Astro 121: Preparing for Summer with Galactic Heat Maps

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This lab presents a framework for probing the Galaxy with models, analyzing radio observations of the Galactic disk, and estimating the mass of a Galactic spiral arm. A strong background for this lab is writing data-taking scripts, applying various calibration techniques, and spatial modelling. Our group took observations of the Galactic disk from longitudes $-8^\circ \leq \ell \leq +245^\circ$ to measure the brightness temperature at various regions of the Galaxy. Mapping the Galaxy required an emphasis on modelling techniques to produce a Galactic heat map. This lab provided us with a strong foundation for large-scale modelling of astrophysical phenomena and estimating Galactic properties.

I. INTRODUCTION

Our Milky Way Galaxy has of a lot of hydrogen (H) that is observable at radio frequencies (1.420405 GHz, 21cm line) due to hyperfine spin-flip transitions in the H atom. The goal of this lab to model and map the Milky Way Galaxy with observations of the 21cm H line taken from the radio antenna at Leuschner Observatory. We write scripts that take power spectra of the Galactic disk (b=0°) along longitudes $-8^\circ \leq \ell \leq +245^\circ$. These power spectra are then translated into brightness temperature-velocity space using gain calibrations and local standard of rest (LSR) velocity corrections. These brightness temperature (T_b) spectra are then carefully mapped onto a Galactic model to produce a spatial representation of Galactic T_b's. These maps of Galactic T_b's are then used to visualize the shape of the Galaxy and estimate the mass of H in one of the spiral arms.

II. TEMPERATURE CALIBRATION + LSR CORRECTION

Our group spatially sampled the Galactic disk through several observations. To plan our observations we relied on the astronomical software `Stellarium` which projected when the Galactic disk was observable from Leuschner. Observations around 5am covered the range $-8^\circ \leq \ell \leq +134^\circ$ and 2pm covered $136^\circ \leq \ell \leq +245^\circ$. We also took calibration data S_{cal} and S_{cold} by pointing a region of the sky away from the Galaxy disk near zenith.

The data our group took from the Leuschner radio antenna was delivered in the form of 10000-block averaged power spectra (S_{Gal}) that corresponded to their respective Galactic ℓ's. Figure 1 plots the calibration data alongside the power spectra at $\ell = 136^\circ$. As expected, S_{cal} (in green) is more powerful than S_{cold} (in blue) because turning on the noise diode injects broadband thermal noise that is captured by the signal chain. S_{cold} and S_{Gal} (in orange) are nearly identical aside from the HI profile originating from the H in the Galaxy.

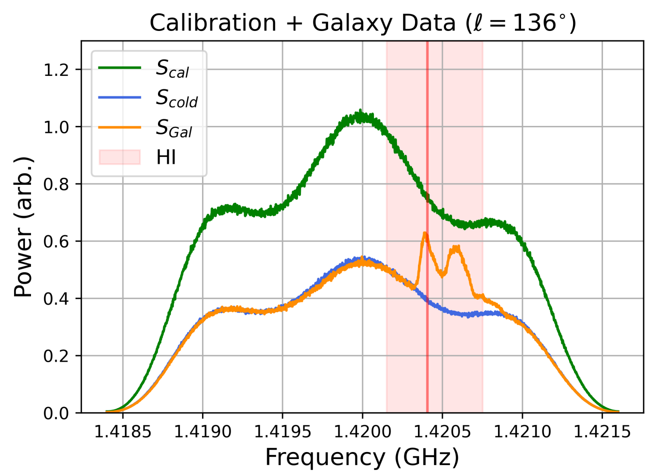

FIG. 1. Power spectra of data used for temperature calibration. S_{cal} and S_{cold} were taken by pointing to an area away from the galactic disk with the noise on and off respectively. S_{cal} is more powerful than S_{cold} due to the thermal noise captured by the signal chain when the noise diode is turned on. The orange curve represents the power spectrum of the galactic disk at $\ell = 136^\circ$ where the 21cm line is observed as the two bumps in the spectra within the HI region. The near-identical baselines of S_{cold} and the galaxy power spectrum are very useful for filter response normalization. These three power spectra are used for temperature calibrations of the Galactic disk calculated with Equation 1.

To calibrate the Galactic T_b's, we use the equation:

$$T_{Gal} = \frac{79K^\circ}{\sum(S_{cal} - S_{cold})} \sum S_{cold} \, \frac{S_{gal}}{S_{cold}} \tag{1}$$

where T_{Gal} is the Galactic T_b at a given ℓ and 79° is the difference in S_{cal} and S_{cold} temperatures for the zeroth polarization. The baseline filter response of T_{Gal} also needed to be subtracted to properly measure a T_b; since S_{Gal} and S_{cold} are nearly identical, the residual baseline ends up being a constant offset that is subtracted off.

Our observed frequencies (ν) are converted to velocities with the equation:

$$v = c(1 - \frac{\nu}{\nu_0}) \tag{2}$$

where c is the speed of light and ν_0 is the frequency of the 21-cm line. This paper will refer to frequency and velocity interchangeably. We need to convert our velocities to the LSR in order to account for the motion of the Sun in the Galaxy. To make future computations easier, we shifted our T_{Gal}'s by convolving the Fourier transform of T_{Gal} with the phase term:

$$e^{-2\pi\Delta\nu t} \tag{3}$$

where t is an array of times dependent on the difference between observed frequencies, and $\Delta\nu$ equals:

$$-\nu_0 \frac{v_{LSR}(t_0, \ell)}{c} \tag{4}$$

We then take the inverse Fourier transform of the convolution to shift the T_{Gal} into a Galactic rest frame. The result of these calibrations are plotted in Figure 2 where we observe how T_b varies with radial velocity and ℓ. These calibrations are the backbone of our data analysis and were carefully computed across all observed longitudes. The dependence of longitude and velocity on brightness temperature ($T_b(\ell, v)$) is crucial for mapping the Galaxy, which is described in the next section.

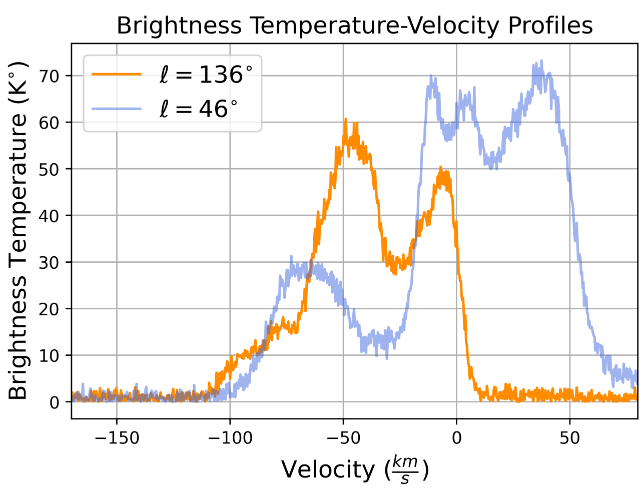

FIG. 2. Brightness temperature-velocity profile of the galactic disk at ℓ=46° and ℓ=136°. The original power spectra were baseline-subtracted/temperature-calibrated using Equation 1 and the x-axis represents the computed Doppler motions with respect to the 21cm line. T_b is multiplied by a phase term to account for motion along the local standard of rest. Focusing on the orange line, the bump around 0 $\frac{\text{km}}{\text{s}}$ represents hydrogen in a region of the galaxy at rest with respect to the Sun. The two bumps around -50 and -80 $\frac{\text{km}}{\text{s}}$ is a spiral arm moving towards the Sun. The amplitudes of the bumps reflect the kinetic energies of the region and the widths of the bumps provide information on the density of hydrogen. The radial velocities are mapped to their corresponding longitudes to model the heat map in Figure 3.

III. MODELLING THE MILKY WAY GALAXY

This section describes the model that was used to map the Milky Way Galaxy. Since T_b is dependent on velocity and longitude, it is necessary for these parameters to be explicitly defined in our model. The basis of our model is a 256×256 pixel grid. The left plot in Figure 3 represents the projected velocities (v_p) of our Galactic model. The axes g_x and g_y represent the defined Galactic topocentric coordinates in kiloparsecs (kpc). The golden star indicates the position of Sun (0,-8.5) relative to the Galactic center (0,0). We computed the v_p's with the function:

$$\mathbf{v_p} = \frac{(\mathbf{v_{px}} - \mathbf{v_\odot}) \cdot (\mathbf{r_{px}} - \mathbf{r_\odot})}{|\mathbf{v_{px}} - \mathbf{v_\odot}|} \tag{5}$$

where $v_\odot$ is the velocity of the Sun relative to the Galaxy (≈220$\frac{km}{s}$), r_{px} is the radius of each pixel relative to the origin, $r_\odot$ is the position of the Sun, and v_{px} is the velocity of each pixel defined as:

$$\mathbf{v_{px}} = 220 \frac{\text{km}}{\text{s}} \frac{\mathbf{r_{px}} \times \hat{\mathbf{z}}}{|\mathbf{r_{px}}|} \tag{6}$$

where $\hat{\mathbf{z}}$ is a unit vector normal to the Galactic plane. The red colors represent regions of the Galaxy moving away from the Sun (i.e. redshift), blue colors represent regions of the Galaxy moving towards the sun (i.e. blueshift), and white colors represent zero Doppler motion relative to the Sun. The velocity model appears to have several internal (blue, red), intermediate (white), and external (red, blue) structures. This comes down to the viewing angle of the Sun: the entire Galaxy acts as one fluid disk rotating in one direction, but regions around the center of the Galaxy will appear to moving with opposite Doppler motion compared to regions outside of the Galactic center. An observer in the $\hat{\mathbf{z}}$ direction sees the white regions rotating, but in the Sun's reference frame the white regions have zero radial motion.

The right plot in Figure 3 is the map of Galactic ℓ's projected onto our topocentric model. The longitude (in degrees) of each pixel (ℓ_{px}) was computed with the function:

$$\ell_{px} = \tan^{-1}(\frac{g_y - g_{y,\odot}}{g_x - g_{x,\odot}}) \tag{7}$$

where $(g_{x,\odot}, g_{y,\odot})$=(0, -8.5). There is a sharp ℓ shift due to our convention $-180° = +180°$. The shaded region in the left plot shows the region of the Galaxy that is observed along $\ell = 136\pm2°$. Since several pixels correspond to the same ℓ, we needed to be very careful when assigning a pixel a T_b. The longitude and velocity maps are crucial for the spatial computation of $T_b(\ell, v)$ described in the next section.

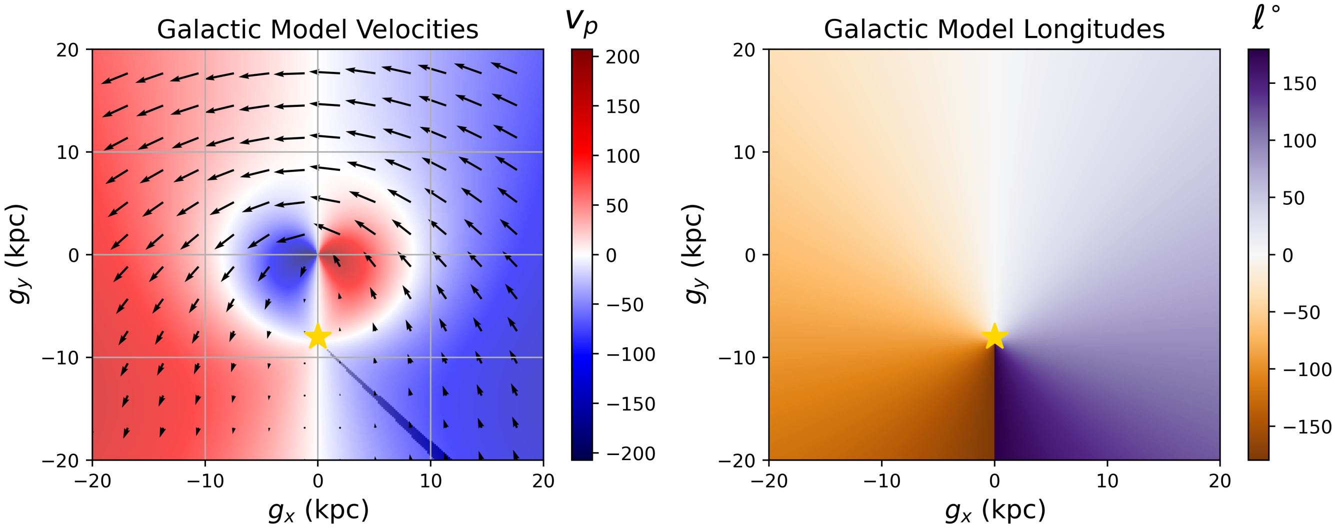

FIG. 3. Model for the Milky Way Galaxy. The axes g_x and g_y model topocentric galactic coordinates in kpc centered around the galactic center and the golden star represents the position of the Sun. Both of these plots are useful for the spatial-mapping of Galactic T_b's in Figure 4. **LEFT:** This is a map of projected velocities (V_p) that were computed with our Galactic model. The arrows indicate the direction of V_p's at each pixer. Color represents the magnitude of V_p and it's Doppler motion relative to the Sun. Redder regions mean that the region of the galaxy is moving away from the Sun (redshift), bluer regions are moving toward the Sun (blueshift), and white regions have net zero Doppler motion. The shaded region in the bottom right highlights pixels within the range $\ell = 136 \pm 2^\circ$. This shaded region is in agreement with Figure 2 due to $\ell = 136^\circ$ only showing hydrogen at negative (blue) and rest (white) velocities. **RIGHT:** This is a map of Galactic longitudes (in degrees) in our topocentric model. White regions are pointed towards the Galactic center and orange/purple regions are longitudes away from the Galactic center. There is a discrete longitude gradient at 180° due to the convention of our longitudes that range from $-180^\circ \leq \ell \leq +180^\circ$.

IV. MAPPING BRIGHTNESS TEMPERATURES + MASS ESTIMATES

The mapping process first starts with an empty 256×256 pixel grid. Since our group observed within a limited frequency bandpass and Galactic ℓ range, we had to define our observed parameters. Since each pixel in the model is assigned a velocity and longitude, we gave each pixel in our map a longitude (ℓ_{xy}) and velocity v_{xy} index corresponding to the model's values and the observed parameters. These indexes are used to map our Galaxy and qualitatively represent brightness temperature as a function of longitude and velocity: $T_{b,xy}(\ell_{xy}, v_{xy})$.

Figure 4 is a heat map of the Galaxy. The longitudes of the heat map have identical indexes to the right plot of Figure 3. The color represents T_b in K°. I chose the color map `viridis` to make it colorblind-friendly. The white pixels represent ℓ's that weren't able to be observed.

All of the figures use the arbitrary longitude $\ell = 136^\circ$ to help cumulatively apply the broad methods and theory together. The temperature spectrum in Figure 2 tell us there is a strong presence of negative velocity (i.e. blueshifted) H, which agrees with the shaded region in the left plot of Figure 3. The indexes assigned to the pixels within $\ell = 136^\circ$ of the heat map are then given a T_b based off the velocity indexes in the temperature spectrum. We made these logical checks across all observed longitudes to confirm that the heat map is in agreement with both observation and model.

The heat map is quite fascinating because of all the hot structures we can observe. Most notably is the central circular region that could represent the hot, dense gas in an inner spiral arm. Another structure we see is the fainter, outer spiral arm that spans the right side of the heat map. I calculated the mass of H in the outer spiral arm with the function:

$$M_{arm} = M_H \frac{\overline{T_b}}{1K^\circ} \frac{\Delta V}{1\frac{cm}{s}} (R\theta)^2 \cdot 10^{18} cm^{-2} \tag{8}$$

where M_H is the mass of a H atom, $\overline{T_b}$ is the average T_b of the bump in each temperature spectrum that corresponded to the spiral arm, ΔV is width of each respective bump, R (in cm) is the estimated distance to the center of the spiral arm, and $\theta = 2^\circ$. An estimate for the mass in the spiral arm from $44^\circ \leq \ell \leq 92^\circ$ was $\approx 7.2 \times 10^{12} M_\odot$. There are uncertainties in $\overline{T_b}$ and ΔV from our gain calibration and LSR correction. I also measured R visually, which contributes to the uncertainty. Increasing the resolution of our model could've also lowered the uncertainty in the mass estimates.

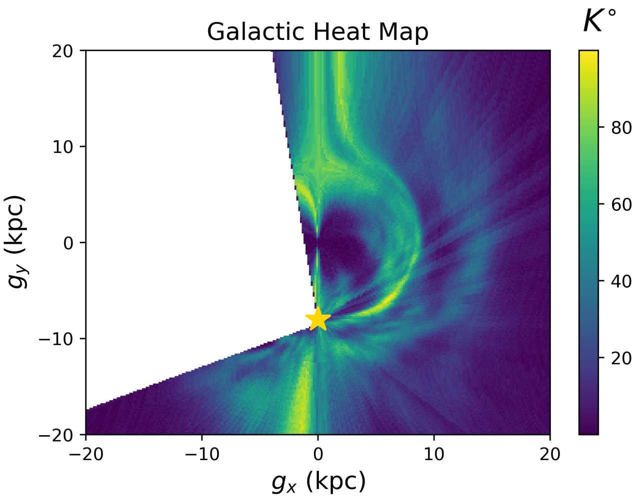

FIG. 4. Heat map of the Galaxy. To make this heat map, the longitudes and frequencies of each pixel are mapped using Figure 3. Each observed temperature spectrum has a corresponding brightness temperature for every longitude and frequency, which are used to assign every pixel a color/temperature (K°). The white region represents Galactic longitudes that weren't observable with Leuschner. The hot circular region in the center of the plot uses observations near the Galactic center ($\ell \approx 0^\circ$) which is known to host hot hydrogen gas orbiting around in the inner spiral arms. This figure was used to estimate the mass hydrogen in the spiral arm from $44^\circ \leq \ell \leq 92^\circ$(visible on the right side of the map), which was about $\approx 7 \times 10^{12} M_\odot$. This mass measurement has uncertainties in the temperature calibration, LSR correction and the resolution of the map.

V. CONCLUSION/REFLECTION

This lab had a strong emphasis on modelling that was initially a major learning curve. The abstract process of using linear algebra to model the Galaxy was quite fascinating and has opened my mind on the various ways we try to understand the universe. We learned how to spatially represent our models with various maps and apply the data our group took to visualize the shape of the Galaxy. The process of estimating the mass of H in the spiral arms was both interesting and humbling: there really is a lot out there!

As a personal note, I really appreciate how Lab 4 applied all of the knowledge we acquired from the previous three labs: signal processing, data analysis, script writing, mapping etc.. The new aspect of spatial modelling make Lab 4 feel unique. Overall, I'm glad I took this class. Thank you for all of your help Aaron, you've greatly broadened my astronomical horizons. Have a great Summer and see you in the next academic year!