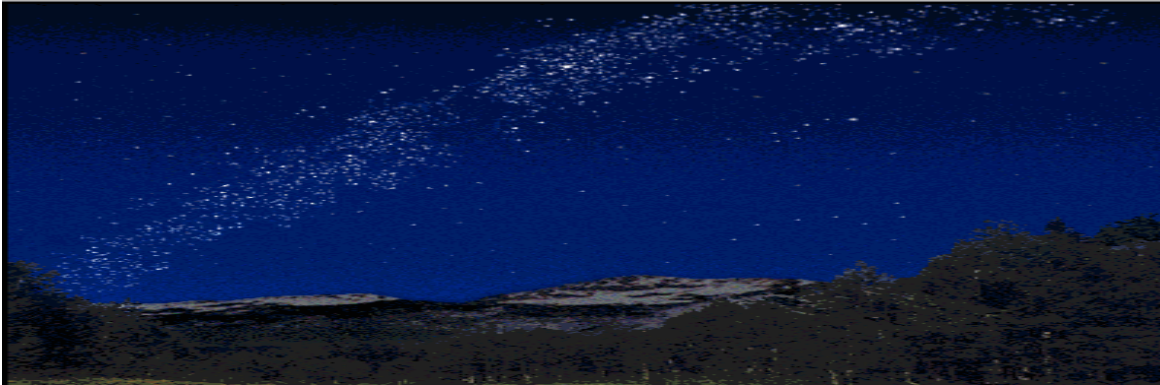


Galactic Rotation Activity*



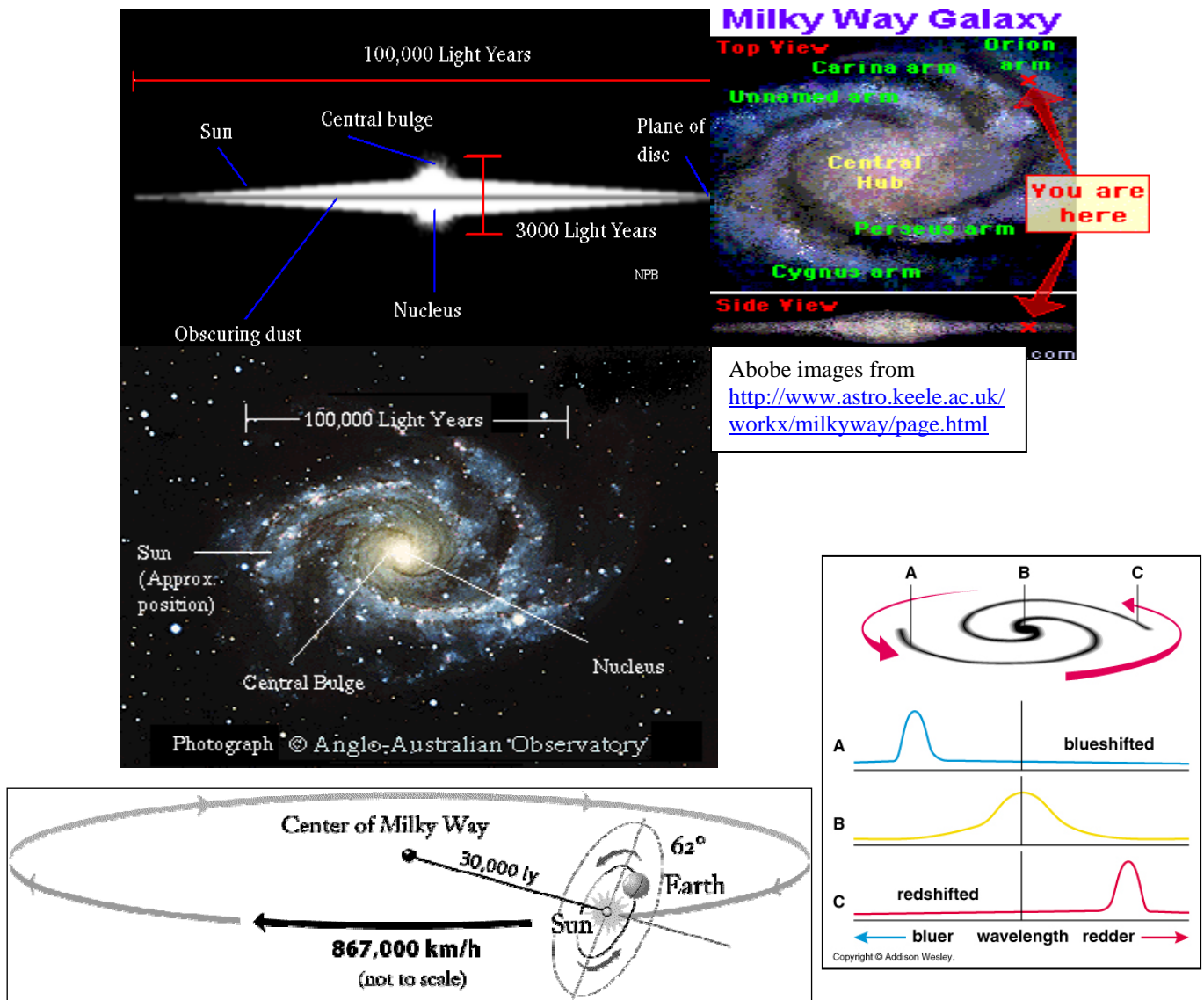
Neutral hydrogen atoms (H I) consist of a single proton and a single electron. The electron and proton can spin in the same direction (parallel) or in the opposite direction (anti-parallel). Spinning charges act like magnets and the parallel spin configuration is similar to magnets having like poles facing each other: they repel. Since it takes more energy for the spins to be parallel than to be anti-parallel, the higher energy parallel state "spin-flips" to the lower energy anti-parallel spin state, emitting a photon at a radio wavelength of 21.1 cm, (frequency of 1420.4 MHz). This is the same technique is the basis for them MRI, used in medicine to map the body in a MRI.

Hydrogen is the most abundant element in the universe; making up 80% of its total mass, Radio astronomers find this 21-cm hydrogen line a very useful probe for studying all sorts of astronomical phenomena from quasars to our own Sun. In addition, the 21-cm line is not as strongly affected by dust as infrared or visible light. In the method described here, the 21-cm line is used to find the differential rotation speeds of our galaxy, the Milky Way, a very dusty place. The Milky Way is a spiral galaxy and the Solar System resides in one of the arms. By observing hydrogen 21-cm emission at different locations along the Galactic plane, the angular velocities can be found relative to the Galactic center. In this activity the angular velocity of different locations along the Galactic plane will be calculated.

*Adopted Haystack website:

<http://www.haystack.mit.edu/edu/undergrad/srt/SRT%20Projects/rotation.html>

The 21-cm Line: Galactic Rotation Activity



Since hydrogen atoms are distributed uniformly throughout the Galaxy, a 21-cm line always will be detected; the only difference will be that the spectra will be shifted **along our line of sight**. This shift, known as the *Doppler shift*, is due to the motion of the Galaxy around its center.

Analyzing the data

The data for this activity was collected by the Small Radio Telescope (SRT) at the Haystack Observatory, Westford, Massachusetts.

There are two options for analyzing the data. You can view the data the way is produced by the SRT in the spreadsheet "Data from the SRT". Or you can view a compressed version of the data in the "Compiled data" spreadsheet. This guide provides step by step instructions on analyzing the as it is produced by the SRT.

In the compiled data version of the average intensity, corrected intensity (baseline correction), frequency channels and velocities have already been calculated.

This website will help you understand the data from the SRT and spreadsheet.

<http://www.haystack.mit.edu/edu/pcr/radio/SRT%20Lessons/5%20%20Understanding%20your%20data.pdf>

The data can be accessed on the website,

<http://www.haystack.mit.edu/edu/pcr/downloads/>, or on a CD ROM from Haystack Observatory.

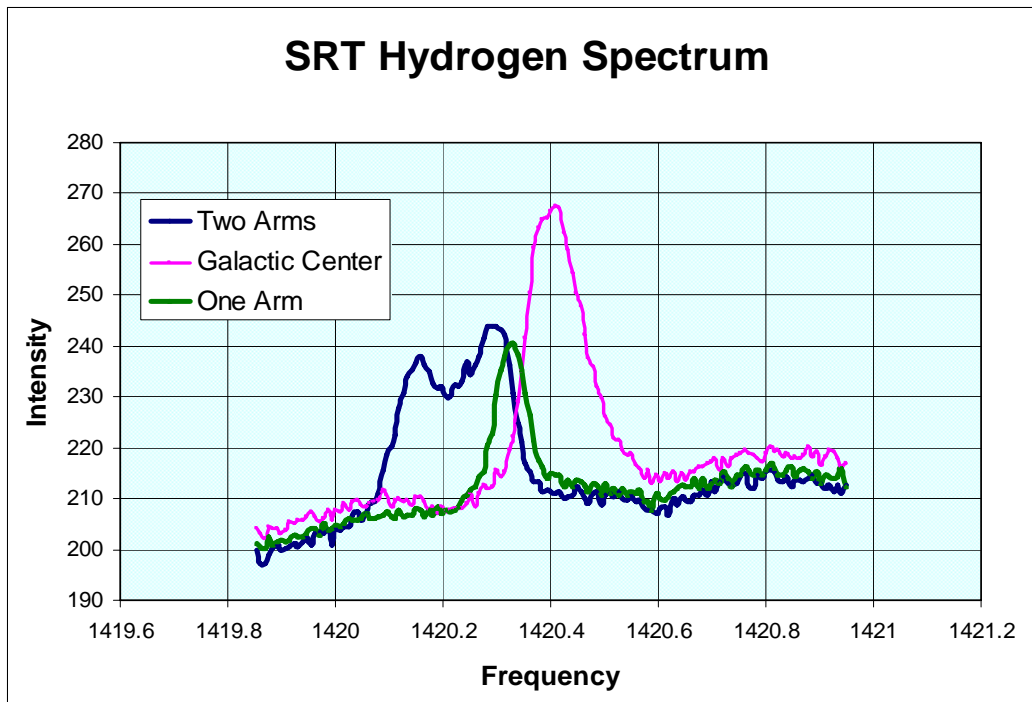
Select "Hydrogen_21cm_Rotation_Data.xls". You will need Excel to open the data. The data corresponds to three different locations in the Galactic Equator.

- 1. Calculate the frequency for each bin.** This data was taken with a central frequency of 1420.4 MHz. The mode has 156 channels, meaning that the separation between the frequencies at which the data was taken is 0.0078125.
 - Go to the "Channel frequency (MHz)" row. Pick the cell next to it and type the first frequency (located in column # F).
 - Recall that the first frequency is 1419.79 MHz and the separation between channel bins is 0.0078125, therefore the frequency for the second channel is $1419.79 + 0.0078125 = 1419.7978125$; for the third channel is $1419.7978125 + 0.0078125$ and so on.
 - Pick the next cell to the right and type " $=L18+0.0078125$ ". Press enter.
 - Highlight this cell and drag it the way across the empty cells on that row.
 - Press the "Ctrl-R" (fill to the right) to fill the rows with the frequency for each channel.
 - ***You might have to expand the columns in order to view the frequency for each channel in decimal form.***
- 2. Calculate the average intensity for each frequency channel.**
 - Go to the "Average Intensity" row.
 - Pick the cell next to it and type in " $=average($ "
 - Draw a box around the data in column L.
 - Close the parenthesis and press enter.
 - Highlight this cell and drag it all the way across the empty cells on that row.

- Press "Ctrl-R" (fill to the right) to calculate the average intensity for each frequency channel.
3. **Graph the intensity of the hydrogen emission as a function of frequency.**
- Click on the chart icon.
 - Click the graph at the second row left corner.
 - Click "Next >".
 - Go to the series tab, not the data range tab.
 - X values:
 - ❖ Click on the red icon to the right. This brings you back to the spreadsheet.
 - ❖ Highlight the cell next to "Channel Frequency (MHz)" and drag it all the way across the values in that row.
 - ❖ Click on the red icon again.
 - Y values:
 - ❖ Click on the red icon to the right.
 - ❖ Highlight the cell next to "Average Intensity" and drag it all the way across the values of that row.
 - ❖ Click on the red icon again.
 - ❖ Click "Next >".
 - Label the axes and title of the graph
 - ❖ Chart title: Intensity vs. frequency
 - ❖ Value (x) axis: Frequency (MHz)
 - ❖ Value (y) axis: Intensity
 - ❖ Click "Next >".
 - Choose the location of your graph.
 - As object in: SRT Data (Best)
 - Click "Finish".
 - Customize your graph
 - ❖ Place the mouse on top of any number on the y axis.
 - ❖ Double left click.
 - ❖ Click on the Scale tab.
 - ❖ Minimum: 200
 - ❖ Maximum: 275
 - ❖ Major unit: 10
 - ❖ Minor unit: 2
 - ❖ Click "OK".

The 21-cm Line: Galactic Rotation Activity

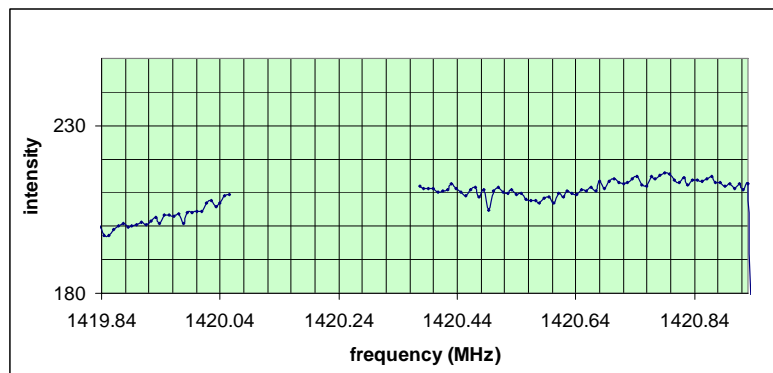
- Do the same thing for the X axis.
 - ❖ Minimum: 1419.84 MHz
 - ❖ Maximum: 1420.93 MHz
 - ❖ Major unit: 0.2
 - ❖ Minor unit: 0.04
 - ❖ Check the value (y) axis box and select crosses at: 1419.84
 - ❖ Click "OK".
- 4. **Draw gridlines.** Right click on any empty space of your chart. Go to Chart Options... go to the Gridlines tab.
- 5. **Customize your graphs.** You can add color to the line connecting the dots and to the background if you would like.
- 6. **Repeat steps 2-5 for the rest of the data.** You will now have 3 graphs that should look similar to graph below.



Removing the Baseline

Notice that the graphs are slanted. This phenomenon is due a systematic error in the instrumentation. You need to remove it!

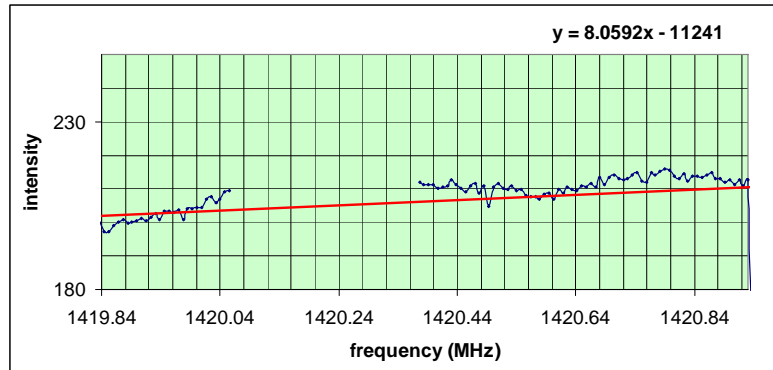
1. Delete the first 5 and last 5 average intensity values. Then save your data, you won't need these values any longer.
2. Now take a look at the intensity values on your spread sheet. Notice that at the beginning the values are pretty steady, with only minor fluctuations. Then the values start to increase, reach a maximum point, start decreasing, and then they start to get steady again.
3. Draw a box around the intensities right when the values start to increase all the way until they stop decreasing again.
 - Delete this data. **Don't save the data!!!**
 - Your graph should look like the graph this:



4. Move the pointer to any value within the graph.
 - Right click, then "Add Trendline..."
 - Click on the "Type" tab, Choose "Linear"
 - Click on the "Options" tab, and check "Display equation on chart"
 - Click "OK".
5. Write the equation for the linear regression:

$$Y = \underline{\hspace{10em}}$$

Your graph should look like the one below:



6. Before you do anything else, click the undo button until you have recovered **ALL** the deleted data from the peak of the graph. **You will need in order to continue!**

7. The linear equation for the example graph is $y = 8.0592x - 11241$. Yours might be slightly different. You will now need to subtract this equation from the average intensity for each frequency channel. (Remember that your equation is different than the one used for this example, so you will have to modify these values according to the linear equation obtained from your graph. To make it easier for you, the numbers that you have to modify are highlighted in blue).
 - Go to the "Baseline correction" row, column Q.
 - Click on this next cell and type: $=L19-((8.0592*L18)-11241)$. Notice that the values in blue correspond to the linear equation for the example graph ($y = 8.0592x - 11241$), these values will be different in your case, so make sure you change them.
 - ❖ L19 is the average intensity for that frequency channel
 - ❖ L18 is the frequency for that particular channel.
 - Highlight this cell and drag it all the way across the empty cells in the row.
 - Press the "Ctrl-R" (fill to the right) to remove the baseline from each channel.
 - Repeat the above for the other two graphs.

Converting the Frequency to Velocity Shift

The velocity of a frequency channel is given by the following equation:

$$v = \frac{(1420.406 - f)V_c}{1420.406 - V_{lsr}}$$

where V_c = velocity of light 299,790 km/s, V_{lsr} = velocity of the observer relative to the local standard of rest (this value is on the last column of the data), and f = frequency of channel.

1. Go to the "Velocity of frequency channel (Km/s)" row. Pick the cell next to it, and type: "=((1420.406-L18)*299790)/(1420.406-\$FK\$18)".
2. Press "Enter."
3. Highlight this cell and drag it all the way across the empty cells in the row.
4. Press the "Ctrl-R" (fill to the right) to fill the rows with the velocity for each channel.
5. L18 = frequency for the first channel
6. \$FK\$18 = V_{lsr} for that particular location
7. Follow the same steps to calculate the velocity for the other two data sets.
8. Type: "=((1420.406-L18)*299790)/(1420.406-\$FK\$43)" for the second data set.
9. Type: "=((1420.406-L18)*299790)/(1420.406-\$FK\$68)" for the third data set.

Graph the Velocities as a Function of Frequency. Follow the above steps to create all three graphs. The only difference is that now the x axis is the velocity (km/s) instead of frequency (MHz).

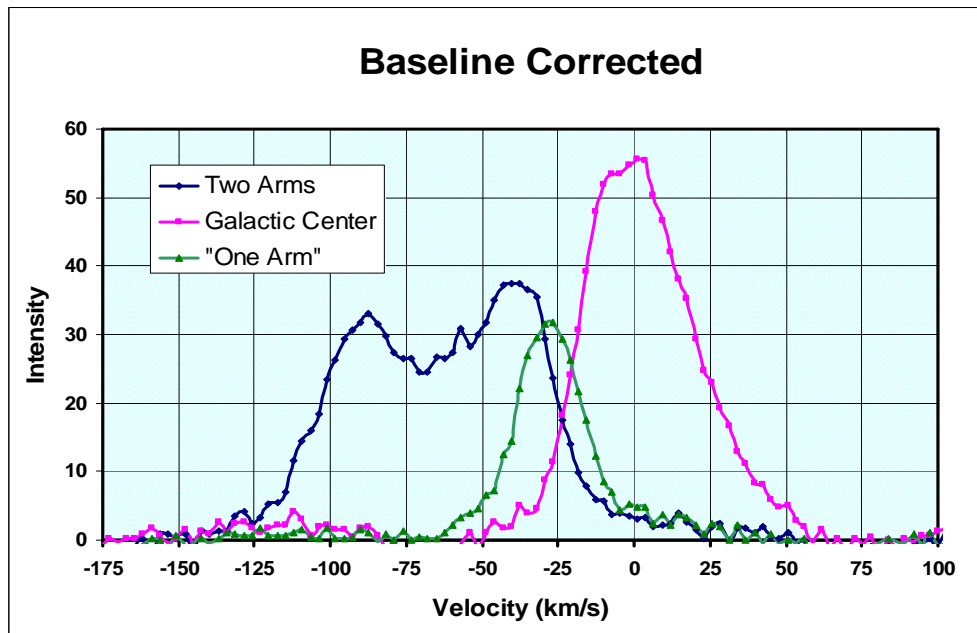
Customize your graph.

1. Place the mouse on top of any number on the x axis. Double left click. Click on the "Scale" tab.
 - Minimum: -110
 - Maximum: 111
 - Major unit: 20
 - Minor unit: 4
 - Check the value (y) axis box and select crosses at: -110
 - Click "Ok".

The 21-cm Line: Galactic Rotation Activity

2. Do the same thing for the y axis.
 - Minimum: 200 Km/s
 - Maximum: 260 Km/s
 - Major unit: 10
 - Minor unit: 2
 - Click "Ok".
3. Add gridlines and customize your graphs.

Your graphs should look like the one below:



Name _____ Period _____ Date _____

Galactic Rotation Activity—SRT Hydrogen Spectrum, Part 2

Hand in your graph and answer the following questions:

1. Notice that the peaks are not at the same location (velocity) on the graph. Use the graph above to find the velocities for each line.
2. What are the implications of a negative velocity?
3. From the direction of the shifts describe the direction of motion of arms relative to the SRT, that is, were the arms were moving toward or away from the SRT while the data was being recorded?

- a) If the galaxy rotated like a solid disk, like a DVD or CD, the speed in the outer edge of the disk has to move *faster* than the inner disk.
- b) From Kepler's Third Law and Newtonian mechanics, $T^2/R^3 = \text{constant}$ (for our solar system) for example, the outer portion of the galaxy should move *slower* than the region around galactic center.
- c) Since the orbital speed is about the same, astronomers conclude that there is a large amount of matter exerting its gravitational influence outside the Sun's orbit that we can't account for. Astronomers find that the stars, dust and gas make up only 10% of the matter necessary to account for the constant orbital speed of our Galaxy. Where is the other 90%?

This unseen matter, called *dark matter*, is one of the unsolved mystery astronomers are examining. We can't account for it at present—we can only experience its effects through the gravitational influence on the rotational motion of the Milky Way.

The 21-cm Line: Galactic Rotation Activity