PHSC12710
Radio Astronomy and the Rotation of the Galaxy
with the Small Radio Telescope (SRT)

Introduction

Observational astronomy using light at radio wavelengths, i.e., meter through millimeter wavelengths, is a relatively new field, starting with Karl Jansky's discovery of radio wavelength emission from the sky in 1933. Jansky worked at Bell Labs and was trying to understand the excess noise in trans-Atlantic radio communications. It was a remarkable discovery, making headlines in the New York Times and leading to the birth of new field. However, Bell Labs did not pursue radio astronomy further at that time. An enthusiast Grote Weber did, however. As a hobby, he built in 1933 the first modern radio telescope in his backyard in Wheaton, IL and used it to map the sky, identifying many interesting astrophysical sources. He was detecting continuum emission, most of the sources were later found to be highly energetic active galactic nuclei emitting a type of radiation called synchrotron emission. In 1944, Hendrik van de Hulst worked out the theory of the hydrogen spin-flip transition, often simply called 21 cm hydrogen emission, which soon became a powerful tool for astronomy. It still is today. The 21 cm line (1420.5 MHz frequency) is used to map the cold neutral hydrogen gas in the Galaxy and other galaxies. It was used to show unambiguously the spiral arms in the Milky Way. It also allows astronomers to measure the rotation curves of galaxies and solve for the enclosed mass. Such measurements have led to the discovery that large halos of an invisible, "dark" matter dominate the mass of galaxies. In this lab you will make such a measurement. In so doing you will learn the basics of radio astronomical observations and use them to measure the rotation of the Milky Way.

The Small Radio Telescope (SRT)

The Small Radio Telescope (SRT) is built using a commercial satellite dish and a specialized radio astronomy receiver. It consists of a 10ft diameter parabolic reflector, which concentrates the radio waves onto a short rod (a dipole) tuned to a frequency of around 1420 MHz. The radio waves from the sky generate small currents in the dipole that are then amplified electronically. The parabolic reflector increases the sensitivity of the telescope and defines its field of view. We can therefore look at individual objects or scan over regions in the sky to obtain a map. Unlike a digital camera that records many pixels of the image simultaneously, the radio telescope measures only one pixel at a time, i.e., it can only measure the flux from one direction in the sky at one time. The telescope is pointed from one position to another in the sky to build up a map of the region.

The radio telescope also provides highly accurate spectroscopic data of the emission from every point. The frequency range of the telescope allows for the detection of the hydrogen line at a frequency of 1420.4 MHz, which will allow us to map the location of hydrogen in the galaxy. Note that radio waves at these frequencies are practically unattenuated by Earth's atmosphere, so we can make our measurements if the sky is cloudy, even if it is raining!

Resolution

The diameter of the telescope and the wavelength of the received radiation (light) determine the resolution of the observations. A double object is said to be *resolved* if we can see that we are looking at two objects rather a single object. If the objects are closer than this limit we will see only one object. The resolution of a telescope is not a totally precise quantity, because we can sometimes obtain better resolution by careful computer processing of the data, but is given approximately by the angular diameter of the *Point Spread Function* (PSF). The PSF is obtained experimentally by observing an object that is small compared to the theoretical resolution of the telescope (a *point source*) and measuring the angular size of the image.

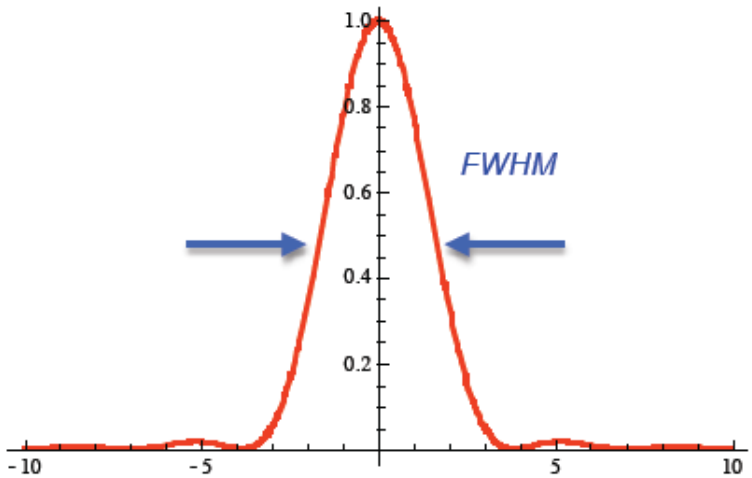


Figure 1: Point Spread Function of a diffraction limited Telescope

The theoretical angular diameter of the PSF is given by:

$$\Delta\theta = \lambda/D$$

where

$\Delta\theta$ is the Full Width diameter of the PSF at Half Power (or Full Width at Half Max, FWHM), in radians
λ is the wavelength of the radiation
D is the diameter of the telescope.

Resolution is an important concept in astronomy, especially radio astronomy. The TA will go over this topic with you in the lab.

Questions for your lab report:

> *(1) What is the expected Full Width Half Maximum (FHWM) beam diameter for the SRT in degrees, given that the frequency of the radiation is 1420 MHz and the telescope is 3.0 meters in diameter?*
> *(2) How does this compare with the angular diameter of the sun?*

Present calculations and answers to these questions in your lab report.

Operating the small radio telescope

To begin operating the telescope, first switch on the grey box next to the designated lab computer, connecting it to the SRT. To start the SRT software, click on the icon with a picture of the telescope called “SRT” on the desktop of the right computer.

Control Buttons

The control panel display has a line of control buttons at the top that set up a command for the telescope. For instance, if you want to change the receiver frequency, you click on the “freq” button. Instructions and help information are then displayed in the help panel below the map while the cursor is pointed to the button (This field is blank when you move the cursor away). If you want to change the frequency, then type data into the data line (e.g. “1420.4 4”), click “enter” or “return”. Be sure you leave a space between 1420.4 (which is the frequency) and the number 4 (which sets the bandwidth of the system). The current observing parameters will be updated in the appropriate box.

Control Display & Sky Map

The control panel shows a map of the current sky in Azimuth and Elevation units. 0 degrees azimuth points North, 90 degrees points East, 180 degrees points South and 270 degrees points West. The horizon is at 0 degrees elevation and Zenith is at 90 degrees. The telescope can point to about 85 degrees in elevation.

The map displays objects visible at the current time. The software tracks an object or a given azimuth and altitude position, including corrections for the rotation of the earth. Also displayed on the map are various individual astronomical sources and a track of dots that show the plane of the Milky Way. The Longitude of points along the equator of the Milky Way are shown as Gxxx, where xxx is the Galactic longitude. We have an unobstructed view of all objects above about 20 degrees.

Pointing the Telescope

You can point to any given position in the sky by clicking on the “AzEl” button and then typing the desired Azimuth and Elevation in the command line at the bottom of the display. (e.g., 30 45 “enter” will send the telescope to a position of 30 degrees azimuth and 45 degrees elevation). When you enter a position you will see a yellow cross and the CMD numbers will change to these numbers.

When "track" shows up in green at the top of the display, the telescope has acquired the position and is tracking it, this holds for sources. If the telescope does not move, then you probably have to click on "track".

Occasionally the telescope motor will get stuck and stall. Normally it fixes itself automatically by going back to the "Stow" position (where it is stowed after every observation), but if it remains stalled for several minutes click "Stow" to do so manually. This can be a nuisance and time-consuming but you should still be able to obtain the necessary data if this happens.

Calibration in Theory

In radio astronomy, it is usual to interpret the measured antenna signal in terms of temperature, as if the measured source is a blackbody, and fills the full field of view of the telescope. This isn't necessarily the case, but it's often a good approximation and gives a physical parameterization of the measured power. For large wavelengths (i.e., for radio waves as in our case), the expected blackbody emission spectrum is well approximated by the Rayleigh-Jeans law:

$$B_\lambda(T) \approx \frac{2c}{\lambda^4}kT$$

so the emitted power (and thus the power measured by the antenna) is simply proportional to the blackbody temperature. Therefore, if the antenna is pointed at a blackbody source, the measured power signal received, P, will be proportional to T, and we can write:

$$P_{received} = \beta\, T_{source}$$

where β is a constant that takes care of all the physical constants, as well as the efficiency of the antenna and amplifiers in the receiver, and so on. The Universe, which is filled by the Cosmic Microwave Background (CMB) radiation (see PHSC12620 – The Big Bang, if you want the details), is effectively an oven of temperature T_{CMB} = 3K, and this is the temperature the antenna will measure if the antenna beam is pointed to a direction in the sky where no radio sources are present.

In practice, the radio telescope receiver has an intrinsic noise, which produces a power signal even in the absence of an astronomical source. To this power, P_{SYS} , we define an equivalent system temperature, T_{SYS} , according to

$$P_{sys} = \boldsymbol{\beta}\, T_{sys}$$

Since this noise is present in all our measurements, we need to know it so we can correct our measurements accordingly, i.e., subtract it from our measurements. The power P_{SYS} can be measured by pointing the SRT toward a direction in the sky without radio sources. In this configuration, the measured power is dominated by the receiver noise, since the contribution from the CMB signal is negligible.

To get rid of the unknown coefficient of proportionality β, we make use of a calibrated radio source of known temperature. For this purpose, the SRT is equipped with a small electronic source of radio waves at the vertex of the telescope dish to allow remote calibration. The equivalent temperature of the calibration source is T_{cal} ~ 200 K. When we switch on the calibration source, we introduce an additional noise temperature of 200 K, and the software notes the new power reading (P_{sys}+P_{cal}). The ratio of these two measurements cancels out the factor β and T_{sys} can be derived.

The SRT software does all of these calculations for you and result is displayed in the middle right window in the SRT console.

Calibration in practice

It is important to first set the frequency of the radiation that will be analyzed by the software. We will start with continuum radiation so we will avoid the Hydrogen line, and instead set the frequency to 1416 MHz.

The control panel display has a line of control buttons at the top that set up a command for the telescope. To change the receiver frequency, you left click on the "freq" button. Instructions and help information are then displayed in the help panel below the map while the cursor is pointed to the button (This field is blank when you move the cursor away).

Lab tasks

- *For continuum radiation, click on the Freq button, then type "1416 1"* in the command line and hit return (the "1" is to set the spectrometer mode – more about that later). **You will not get reasonable or consistent results for the calibration if the frequency has not been set.**

- Click on the AzEl button and type an Az and El for a blank part of the sky (e.g., azimuth and elevation: 10 35; check on the display to make sure you select coordinates away from the Galactic plane and from the Sun) into the data input line at the bottom of the control panel (see Fig. 2) and then hit "enter". You should see the telescope in the left hand display start to move in elevation. The telescope position is printed out in the top right panel of the control display. The top line gives the command position (which should reflect the position you typed in for AzEl) and the next line gives the actual position.

  Note: the system uses a single cable to transmit both control and measurement data so while the telescope is moving to a new command position there will be no data (and possibly no display) during the slew (this can be frustrating, so try to be patient!).

- When the telescope position is settled (i.e., the cross on the sky display is red and the "Track" button at the top of the display is green), click "Clear" and write down the raw output power and temperature (see figure 1). Click on Cal button and watch these numbers. The system will record the output power itself and then switch on the noise source. The computer will then calculate the temperature of the sky at that point, which includes the system noise temperature. *Note that you should "Clear" before each new observation, for both calibration and data, since the telescope is continually integrating and thus keeps all the previous data since it was last cleared.*

- Repeat this calibration a few times, waiting about 1 minute between observations. The first calibration of the run requires a few cycles. Once you have a stable system temperature, record the sky counts temperature (it is shown in units of degrees Kelvin in the text above the cmd line) and system temperature from the middle right panel of the console. Note that the sky temperature will still be fluctuating some: estimate a range and average value.

Background Noise

The telescope is sensitive to all sources on the sky, as well as buildings, etc. Although the telescope is most sensitive over a small area of sky it does have some low sensitivity to sources at much larger angles from its pointing position. Radio power generated by cell phone towers and wireless devices within buildings can cause significant addition signals even though the 1420 MHz band that we are using is protected for radio astronomy by law against such interference. Communication devices operate near our frequency and do not always suppress power in our frequency bands; although the fraction of the radio power in these sidebands is tiny, our telescope is very sensitive and we can detect this interference. Man made interference can be distinguished from astronomical sources because it is usually fixed in position while astronomical sources move across the sky.

Is the radio sky uniform in Hyde Park?

Given that there are background sources that can interfere with our measurements of real sky signal, before we proceed to make any measurements, it is instructive to explore just how uniform the sky is in Hyde Park.

<u>Lab tasks:</u>

- Make sure the frequency is set to 1416 MHz by clicking on freq and typing in 1416 1

- From the telescope pointing that you used in the previous exercise (say [az,el]=[10,35]) point the telescope 15 degrees lower in elevation (at the same azimuth) and 20, and 40 degrees higher in elevation. Repeat the calibration at each of these positions 2-3 times and record azimuth and elevation of the pointings and values of the sky temperature and system temperature displayed by the SRT console. Avoid labeled astronomical objects.

- After you are done with measurements at different elevation, return to your original elevation and change azimuth with step of 50 or 75 degrees (at constant elevation) and repeat calibrations 2-3 times at each pointing. Record azimuth and elevation of the pointings and values of the sky temperature and system temperature displayed by the SRT console.

Lab report question:

(3) How uniform is the radio sky around Hyde Park? In your lab report, discuss the uniformity of the sky signal and system temperature based on your measurements. Include a table of your measurements and your interpretation and conclusions.

Measuring the velocity of Hydrogen clouds in the galaxy

Hydrogen is the most common element in the universe. It exists in interstellar space as individual atoms, each atom consisting of a proton and an electron. Both particles have a property called *spin* and a hydrogen atom can exist either with the spins of the proton and electron parallel or anti-parallel. Sometimes the atom changes its spin state and, in doing this, emits a radio wave at a precisely known frequency of 1420.4 MHz corresponding to the wavelength of 21cm. By tuning the SRT receiver to this frequency, we can directly measure the amount of hydrogen in that direction and, importantly, its velocity.

We can measure its velocity through the effect known as *Doppler Shift*. When an object is moving towards or away from an observer, the wavelengths of the light observed from the object get compressed or stretched. Since the wavelength and frequency of light are inversely related, frequencies are respectively increased or decreased. This is called Doppler Shift. Thus if we know the intrinsic frequency at which an object emits – in this case from the fundamental physics of the Hydrogen spin-flip transition – then we can calculate the velocity of that object with respect to our observational frame of reference – in this case the Earth. Your TA will go over this important concept with you in more detail during the first lab section. (Make sure you understand what’s going on and ask questions if you are confused!)

To do this, the SRT receiver measures the flux at a number of very finely spaced frequencies, typically 7.5 kHz wide and spaced 7.5 kHz apart, and so can produce a spectrum of the hydrogen line. This allows us to measure the Doppler shift of the atomic hydrogen clouds in the interstellar space of the Milky Way emitting the radio waves and allows us to measure the rotation velocity of that gas around the center of our Galaxy.

Lab report question:

(4) What is the smallest difference in Doppler shift in km/sec you would expect to measure, assuming the resolution is set by the channel bandwidth of 7.5 kHz? Provide the equation and your calculation to

support your answer in your lab report.

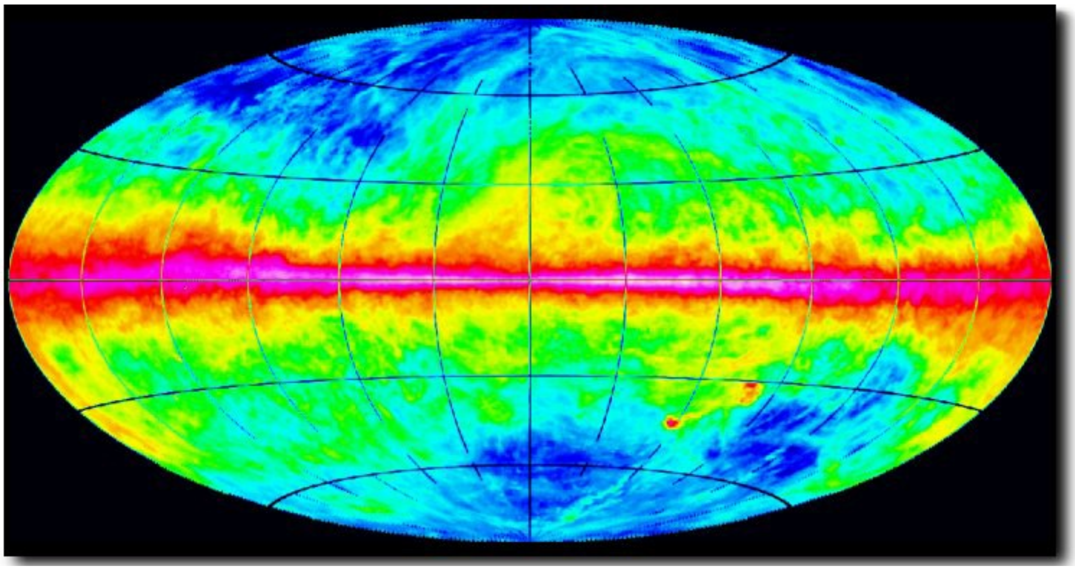


Figure 3: The diffuse Hydrogen 21 cm emission over the entire sky shown in Galactic coordinates with the Galactic center in the middle. Red indicates intense emission, while blue indicates very weak emission.

Rotation of the Galaxy and Dark Matter

New stars are formed in our Galaxy in huge clouds of gas and dust. When we look at the sky at optical wavelengths we see nearby stars, but the dust acts like a fog in interstellar space and this limits the distance to which we can see stars in our Galaxy; it was this effect that made early astronomers think that we were near the center of our Galaxy. At radio wavelengths there is almost no absorption and flux at 21 cm is large due to large amount of atomic hydrogen in diffuse gas clouds between stars. This means that we can see these clouds right across the Galaxy even with a small radio telescope. By making various assumptions we can measure the rotation of the Galaxy and map out its structure. We first have to assume that the clouds move round the galaxy in approximately circular orbits with a velocity that depends only on the distance from the center of the Galaxy. This is shown in Figure 4a. The reasoning behind such assumption is that we see gas moving in such circular motion in other galaxies, which we can view from the outside.

The Sun is moving around the center of the Milky Way in an orbit close to circle. The radius of this circle is measured independently and is about 8.5 kpc (i.e., the distance from the Sun to the center of our Galaxy is 8.5 kpc). If we look through the Galaxy we will see clouds also moving around the center of the Milky Way at different distances from the center and with different velocities. The Doppler shift that can be measured with SRT can only measure the radial component of velocity (i.e., the velocity along our line of sight) and not the total velocity of the gas. The velocity we measure with SRT is the difference in velocity between us and the cloud measured along the line of sight (indicated by the red vectors in Figure 4a). In any given direction we will see a number of clouds moving at different velocities to our line of sight so that the radio spectrum will look like Figure 4b.

The radio flux from any cloud depends on the number of hydrogen atoms in the cloud itself. Atoms within the cloud have their own random motions so that we see a spread in frequencies from each cloud (see Figure 4b). The mean frequency depends on the difference in circular velocity between the cloud and the Sun and on a geometric effect introduced because we are only measuring the velocity along the line of sight.

We should note that, initially, the line of sight velocity gets larger as we look at clouds rotating nearer to the center of the galaxy. However, at some distance (in this case cloud 4) there is a maximum line of site velocity. This cloud is going away from us directly along our line of sight. Clouds further away appear to have a smaller line of sight velocity. We can determine this maximum velocity by measuring in the radio spectrum the maximum Doppler shifted frequency (see Figure 4b).

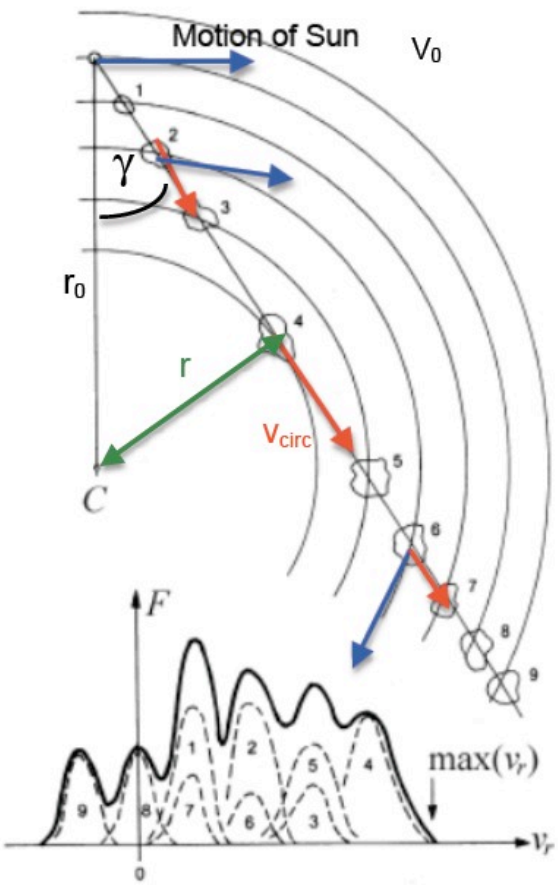


Figure 4a: Geometry of measuring lines of sight in our galaxy. The Sun, all the billions of other stars in the galactic disk, and all of the emitting hydrogen gas between the stars orbit in the same direction, in circular orbits confined to a plane.

Figure 4b: Corresponding frequency spectrum. The hydrogen lines corresponding to individual clouds are indicated by dashed lines.

We measure Galactic coordinates in a heliocentric frame of reference. The center of the galaxy is at 0 degrees longitude and the angle above the plane, as viewed from the Earth is given as a latitude. When we point at a given longitude, in the galactic plane, we measure the difference between the line of sight velocities of all the different clouds relative to the Sun's line of sight velocity to that direction.

What we are hoping to measure is the actual velocity of clouds as they circle the galaxy and for this we have to know the velocity of the Sun going round the Galaxy. It turns out that we cannot measure this velocity from 21 cm line observations because we need to measure the solar motion using a frame of reference outside the disk of the galaxy that does not rotate. One such reference frame is the halo of globular clusters that surround the Galaxy, another is the reference frame of distant galaxies. By measuring their Doppler shifts using the spectra of their stars, we can measure a mean velocity of the sun. The best estimate is that the objects at the same distance as the Sun from the center of the Galaxy rotate in a circular orbit at an average circular velocity of 220 km/sec.

There is additional motion due to the Earth's rotation around the Sun and the Sun's own motion. Working out all these extra velocities is tedious, but fortunately the SRT software calculates them for us, and provides velocity relative to the Local Standard of Rest (VLSR). The VLSR is given in km/sec in the control panel and the measured velocities are referred to this VLSR. You will also see that the spectrum of radio emission, which you can get by clicking on the spectrum window also shows radio flux as a function of both frequency and VSLR.

From the geometry of Figure 4a, the velocity of the Sun in the line of sight for a given galactic longitude γ is given by:

$$V_{sun}(\gamma) = 220 \sin(\gamma)$$

As discussed above, in any one direction of galactic longitude we can measure the maximum velocity of the spectrum, V_{max} (the rightmost edge of the emission for cloud 4 in Fig. 4b). By geometry from Figure 4a, for a given longitude γ the distance of the cloud to the center of the Galaxy is

$$r = r_0 \sin(\gamma)$$

where r_0 = 8.5 kpc is the distance of the sun to the center of the Galaxy. The corresponding circular velocity is given by:

$$V_c(r) = V_{max}(\gamma) + V_{sun}(\gamma)$$

To measure rotation curve of the Galaxy we need to measure V_{max} for various distances r, that is for different Galactic longitudes γ. We are now ready to perform such a measurement. Before we proceed, pause and think about what you are about to do: you are about to detect and analyze radio emission from Hydrogen atoms in interstellar space thousands of light years away (i.e., it travelled to us for periods of time comparable to the history of human civilization). Note that depending on the time of observation, not all galactic longitudes are visible in the sky. How much we could measure with the SRT directly, depends on which portion of the Galactic disk plane is accessible to observation (i.e., up in the Chicago sky at the time of your lab session). Sometimes, only sources between 90 and 270 degrees are visible during the lab session: in such case, you can still get the spectrum of 21 cm emission from interstellar atomic hydrogen, but you cannot use your SRT data to measure the rotation velocity of the galaxy. Instead we will use data from an online all-sky 21 cm hydrogen survey. No matter what time of the year the lab is performed, we need the online data for galactic longitudes between -10 and -90 degrees as this portion of the sky is never visible from Chicago.

Lab report question:

> *(5) In your lab report please explain why we cannot use longitudes larger than 90 degrees (or more negative than -90 degrees) to obtain rotation curve of the Galaxy. Use Fig. 4a in in your reasoning.*

You might wonder why we care about the rotation of the galaxy in the first place. Ultimately, the goal of this lab is to map out the *rotation curve*– the profile of stellar orbital velocities as a function of radius from the galactic center – of the galaxy, which tells us about the *mass distribution* of the galaxy. The gravitational field caused by the mass distribution of the galaxy determines the velocities of stellar orbits. Assuming spherical symmetry (which is not accurate in detail but a good first approximation), we can relate the velocities of stars at a radius r to the enclosed mass distribution by

$$M(< r) = \frac{v(r)^2 r}{G}$$

Therefore, by measuring v as a function of r we can estimate the enclosed mass distribution. You will see that the distribution of mass cannot be accounted for by the observable galactic disk alone, thus providing evidence for an “invisible” matter component termed *Dark Matter.*

Setting the receiver frequency for Hydrogen and calibration

First set the frequency of the receiver to the Hydrogen at 1420.4 MHz. To change the frequency and set the spectrometer, first click on “freq” then 1420.4 4 on cmd line and hit “enter”. Be sure you leave a space between that 1420.4 (which is the frequency) and the number 4 (which sets the bandwidth of the system for the largest velocity coverage).

You now calibrate the system but we now have to worry about Hydrogen emission from the sky messing up the calibration. We can avoid this either by moving the telescope to a position far off source (which may still be contaminated by another source of Hydrogen emission) or by changing the frequency just for the calibration and then switching it back afterwards. To calibrate with a frequency offset when the system is on the target, first change the frequency to

1423 4, which is sufficiently far away from the hydrogen line that you are measuring only the receiver noise and thermal background.

Note that if you have spectral features showing up in your calibration spectrum, then the sky position you used for your calibration probably had strong Hydrogen emission. Try to calibrate at another position, or at an offset frequency as described above.

Lab tasks:

- Perform the calibration procedure, as described above. The offset frequency method is recommended.

- Bring up an Excel window to record your work. Before each observation enter the galactic longitude of your pointing and then copy the spectrum you obtain below this.

- In the control panel, the positions of different Galactic longitudes along the equator are indicated by Gxxx (where xxx is in degrees). If you see longitude of 90 degrees and smaller, start at the longitude of 90 degrees and work your way down to the smallest longitude you can observe down to zero if the center of our Galaxy (coincident with the source named Sgr A). If you cannot observe longitudes smaller than 90 degrees observe one or two longitudes that are up in the sky. This will give you an idea about the spectrum of clouds in the Galaxy, but we will use other data to construct rotation curves (see below). Note that galactic coordinates labeled in the SRT display can be pointed to by clicking on them – for the rest you have to estimate (or look up) the Az El of the desired longitude on the galactic plane.

- Move to your first pointing and press Clear button to clear the spectrum accumulated by the SRT.

- Set the frequency to 1420.4 4 and obtain the spectrum for the galactic longitudes visible in the sky by integrating for 10-20 seconds (or longer) along the same pointing.

- After integration click on the spectrum window to get a detailed plot of the spectrum in a separate window. You will see emission flux as a function of frequency and VSLR. Estimate that maximum velocity of the clouds visible in the spectrum (similar to cloud 4 in Fig. 4b).

- Record the spectrum by first clicking on the spectrum in the viewer to bring up the detailed plot, then use Alt-PrintScreen to capture the plot in the clipboard and then press Ctrl-V to paste the clipboard in the Excel window. Be sure to maximize the window size to make your plot as legible as possible.

- Proceed to the next Galactic longitude available for observation. Press Clear button to clear the spectrum before you make observation at each new longitude. Record longitude and spectrum in the Excel file along with your estimate of the maximum velocity for each pointing.

If some or all longitudes between 0 and 90 degrees are not observable at the time of your lab, we will use the all-sky survey of 21 cm hydrogen emission performed by astronomers and available online. We will also use it to obtain data at galactic longitudes from -10 to -90, which are always below the horizon from Chicago. The all-sky survey of radio emission (see Fig. 3) was obtained by a collaboration of astronomers at Leiden, Argentine and Bonn (LAB survey). The web site is at https://www.astro.uni-bonn.de/hisurvey/AllSky_profiles/.

The LAB survey input form is shown in Figure 5. To obtain a spectrum from the LAB survey for a position along the galactic equator, select Galactic coordinates longitude and altitude = (l,b) for the coordinate system, input your desired l and b (l here is the same as γ used in Fig. 4). For all your pointings b=0. Select LAB Survey only. You can also select the "effective" beam FWHM. The angular resolution of the LAB survey is 40 arcminutes (0.67 degrees). In Figure 5 and 6 we have used 0.2 degrees, in this case the program returns the average spectra for a 0.2 degree patch of the sky for comparison with the measurements you made with the SRT.

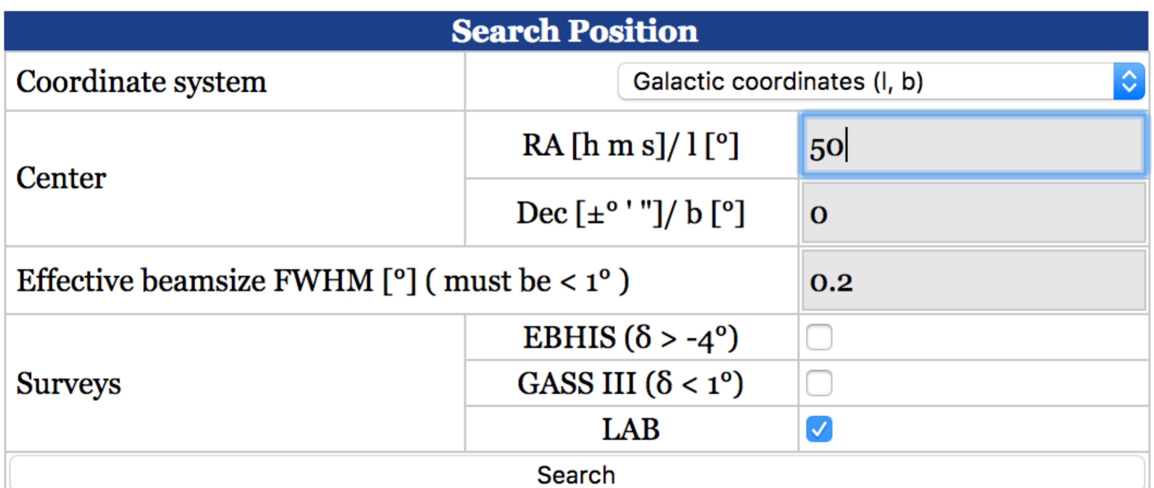
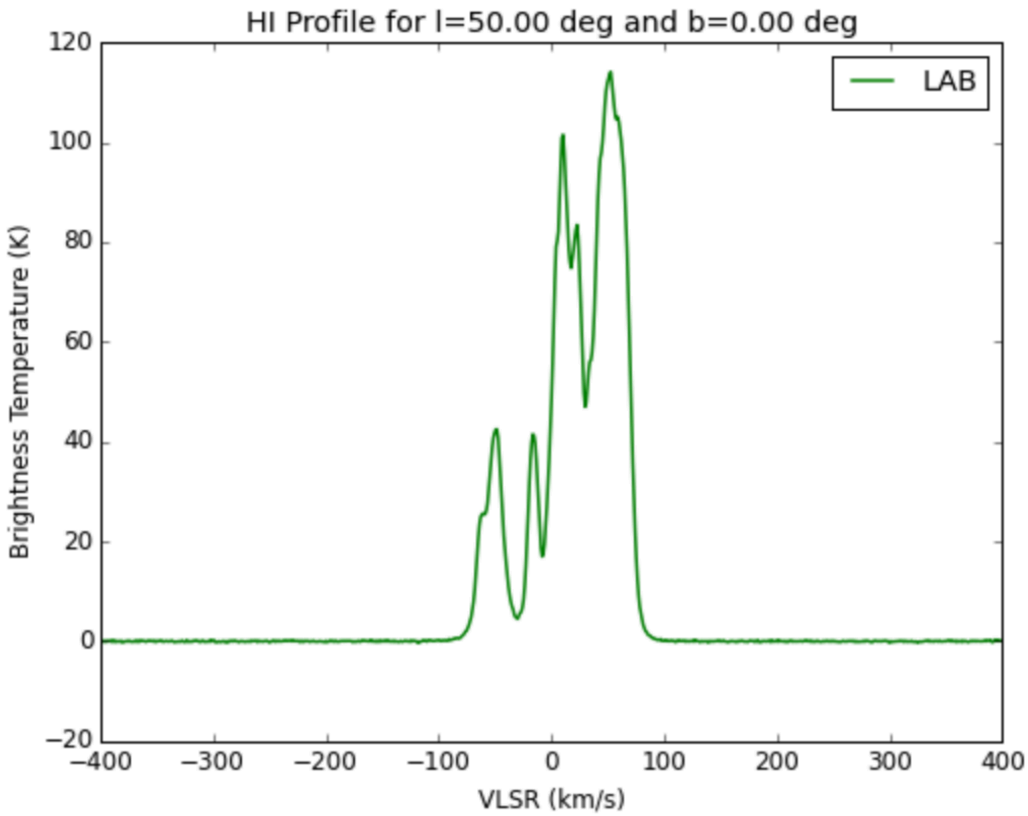


Figure 5: The input form for accessing the LAB spectra. The resulting output is shown in Figure 6 below (note that the form resets after each search).

Lab tasks:

- Obtain spectra from the LAB survey along the galactic equator for the longitudes that you could not observe with SRT. Measure the maximum radial velocity, V_{max} (note these will be max positive for longitudes 10 to 90 deg. and max negative for longitudes -10 to -90 deg.). You will note that the spectrum does not provide a clean maximum velocity. Try to think about the best way to measure maximum velocity. Discussion possible options with your TA. Once you decided on the particular algorithm to estimate maximum velocity stick with the same algorithm for all longitudes. If you want more precision, you can download the spectra in digital form from the site.
- Re-observe one of the longitudes that you have observed with the SRT and compare the spectrum you get from the LAB survey to that you have obtained with the SRT. Discuss any similarities and differences that you may find. You can also substitute any source on the sky for making the comparison of the SRT and the LAB survey spectra.
- Assuming a distance from the Sun to the galactic center of 8.5 kpc and a circular velocity of 220 km/sec at this radius, fill in Table 1 with the results of your calculations using your measurements of V_{max} and equations above.
- Plot the circular velocity you obtain with eq. 3 against tangential distance for each longitude. You can make your plot either in Excel or any other plotting program you are comfortable with.



Position		
Requested	l [°]	50.00
	b [°]	0.00
	RA [°]	290.83
	Dec [°]	15.14
Column Densities		
EBHIS	0.200° Beam	0.135E+23
GASS III	0.266° Beam	0.00
LAB	Interpolated	0.142E+23
	Nearest gridpoint	0.142E+23

Figure 6: Resulting HI spectra and the LAB query.

Galactic Longitude (degrees)	Tangential distance (kpc) r	Maximum LSR velocity V_{max}(km/sec)	Line of sight solar velocity V_{sun} (km/sec)	Circular velocity V_c (km/sec)
10				
20				
30				
40				
50				
60				
70				
80				
90				
-10				
-20				
-30				
-40				
-50				
-60				
-70				
-80				
-90				

Table 1: Data table for measurement of the rotation velocity of the Galaxy

Lab report questions:

(6) Compare a spectra from the LAB with FWHM beam of 0.267 degrees to that with 9 degrees (like the SRT). Why might these plots look different? Compare these both to the spectra you measure with the SRT for any source on the sky. Present the spectra and your thoughts in your lab report.

(7) Include the filled out table (or printed from excel) and the plot of your measured circular velocity vs longitude in your lab report. What does this say about the mass distribution of the Galaxy? Include your answer in your lab report.

Stowing the telescope

When you have finished with the SRT don't forget to stow it. Put the cursor on the STOW button, click and watch the television camera to see that the telescope does stow. When it is stationary in this position, turn off the control box power and exit the control program.