Measurement of Galactic Rotation Curve

Objective:
By observing the 21cm hydrogen lines at different points along the Galactic plane, we can create a rotational curve for the Milky Way Galaxy, which can provide an indirect indication of dark matter.

Introduction:
From pictures of distant galaxies, it is clear that most luminous matter locates in the centre of a galaxy and then falls off exponentially further out. This leads us to believe that we can model it as having all the mass in the centre and the gravity felt by objects further out is simply given by Newton's law of gravitation,

$$F = GMm/r^2,$$

where r is the distance from the galactic centre to the orbiting object. This gravitational force must then provide the centripetal force

$$F = m\,v^2/r$$

to keep an object far out in the galaxy moving in an essentially circular orbit. Equating these two expressions, we see that the velocity of objects moving in circular orbits far from the centres of the galaxies should go as

$$v\,r^{-1/2}.$$

So we should expect that if we graphed v vs r, we should find a decreasing curve. If we find anything else, some explaining will have to take place.

To verify this, we can determine the velocity of the emitting regions using the Doppler Effect. Any Doppler shift of the 21cm (1420.406MHz) hydrogen line will tell us about the velocity of the hydrogen cloud relative to an observer.

In reality, there are several motions needed to be considered, including the motion of the Sun relative to the local standard of rest and around the Galactic centre, the motion of the Earth around the Sun, and the spin of the Earth. The SRT software will take care of most of them. You only need to consider the motion of the Sun around the Galactic centre in the calculation.

In the diagram below, the tangential velocity v equals to the rotational velocity ω times the distance r from rotation axis, i.e. $v = r\omega$. If you are looking through the Galaxy at an angle γ from the centre, the velocity of the gas at radius R projected along the line of sight minus the velocity of the Sun projected on the same line is

$$V = V_{source} - V_{sun} = \omega R sin\delta - \omega_0 R_0 sin\gamma,$$

where

V_{source} = projected source's velocity along line of sight
V_{sun} = projected sun's velocity along line of sight
ω = angular velocity of source at distance R
ω_0 = angular velocity of Sun at distance R_0
R_0 = distance of Sun to the Galactic centre
γ = Galactic longitude of source
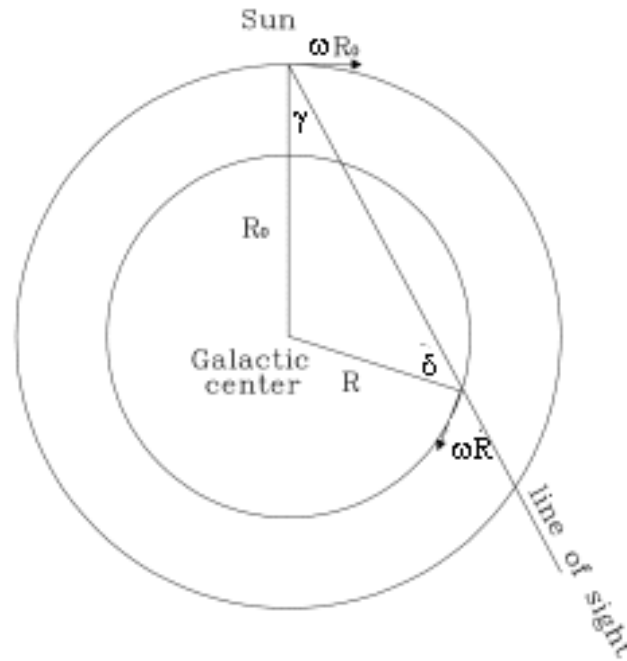
The maximum velocity occurs where the line of site is tangential to the circular motion, i.e. $\delta = 90°$ and we find that

$$V_{max} = \omega R - \omega_0 R_0 sin\gamma$$

where $V_{rot} = \omega R$ is the rotational velocity and $R = R_0 sin\gamma$.

Hence,

$$V_{rot} = V_{max} + \omega_0 R_0 sin\gamma.$$

From other measurements, we know that our Sun has a Galactic rotational velocity and distance of

$$\omega_0 R_0 = 218 \, km/s$$

$$R_0 = 2.6 \times 10^{17} km,$$

respectively. Now you have all of the background you need. V_{max} can be found using the Doppler shift.

You will make observations at various Galactic longtitudes, then determine the maximum radial velocity from the Doppler shift

$$v = \frac{\Delta /}{} c,$$

where Δ is the difference between the observed wavelength and the known wavelength corresponding to the frequency of 1420.4MHz, and c is the speed of light.

Clearly, the largest Δ corresponds to the cloud with the highest velocity V_{max} (i.e., the one whose tangential velocity is along our line of sight) and given the wave equation $v = f$, we see that the largest wavelength corresponds to the smallest (or lowest frequency). This frequency (or frequency bin) is then identified in the data as the lowest frequency around 1420.4MHz that has a non-zero intensity.

Finally we have to take into account the velocity of the observer relative to the local standard of rest, which includes the spin of the Earth, motion of the Earth around the Sun and motion of the Sun relative to the local standard of rest. The SRT has a real time programme to calculate the sum of all these velocity projected onto the line of sight. This is shown by V_{LSR} on the screen. After the correction, the tangential velocity of the source along our line of sight is,

$$V = \frac{(f_0 - f)c}{f_0} - V_{LSR},$$

with f_0 the central frequency, which is 1420.406 Hz in our case. The channel frequency f can be obtained from the intensity-frequency spectrum after observation by adding a calibration to the observation frequency,

$$f = f_{obs} + 0.04 MHz.$$

The maximum velocity V_{max} can be estimated by finding the minimum frequency of the emission.

You are now ready to take your data and process it so that you can graph velocity versus radial distance from the galactic centre. It will be helpful to use units of km/s for the velocity and kiloparsecs (kpc) for the distance. ($1 kpc = 3.08568 \times 10^{16} km$)

Procedure:

1. Measurements should be made when the Galactic centre is observable by the SRT and better the Galactic Plane (the dotted line in the sky map) is nearly vertical in the sky.

2. Click the "freq" button then type "1420.4 4" to set the center frequency to 1420.4MHz and to mode 4 which has a bandwidth of 1.5MHz.

3. Move the telescope to the Galactic centre (i.e. Sgr A) and then scanning the Galactic plane in increments of 10° (or 5°). This can be done either use a script or manually:

   (a) Use a script (recommended method). Click "Rcmdfl" button and then type the command file name "galactic.cmd". This will scan the Galactic Plane in 10° increment and save the data files as g00.dat, g10.dat, ... etc.
   (Important!) While observing, write down V_{LSR} of EACH pointing, which is displayed in the lower right panel of the screen. You need that for calculation later.

   (b) Manual pointing. Point at Sgr A, click the "record" button and then type a file name (e.g. g00.rad) to begin record. Take 30-60s of data. Click "record" again to stop recording. Write down V_{LSR}. Click "Azel" button to slew the telescope. You may need to try a few times until it points to "Galactic l=10 b=0" as displayed in the upper right panel of the screen. Now click "record" type a file name (e.g. g10.rad), and repeat for every 10° in l until 90°.

4. (Optional) To verify that the signal we detected is from the Milkyway, you can move telescope to a blank background (at least 40° away from the Galactic plane) and then record the background control data. Name the file bg.rad and record for 60 seconds.

5. Stow the telescope and exit the program.

6. Copy the data files from c:\SRTvsrt to your own computer using a usb drive.

Analysis

You now have 11 spectra with 156 frequency bins recorded in 11 separate .rad files (one background and ten galactic longitudes), which are txt files. Before the data can be analyzed, it has to be formatted in Microsoft Excel.

1. Open the .rad files using Microsoft Excel Spreadsheet programme. When the Text Import Wizard comes up, select the "Delimited" option under the Original data Type box, and then click next. In the second Text Import Wizard box, check the delimiters "space" and then click next. In the third window, select "finish".

2. Here are what each column represents:

Column	
1	Date and time
2-3	Pointing (az,el)

4-5	Offset (az,el)
6	Freq. of the first channel (MHz)
7	Channel width (MHz)
8	Mode
9	Total no. of channels
10-end	Data (power in each channel)

3. You should have a total of 156 channels (check it). You first need to convert the channels into frequency, using the information in columns 6 and 7. (Use a formula, do not convert each column by hand.)
4. For each frequency channel, find the time average of the power counts over the whole exposure time. This can be done by creating a new row, type "=average(XM:YM)", where XM:YM is the range.
5. Plot a scattered graph of power against frequency using the averaged counts values in Excel. You will see the two edges clearly fall off in your plot. Delete all these data points near the edge, which are receiver noise.
6. Add a new row and calculate the corresponding velocity for each frequency values.
7. Now plot a graph of power counts against velocity using the scattered graph.
8. You should see the intensity rises and falls. At large velocity, determine the point at which the intensity first drops to the background level (see the example plot below). Record the velocity. This is V_{max}. You may locate that data point with a different colour to highlight it on the spectrum.

Repeat the above procedures for all other Galactic longitudes.

9. In a new table, calculate V_{rot} and the radial distance R (kpc) from the Galactic Centre for each longitudes. Also put V_{max} you find into a column.
10. Plot the Galactic rotation curve using information above, i.e. V_{rot} (km/s) against R. You are required to hand in one spreadsheet file that contains all the spectra and the final Galactic rotation curve.
11. (Optional) Repeat the observation for an increment of 5° of galactic longitude for a higher accuracy.

frequency (MHz)
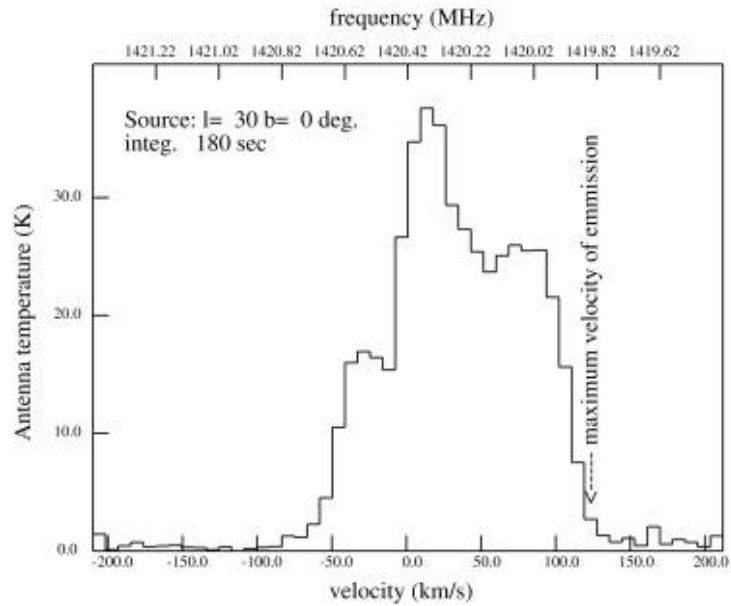
SRT

g30.rad

Questions:

1. How is the 21-cm hydrogen line produced in neutral hydrogen? Explain why we can use the hydrogen line as an indicator in our observation analysis.

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2. Describe what you see in your rotation curve. Does one line or curve of best fit account for the entire data set? If so, what is the best fit? If not, at what distance does a break occur?

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6

3. Based on your graph, what can you say about the Galactic mass distribution?

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4. Suggest an up-to-date astrophysics explanation for the discrepancy between the Galactic rotation curve and the result expected from Newton's law.

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5. Can we do this observation in any time of a year? Why?

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Reference: Kiley Pulliam & Laura A. Whitlock, Listen Up!: Laboratory Exercises for Introductory Radio Astronomy with a Small Radio Telescope, iUniverse, 2008