Reconstructing the Milky Way with the 21 cm Hydrogen Line

Instructor Version

Introduction

Neutral hydrogen gas is found throughout the Milky Way and naturally emits radio waves at a wavelength of approximately 21 cm. Because of its long wavelength, this radiation can travel through the interstellar dust that blocks much of our view at visible wavelengths, allowing astronomers to trace hydrogen gas across the Galaxy. In this lab, you will use 21 cm observations to study how hydrogen is distributed and how it moves through the Milky Way. You will begin by learning to recognize the hydrogen line and interpret Doppler shifts in radio spectra. You will then compare observations across the Milky Way to investigate where neutral hydrogen is most strongly concentrated, and what it can tell us about the structure and dynamics of our home galaxy.

Part 1: The 21 cm Hydrogen Line

Recognizing the 21 cm Line

Hydrogen is the simplest and most abundant element in the universe, making up ∼90% of all atoms. Neutral hydrogen, composed of one proton and one electron bound together, naturally emits radio waves at a wavelength of ∼21 centimeters.

Protons and electrons have a fundamental property called **spin**, an intrinsic quantum property that behaves like angular momentum. In a neutral hydrogen atom, the spins of the proton and electron can be in one of two possible states: **aligned** or **anti-aligned**, Figure 1. When the spins are in the anti-aligned state, the hydrogen has slightly less energy than the aligned state, thus it is a more stable configuration. A hydrogen atom in the aligned state will eventually flip its spin to the anti-aligned state, called a spin-flip transition, releasing the difference in energy as a photon. The energy difference between the aligned and anti-aligned states is very small, so the emitted photon has a very long wavelength of ∼**21 cm**, corresponding to a frequency of ∼**1420 MHz**. Although this spin-flip transition is rare for a single atom (mean transition time of ∼11 million years), the enormous population of neutral hydrogen atoms in the universe makes the 21 cm line strong enough to be easily detected with radio telescopes.

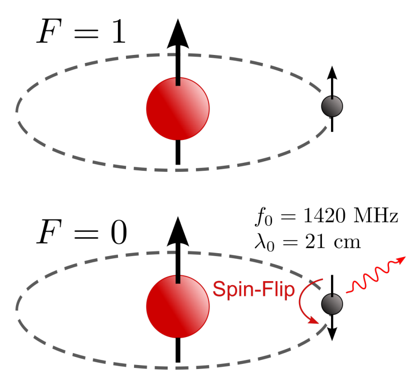


Figure 1: A neutral hydrogen atom undergoing a spin-flip transition, releasing a photon with a wavelength of ∼21 cm and frequency of ∼1420 MHz.

The 21 cm line is especially useful in astronomy because these long-wavelength photons can travel through the interstellar and intergalactic dust that blocks much of our view in visible light. This makes the 21 cm line a powerful tool for studying the structure and dynamics of the Milky Way, providing evidence for dark matter, probing the structure of other galaxies, and studying the evolution of the universe as a whole.

For each statement below, decide whether it is true or false. Justify your answer in 1-2 sentences.

1. Because the 21 cm transition is very rare for any one hydrogen atom, it's not useful for astronomy.

   False. A single neutral hydrogen atom undergoes the spin-flip transition very rarely, but the Milky Way contains an enormous number of neutral hydrogen atoms. Taken together, they produce enough 21 cm emission to be detected and used to trace the large-scale distribution of gas in the Galaxy.

2. Visible light observations alone would be just as effective as 21 cm observations for mapping the hydrogen gas across the Milky Way.

   False. Visible light is strongly blocked by interstellar dust, especially along the Galactic plane. The 21 cm line is much more effective for mapping hydrogen because radio waves at this wavelength can pass through that dust and reveal regions of the Galaxy that are hidden in visible light.

3. Even though the 21 cm photon comes from a tiny energy difference, it can still reveal large-scale structure in the Milky Way.

   True. The energy difference between the aligned and anti-aligned spin states is very small, but the resulting 21 cm emission is still extremely useful because neutral hydrogen is so abundant. That lets astronomers use the line to study the large-scale structure and dynamics of the Milky Way.

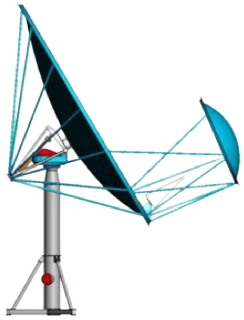
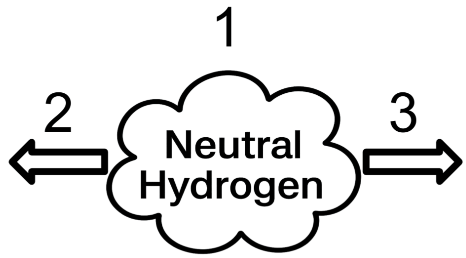
Doppler Shifts and Radial Motion

When a source of waves moves towards or away from an observer, the observed frequency will change. This is called the **Doppler effect**. If the source is not moving towards or away from the observer, the observed frequency stays at its rest value.

- Motion toward the observer shifts the signal to a higher frequency, called a **blueshift**
- Motion away from the observer shifts it to a lower frequency, called a **redshift**.

For the 21 cm line, the rest frequency is 1420.40575 MHz. This is the frequency we would observe if a cloud of hydrogen gas had no motion toward or away from us. If the cloud is moving toward us, the line is shifted to a higher frequency. If the cloud is moving away from us, the line is shifted to a lower frequency. In astronomy, this kind of toward-or-away motion is called **radial motion**. A gas cloud may be moving through space in many directions at once, but the Doppler shift only tells us about the part of its motion that lies along our line of sight.

Below are three simple hydrogen cloud scenarios and three example spectra. On the next page, **match each cloud to the spectrum you think it would produce and explain your reasoning.**

Scenario 1 → Spectrum B

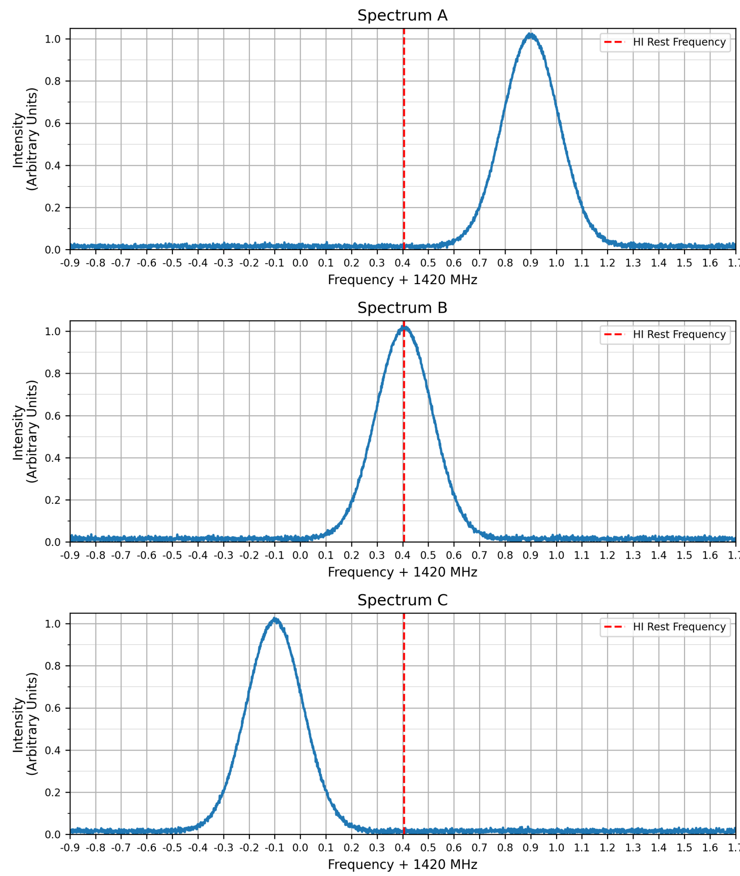
Reason:
No radial velocity → rest frequency

Scenario 2 → Spectrum A

Reason:
Motion towards → blueshift → higher frequency

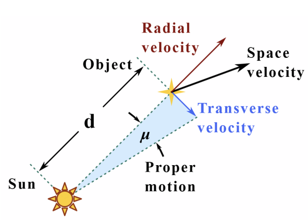
Scenario 3 → Spectrum C

Reason:
Motion away → redshift → lower frequency



The Doppler effect tells us only about motion along our line of sight, called **radial velocity**. A hydrogen cloud may be moving through space in many directions, but only the part of that motion directed toward or away from the observer changes the observed frequency. Motion perpendicular to the line of sight does not produce a Doppler shift. This means that a spectrum can reveal whether gas is moving toward us or away from us, but not its full three-dimensional motion. Equation 1 allows you to calculate the radial velocity given the rest frequency, f_{rest}, the observed frequency, $f_{observed}$, and the speed of light, c.

$$v_{\text{radial}} = c \times \frac{f_{\text{rest}} - f_{\text{observed}}}{f_{\text{rest}}} \tag{1}$$



For each spectrum, approximate the frequency of the peak, calculate its radial velocity using equation 1, and state whether it is moving towards, away, or at rest. The x-axis is written in offset form. Add the value shown on the axis to 1420 MHz to get the full frequency. Example: 0.7 MHz on the axis means 1420.7 MHz. Use the following values for your calculations:

Instructor note: Because students are estimating the peak frequency by eye from the plot, small numerical differences are acceptable. Focus on whether they correctly identify the direction of motion and use the sign convention consistently: negative radial velocity = toward us (blueshift), positive radial velocity = away from us (redshift).

- $f_{rest} = 1420.40575$ MHz
- $c = 3 \times 10^8$ m/s or 300,000,000 m/s

Spectrum A:

$f_{observed} = 1420.9$ MHz

$v_{radial} = (3 \times 10^8)\frac{1420.40575 - 1420.9}{1420.40575}$

$v_{radial} \approx$ -104,300 m/s   **[Towards]** | Away | Rest

Spectrum B:

$f_{observed} = f_{rest} = 1420.40575$ MHz

$v_{radial} = (3 \times 10^8)\frac{1420.40575 - 1420.40575}{1420.40575}$

$v_{radial} =$ 0 m/s   Towards | Away | **[Rest]**

Spectrum C:

$f_{observed} = 1419.9$ MHz

$v_{radial} = (3 \times 10^8)\frac{1420.40575 - 1419.9}{1420.40575}$

$v_{radial} \approx$ +106,740 m/s   Towards | **[Away]** | Rest

Part 2: What Type of Galaxy is the Milky Way?

The Milky Way in Visible Light

Before the advent of radio astronomy, visible-light views of the sky, such as Figure 2, were all astronomers had to infer the structure of the Milky Way. From our vantage point within the galaxy, this was a difficult problem to solve. We see the Milky Way edge-on as a bright band stretching across the sky, and much of that view is obscured by interstellar dust. As a result, visible light alone was not enough to reveal the Galaxy's full large-scale structure. Radio astronomy helped solve this problem because the 21 cm radio waves emitted by neutral hydrogen can pass through the dust that blocks visible light, allowing astronomers to trace hydrogen gas across more of the Milky Way that was previously hidden from view.

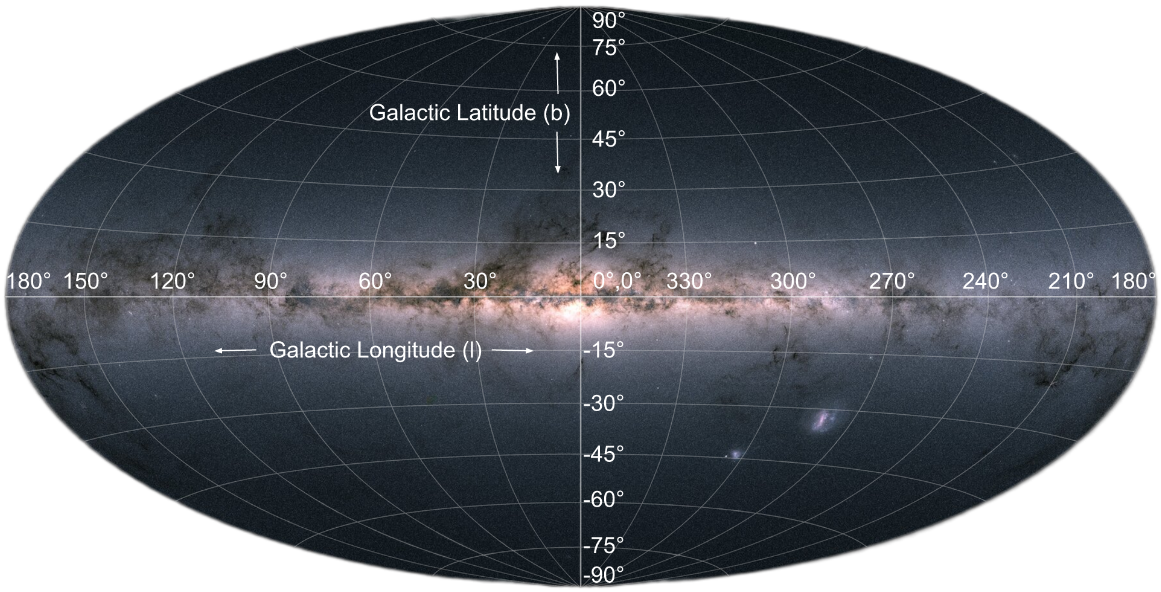


Figure 2: All sky map taken by the Gaia spacecraft showing the Milky Way in visible light, overlaid with Galactic coordinates.

To describe where we are looking in the Milky Way, astronomers commonly use Galactic Coordinates (l, b). Galactic longitude (l) tells us the direction we are looking along the plane of the Galaxy. Galactic latitude (b) tells us how far above or below the plane of the Milky Way we are looking. A latitude of $b = 0°$ lies directly along the central band of the Milky Way, while positive and negative values of b point above and below it, respectively.

From this visible-light view alone, it is difficult to determine the true large-scale shape of the Milky Way. To guide our investigation, we will compare our observations to the major types of galaxies seen elsewhere in the universe.

Types of Galaxies

Astronomers classify galaxies into several broad types, shown in Figure 3, including elliptical, irregular, and spiral galaxies. Elliptical galaxies generally contain relatively little cold gas and are not dominated by a thin gas-rich disk. Irregular galaxies can contain clumpy gas, but they do not usually show a clear, organized large-scale disk structure seen in spiral galaxies. Spiral galaxies contain large amounts of neutral hydrogen concentrated in a thin disk, with that gas often gathered into larger structures such as spiral arms. As you work through the next activities, use these galaxy types as competing models for the Milky Way and decide which one is best supported by the 21 cm evidence.

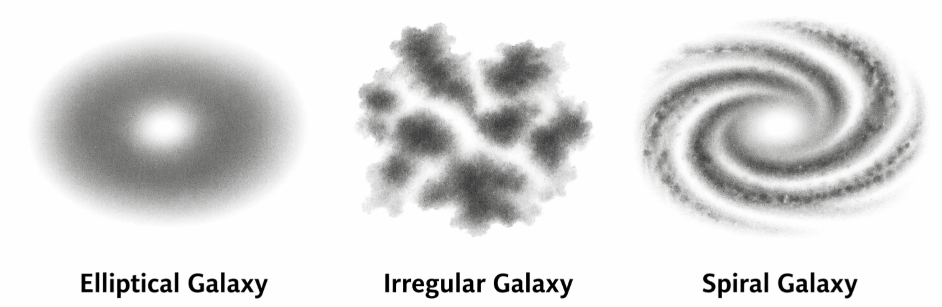


Figure 3: Simplified diagrams of three common galaxy types: elliptical, irregular, and spiral.

Is Neutral Hydrogen Concentrated in the Galactic Plane?

The visible light image of the Milky Way suggests that much of the Galaxy's gas and dust is concentrated along a narrow band across the sky. We will now test whether the neutral hydrogen traced by the 21 cm line follows the same pattern.

On the next page are spectra taken at different Galactic coordinates, both on and off the Galactic plane. Compare these spectra with each other to investigate where the hydrogen is most strongly concentrated. Pay particular attention to how the spectra change with Galactic latitude.

Estimate the maximum peak intensity for each pointing:

Instructor note: Student estimates will vary slightly because the peak intensities are read from plots rather than measured exactly. The key pattern is that the two spectra at b=0°are much stronger than the off-plane spectra, supporting the conclusion that neutral hydrogen is concentrated near the Galactic plane.

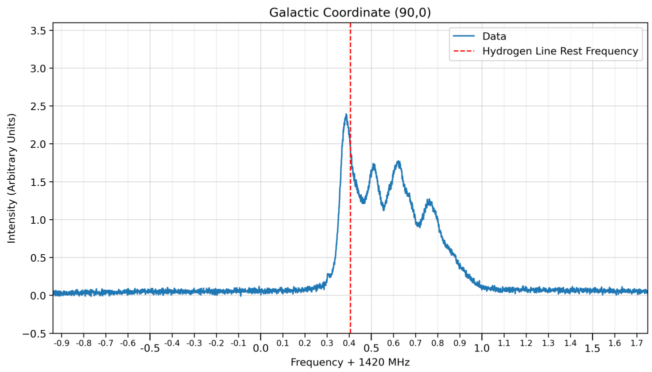
Galactic Coordinate (90,0) $\sim$ 2.4 Galactic Coordinate (90,-5) $\sim$ 0.3
Galactic Coordinate (210,0) $\sim$ 0.8 Galactic Coordinate (210,10) $\sim$ 0.1

Which observational parameter most strongly influences the peak intensity? Explain.

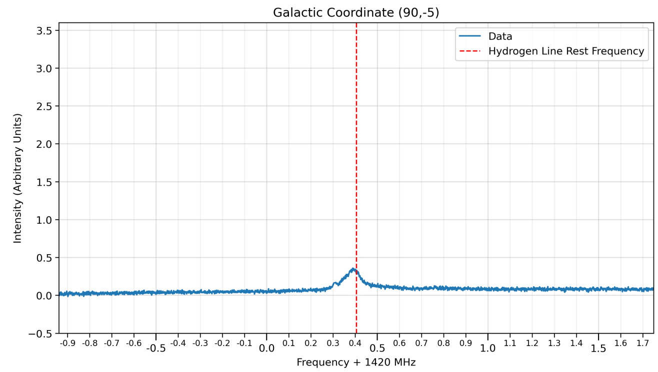
The observational parameter that most strongly influences the peak intensity is Galactic latitude, b. At both longitudes shown, the spectra taken on the Galactic plane (b = 0°) have much stronger 21 cm emission than the spectra taken off the plane (b = -5°and b = 10°). This indicates that most of the neutral hydrogen is concentrated in a relatively thin Galactic disk rather than spread evenly above and below it.

Which hypothesis is better supported by the data?

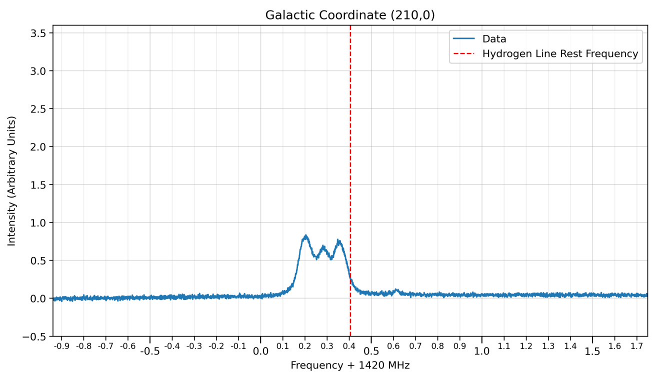
Hypothesis A: Neutral hydrogen is distributed roughly uniformly throughout the Galaxy.
Hypothesis B: Neutral hydrogen is concentrated near the Galactic plane.



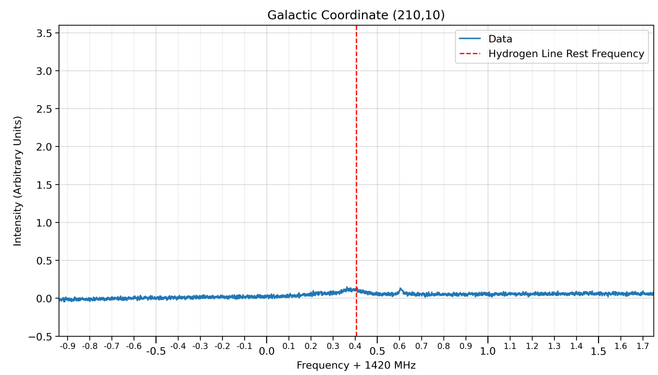
Galactic Coordinate (90,0)



Galactic Coordinate (90,-5)



Galactic Coordinate (210,0)

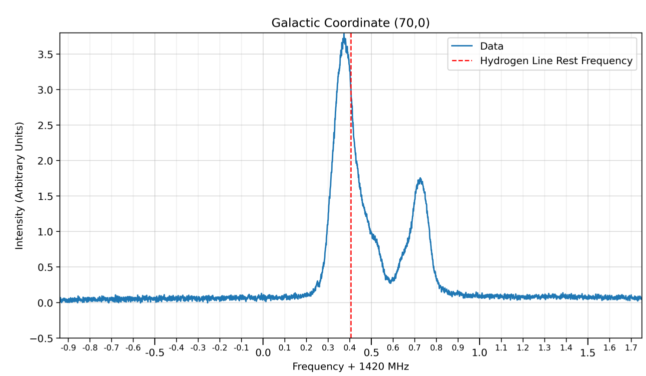


Galactic Coordinate (210,10)

The data better supports hypothesis B because: The strongest emission is seen in the two spectra at b = 0°, while the off-plane spectra are much weaker. If hydrogen were distributed uniformly throughout the Galaxy, we would not expect such a strong drop in peak intensity only a few degrees away from the plane.

Is the Galactic Disk Smooth or Structured?

In the previous activity you found that the strongest 21 cm emission comes from pointings near the Galactic plane. This tells us that much of the neutral hydrogen in the Milky Way is concentrated in a thin disk. We can now ask a broader question: how is hydrogen distributed within the Galactic disk? We will compare two possible explanations for how hydrogen is distributed in the Galactic disk:



Hypothesis A: Neutral hydrogen is spread smoothly throughout the disk.

Hypothesis B: Neutral hydrogen is concentrated in distinct regions within the disk.

The spectrum to the right was taken at Galactic coordinate $(70, 0)$. Because this pointing lies on the Galactic plane, the line of sight passes through the Galactic disk and can intersect multiple hydrogen-rich regions along that path. **Use this spectrum to answer the following questions:**

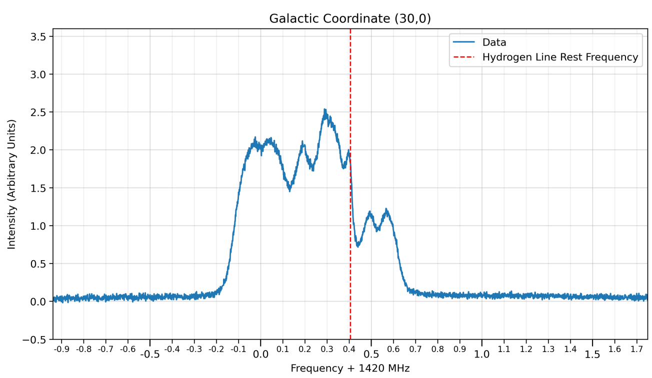
1. How many clear hydrogen emission peaks are visible in the spectrum? Two

2. Does this spectrum seem more consistent with hydrogen spread smoothly through the disk, or with hydrogen concentrated in several distinct regions along the same line of sight? Explain your reasoning, referring to the number and shape of the peaks in the spectrum.

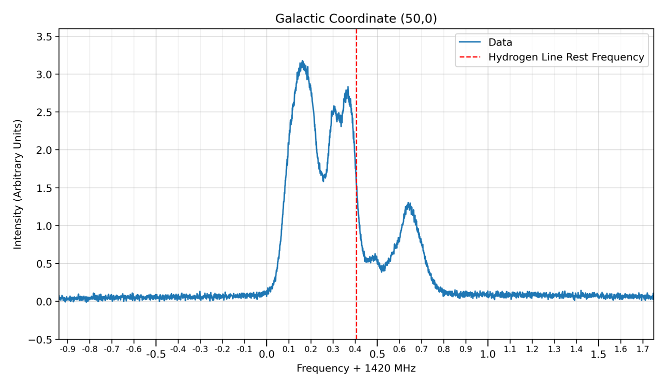
   This spectrum is more consistent with hydrogen concentrated in several distinct regions along the same line of sight. If the hydrogen were spread smoothly through the disk, we would expect a broader, smoother feature rather than multiple separated peaks. Instead, the spectrum shows two distinct peaks with different frequencies, suggesting that the line of sight intersects multiple hydrogen-rich regions moving at different radial velocities. This supports **Hypothesis B: Neutral hydrogen is concentrated in distinct regions within the disk.**

How Does Hydrogen Structure Change Across the Galaxy?

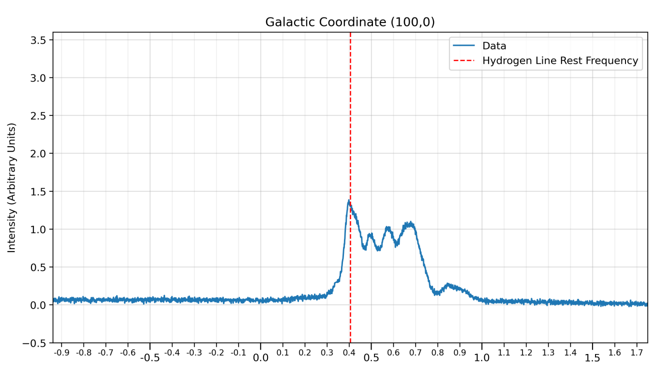
We now examine how the structure of neutral hydrogen changes across the Galactic disk by comparing spectra taken at different Galactic longitudes. All of the following spectra are on the Galactic plane, so any differences you observe reflect how hydrogen structure varies with Galactic longitude.



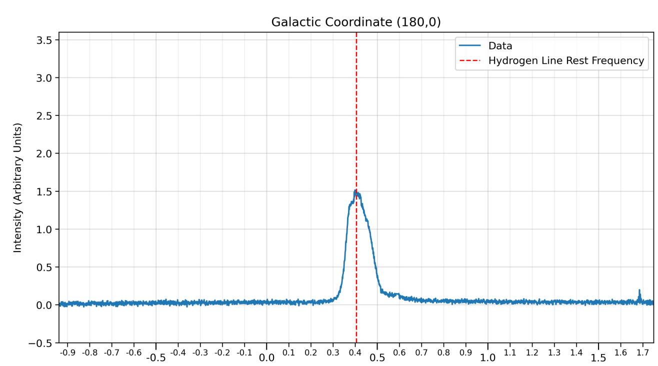
Galactic Coordinate (30,0)



Galactic Coordinate (50,0)



Galactic Coordinate (100,0)



Galactic Coordinate (180,0)

1. How do the number of clear peaks and the maximum peak intensity change from one Galactic longitude to another? Do these changes appear gradual, abrupt, or random?

The spectra at (30,0) and (50,0) show several strong peaks, with (50,0) having the largest peak intensity. The spectrum at (100,0) still shows multiple peaks, but they are weaker, while (180,0) is dominated by a single narrower peak. These changes do not appear random. They show a systematic variation with longitude.

Instructor note: Students may count slightly different numbers of peaks in some spectra, especially at (30,0) and (100,0). That is fine. What matters is that the spectra change systematically with Galactic longitude and do not all have the same shape or strength.

2. Do these spectra suggest that hydrogen is spread smoothly throughout the Galactic plane, or concentrated in larger regions within the plane? Support your answer with specific observations.

   These spectra suggest that hydrogen is concentrated in larger regions within the Galactic plane, not spread smoothly throughout it. If the hydrogen were distributed smoothly, we would expect the spectra to look more similar and more uniform from one longitude to another. Instead, some directions show multiple strong peaks, while others show fewer or weaker peaks, indicating that certain lines of sight pass through larger hydrogen-rich regions and others do not.

3. Does the variation in hydrogen structure across Galactic longitude appear random, or does it show a systematic pattern? Explain your reasoning using specific features from the spectra.

   As Galactic longitude changes, the spectra change in an organized way: some longitudes show complex, multi-peaked structure, while others show simpler or weaker emission. For example, (30,0), (50,0), and (100,0) all show multiple peaks, but (180,0) is much simpler and dominated by one main peak.

4. What does a systematic pattern in hydrogen structure suggest about how gas is organized on large scales within the Milky Way?

   A systematic pattern suggests that the gas is organized into large-scale structures within the Galactic disk rather than being distributed uniformly or randomly. In other words, the Milky Way's neutral hydrogen appears to be concentrated in extended regions that change predictably with direction, consistent with a structured disk such as a spiral galaxy.

What Type of Galaxy is the Milky Way?

We can now compare the patterns we have observed to what we expect for different types of galaxies. Consider what each type of galaxy would predict for the observations you have made so far:

Galaxy Type	Disk	Structure	Longitude Pattern
Elliptical	No thin disk	Weak structure	No clear pattern
Irregular	Not disk-like	Clumpy	Random
Spiral	Thin disk	Multiple peaks	Systematic

Compare these predictions to the patterns you observed in the previous sections to determine which model best matches the data. If the Milky Way were an elliptical galaxy, we would not expect strong neutral-hydrogen emission to be concentrated in a thin plane. If it were an irregular galaxy, we might expect clumpy hydrogen with no clear, systematic pattern across the Galactic plane. If it were a spiral galaxy, we would expect neutral hydrogen to be concentrated in the Galactic plane and to appear in larger concentrations within that plane, rather than being spread smoothly.

1. Which broad galaxy type is best supported by the evidence so far? Support your answer with at least two specific observations from the previous sections.

Hypothesis A: The Milky Way is an **elliptical galaxy**, so its neutral hydrogen should not be strongly concentrated in a thin Galactic plane.

Hypothesis B: The Milky Way is an **irregular galaxy**, so its neutral hydrogen may be clumpy, but it should not show a clear disk-like pattern tied to the Galactic plane.

Hypothesis C: The Milky Way is a **spiral galaxy**, so its neutral hydrogen should be concentrated in a thin disk and organized into larger structures within that disk, such as spiral arms.

The evidence best supports Hypothesis C: the Milky Way is a spiral galaxy. First, the 21 cm emission is strongest near the Galactic plane, which shows that neutral hydrogen is concentrated in a thin disk rather than distributed uniformly throughout the Galaxy. Second, the spectra along the plane show multiple peaks and change systematically with Galactic longitude, indicating that the gas is organized into larger structures within that disk rather than being smooth or random. This combination fits a spiral galaxy better than an elliptical or irregular galaxy.

2. If the Milky Way is most consistent with a spiral galaxy, what does this suggest about how its neutral hydrogen is arranged on large scales?

   It suggests that the neutral hydrogen is arranged in a thin, structured Galactic disk, with the gas concentrated in larger regions within that disk rather than spread smoothly everywhere. On large scales, this is consistent with hydrogen being organized into features such as spiral arms.

Is the Milky Way Rotating?

In the previous section, you found that neutral hydrogen is not spread smoothly throughout the Galactic plane, but instead shows a systematic pattern of structure across different Galactic longitudes. We can now ask a new question: how is that hydrogen moving? If the Milky Way were static, then Doppler shifts of the 21 cm line would not show a clear large-scale pattern with Galactic longitude. If instead the Milky Way is rotating, then hydrogen should show a systematic pattern of redshift and blueshift across the Galactic plane.

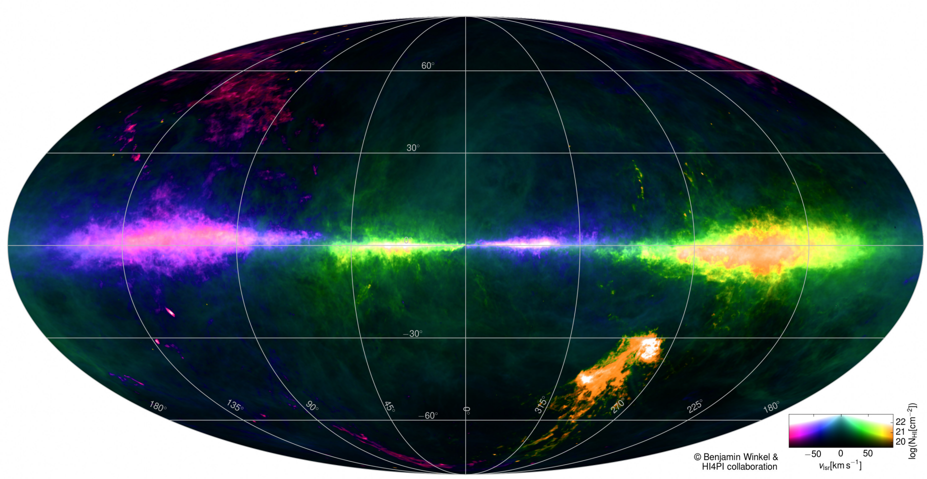


Figure 4: An all-sky map of neutral hydrogen emission, color coded by Doppler shift. Purple/blue represents blueshift, while green/orange represent redshift. The Galactic plane runs horizontally through the center of the image. *Image credit: Galactic All-Sky Survey (GASS) and the Effelsberg-Bonn HI Survey (EBHIS).*

1. As you move across the Galactic plane, how does the pattern of Doppler shift change? Describe how regions of redshift and blueshift are arranged across the sky.

   As you move across the Galactic plane, the Doppler shift changes in a systematic way. One large region of the plane is dominated by blueshifted hydrogen, while another large region is dominated by redshifted hydrogen, with the pattern reversing across the sky rather than appearing mixed at random. This suggests organized large-scale motion in the gas.

2. If the Milky Way were static (i.e. non-rotating), what would you expect this all-sky Doppler shift map to look like? How does the observed map differ from that expectation?

   If the Milky Way were static, we would expect the 21 cm line to stay close to its rest frequency across the sky, so the Doppler shift map would show little or no large-scale pattern of redshift and blueshift. Instead, the observed map shows broad, organized regions of redshifted and blueshifted hydrogen across the Galactic plane. That is very different from the expectation for a non-rotating galaxy.

3. Which of the following hypotheses is better supported by the evidence? Support your answer with at least two specific observations from the Doppler shift map and/or the spectra in the previous section.

   Hypothesis A: The Milky Way is static or non-rotating.

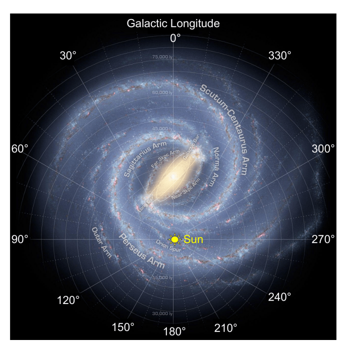
   Hypothesis B: The Milky Way is rotating.

   The evidence better supports Hypothesis B: The Milky Way is rotating. First, the Doppler shift map shows a clear large-scale arrangement of redshifted hydrogen in one part of the Galactic plane and blueshifted hydrogen in another, which is what we expect from rotation. Second, the spectra from different Galactic longitudes show that the hydrogen line appears at different shifted frequencies depending on direction, again indicating systematic motion rather than a static Galaxy.

Reconstructing the Milky Way

Over the course of this lab, you have used 21 cm observations to piece together the structure and dynamics of the Milky Way. First, you found that the strongest hydrogen emission comes from directions near the Galactic plane, showing that most neutral hydrogen is concentrated in a thin disk. Next, you compared spectra taken at different Galactic longitudes and found that the hydrogen is not spread smoothly throughout that disk, but instead appears concentrated in larger structures along some directions. Finally, you examined how the pattern of redshifted and blueshifted hydrogen changes across the sky, providing evidence that the Milky Way is rotating. Taken together, these observations show that the Milky Way is a rotating, structured, gas-rich disk galaxy, consistent with a spiral galaxy.

Although we cannot step outside the Milky Way to view it directly, radio astronomy allows us to reconstruct its large-scale structure by tracing neutral hydrogen through the dust that blocks visible light. A face-on view of the Milky Way, inferred from observations like these, is shown in Figure **??**.



Use everything you've learned in the previous sections to answer the following questions:

1. What evidence from this lab suggests that most hydrogen lies in a thin Galactic disk?

The strongest 21 cm emission is seen at pointings near the Galactic plane and becomes much weaker at pointings above or below it. This shows that most neutral hydrogen is concentrated in a thin disk rather than distributed uniformly in all directions.

2. What evidence suggests that the hydrogen is not spread smoothly throughout the disk?

The spectra along the Galactic plane do not all look the same. Some directions show multiple strong peaks, while others show fewer or weaker peaks, which means the hydrogen is concentrated in larger regions rather than spread smoothly throughout the disk.

3. What evidence suggests that the Milky Way is rotating?

The Doppler shift pattern changes systematically across the Galactic plane, with large regions of redshift in one part of the sky and blueshift in another. This organized pattern shows that the hydrogen gas is undergoing large-scale motion consistent with Galactic rotation.

4. In 3–4 sentences, describe what the Milky Way appears to look like based on the evidence from this lab, including its structure and motion.

The Milky Way appears to be a gas-rich disk galaxy with most of its neutral hydrogen concentrated in a thin Galactic plane. That hydrogen is not spread smoothly through the disk, but instead is gathered into larger structures along some directions. The systematic pattern of redshifts and blueshifts shows that the Galaxy is rotating. Taken together, these observations are most consistent with the Milky Way being a rotating spiral galaxy.