

# (Astro)Physics 343 – Spring 2010

## Lab # 4: Measuring the Milky Way's Rotation Curve

**Observations:** week of 22 March 2010

**Reports due:** 5 April 2010

**Purpose:** In the previous lab, you have measured the thickness of the HI layer in the Milky Way at a fixed Galactic longitude  $\ell$  by making measurements at multiple Galactic latitudes  $b$ . In this lab, you will extract information about the rotation curve of the Milky Way using HI measurements at multiple longitudes in the Galactic plane (i.e., at  $b = 0$ ). You will make one new measurement yourself, in order to familiarize yourself with the format of the larger archival dataset that will be the basis for your main analysis.

**Before the lab period:** Prepare a command file that records the following data in receiver mode 4 for each of *two* central frequencies, 1420.7 MHz and 1419.6 MHz:

- 20 seconds at  $b = 0$  at an arbitrary  $\ell$ ;
- 20 seconds at an azimuth offset of  $+30^\circ$  relative to the first position; and
- 20 seconds at an azimuth offset of  $-30^\circ$  relative to the first position.

You should think carefully about the most efficient way to sequence these observations so that you minimize execution time.

### Procedure:

During your lab period, you and your teammates should produce a single consensus script that obtains data at these six frequency–pointing settings at either (a) a Galactic longitude that is observable during your lab period, or (b) a Galactic longitude that is observable at a fixed time during the morning of the following day. If you opt for the latter, add a start time to the beginning of your script so that it can be run in service mode, and use the SRT software in simulation mode to confirm that all three positions are actually observable for a script that begins at that start time. Service mode data will be emailed later in the week.

### Analysis:

For the new data taken by/for your team, you should do the following on your own:

1. Compute the six time–averaged spectra that result from observations of your two central frequencies and three sky positions.
2. Ignoring both sets of end frequency channels (which have poor receiver response), combine the two spectra for each of your three sky positions so that you end up with *three* continuous spectra.
3. Average the two spectra at the  $\pm 30^\circ$  offset positions, and subtract them from the spectrum at the  $b = 0$  position. Assuming that  $T_{\text{sys}}$  dependence will be the same whether the telescope was pointing at or away from the Galactic plane, this step will effectively *remove* the system temperature from the HI data.

4. Generate plots of (a) the three original time-averaged spectra, and (b) the final H I spectrum, vs. frequency. The plot of the final H I spectrum should include appropriate error bars on each point, and you should explain how you derived these.

For a more comprehensive analysis, you should make use of the 25 archival datasets with the same format as your new one that have been made available at

<http://www.physics.rutgers.edu/ugrad/343/lab4data/>

These files are named according to the Galactic longitudes at which they were observed; they are already in Excel format and include plots of antenna temperature (from which system temperature has been removed, as above) vs. frequency. (Note that the formatting of the plots may not be uniform; this is often the case for archival data compiled from many different sources.) Using these files, do the following on your own:

1. For each  $\ell$ , calculate after inspection of the archival data which radial (line-of-sight) velocities show the most highly redshifted ( $v > 0$ ) and blueshifted ( $v < 0$ ) H I emission. Recall that the rest frequency of the H I line is 1420.4 MHz. You should use your best judgment to estimate (and justify) the *uncertainties* in these extremal velocities.
2. The observed radial velocities need to be corrected for the motion of the Earth around the Sun. For the date on which the archival observations were taken, this means shifting the velocity scale by the following amounts as a function of Galactic longitude at  $b = 0$ :

$\ell$	$\Delta v$ (km s <sup>-1</sup> )
-10	28.8
-5	29.4
0	29.8
5	29.8
10	29.7
20	28.9
30	27.2
40	24.6
50	21.4
60	17.4
70	13.0
80	8.1
90	2.8
100	-2.2
120	-12.2
140	-20.8
160	-26.8
180	-29.6
200	-28.9
220	-24.6
240	-17.4

For values of  $\ell$  not in this table, you should interpolate between two longitudes that are listed.

3. The observed radial velocities *also* need to be corrected for the motion of the Sun with respect to the “local standard of rest” (LSR), an idealized reference frame that follows the Galactic rotation perfectly. Schönrich, Binney & Dehnen (2010, MNRAS, in press; the preprint is arXiv:0912.3693) suggest that the components of the motion of the Sun with respect to the LSR are  $11.10 \pm 0.72 \text{ km s}^{-1}$  towards the Galactic center,  $12.24 \pm 0.47 \text{ km s}^{-1}$  in the direction of the Sun’s rotation around the Galactic center, and  $7.25 \pm 0.37 \text{ km s}^{-1}$  towards the north Galactic pole. To correct a radial velocity in a particular direction, calculate the component of the Sun’s motion with respect to the LSR and add it to the correction for the Earth’s motion around the Sun.
4. Produce a table listing the extremal (maximum and minimum) velocities with significant HI emission as a function of  $\ell$ , both before and after correction.
5. Compare the results for  $\ell = 0^\circ$  and  $\ell = 180^\circ$  to the expectation for a rotating disk. Does most or all of this gas have zero radial velocity? How similar are the two spectra, and can you give reason(s) for which gas along these two sightlines might have nonzero radial velocities?
6. Make a plot of the corrected extremal velocities for  $-10^\circ \leq \ell \leq +90^\circ$ .
7. Considering now the gas in the range  $-10^\circ \leq \ell \leq +90^\circ$ , calculate the radius of the tangent point  $R_{\min}$  for each observed Galactic longitude, assuming the distance to the Galactic center is  $R_0 = 7.94 \text{ kpc}$ .
8. Calculate the circular velocity for each longitude,  $\Theta(R_{\min})$ , on the assumption that  $\Theta(R_0) = 220 \text{ km s}^{-1}$ . Plot the rotation curve  $\Theta(R_{\min})$  vs.  $R_{\min}$ , along with the appropriate uncertainties.
9. Use your derived rotation curve to calculate the mass interior to  $R_{\min}$ , i.e.,  $M(< R_{\min})$ , as a function of galactocentric radius.
10. If the *width* of the HI velocity profile is due to turbulent motions in the gas along the line of sight, use the FWHM of that peak to estimate a characteristic turbulent velocity width within the disk of the Milky Way as a whole.