Lab #7: Rotation Curve of the Milky Way in HI*

March 26, 2012

Due March 30, 2012

Objectives:

To determine the tangent velocity of HI clouds using 21 cm data.

To determine the orbital velocity and orbital radius of the clouds via the tangent point method.

To construct a rotation curve of the galaxy based on these measurements.

Needed:

MATLAB

Data from the VLA Galactic Plane Survey (VGPS) and the Canadian Galactic Plane Survey (CGPS)

*Note that this lab borrows and modifies the introduction from the Galactic Rotation Curve project from MIT's Haystack Observatory SRT projects (`http://www.haystack.mit.edu/edu/undergrad/srt/SRT%20Projects/rotate.pdf`).

1 Introduction

Hydrogen is the most abundant element in the cosmos; it makes up 80% of the universes mass. Therefore, it is no surprise that one of the most significant spectral lines in radio astronomy is the 21-cm neutral hydrogen (HI) line. In interstellar space, gas is extremely cold. Therefore, hydrogen atoms in the interstellar medium are at such low temperatures (100 K) that they are in the ground electronic state. This means that the electron is as close to the nucleus as it can get, and it has the lowest allowed energy.

A neutral hydrogen atom consists of one proton and one electron, in orbit around the nucleus. Both the proton and the electron spin about their individual axes, but they do not spin in just one direction. They can spin in the same direction (parallel) or in opposite directions (anti-parallel). The energy carried by the atom in the parallel spin is greater than the energy it has in the anti-parallel spin. Therefore, when the spin state flips from parallel to anti parallel, energy (in the form of a low energy photon) is emitted at a radio wavelength of 21-cm. This 21-cm radio spectral line corresponds to a frequency of 1.420 GHz.

HI radiation is not impeded by interstellar dust. Optical observations of the Galaxy are limited due to the interstellar dust, which does not allow the penetration of light waves. However, this problem does not arise when making radio measurements of the HI clouds. Radiation from these clouds can be detected anywhere in our Galaxy.

Measurements of the HI clouds in the Galaxy can be used in many ways, but today's lab shall use the 21-cm line to create the rotation curve for our Milky Way Galaxy.

2 Theory

If hydrogen atoms are distributed uniformly throughout the Galaxy, a 21-cm line will be detected from all points along the line of sight of our telescope. The only difference will be that all of these spectra will have different redshifts. We can use the tangent point method to determine which redshift corresponds to which distance from the Galactic Center. In Figure 1, our line of sight intersects with clouds A, B, and C.

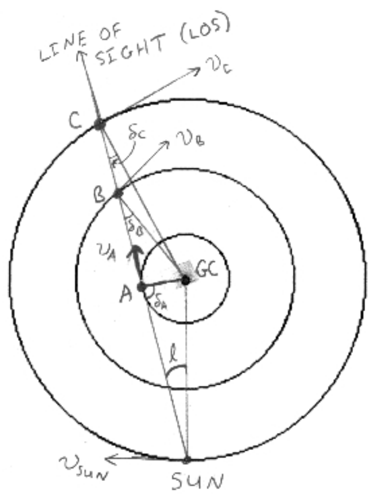

Figure 1: The line of sight through the Galaxy (looking down from the Galactic North Pole).

Note that our line of sight is tangent to the orbit of cloud A, and so cloud A's orbital velocity is entirely along our line of sight. The orbits of clouds B and C, however, are not tangent to our line of sight, and so we can measure only a component of their orbital velocities. Thus, for this particular line of sight (along the Galactic Longitude ℓ), the largest velocity we measure will correspond to cloud A (i.e. the cloud whose orbit is tangent to our line of sight). Because we are looking at the first quadrant (i.e. $\ell = 0$ to 90 degrees), the Galaxy is rotating away from us, which means the largest velocity should be that with the largest redshift. A redshifted spectral line will have a smaller frequency than its rest frequency, from $c = \lambda f$. The velocity of the tangent point cloud can then be found by taking the smallest frequency for which there is signal, and using the redshift equation:

$$v_{tan} = \frac{c * (f_{rest} - f_{obs})}{f_{obs}}$$

where $f_{rest} = 1420.406$ MHz, f_{obs} is the smallest frequency from the data (see Figure 3, in the Procedure section), and c is the speed of light, 2.997925 x 10^5 km/s.

We must remember, however, that the Sun is also orbiting around the Galaxy, and, furthermore, the Earth is rotating on its axis as well as orbiting about the Sun. These motions introduce extra signal to the redshift detected from the Galactic HI clouds. The motions of the Earth depend on the location of your telescope and time of day of the observation, and so the data you will use has already been corrected for these motions. These corrections ensure that the redshift equation given above will work. That leaves to you the correction for the Sun's motion about the Galactic Center. The Sun's orbital speed about the Galactic Center is generally accepted to be $v_{Sun} = 220$ km/s, at a radius $R_0 = 8.5$ kpc. The component of this motion included in your redshift measurements depends upon the line of sight. In Figure 2, we see that the line of sight component of the Sun's orbital velocity is $v_{LOS} = v_{Sun} * sin(\ell)$, where ℓ is the Galactic Longitude.

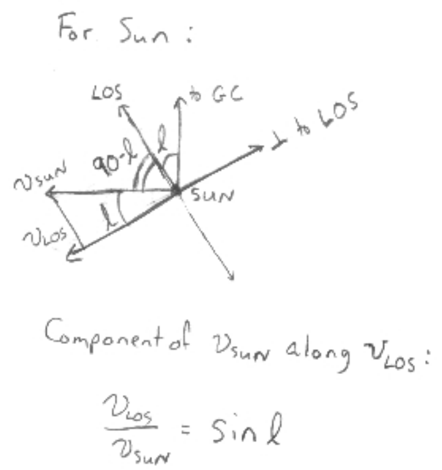

Figure 2: Component of the Sun's orbital motion along the line of sight.

Since we are moving *toward* the clouds we are measuring, the relative velocity between us and the cloud is too small. Thus you must add the line of sight velocity of the Sun to your measured velocity in order to get the full orbital velocity of the cloud:

$$v_{orbital} = v_{tan} + v_{LOS} = v_{tan} + v_{Sun} * sin(\ell)$$

Notice that the sign convention here means that the equation still works if you are in the third or fourth quadrants (ℓ greater than 180 degrees), because $sin(\ell)$ becomes negative. This subtracts velocity from the tangent velocity you would measure, which is good, because we're moving away from the clouds in those quadrants, meaning that our relative velocities are too large.

To plot the rotation curve of the Galaxy, we need one more piece of information: the distance of the tangent point cloud from the Galactic Center. Note that in Figure 1, the triangle between the Sun, cloud A (the tangent point cloud in this figure), and the Galactic Center must be a right triangle, with $\delta_a = 90$ degrees. Thus from simple trigonometry, cloud A's distance R from the Galactic center is given by:

$$R = R_0 * sin(\ell)$$

where $R_0 = 8.5$ kpc and again, ℓ is Galactic Longitude.

When astronomers first plotted the Galaxy's rotation curve, they discovered that the curve appears rather flat. This result was quite surprising, because there is a clear drop-off in luminous material as you move from the center of the Galaxy out to its edges. The distribution of luminous matter suggested that most of the mass of the Galaxy was concentrated near the center. If this were true, it would mean that in the Galactic outskirts, the velocity should fall off as $R^{-1/2}$, just as the orbital velocities in our solar system do. The mass interior to the orbit and the distance from the center are both important in the orbital speed law:

$$v = \sqrt{\frac{GM_{<R}}{R}}$$

where $M_{<R}$ is the mass interior to the radius R of the orbit. Like in our solar system, outside a certain radius (essentially the radius of the Sun, in the solar system's case), you are no longer adding significant mass to the total mass interior to the orbit. Thus your orbital speed is dominated only by how far you are from the center of the total mass (the $R^{-1/2}$). To produce the flat rotation curve instead, that must mean that we are still adding significant amounts of material to the total mass at increasing distances from the Galactic Center, but we can't see any of it!

3 Procedure

1) Open a new folder in the A121 folder and name the folder using your (and your partner's) intials and the number 7, since this is lab 7. Then go the the lab website `http://www.astro.umd.edu/~cychen/MATLAB/ASTR121/labHI/` (the capitalizations are important!) and download the lon##.dat files as well as the TheoCurve.dat file into your folder. Open MATLAB and put yourself into your folder.

As always, open a blank m-file and use it to keep a record of the commands you need to reproduce your work. Please, please, PLEASE for the sake of the trees (and my back, when I put the collected labs in my backpack), **do NOT keep the commands to load all the files and plot them. You can replace all of the load/plot commands of the files in your m-file by just loading the .mat file which you will be instructed to create in step 3.**

2) For each of the lon##.dat files (making sure to go through them in order of the number of the file, which is the Galactic Longitude you are looking at), you should:

a) Load the file using the **load** command (refer to the "Input and Output" tutorial on the lab's website if you need a reminder). NOTE: if you use the up arrow, it will repeat your last command and allow you to edit it. If you hit the up arrow twice, it will go back two commands, and so on. This will make step 2 go much faster, and make it easier to keep track of what file you're on!

b) Plot the spectrum. In this case, the first column is frequency (rather than wavelength), measured in MHz, and the second column is brightness temperature, in units of K, which is a measurement similar to flux that is popular among radio astronomers. Remember, if you have an array named, say, "arr", then you can call the first column of the array using arr(:,1) and the second column using arr(:,2).

c) Using **ginput** (see the "Graphical Input" tutorial on the lab website as well as the "Orbital velocity of the cloud" tutorial if you need a reminder of how to use it), record the smallest frequency for which there is a signal, as shown in Figure 3. You do NOT need the brightness temperature information, just the frequency. Again, use the up arrow to repeat your ginput commands, so that you keep track of which index in the frequency array you are on. You should end with 13 frequencies.

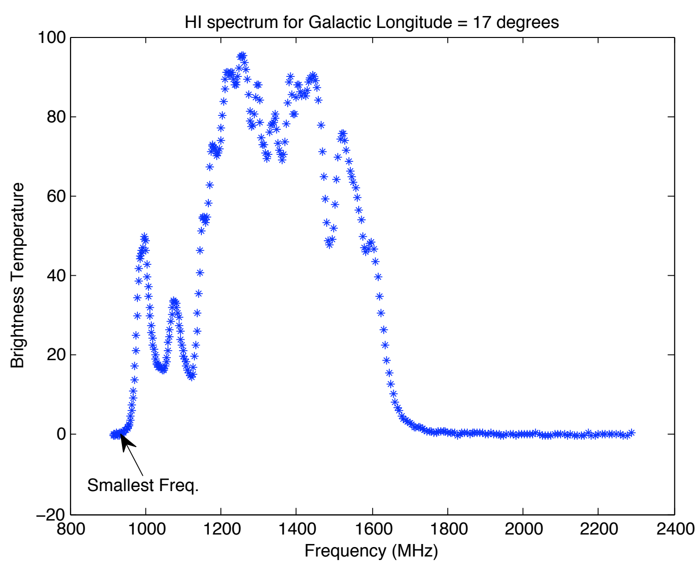

Figure 3: Finding the smallest frequency

3) Once you have recorded the smallest frequency for all of the lon##.dat files (there should be 13):

a) Save the array containing all of the values as a .mat file so that you have a record of them. Say you wanted to save an array named "arr" as a .mat file. Then you would type:

```
>> save arr.mat arr
```

which will save the variable "arr" exactly as you had it stored in your workspace (make sure you include the .mat ending on the filename). That way, if you need to finish the lab at home, you have a record of the values you got from **ginput** and won't have to repeat the process. Just don't forget to take the .mat file along with your m-file! b) To replace the load/plot commands in your m-file, just use the load command:

```
>> load arr.mat
```

where "arr.mat" is the name you gave your file.

c) Make sure you have a hardcopy of your frequencies to hand in with your code, so that I can see them. This can easily be done in one of two ways:

1) Double-click on the icon for your frequency array in the workspace window, which will open the variable editor. There's a print icon in the variable editor. Make note of the units on the printout.

2) You can publish your m-file. To do it this way, to ensure you get a good number of decimal places, create an array which subtracts off 1400 from the values and let MATLAB print the output (i.e. don't use a semi-colon). Right after loading the frequency array and doing the subtraction of 1400, put a line in your m-file which contains just 2 percent signs, which will then publish the result immediately after the subtraction is performed in the code. Include a comment on the line in which you do the subtraction, by using a percent sign after the code and before the comment, noting that the units are in MHz. There is more information on publishing m-files located in the "Write, Run, and Publish script M-Files" tutorial.

4) Make an array of the Galactic Longitudes of your data files, and use the equations given in the Theory section of this lab hand-out to find the orbital velocities that correspond to the frequencies you have measured. Remember that you need to add in the component of the Sun's orbital motion along the line of sight in your total velocity! The Galactic Longitude ℓ for each observation is the ## in the filename lon##.dat. Make sure to **convert from degrees to radians** to use ℓ in the **sin** function, because MATLAB expects the angles in radians! Either include a printout of your velocities (and write the units on by hand), or publish your m-file, without suppressing the output of your velocity calculations (and including a comment with your units), so that you have a record of your velocities to use in the Questions section.

5) Use the equations in the Theory section of the lab hand-out to now find the distance R from the center for each of your observations. Also make sure you have a record (either by printing them out or publishing your m-file) of the radii you calculate to use in the Questions section. Include your units somehow.

6) Add the Sun's orbital velocity (220 km/s) and orbital radius (8.5 kpc) to your velocity and radius arrays. If you named your two arrays "vel" and "rad", then you would do this by:

```
>> vel(14) = 220; rad(14) = 8.5;
```

assuming you calculated your velocities in km/s and your radii in kpc. This makes the Sun's data the 14th entry in each array (because you should have 13 entries in each array, 1 for each of the 13 lon##.dat files).

7) Plot the orbital velocities (y-axis) vs the radii (x-axis). It doesn't look very flat, does it? That's because of the scaling of the y-axis. Load the TheoCurve.dat file, which has radius (in kpc) in the first column and velocity (in km/s) in the second column, and overplot this curve onto your calculated curve for the Milky Way. **Include a legend** noting which linestyle or symbol you used for your measured curve and the theoretical curve, and, as always, give the plot appropriate axes labels (include the units) and a title. Now your measured curve looks pretty flat, doesn't it? Refer to the plot of the Milky Way rotation curve included on the last page of this lab (Figure 4) to see just how far this flatness extends (and to make sure your values are reasonable).

This theoretical curve is what the rotation curve would look like if the majority of the mass of the Galaxy was concentrated in the center. The initial bump is caused as you add lots of mass as you go out in radius for about the first kiloparsec, and then the long decline is due to just the $R^{-1/2}$ factor, as you no longer add significant amounts of mass to the total mass.

4 What Should You Hand In?

Please don't hand in the whole lab hand-out. If you write your answers to the questions below on this page, only hand in this page.

You should hand in the following:
a) your code (excluding loading all the lon##.dat files and plotting them, as described in the procedure)
b) some sort of hardcopy record of your measured frequencies and your final calculated velocities and radii (include units!)
c) the plot of your measured rotation curve with overplotted theoretical curve, including a legend, title, and axes labels
d) and the answers to the following questions (make sure you give your final answer somehow and include units, if you do the calculations within MATLAB. and make sure you each submit your own, individual answers to the questions, unless it's a calculation in the MATLAB code):

1) Why can we only use the 21 cm line to measure atomic hydrogen (HI) and not molecular hydrogen (H_2)?

2) Calculate the amount of mass inside the radius for your measured $\ell = 65$ degrees velocity.

3) Estimate the velocity at the radius corresponding to $\ell = 65$ degrees for the theoretical curve from your plot, and use it to calculate the theoretical mass inside the curve. How many times bigger is your mass from the measured velocity?

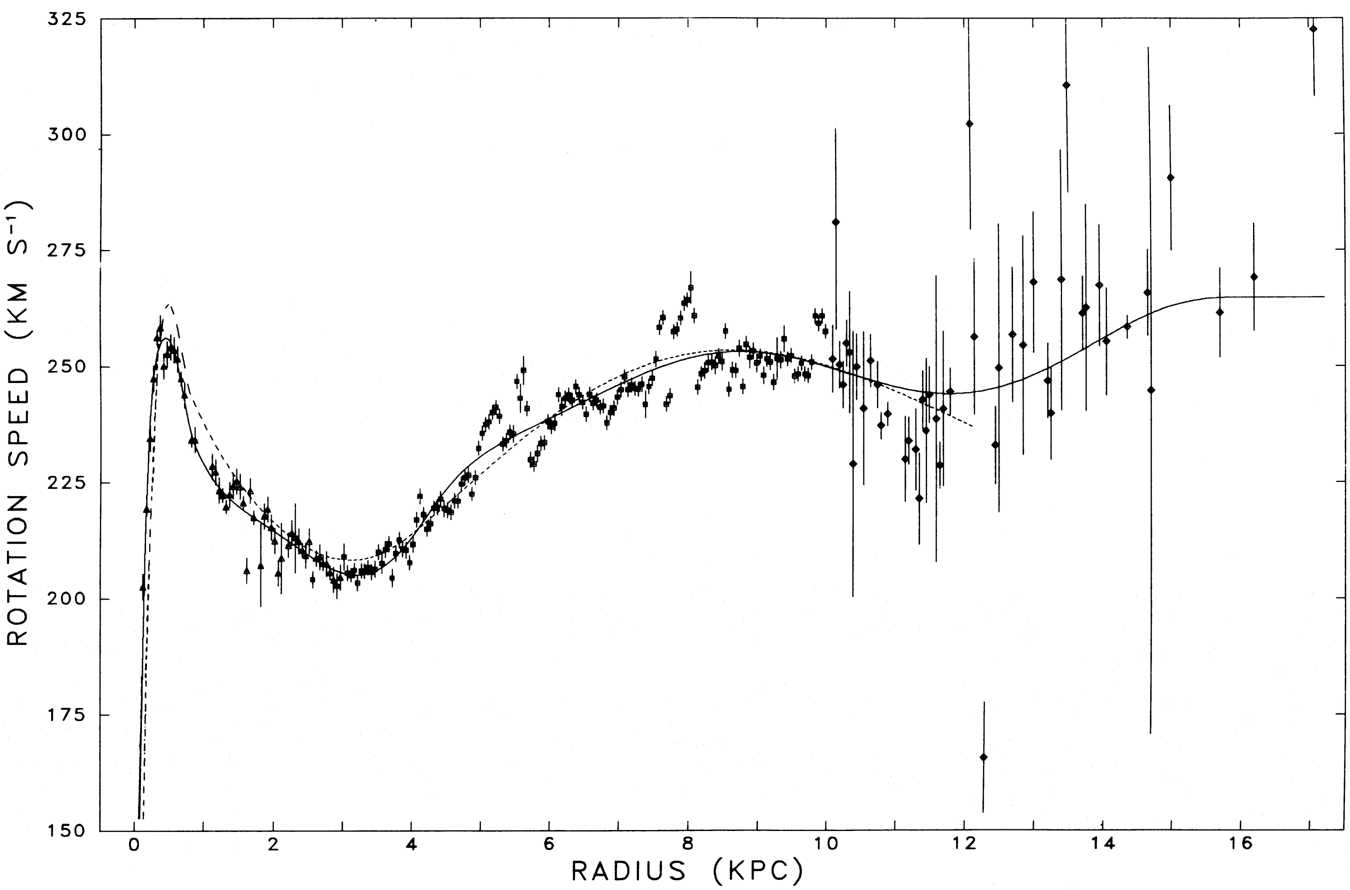

Figure 4: The measured rotation curve from Clemens, ApJ 295:422-436, 1985 August 15 (including data from several other papers).