Reconstructing the Milky Way with the 21 cm Hydrogen Line

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.

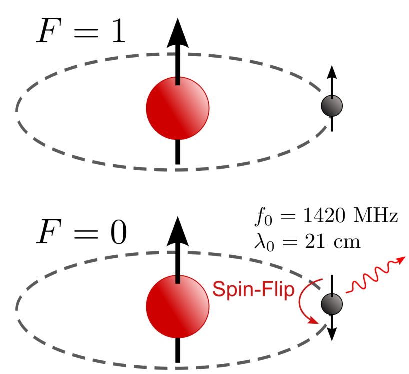


Figure 1: A neutral hydrogen atom undergoing a spin-flip transition, releasing a photon with a wavelength of ∼21 cm and frequency of ∼1420 MHz.

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.

   ____

   ____

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

   ____

   ____

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

   ____

   ____

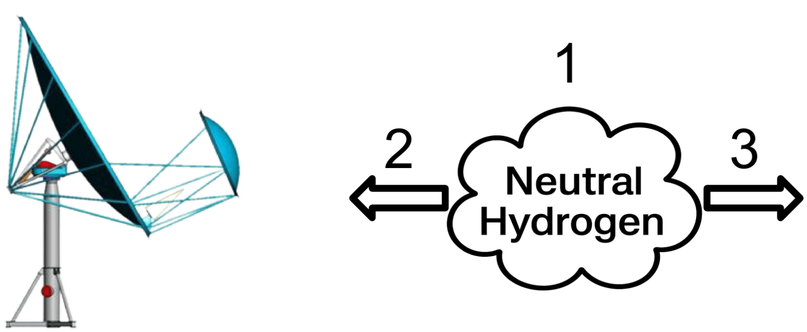
Doppler Shifts and Radial Motion

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 ______

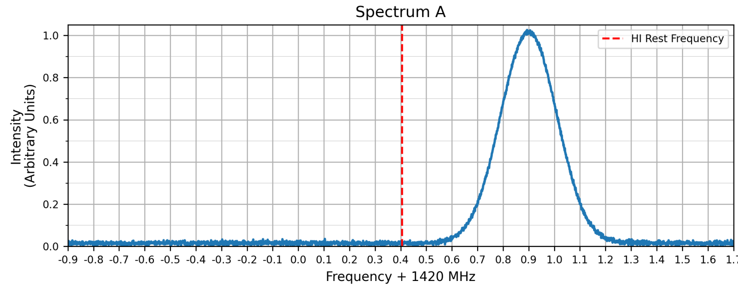
Reason: ________________________________

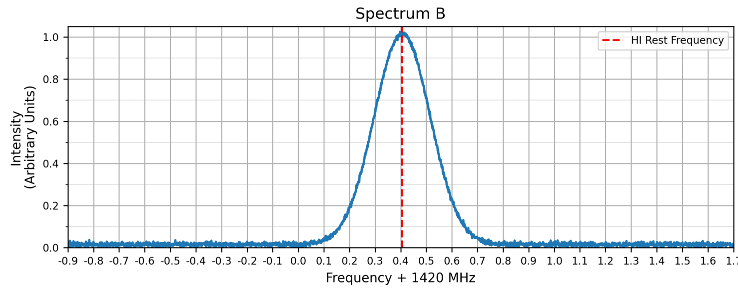
Scenario 2 → Spectrum ______

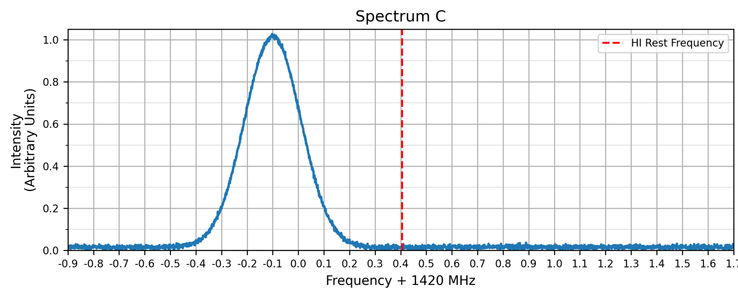
Reason: ________________________________

Scenario 3 → Spectrum ______

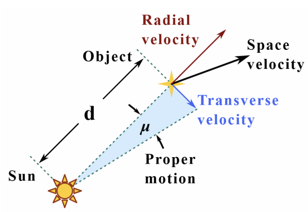
Reason: ________________________________







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.



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

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:

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

Spectrum A: $v_{radial} =$ ________________ m/s Towards | Away | Rest

Spectrum B: $v_{radial} =$ ________________ m/s Towards | Away | Rest

Spectrum C: $v_{radial} =$ ________________ 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.

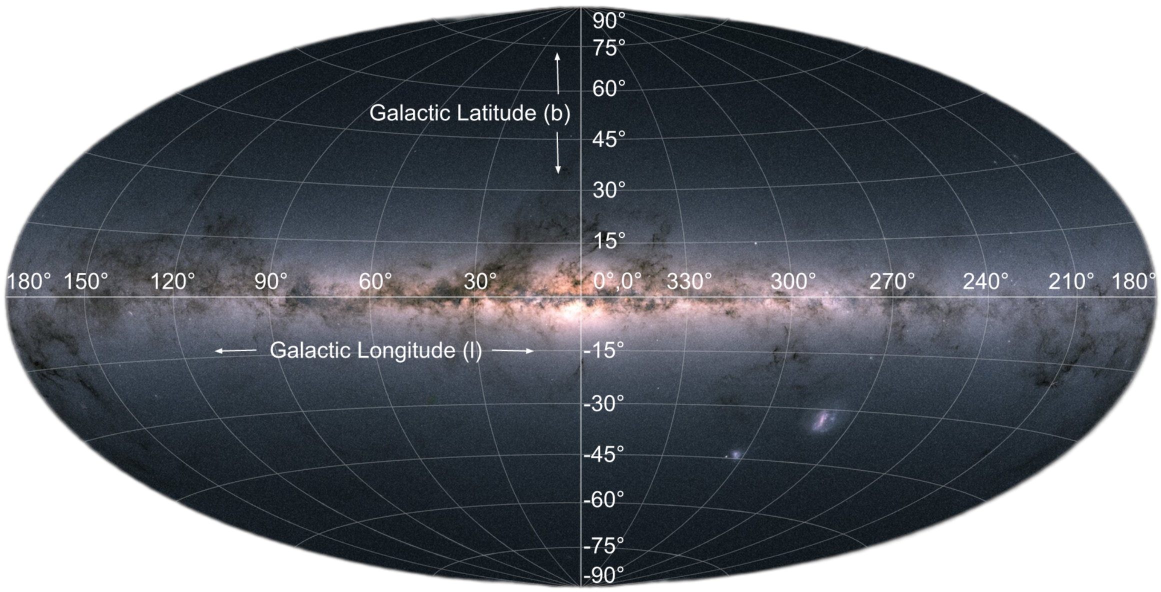


Figure 2: All sky map taken by the Gaia spacecraft showing the Milky Way in visible light, overlaid with Galactic coordinates.

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.

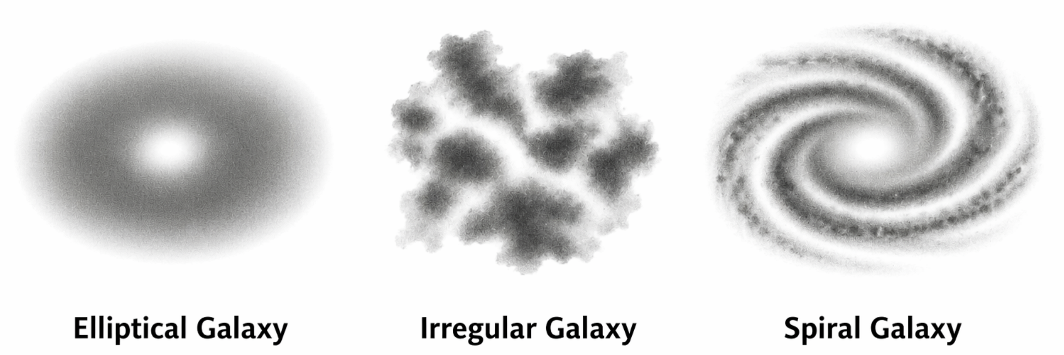


Figure 3: Simplified diagrams of three common galaxy types: elliptical, irregular, and spiral.

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:

Galactic Coordinate (90,0) __________ Galactic Coordinate (90,-5) __________

Galactic Coordinate (210,0) __________ Galactic Coordinate (210,10) __________

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

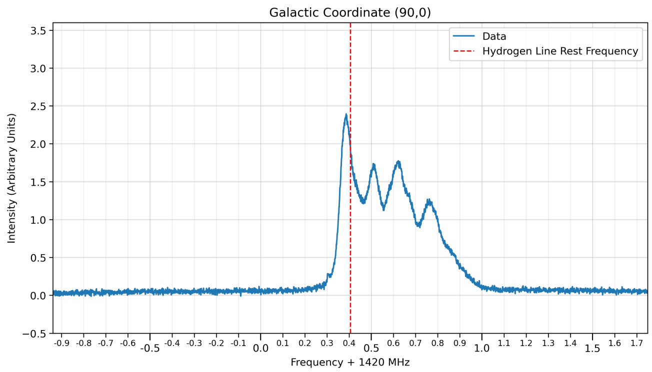
____

____

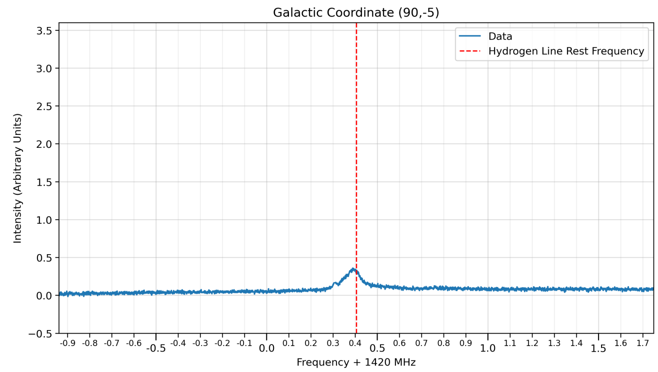
Which hypothesis is better supported by the data?

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

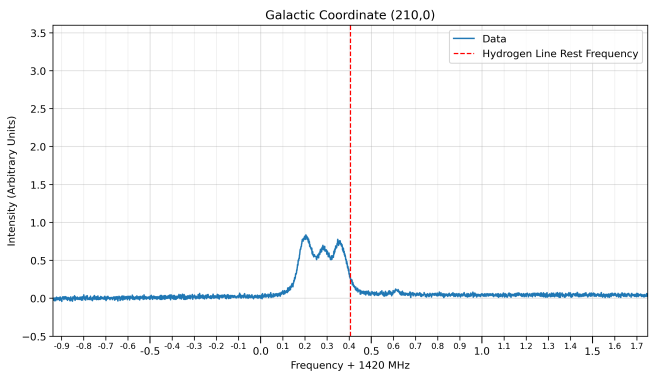
The data better supports hypothesis __________ because ____



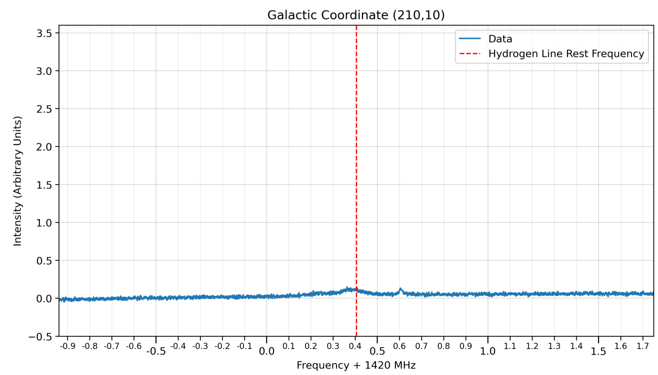
Galactic Coordinate (90,0)



Galactic Coordinate (90,-5)



Galactic Coordinate (210,0)



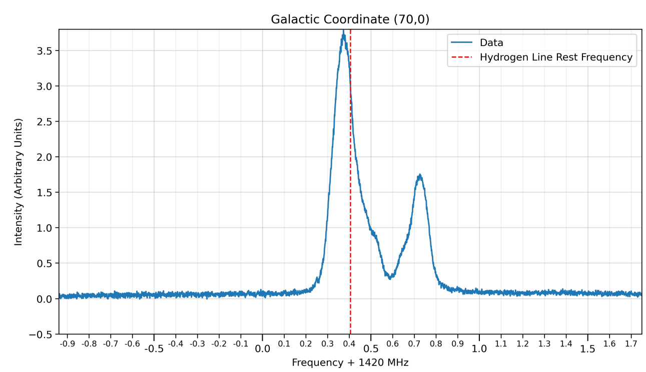
Galactic Coordinate (210,10)

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?

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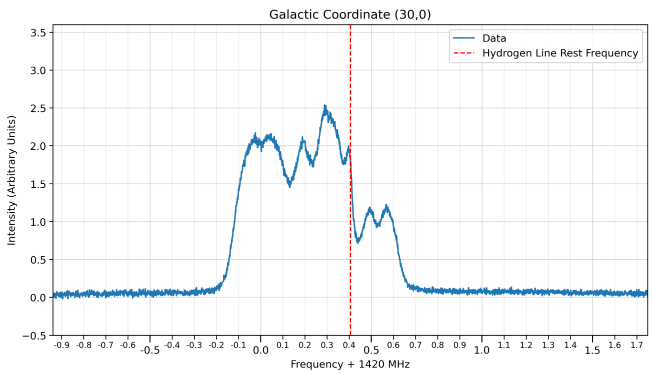
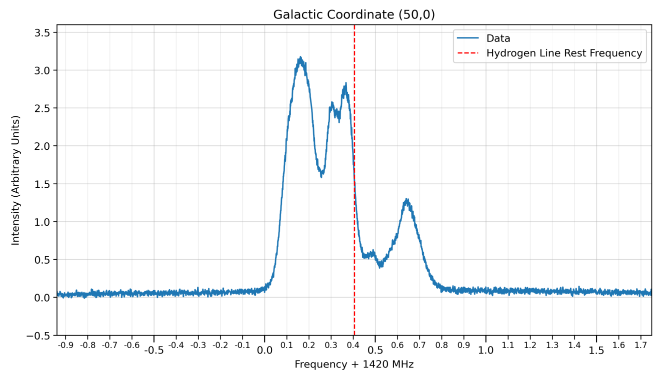
2. Does this spectrum seem more consistent with hydrogen spread smoothly through the disk, or with hydrogen concentrated in several distinct regions along the same line of sight? Explain your reasoning, referring to the number and shape of the peaks in the spectrum.

How Does Hydrogen Structure Change Across the Galaxy?

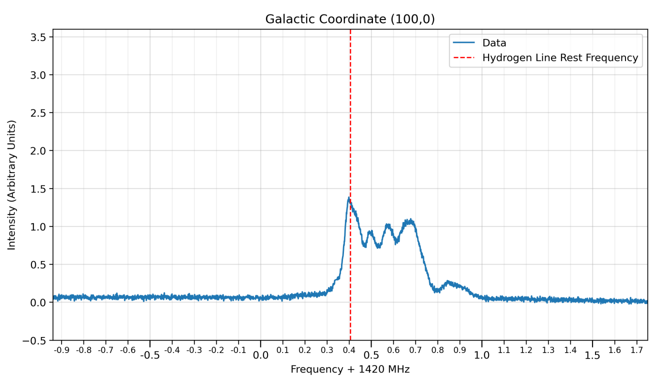
We now examine how the structure of neutral hydrogen changes across the Galactic disk by comparing spectra taken at different Galactic longitudes. All of the following spectra are on the Galactic plane, so any differences you observe reflect how hydrogen structure varies with Galactic longitude.



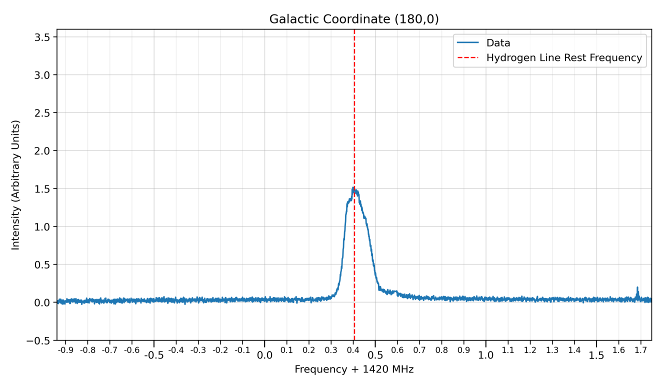
Galactic Coordinate (30,0)



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?

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.

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.

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

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.

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?

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.

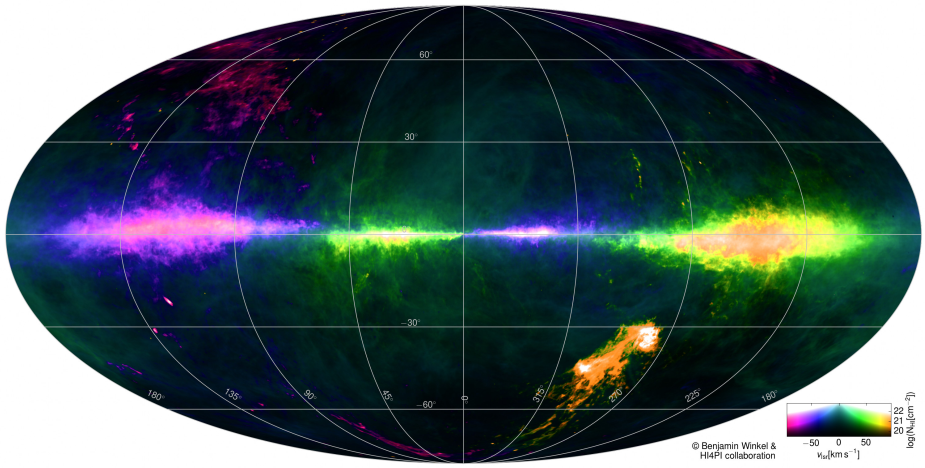


Figure 4: An all-sky map of neutral hydrogen emission, color coded by Doppler shift. Purple/blue represents blueshift, while green/orange represent redshift. The Galactic plane runs horizontally through the center of the image. *Image credit: Galactic All-Sky Survey (GASS) and the Effelsberg-Bonn HI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

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   ____

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?

   ____

   ____

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.

   ____

   ____

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 5.

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?

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

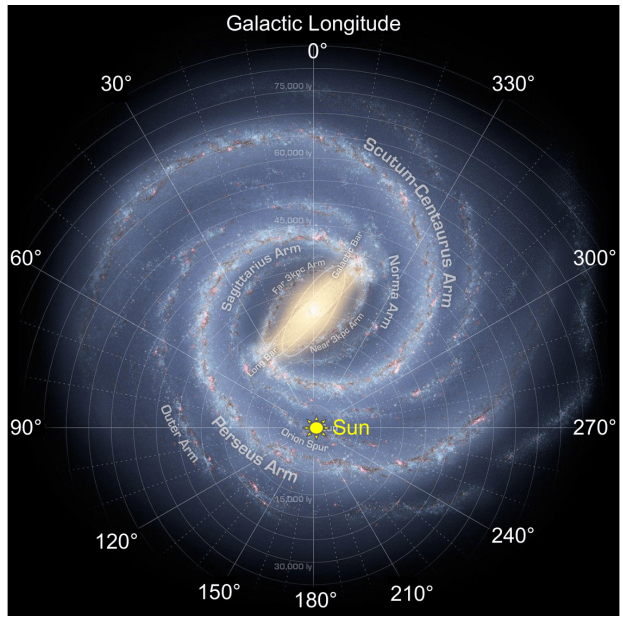

Figure 5: Face-on view of the Milky Way showing its spiral-arm structure and the location of the Sun.

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

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.