

Astronomy 3
Lab 3: Our Galaxy's Rotation Curve
Due Friday, Feb. 28

1 Important Information

This lab will run on Tuesdays/Thursdays from Tuesday, Feb. 11-Thursday, Feb. 20. Sign-ups will be done on the webpage as was done for the Solar lab. This time, however, only two people will come in at a time for each half hour slot, because only one of the computers in 200 Wilder can be used for this lab. Your T.A. will help you collect your data, so it should only take you a half hour or less.

2 Introduction

In this lab you will determine the rotation curve of our Galaxy using the Small Radio Telescope (SRT) located on the roof of Wilder. The rotation curve shows the orbital velocity of material in the Galaxy (such as stars and gas) as a function of distance from the Galactic center. As we'll discuss in class, if the majority of the Galaxy's mass was concentrated towards its center (where it looks brightest) then the stars and gas orbiting at larger radii should orbit at speeds determined by Kepler's second law. In other words, you would expect the material further out to orbit more slowly (just like Jupiter orbits around the Sun more slowly than Earth does). However, as you'll see from this lab, the rotation rate of material in the Galaxy does not follow this expected rule, thus we must conclude that most of the mass is *not* at the center of the Galaxy. This is important, because most of the luminous matter (stuff we can see) *is* at the center. The rotation curve tells us there must be a lot of mass further out near the edges of the Galaxy that we can't see. This "extra mass" is called Dark Matter and its existence was first shown using the rotation curve of our Galaxy. Today, astronomers know that most of the mass in the Universe is Dark Matter. Moreover, we don't currently know what it is (although there are of course several theories). Note that this is another example of how we use gravity to determine the way in which mass is distributed in the Universe.

In this lab, you will repeat the original experiment by measuring the velocity of material in the Galaxy at different distances from its center. Hydrogen, of course, is the most abundant element in the Universe, and our Galaxy is filled with huge clouds of neutral Hydrogen called HII regions. One of the energy transitions of Hydrogen causes the emission of electromagnetic radiation with a wavelength of 21 cm. This is called the "21 cm line" and also has a frequency of 1420.406 MHz so it lies in the radio band.

Measuring the Doppler shift of the 21 cm line will allow you to determine the radial velocity of gas at different locations in the Galaxy. One of the advantages of observing at this wavelength is that 21 cm emission can penetrate a lot of the dust in the Galaxy where visible light would be scattered and absorbed. Thus, your view will not be obscured by all

the dust and you'll be able to see material at rather large distances. Another advantage is that observations in the radio band are not affected by bad weather, so you should be able to do this lab rain (or snow) or shine.

Galactic Coordinates: Imagine you are looking at the Milky Way in the sky (which lies in the plane of our Galaxy) and you point your right hand towards the Galactic center which lies in the constellation Sagittarius. Now, imagine swinging your left hand along the Milky Way while keeping your right hand pointed at the Galactic Center. As you swing your left hand to the left, the angle between your arms increases. This angle is called the galactic longitude, l , and it runs from 0° to 360° . The Galactic center is defined to have a galactic longitude $l = 0^\circ$, and the anti-center (direction directly opposite the center) has $l = 180^\circ$.

The other galactic coordinate is, as you may have guessed, galactic *latitude* which is given the symbol, b (don't ask me why). Galactic latitude measures the angle off the plane of the Milky Way. All points in the plane of our Galaxy have $b = 0^\circ$.

In this lab, you'll be making measurements in the plane of the Galaxy ($b = 0^\circ$) but at a range of different Galactic longitudes, so its important that you understand this coordinate system! For more information about rotation curves and the Milky Way, you can also refer to Section 17.4 and Chapter 18 in your textbook.

3 Observations

Each of you (or you and your lab partner), with the help of your T.A., will make an observation of the velocity profile of the Galaxy at one Galactic longitude. To do this, you will collect a spectrum centered near a frequency of 1420.4 MHz (the frequency of the 21 cm line). You will analyze this spectrum to determine the maximum velocity of neutral Hydrogen at that one longitude. I will combine the results from each group and distribute all the velocities to you. You will then use all the data collected by the class to determine the Galactic rotation curve.

One of the PC's (called astro3) in room 200 Wilder runs the SRT. You and your partner will work with the T.A. to collect your data with this computer. You will *not* need to go on the roof where the radio telescope is located, since everything is done using this computer, including pointing the telescope, setting the frequencies and recording the data,

Pointing the Telescope: Positions along the Galactic plane have been pre-programmed into the computer and the visible sources are shown on the screen (ask your T.A. to explain this to you). Clicking on any of these pre-programmed sources will move the telescope to the appropriate location. For example, to point the telescope to Galactic coordinates $l = 70^\circ$, $b = 0^\circ$, click on GAL070. After clicking on a particular target, it will appear red on the screen and the telescope will start to move. You can view the telescope's progress by looking at the status area located at the top left-hand side of the screen. It will say "waiting on elevation" or "waiting on azimuth". It will take a minute or two to point to the selected target. After the telescope gets to the right location, it will track that point in the sky.

Setting the Frequency: Now that the telescope is pointed where you want it, you need to set an appropriate frequency range where you would like to collect your data. Click the **freq** button at the top of the screen, then click in the text area at the very bottom. Enter three numbers: the center frequency, the number of frequency bins, and the bin spacing. For example, type: **1420.4 35 0.04**

With these settings, the telescope will measure the power (signal strength) at 35 different frequencies centered around 1420.4 MHz. If all the Hydrogen in the Universe was at rest (not moving) you'd expect to see a peak in the power at 1420.406 MHz. Since the gas along your line of sight is moving at different velocities, you will instead see power at a range of frequencies above and below 1420.4 MHz.

Collecting your Data: To record data, click on the **record** button and enter a file name with the following format: "yourlastnames.l". For example, if Rob and I were taking data from a galactic longitude of 70° together, we would call our data file MillanMichell.070

Allow the program to accumulate data for about 5 minutes and then click **record** again to stop recording.

Part of the data you just collected will be signal from the Galaxy just like you wanted. However, there will also be some signal from background sources such as the instrument itself. You'll need to be able to subtract the instrumental effects so you end up with just the signal from the Galaxy. To determine the background signal, point the telescope away from the Galactic plane. To do this, click the **offset** button and type in "-30 0" and press Enter. This will move the telescope horizontally 30° to the left. This should give you a good background spectrum. Again record data for 5 minutes and this time call your filename "yourlastnames.bkg". **Make sure to reset the offset when you're done so the next person points the telescope where they want instead of 30° off!** To do this, click **offset** again and enter "0 0".

One more thing you'll need to finish the lab is v_{lsr} . This is the velocity of the Sun's orbital motion around the Galaxy and you'll need it to correct your data (see below). v_{lsr} is calculated by the computer and is shown on the screen, so write it down.

Finally, fill out the attached Data Sheet and hand it to your T.A. This will serve as a sign-in sheet for the lab and will allow us to find your data file. The data you recorded is a big long list of numbers that you really don't care about. What you really need to finish the lab is the average of all the data you took over the 5 minute period. We will average your data together for you, do the background subtraction, and email you the results.

4 Analysis

Now that you have collected your data and I have averaged it for you, you should have an average spectrum (power versus frequency) at one Galactic longitude. With this data, you will determine the orbital velocity of the Galaxy at one distance from the Galactic center. The method to do this just involves a little geometry. Figure 1 shows a cartoon drawing

of part of our Galaxy. C denotes the Galactic center, and S indicates the position of the Sun. R is just the distance between the Sun and the center ($R = 8.5$ kpc). Each point in the Galaxy basically moves in a circular orbit around the Galactic center. The direction of motion of the Sun is indicated with an arrow and likewise the directions of motion of the points B and T are indicated by other arrows. Each point is moving in the direction tangent to a circle about the center.

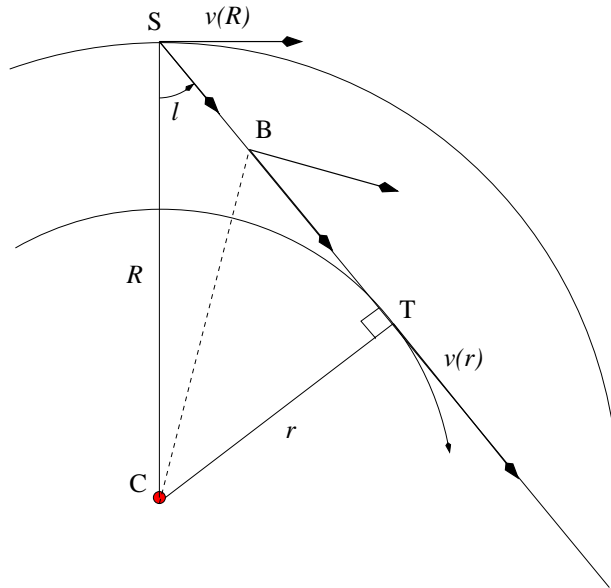


Figure 1

Now imagine you are looking out from the Earth (which is essentially in the same location as the Sun, so at point S) in the direction of Galactic longitude, l and towards the point, B . There are actually HII regions emitting the 21 cm radiation all along that path in the direction of l . Recall that when you measure the Doppler shift, you only measure the *radial* velocity of a source. At point B , the radial velocity is only one component of the total velocity. This is also true for most of the points along the direction l . At each of those points, you will measure a different fraction of the total velocity at that point, thus the emission from each point along that path will be Doppler shifted by a different amount. This is the reason that you detected power at a range of frequencies for a single Galactic longitude when you collected your data. You were just detecting emission from a lot of different HII regions all along the line of sight.

There is one special point along the path in the direction of l where the radial velocity equals the total velocity, and that is point T in the diagram. At this point, the direction of motion (tangent to the circle) lies along your line of sight (i.e. the line connecting S , B and T). At T , you measure the *total* velocity since all the motion is directed radially outward from you. Since you measure the total velocity at point T and not just a fraction of the total, you will measure the largest velocity from that point. This also corresponds to largest Doppler shift. So, when you plot your data in #1 below, the lowest frequency where you detect power corresponds to the point T in the diagram for the particular Galactic longitude

where you collected your data. This same argument applies for all Galactic longitudes less than 90° . You can convert this minimum frequency to the maximum velocity using the Doppler shift formula.

The point T lies at a distance r from the Galactic center. With a little trigonometry, notice that

$$\sin l = \frac{r}{R} \quad (1)$$

Thus, for each Galactic longitude, l , the tangent point, T is located at a distance

$$r = R \sin l \quad (2)$$

from the Galactic center. Therefore the maximum velocity you calculate from looking at your data is just the orbital velocity of the Galaxy at a distance r , and that is exactly what you're after! If this is confusing to you, don't worry; the procedure below will lead you through the steps.

1. Plot the average spectrum from the data file that was emailed to you. Plot frequency on the horizontal axis and signal strength on the vertical axis.
2. From your plot, determine the minimum frequency where you detected significant power. You'll have to do this by eye, so explain in a sentence or two how you picked the minimum frequency. Ask your T.A. for help if you need it.
3. Convert the minimum frequency you found from your plot to a velocity using the Doppler shift formula below. You learned the formula for the radial velocity in terms of the wavelength shift in class. A similar formula gives the radial velocity in terms of the frequency shift:

$$v_r = \frac{(f_0 - f)c}{f_0} \quad (3)$$

where f_0 is the rest frequency (equal to 1420.406 MHz), f is the observed (Doppler shifted frequency) and c is the speed of light.

4. The Sun is also orbiting around the Galactic center so it is moving relative to everything else. Therefore, the last thing you need to do to get the velocity at your galactic longitude is to subtract out the Sun's motion. You should have written down v_{lsr} when you were in the lab. lsr just stands for "local standard of rest". Subtract v_{lsr} from your maximum velocity to get the velocity of the Galaxy at your galactic longitude. Make sure you use the correct units! v_{lsr} is given in km/s.
5. Now you have the maximum velocity for your galactic longitude. The last step is to convert galactic longitude to a radial distance from the Galactic center. Use Equation 2 to calculate r .

6. Now, email your velocity and distance to me. I will compile the list of velocities for all the different distances and mail each of you the entire list.
7. *The Galactic Rotation Curve:* Using the entire list of data sent to you, plot $v(r)$ versus r , putting v on the vertical axis and r on the horizontal axis. Compare your rotation curve with the rotation curve for our Galaxy shown in your textbook.

DATA SHEET FOR LAB 3

Date and Time: _____

Name 1: _____

Name 2: _____

v_{lsr} for your observations: _____

On-source data file name: _____

Background data file name: _____

Please double check that these match exactly the filenames...otherwise we won't be able to find your data!