7. THE ROTATION CURVE AND MASS OF THE GALAXY: DARK MATTER

GOALS

In this lab, you will learn:

1. How to measure the speeds at which matter orbits our galaxy.

2. How to measure the rotation curve of our galaxy, and use it to determine if our galaxy's mass is concentrated at its center or spread throughout its disk.

3. How to measure the mass of our galaxy within different radii from its center, and use this information to determine if our galaxy is composed primarily of visible matter or of a combination of visible and dark matter.

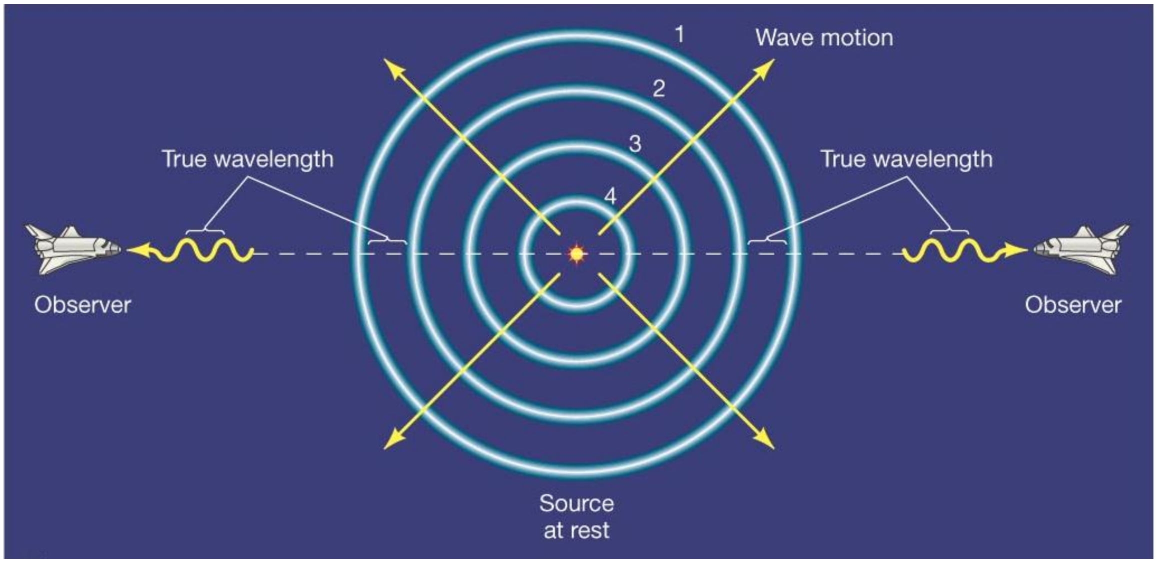
EQUIPMENT

Computer with internet connection

BACKGROUND

A. DOPPLER EFFECT

Consider a source of light. If the source is stationary with respect to observers, the observed wavelength λ_{obs} will be the same as the emitted wavelength λ_{em}:



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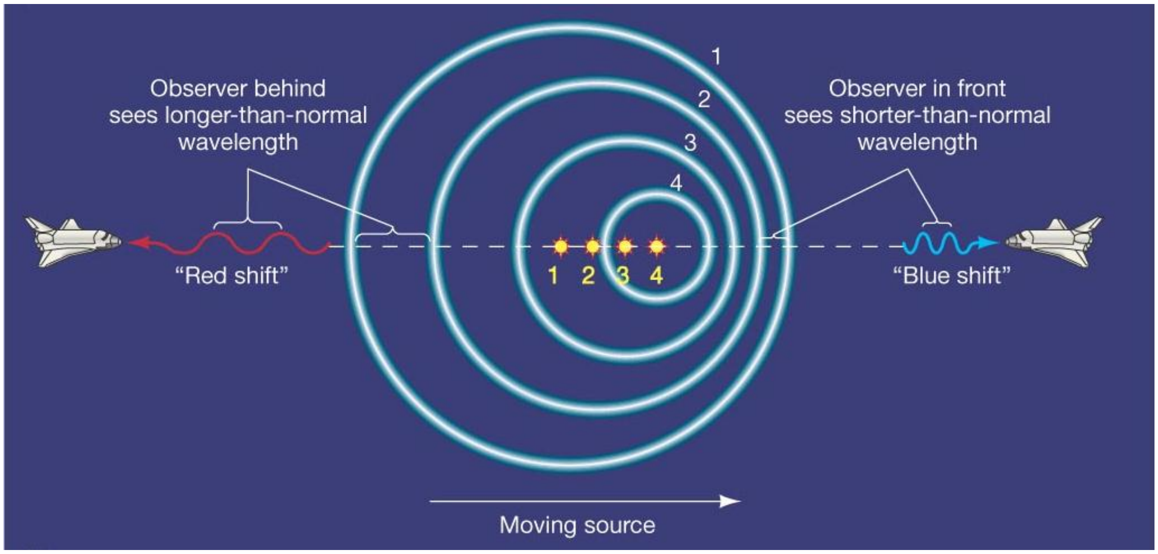
But if the source is moving with respect to observers, the waves will be compressed in the direction of motion, resulting in a shorter observed wavelength, or bluer light. Similarly, the waves will be stretched out in the opposite direction, resulting in longer observed wavelengths, or redder light:



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Mathematically, if the source is moving toward the observer, the observed wavelength λ_{obs} will be shorter than the emitted wavelength λ_{em} by $\Delta\lambda$:

$$\boldsymbol{\lambda_{obs} = \lambda_{em} - \Delta\lambda}$$

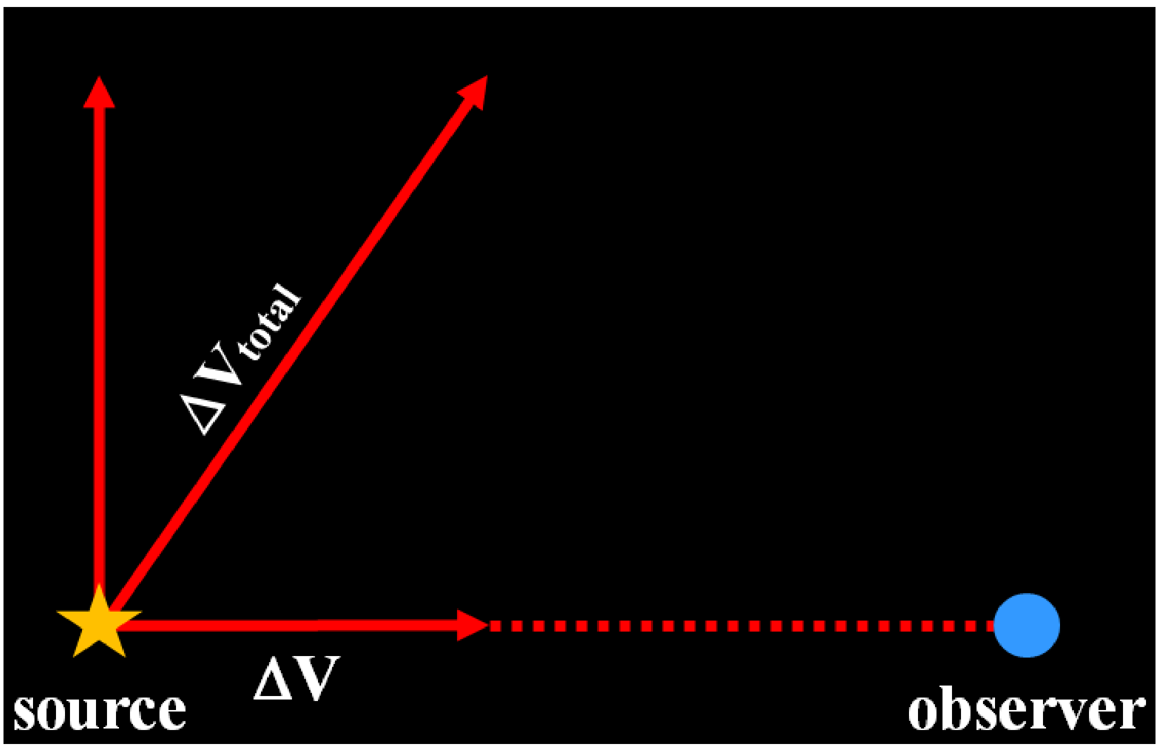
And if the source is moving away from the observer, the observed wavelength λ_{obs} will be longer than the emitted wavelength λ_{em} by $\Delta\lambda$:

$$\boldsymbol{\lambda_{obs} = \lambda_{em} + \Delta\lambda}$$

In both cases, the change in wavelength $\boldsymbol{\Delta\lambda}$ is given by:

$$\boldsymbol{\Delta\lambda = \lambda_{em} \times \Delta V/c}$$

where $\boldsymbol{\Delta V_{total}}$ is the source's speed relative to the observer and $\boldsymbol{\Delta V}$ is the *component* of ΔV_{total} *along the line of sight between the source and the observer*:



B. 21-CM EMISSION LINE

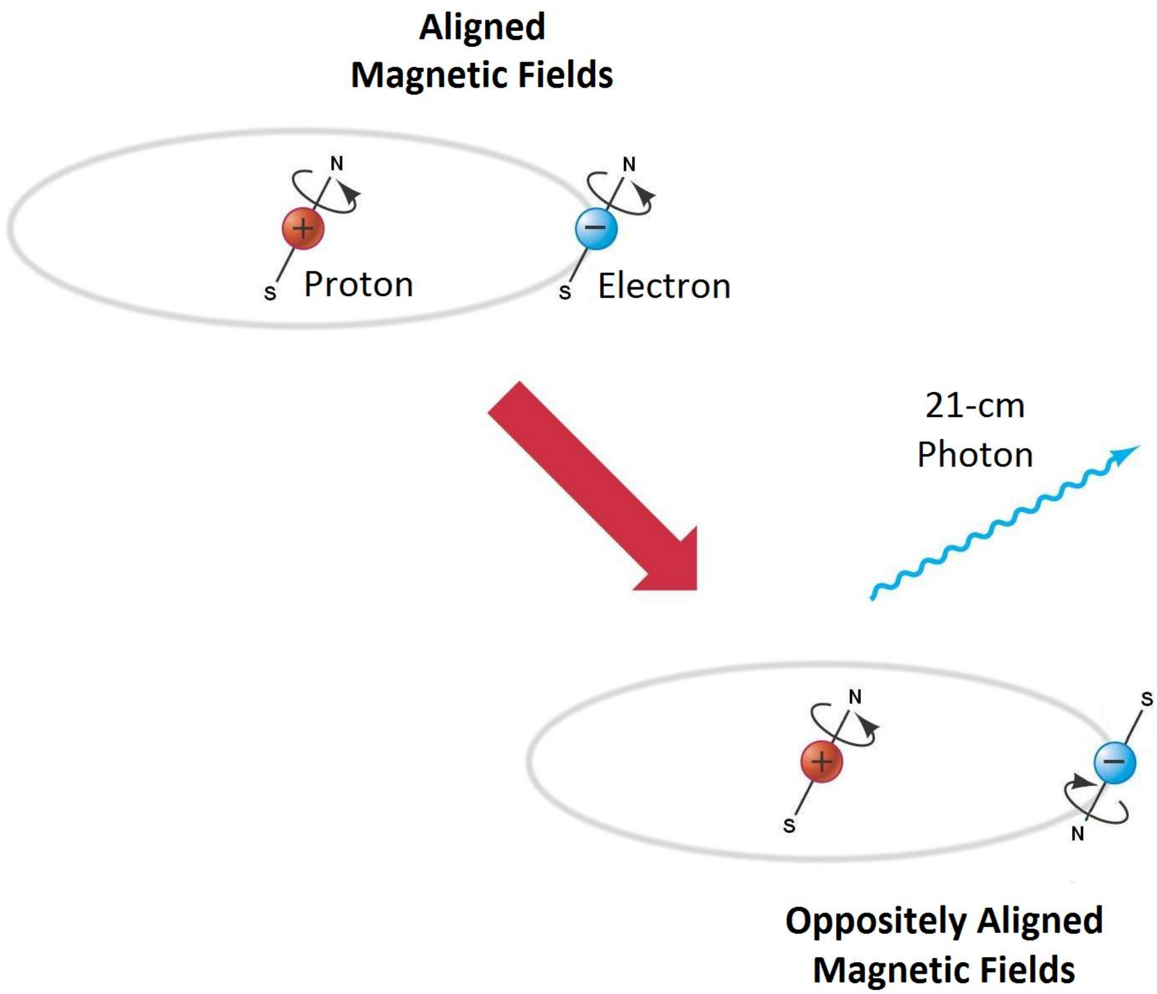
If we want to measure Doppler shifts of matter orbiting our galaxy, we must look in the plane of our galaxy. However, dust blocks visible light in the plane of our galaxy:

(Photo Credit: Digital Sky, LLC)

Consequently, we must observe at a different wavelength.

Radio waves penetrate dust as if it were not even there. Furthermore, our galaxy consists primarily of cold hydrogen gas, and cold hydrogen gas emits light at 21 cm, a radio wavelength.

Cold hydrogen gas consists of a proton and an electron in the ground state. Because both particles are charged and spinning, they have magnetic fields along their rotation axes. Like bar magnets, it takes more energy to keep them together if their magnetic fields are aligned than if they are oppositely aligned. If a hydrogen atom is in the aligned state, after an average timescale of 11 million years, it will randomly de-excite to the oppositely aligned state, releasing the small difference in energy as a 21 cm photon:



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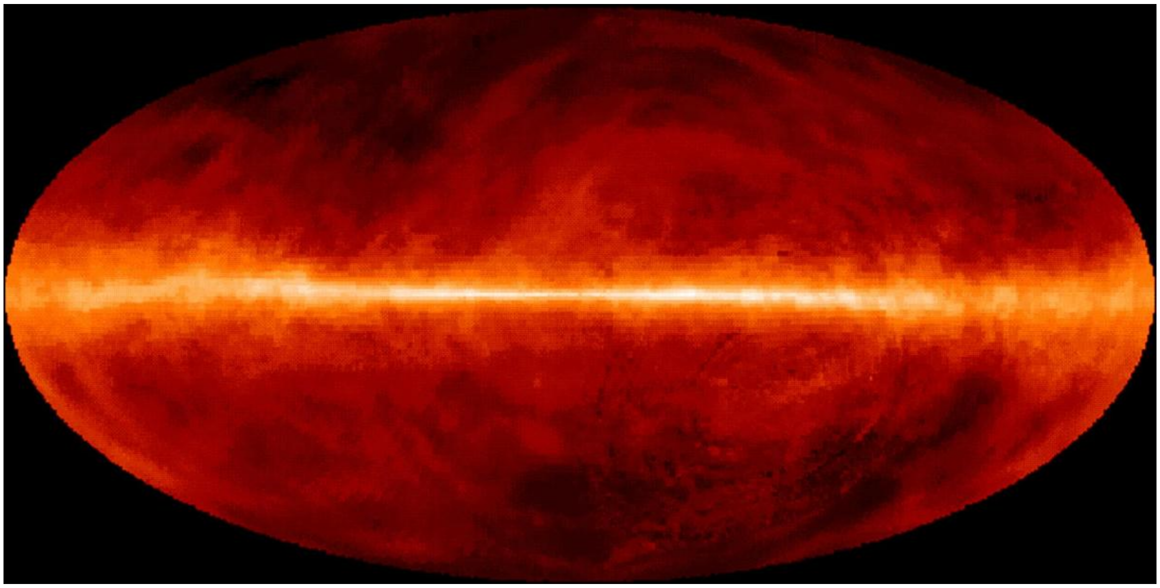
Although this is a rare occurrence, cold hydrogen gas is so abundant in our galaxy that this results in a strong signal, making the plane of our galaxy glow at this radio wavelength:

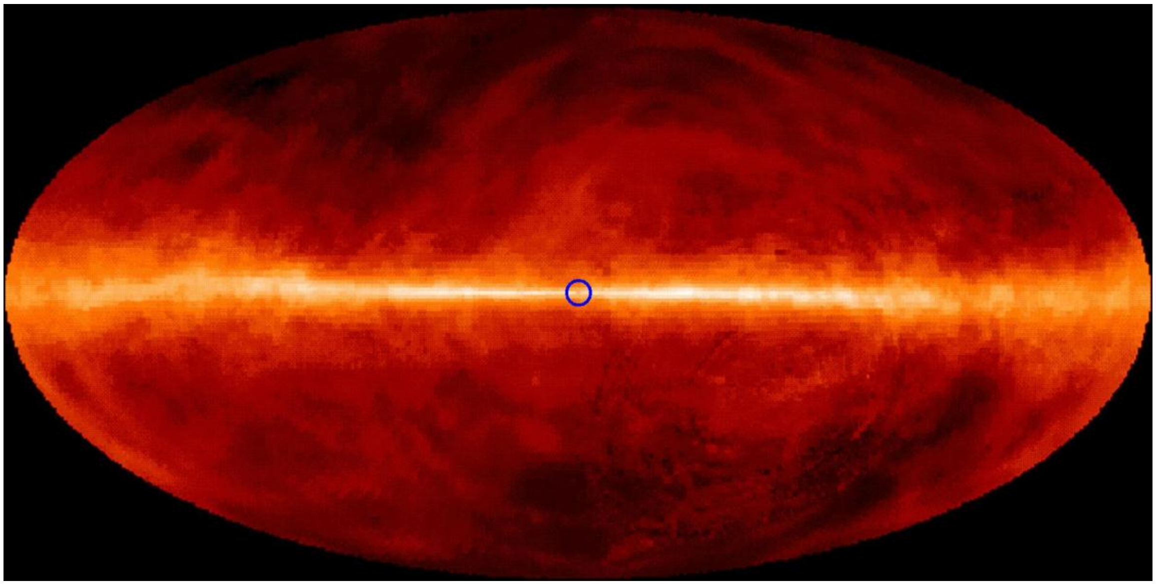


(Photo Credit: Leiden/Dwingeloo Survey of Galactic Neutral Hydrogen)

C. ROTATION CURVE

C.1. Radio Spectra

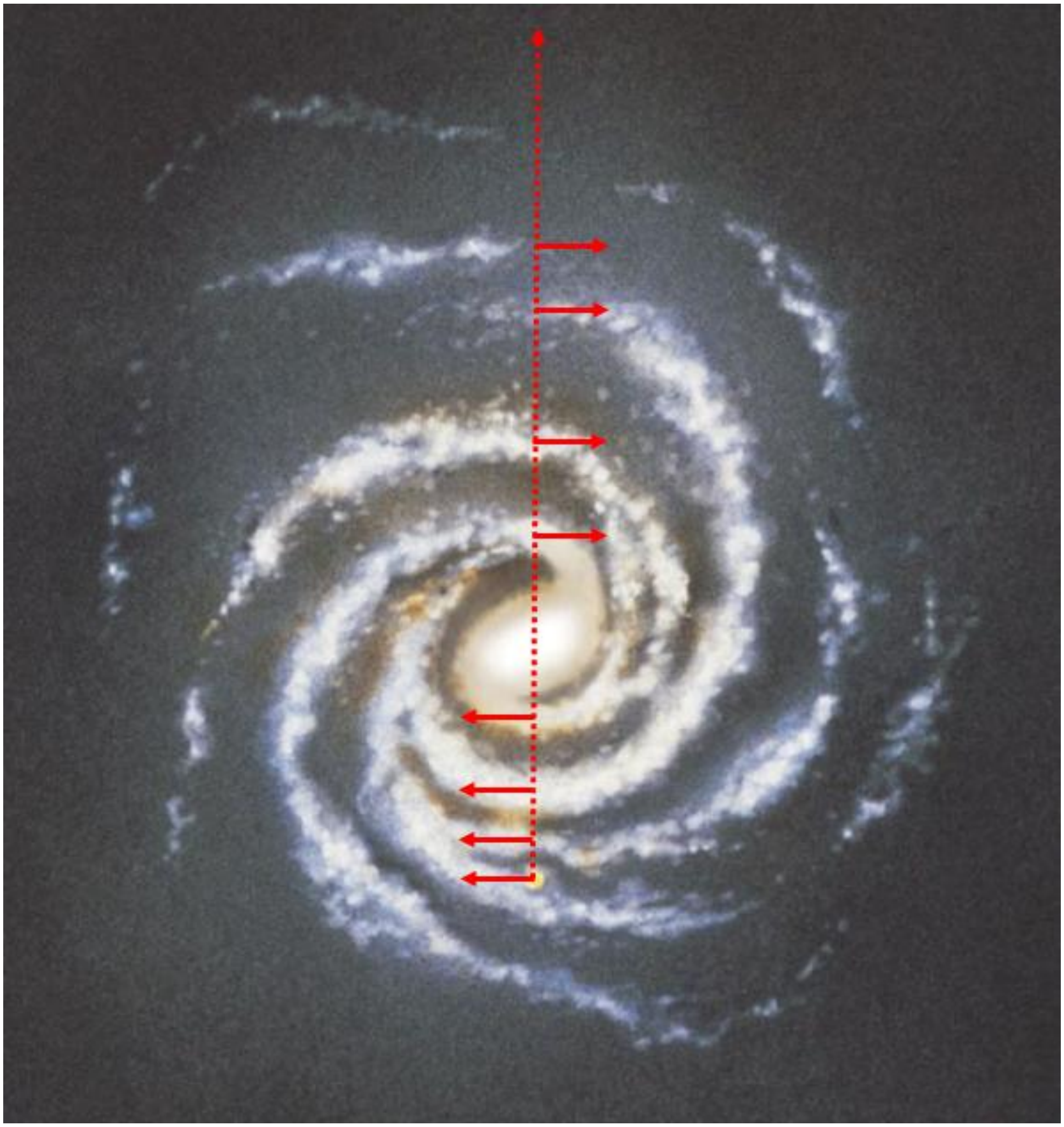
Consider taking a radio spectrum of the center of our galaxy:



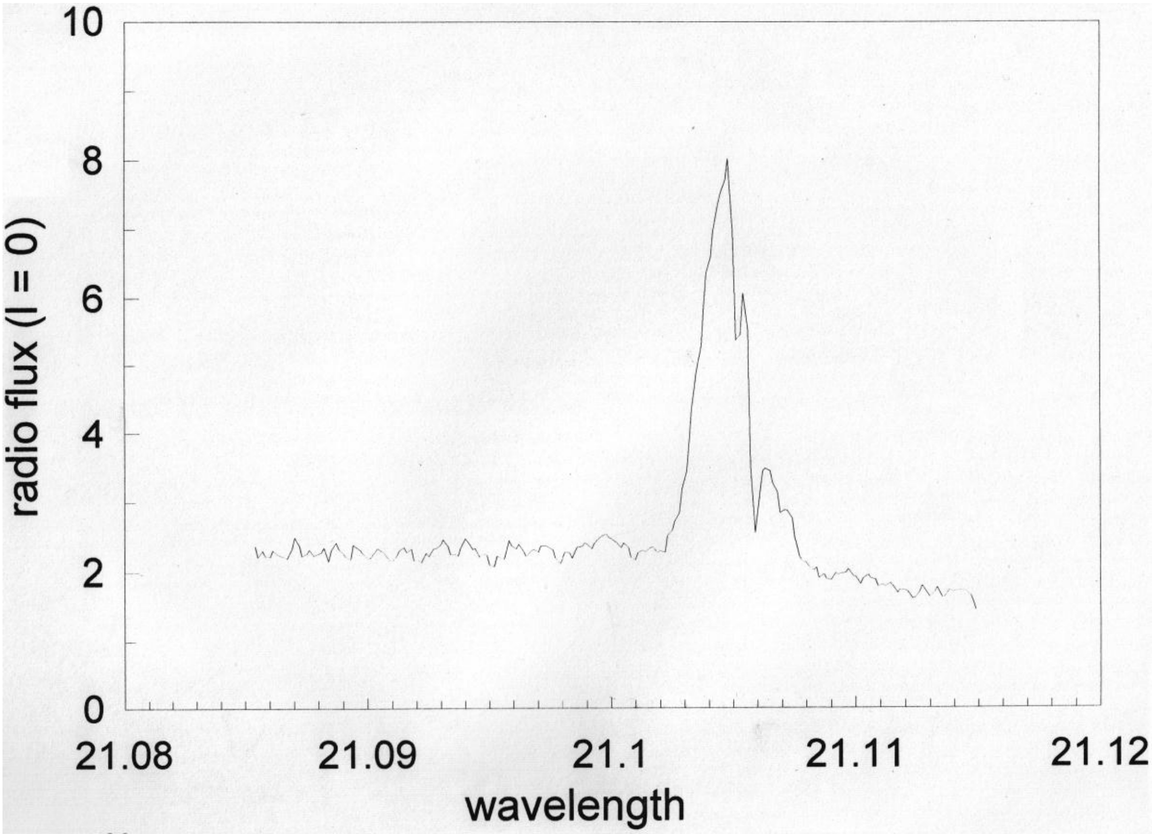
(Photo Credit: Leiden/Dwingeloo Survey of Galactic Neutral Hydrogen)

What would it look like around 21 cm?

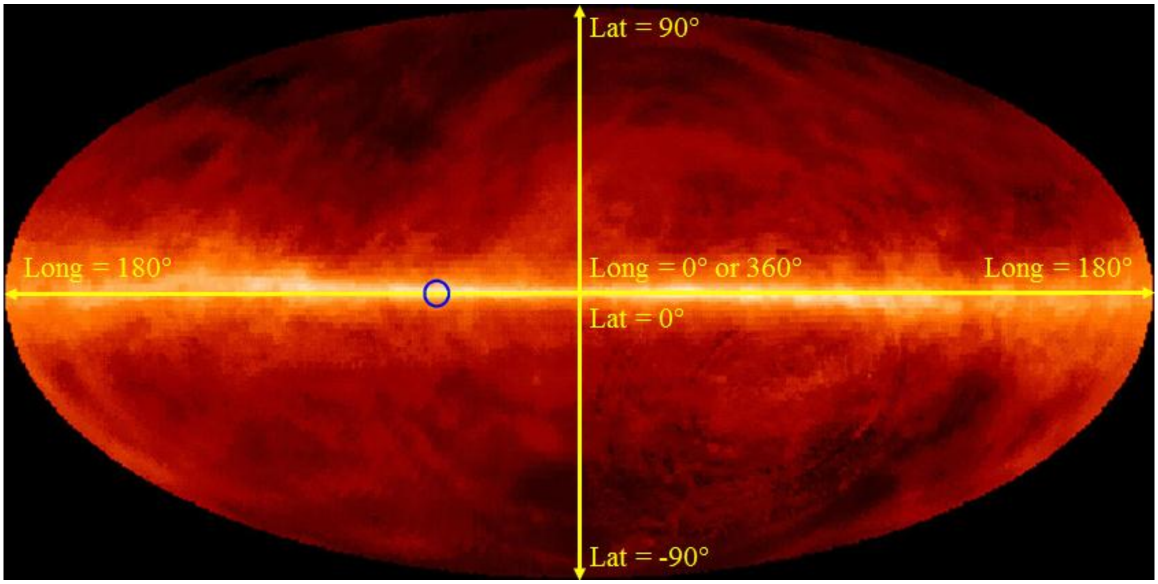
To figure this out, consider the following figure, which shows what our galaxy might look like face on. Our location is marked by the yellow dot near the bottom of the figure. The dotted line marks the line of sight from us to (and through) the center of our galaxy:



Notice that the line of sight intersects spiral arms of our galaxy, and hence cold hydrogen gas, at many points. However, at all of these points, the gas is orbiting our galaxy neither toward us nor away from us, but perpendicular to the line of sight. Consequently, the 21-cm light that this gas is emitting is neither blueshifted nor redshifted. The radio spectrum should simply consist of a single emission line with $\lambda_{obs} = \lambda_{em}$:

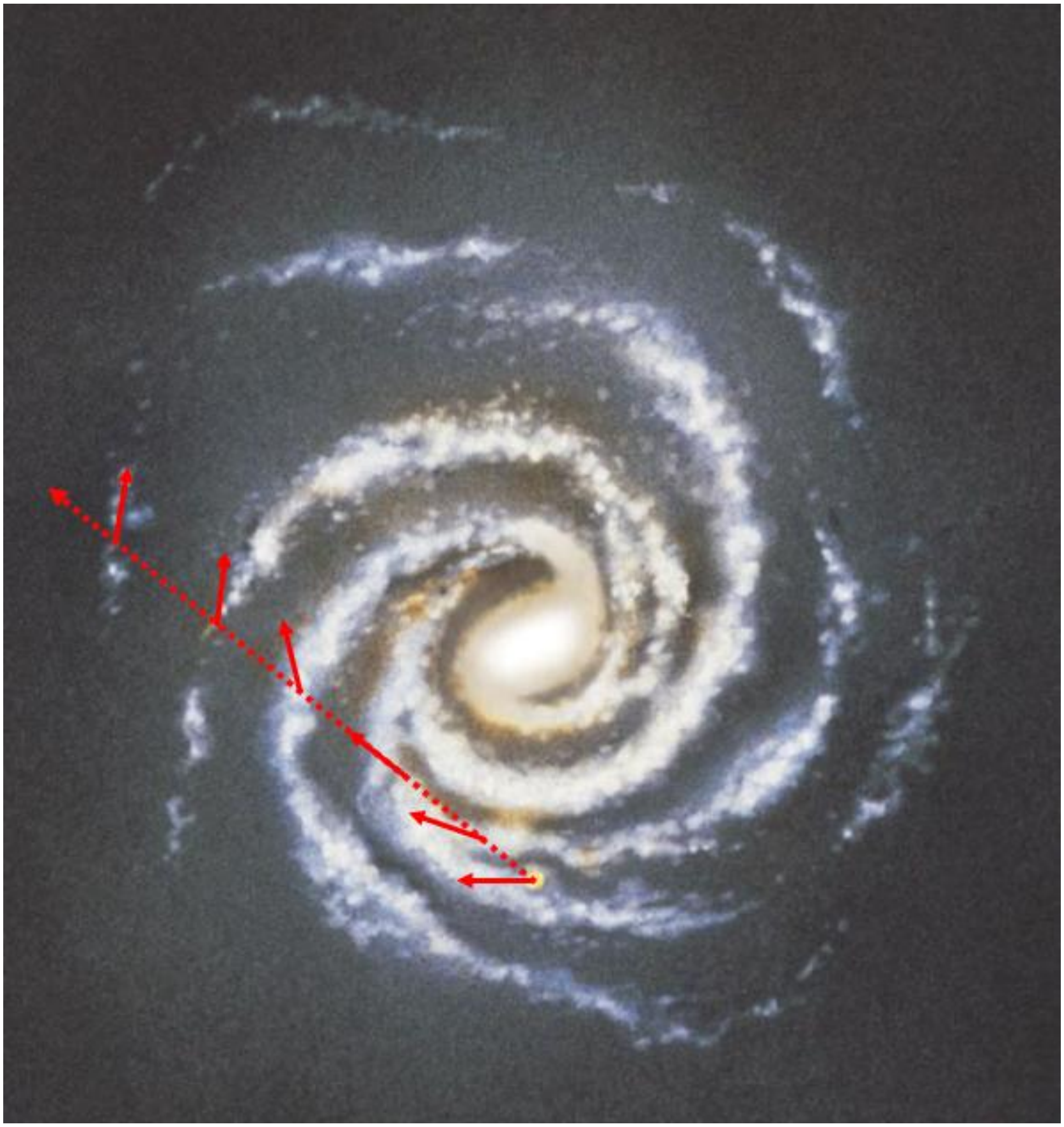


Now consider taking a radio spectrum not of the center of our galaxy, but at a greater Galactic longitude (see Lab 6):

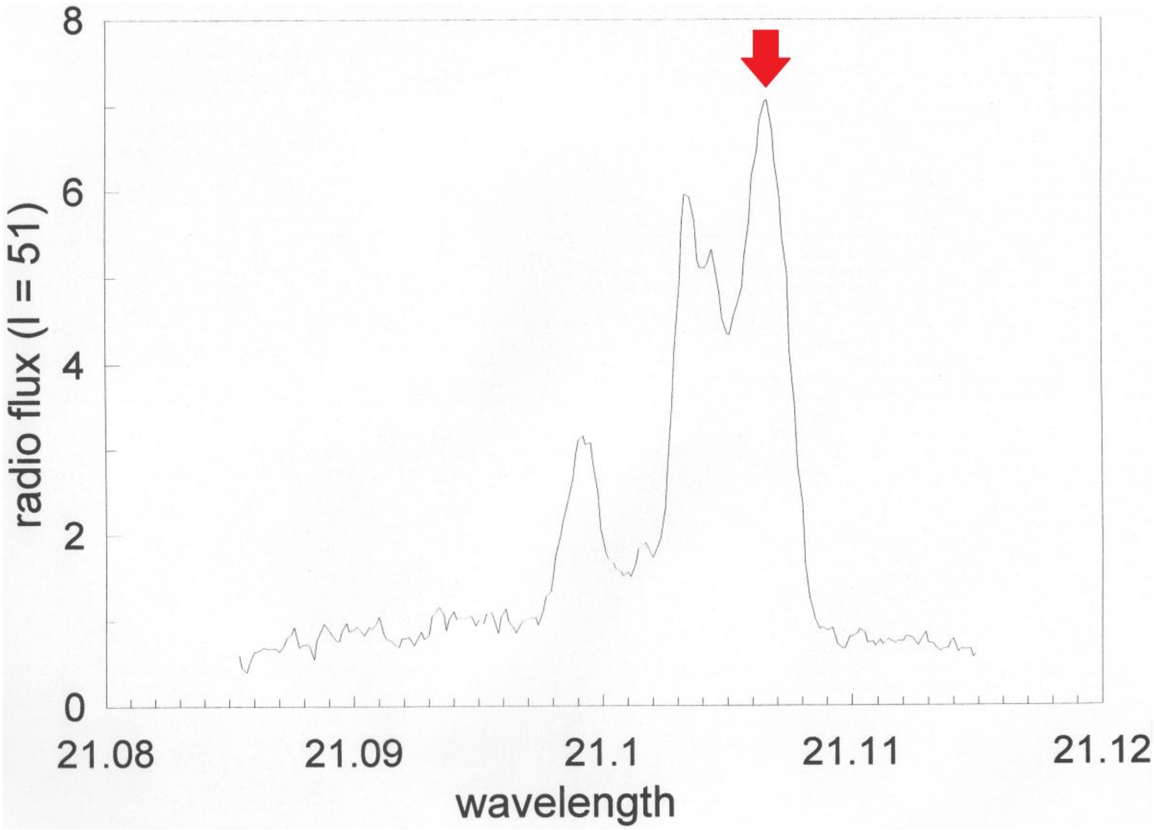


(Photo Credit: Leiden/Dwingeloo Survey of Galactic Neutral Hydrogen)

In this case, the line of sight intersects spiral arms, and hence cold hydrogen gas, at different points. Furthermore, these regions of gas are orbiting our galaxy not perpendicular to the line of sight, but each with a different component of its speed along the line of sight:



Consequently, the 21-cm light that these regions of gas are emitting should be Doppler shifted each by a different amount, resulting in a more complicated spectrum:



However, one of these regions of gas is special, because its motion is neither to the left nor to the right of the line of sight, but along the line of sight. Consequently, the 21-cm light that this region of gas is emitting should be more redshifted than that of any other region along this line of site. This most-redshifted emission is marked by the red arrow in the above spectrum.

C.2. Measuring Radial Distances and Orbital Speeds

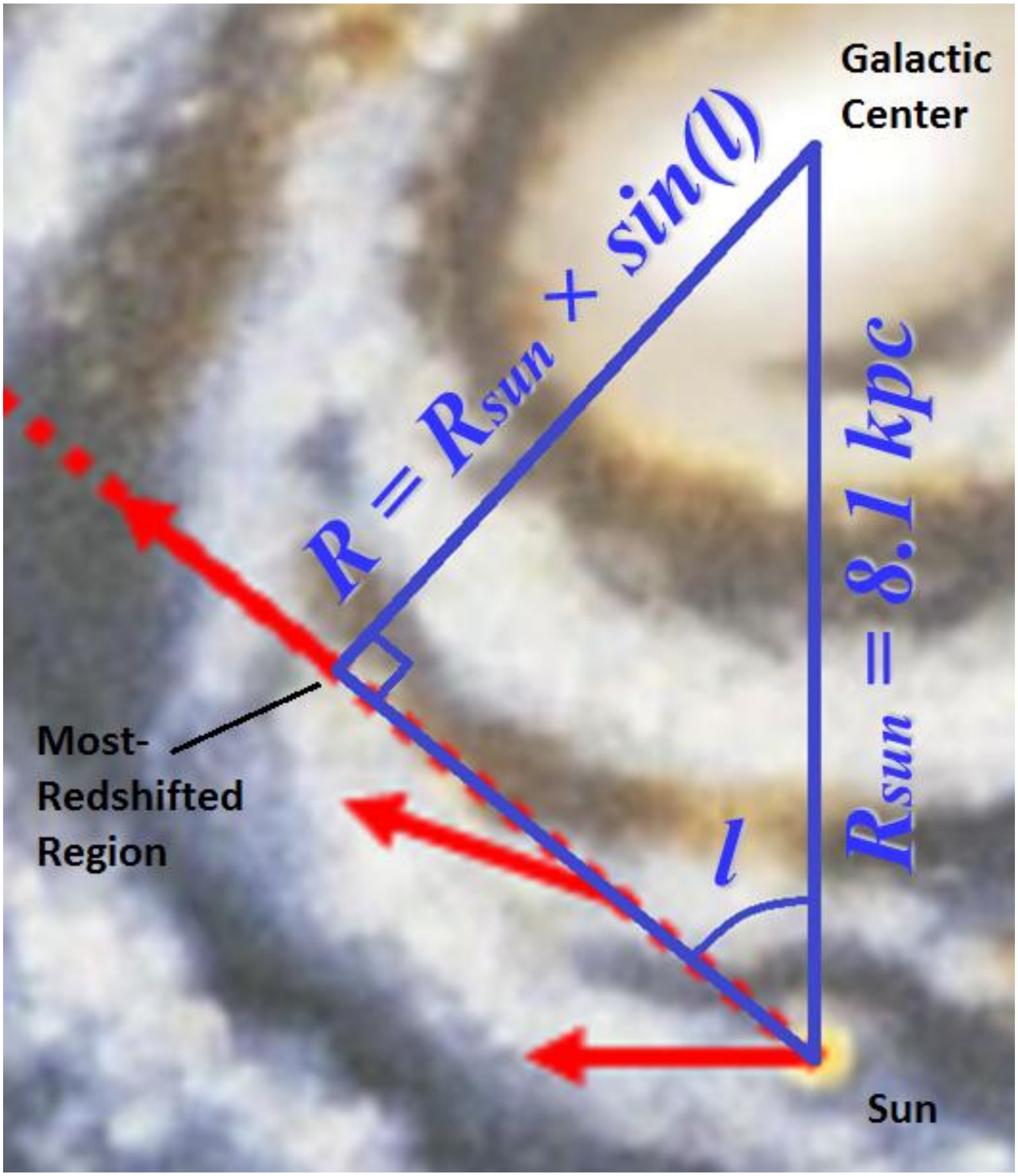
The most-redshifted region of gas along any line of sight is special because both (1) its distance from the center of our galaxy **R** and (2) its orbital speed around our galaxy **V** can be easily calculated.

By calculating R and V for many lines of sight (i.e., for many Galactic longitudes), we can determine how the speed at which our galaxy rotates changes with distance from its center. This is called our galaxy's **rotation curve**.

With our galaxy's rotation curve, we can then determine how much mass must be present within any radius R to make our galaxy rotate at speed V at this radius. I.e., we can "weigh" our galaxy out to any radius R!

1. Measuring Radial Distances

First, consider a single line of sight. The most-redshifted region's distance from the center of our galaxy R can be calculated from (1) our distance from the center of our galaxy $\mathbf{R_{sun}}$ = 8.1 kpc, which we measured in Lab 6, and (2) the Galactic longitude **l** at which the spectrum was taken:



Note: When using this equation, with l measured in degrees, your calculator must be in degrees mode, not radians mode.

2. Measuring Orbital Speeds

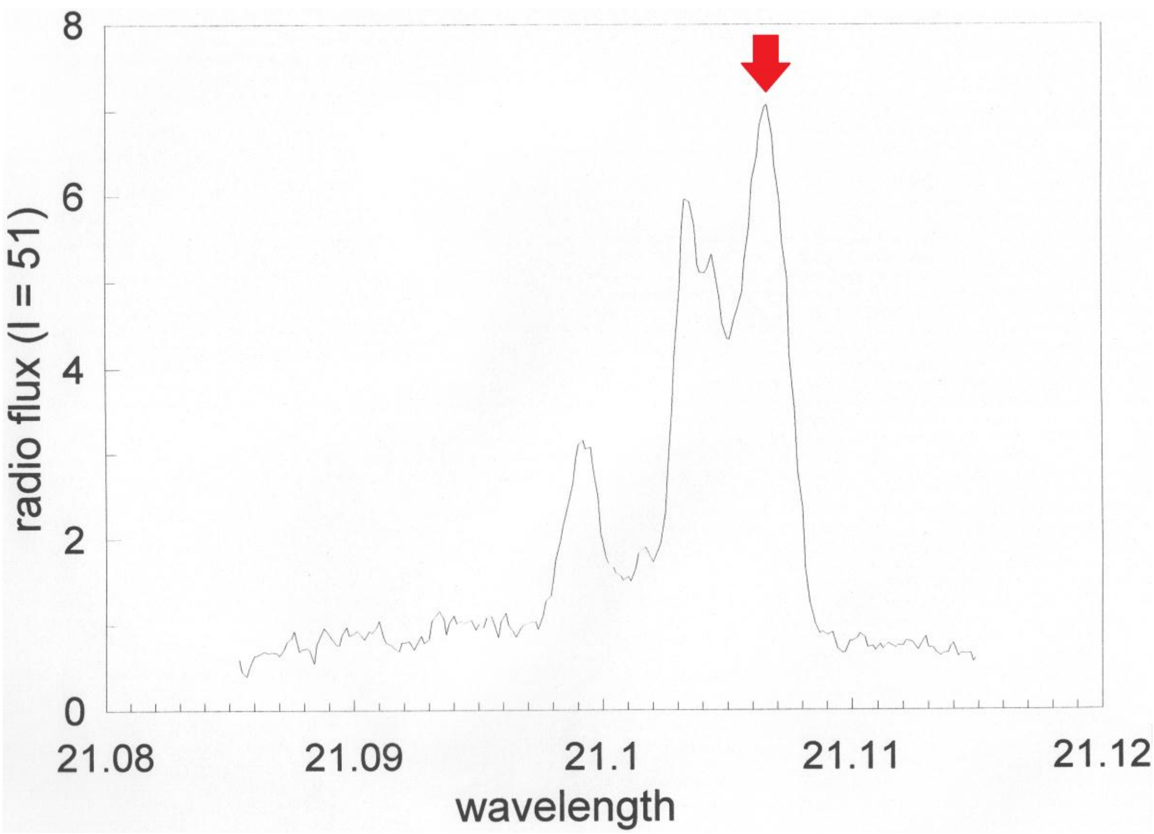
The most-redshifted region's orbital speed around our galaxy is the same as the component of its speed along the line of sight V. The *difference* between V and the component of *our* speed along the line of sight is given by the Doppler effect equation from Section A, here solved for ΔV:

$$\mathbf{\Delta V = c \times \Delta\lambda / \lambda_{em}}$$

where

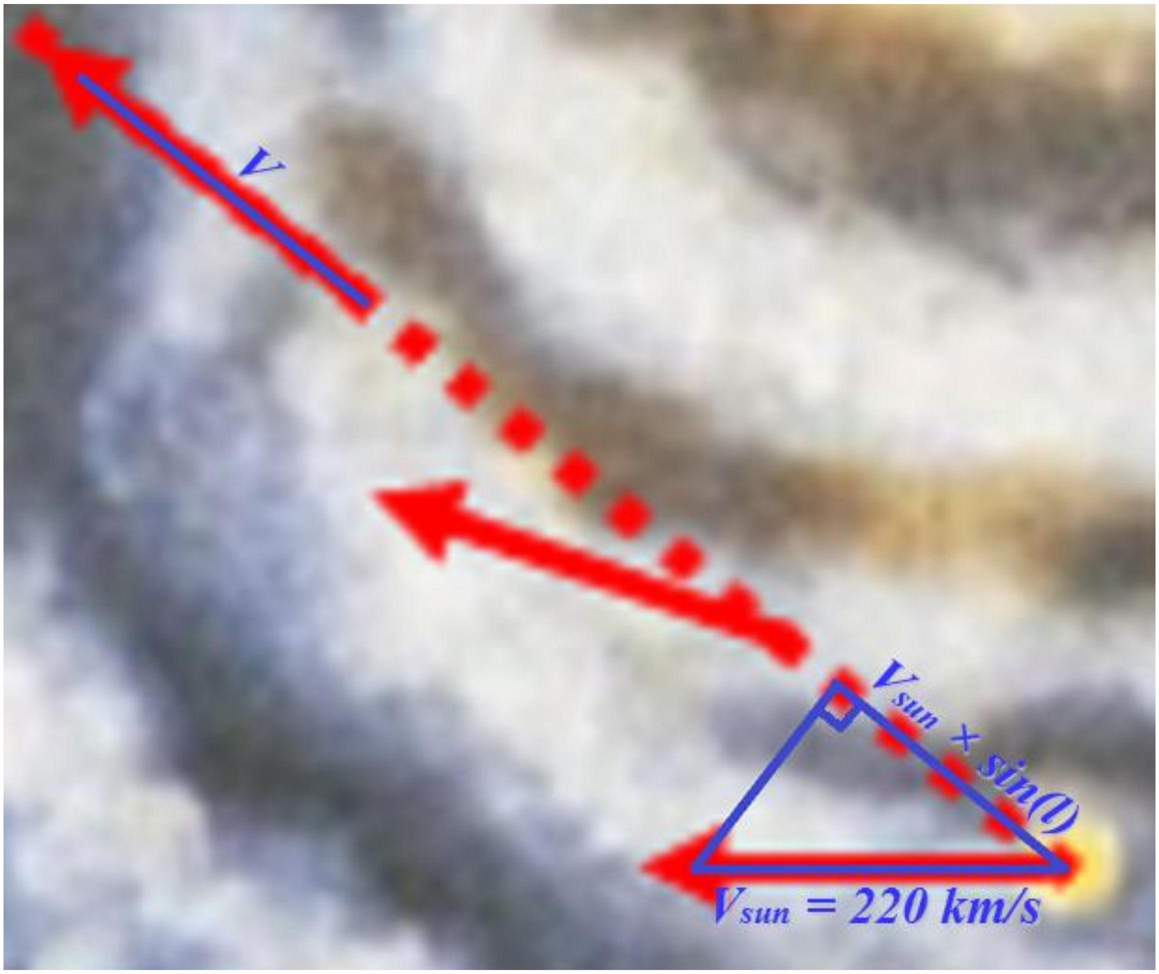
$$\mathbf{\Delta\lambda = \lambda_{obs} - \lambda_{em}}$$

and λ_{obs} is the wavelength of the most-redshifted component of the spectrum:



and λ_{em} = 21.106 cm is the precise wavelength at which cold hydrogen gas emits.

The component of *our* speed along the line of sight can be calculated from (1) our orbital speed around our galaxy $\mathbf{V_{sun}}$ = 220 km/s, which has been measured with respect to other galaxies in all directions around us, and (2) the Galactic longitude l at which the spectrum was taken:



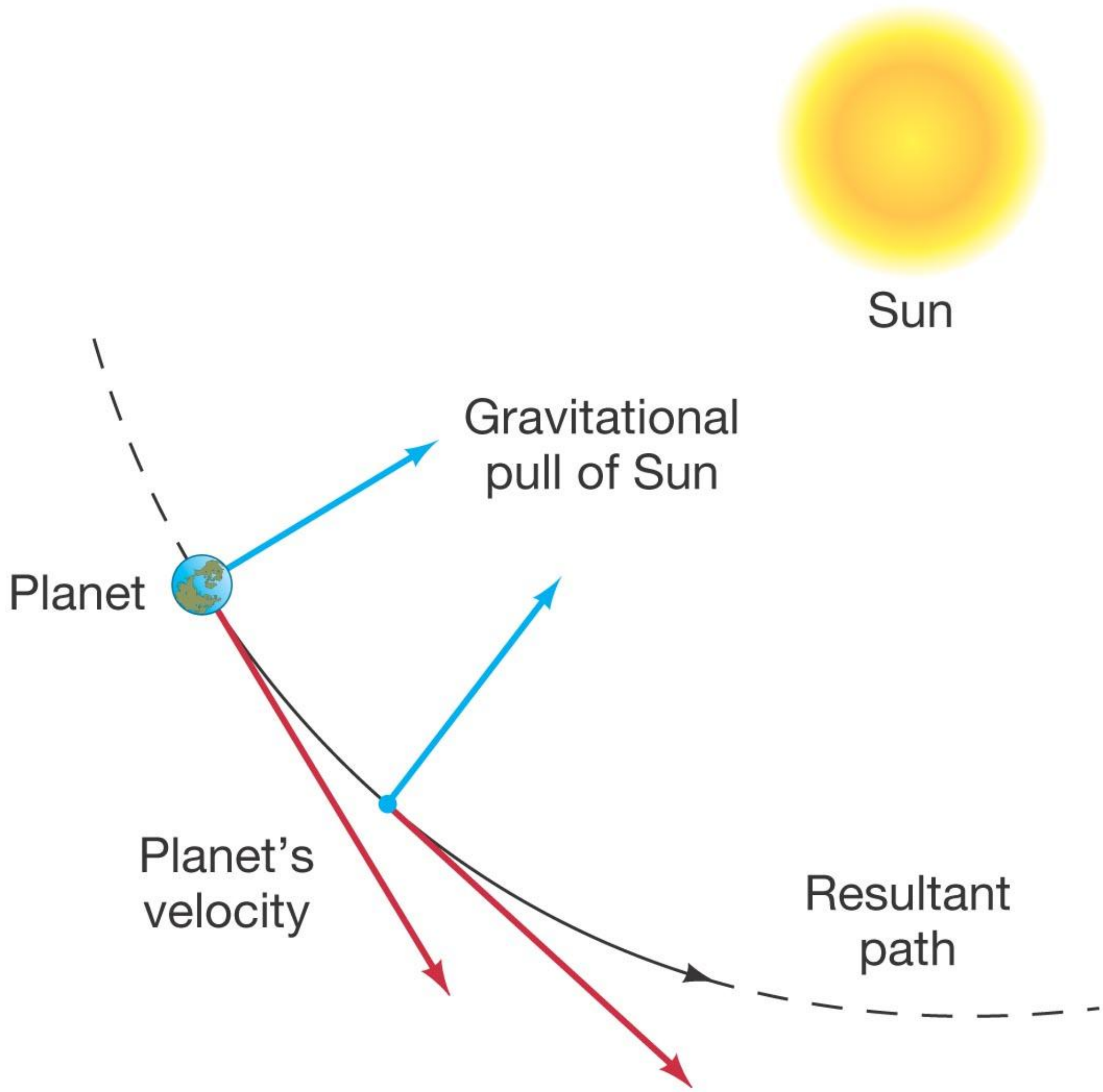
Consequently, the most-redshifted region's orbital speed around our galaxy is given by:

$$\mathbf{V = \Delta V + [V_{sun} \times sin(l)]}$$

By taking spectra at many Galactic longitudes (Section A of the procedure) and calculating R and V of the most-redshifted region of gas from each spectrum (Section B of the procedure), you will measure how the speed at which our galaxy rotates changes with distance from its center: our galaxy's rotation curve.

D. RADIAL MASS DISTRIBUTION

Consider Earth orbiting the sun. It is currently at distance R and moving at speed V. If the sun suddenly had no mass, Earth would continue along its current trajectory, leaving the sun. If the sun suddenly had infinite mass, it would deflect Earth's trajectory into the sun. Consequently, the sun must have just the right amount of mass to constantly deflect Earth's trajectory into its near-circular orbit:



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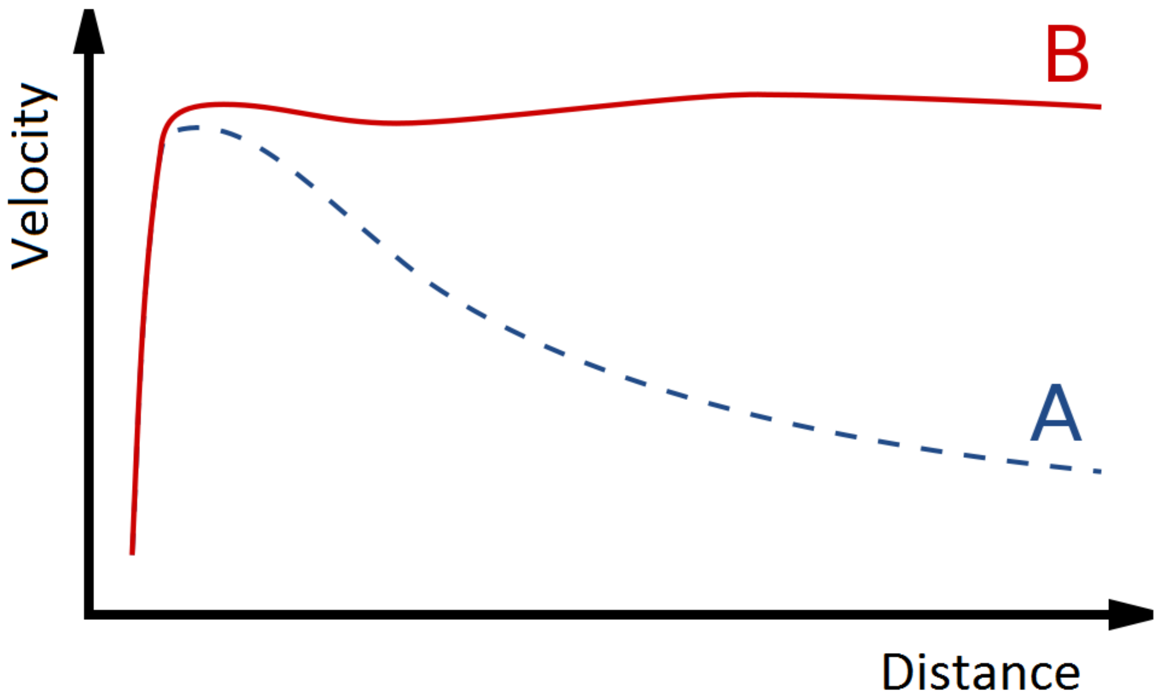
The amount of mass required to keep an object that is moving at speed V in a circular orbit of radius R is:

$M(<R) = V^2R / G$

where M(<R) is the total mass within radius R. In the case of the solar system, nearly all of the mass is concentrated at the center, in the sun. Hence, $M(<R) \approx M_{sun}$ for any R. Solving for V yields:

$V = [GM_{sun} / R]^{1/2}$

Consequently, V decreases as R increases. E.g., Mercury moves quickly but Neptune moves slowly. This is called a **Keplerian rotation curve** and is depicted as curve A below:



(Image Credit: Phil Hibbs)

Now consider galaxies. If most of the mass is concentrated at or near the center, galaxies should also have Keplerian rotation curves. But if the mass is spread throughout the disk, M(<R) will increase with R, in which case:

$$V = [GM(<R) / R]^{1/2}$$

If M(<R) increases in proportion to R, they cancel out and V is approximately constant. This is called a **flat rotation curve** and is depicted as curve B above.

By measuring our galaxy's rotation curve, you can determine whether its mass is concentrated at or near its center or is spread throughout its disk. You can also use the first equation of this section to calculate how much mass must be contained within any radius M(<R) to make the matter at that radius orbit in a circular (or near-circular) orbit. I.e., you can "weigh" our galaxy out to any radius R!

PROCEDURE

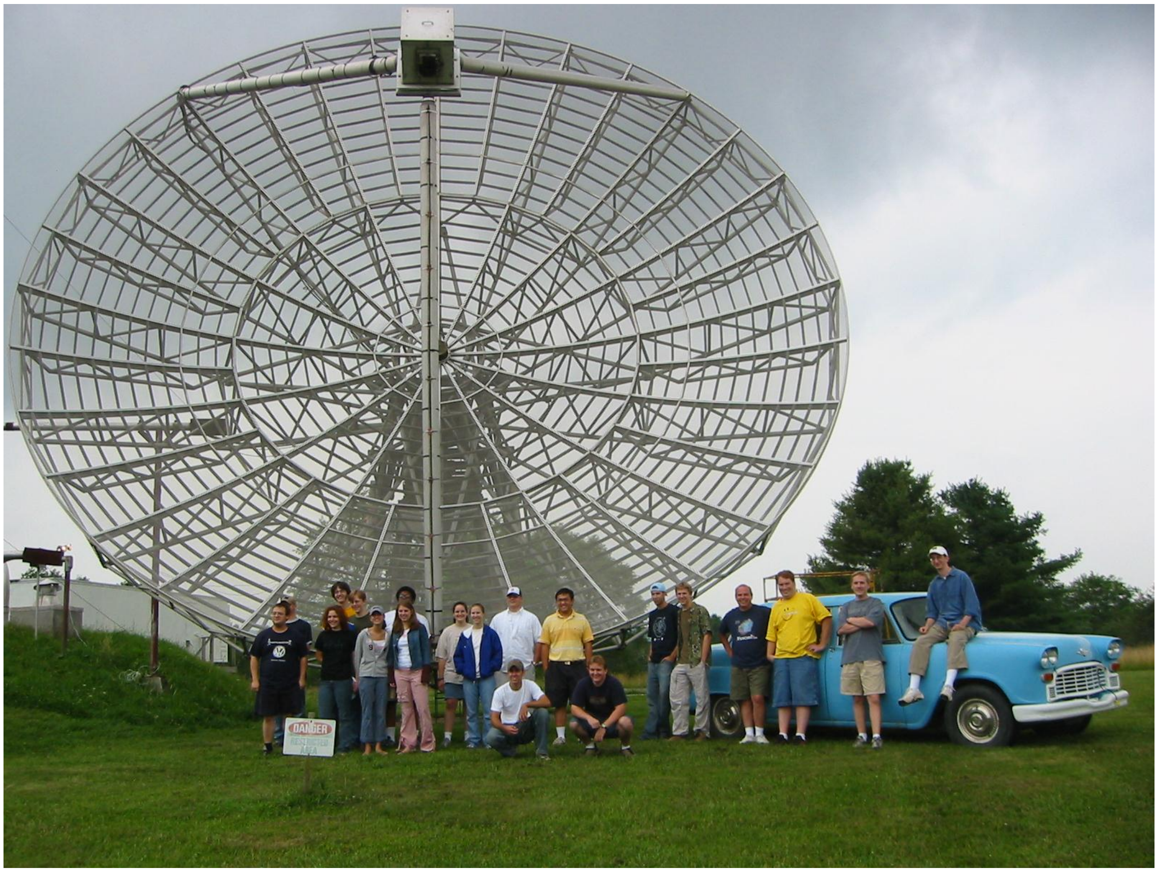
A. RADIO SKYNET

Funded by the American Recovery and Reinvestment Act through the National Science Foundation, Skynet is expanding to control not only visible-light telescopes like PROMPT, but also near-infrared and radio telescopes. In collaboration with the National Radio Astronomy Observatory (NRAO) in Green Bank, WV, our first radio telescope will be their 20-meter diameter telescope:

(Photo Credit: Bill Saxton/NRAO)

Twice the diameter of the world's largest visible-light telescope, this telescope, once refurbished, will be available for use through Skynet's web page and will be as easy to use as Skynet's visible-light telescopes. Furthermore, one of its capabilities will be 21-cm spectroscopy.

However, this project has just gotten underway. Until then, we will use radio spectra that students have acquired with NRAO-Green Bank's 40-foot (12-meter) diameter telescope:

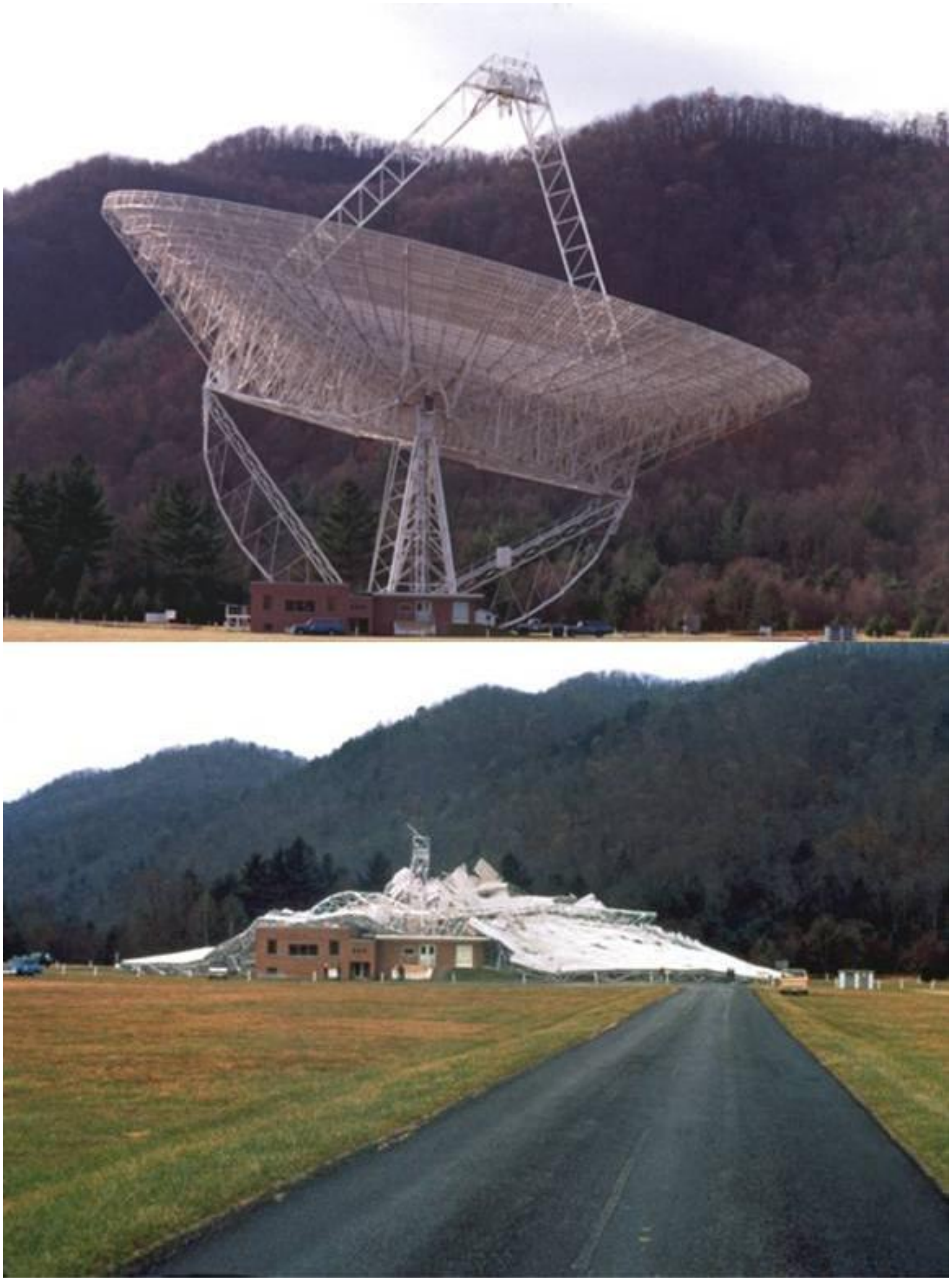


Each summer, we take 15 students from across the country on a 1-week trip to NRAO-Green Bank, where they use this telescope and learn radio astronomy. If interested in applying, you can find more information here:

http://www.physics.unc.edu/~reichart/erira.html

Their spectra are linked in Table 1 of Section B.

Although small for a radio telescope, NRAO-Green Bank's 40-foot diameter telescope has a nice 21-cm spectrograph. It was the 21-cm spectrograph of NRAO-Green Bank's 300-foot (91-meter) diameter telescope before it collapsed in 1988:



(Photo Credit: NRAO)

B. ROTATION CURVE

Use the radio spectra obtained with NRAO-Green Bank's 40-foot diameter radio telescope to measure the rotation curve of our galaxy:

1. For each Galactic longitude in Column 1 of Data Table 1 below, click on the link to the corresponding radio spectrum and estimate λ_{obs} of the most-redshifted region. Record this value to the nearest 0.001 cm in Column 2.

2. Using equations from Background Section C.2, calculate ΔV. Use λ_{em} = 21.106 cm and c = 3.00×10^5 km/s. Record this to the nearest 1 km/s in Column 3.

3. Calculate the component of *our* speed along each line of sight $V_{sun} \times \sin(l)$. Use V_{sun} = 220 km/s. Note: Your calculator must be in degrees mode. Record this to the nearest 1 km/s in Column 4.

4. Using equations from Background Section C.2, calculate V. Record this to the nearest 1 km/s in Column 5.

5. Using equations from Background Section C.2, calculate R. Use R_{sun} = 8.1 kpc. Note: Your calculator must be in degrees mode. Record this to the nearest 0.1 kpc in Column 6.

Data Table 1: Orbital Speeds and Radial Distances (18 points)

l (degrees)	λ_{obs} (cm)	ΔV (km/s)	$V_{sun} \times \sin(l)$ (km/s)	V (km/s)	R (kpc)
0					
3					
6					
21					
24					
27					
39					
45					
51					
60					
63					
69					
72					
75					
78					
81					
84					

Present your calculation for ΔV for the l = 84º line of sight. (3 points)

Present your calculation for $V_{sun} \times \sin(l)$ for the l = 84º line of sight. (2 points)

Present your calculation for V for the l = 84º line of sight. (3 points)

Present your calculation for R for the l = 84º line of sight. (3 points)

Go to:

http://skynet.unc.edu/ASTR101L/graph/

Make a graph of V vs. R. Save your final graph as a png file.

Upload your final png graph here (5 points):

Is our galaxy's rotation curve more consistent with a Keplerian or a flat rotation curve? (2 points)

A. **Keplerian**
B. **Flat**

Is our galaxy's mass concentrated at/near its center or spread throughout its disk? (2 points)

A. **Concentrated at/near center**
B. **Spread throughout disk**

Discuss significant sources of error. (2 points)

C. ENCLOSED MASS

For each radius R in Data Table 1, use the first equation from Background Section D to calculate the mass enclosed within this radius M(<R) in billions of solar masses (10^9 M_{sun}). Use V in km/s, R in kpc, and G = 4302 $(km/s)^2 \times kpc / (10^9 M_{sun})$. Record this value to the nearest 0.1 billion solar masses in Data Table 2 below.

Data Table 2: Enclosed Mass (5.1 points)

l (degrees)	M(<R) (10^9 M_{sun})
0	
3	
6	
21	
24	
27	
39	
45	
51	
60	
63	
69	
72	
75	
78	
81	
84	

Present your calculation for M(<R) for the l = 84º line of sight. (3 points)

Orbiting beyond the visible-light edge of our galaxy (to the right in the image below) are two dwarf galaxies called the Large and Small Magellanic Clouds (to the left in the image below):

(Photo Credit: CTIO/NOAO)

Their orbital speeds and radial distances have been measured by other means and are listed in Data Table 3 below. As above, calculate the mass enclosed within these radii M(<R) in billions of solar masses. Record these values to the nearest 0.1 billion solar masses in Data Table 3 below.

Data Table 3: Enclosed Mass (0.9 points)

Object	**V (km/s)**	**R (kpc)**	**M(<R) (10^9 M_{sun})**
LMC	265	48.5	
SMC	253	61	

Go to:

http://skynet.unc.edu/ASTR101L/graph/

Using the radii and enclosed masses in both Data Table 2 and Data Table 3, make a graph of M(<R) vs. R. Save your final graph as a png file.

Upload your final png graph here (5 points):

Using your graph, estimate the mass of our galaxy within the sun's radius R = 8.1 kpc? (2 points)

As we measured in Lab 6, our galaxy is about 34 kpc in diameter, so it is about 17 kpc in radius. Using your graph, estimate the mass of our galaxy within its visible-light radius R = 17 kpc? (2 points)

Using your graph, estimate the mass of our galaxy within R = 61 kpc, the radius at which the Small Magellanic Cloud orbits? (2 points)

Consequently, how much mass is between R = 17 kpc and R = 61 kpc? (2 points)

Is the mass outside the visible part of our galaxy less or more than the mass inside the visible part of our galaxy? (2 points)

A. **Less**
B. **More**

The masses of the Large and Small Magellanic Clouds are negligible in comparison (only 10 and 7 billion solar masses, respectively). Within 61 kpc, is our galaxy more visible matter, like stars and gas, or more dark matter? (2 points)

A. **Visible**
B. **Dark**

Research and discuss dark matter. (3 points)