, Longitude: -122 09.4 East

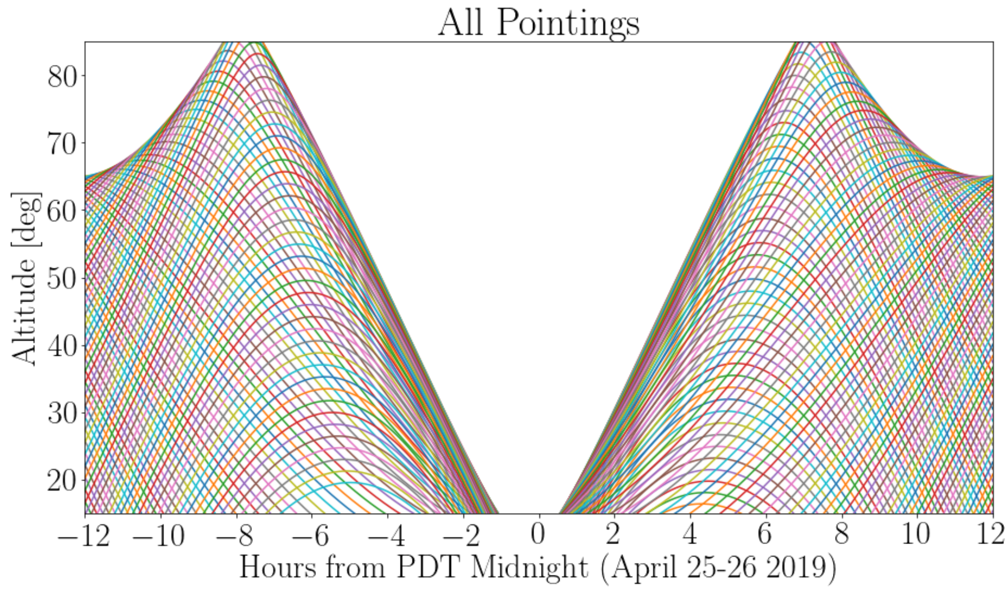

Figure 1: A plot of all the elevations of pointings we set out to make in this survey. y-axis limits correspond to the limits of the telescope. Using plots like this allowed us to schedule observations at the correct times. Made using the `Astropy` package.

to the telescopes pointing limitations and our position in the Northern Hemisphere, corresponds to the range $-10^\circ \leq l \leq 250^\circ$ with $b = 0^\circ$. Remotely setting the local oscillator to 635 MHz allows us to mix our hydrogen signal from 1420 MHz down to 150 MHz. Unlike the previous labs, the work of calculating Fourier power spectra of this signal is done for us automatically using the ROACH (Reconfigurable Open Architecture Computing Hardware) which is a standalone FPGA processing board. Thus we ultimately read out power spectra from the ROACH, from which we extract all the information we need.

2.1 Scheduling Observations

Now that we have transitioned to larger scale surveys than we have previously dealt with, we needed a more efficient way to organize our observations and prioritize where to start. So, we first mapped out when and where each one would be visible to our telescope (See figure 1) then after each pointing we updated the list of completed observations to avoid making the same one twice. With this in place we began taking data using `leuschner.Spectrometer.read_spec` to capture 20 spectra for every pointing in a FITS file.

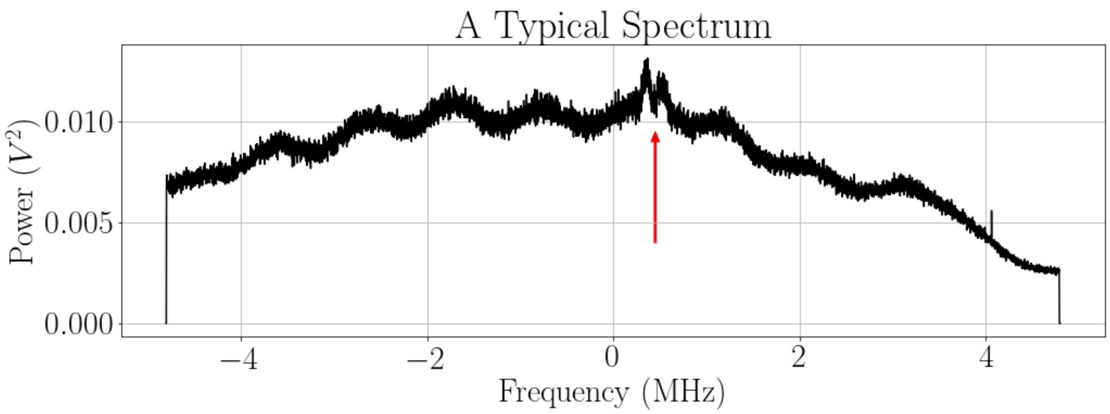

Figure 2: fig:A typical spectra from the many we collected. Notably, the baseline is sinusoidal as well as time dependent, which makes it a challenge to effectively remove. The arrow indicates the signal we wanted to preserve, highlighting the fact that where it lands on the baseline (whether a peak or trough) can have a significant effect.

3 Calibration

With all the spectra in hand, the first step in our analysis was to calibrate each one as it was immediately clear the large sinusoidal baseline (See figure 2) would distort our results. Having learned this baseline is likely from the signal being reflected back into the dish, we knew it should be removed. To handle this we used `Medfilt` from `Scipy.Signals`, to set to zero any deviations from the baseline which were greater than 180 i.e. the hydrogen signal, then use `scipy.interpolate.interp1d` to fill in the missing data which finally, we could remove from each observation. This produced the smoothed, flattened spectra we used to calculate physical quantities

Just as in the previous labs, the physical quantities are more meaningful than the voltages we read out from the telescope. So we again convert to brightness temperature using the gain factor and calculate the velocity using the standard Doppler shift:

$$\frac{v}{c} = \frac{\Delta\nu}{\nu_0}$$

Where, c is the speed of light, $\Delta\nu$ is the difference in frequency from the 21 cm emission $\nu_0 = 1420.4\,\text{MHz}$. Then, we use `ugradio.doppler.get_projected_velocity` to correct for our own movement.

4 Mapping

With a method of calculating velocities in place, we begin by creating a a map of the expected Doppler velocities seen in Figure 3. To create this, we start with a 30

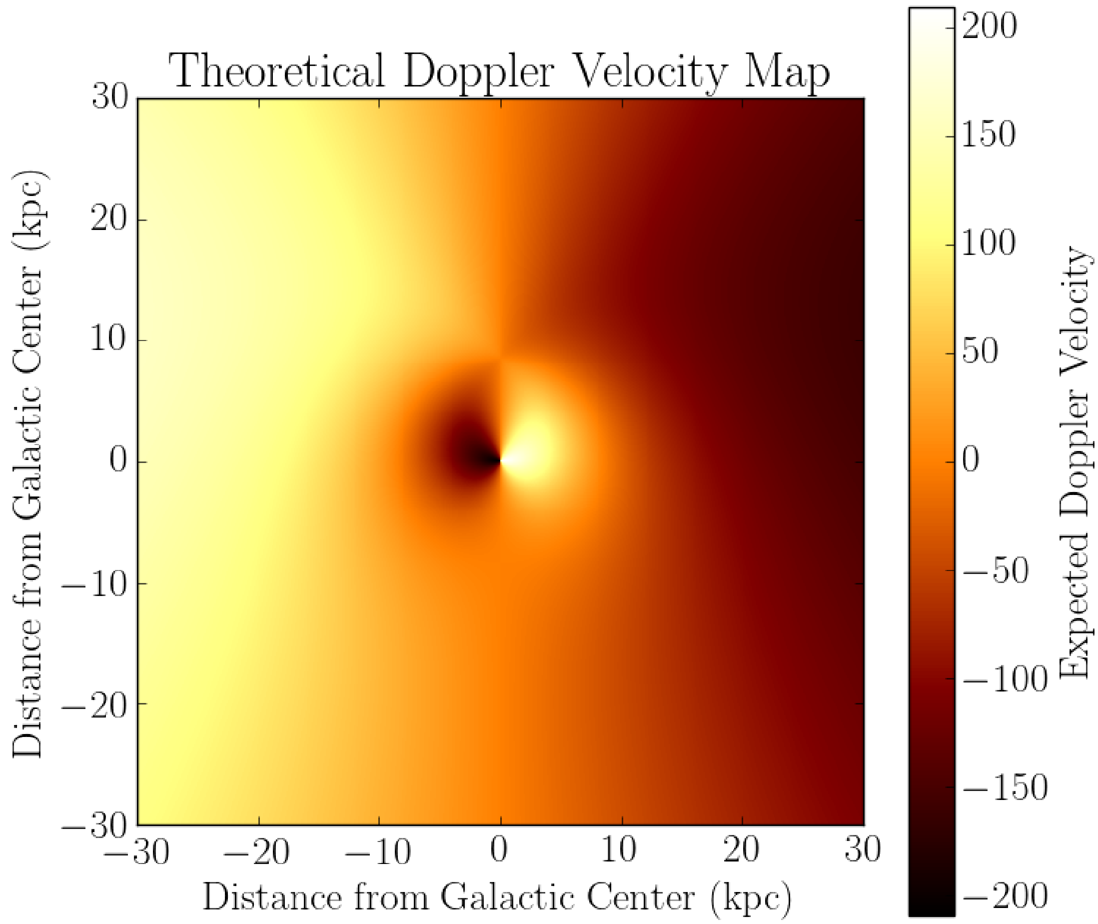

Figure 3: This is a face on view of the Galaxy plotting Doppler velocities relative to the Earth, which is at a position (0, 8.5. As expected, we see a division of the velocities as some are moving away and some are moving toward us as well as high velocities near the center.

kpc by 30 kpc grid then assign a velocity vector to each point. Assuming that the approximate tangential velocity is $220\,\mathrm{km\,s^{-1}}$ we then calculate a doppler velocity with respect to the Sun:

$$\vec{v}_1 - \vec{v}_0 = \frac{\vec{r}_1 - \vec{r}_0}{|\vec{r}_1 - \vec{r}_0|}$$

Where, $\vec{v}_0$ is our velocity and $\vec{v}_1$ is the velocity of the desired point. With this we can then match Doppler velocities calculated from our observations to expected Doppler velocities in this grid. This fills out the grid with real data and importantly assigns a position in the galaxy to each emission which we can use to calculate hydrogen density. While we were not able to generate this plot (Figure 4) we know it should reveal the spiral structure, similar to this plot from a paper by E.S. Levine, Leo Blitz, and Carl Heiles (professors in this department).

5 Conclusion

In this lab we set out to learn how to process data into images while at the same time conducting a large survey of our own galaxy, both of which have challenged astronomers for many years. We had some successes calculating various physical properties such as the mass within the solar circle and making a map of the expected velocity distribution. Though we did not fully accomplish our goals, we have made great strides in our programming and technical skills. With more time, we could have conducted more observations and made even more detailed maps but every survey must stop somewhere so ours stops here.

6 Acknowledgements

I would like to thank my group I♡Radio for their help in completing this lab, Professor Parsons for his teaching this semester and the lab engineer Frank Latora for his technical support.

7 Appendix: Code Documentation

```
 def get_average_spectra(spectra,n_spectra):
    '''
    Averages over all n_spectra from an observation
    Parameters:
    spectra(fits): file containing spectra from observation
    n_spectra(int):Number of spectra contained within the file
    Returns:
    averaged_spectra(array)
    '''
def get_gain(noise_on, noise_off):
    '''
    Calculates the gain used to converts spectra
    to units of temperature brightness (Kelvin).
```

```
Parameters:
noise_on (array): spectra with noise diode on
noise_off (array): spectra with noise diode off

Returns:
gain (float)
'''
```

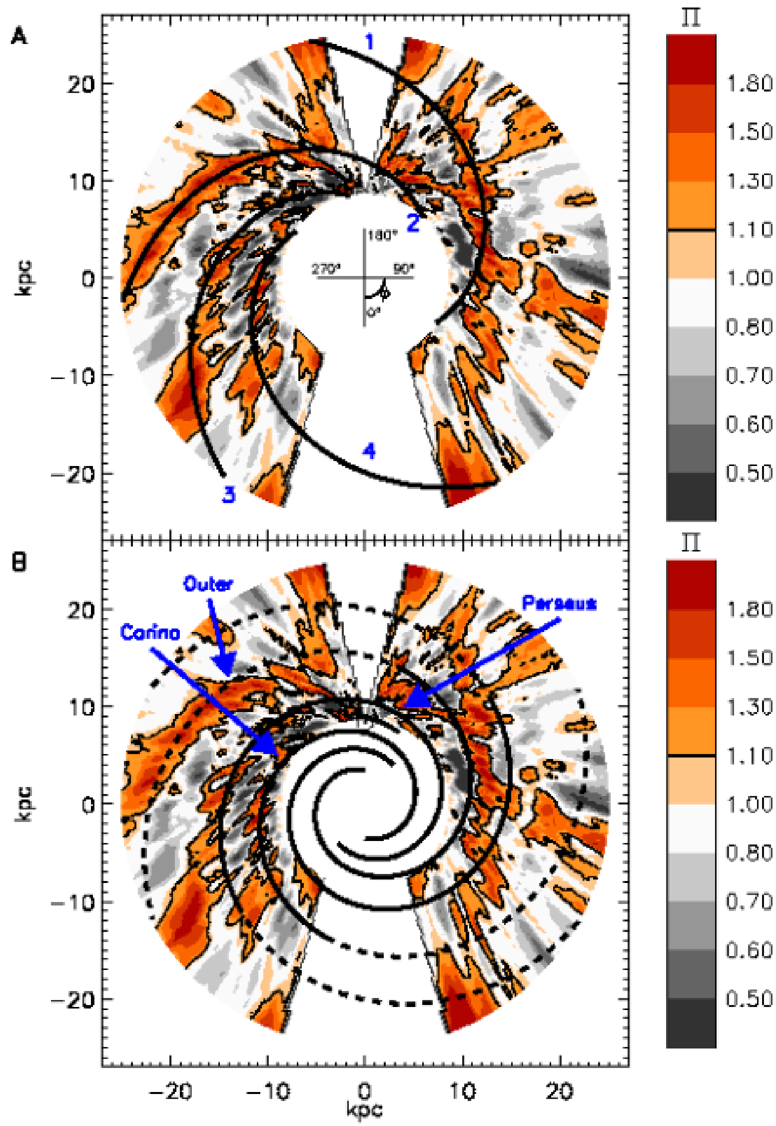

Figure 4: Figure from a a paper by E.S. Levine, Leo Blitz, and Carl Heiles, which plots hydrogen density versus distance along with a theoretical model for spiral arms. Had we been able to do this we would have expected similar results except without much of the data in the left half as it is out of range of our telescope.