

## The Hydrogen 21-cm Emission Line\*

### Gas

About 99% of the interstellar medium (ISM) is gas: About 90% atomic or molecular hydrogen, 10% helium, and traces of other elements. Dust scatters and absorbs visible light much more than a gas. The interstellar gas can be seen when you look at the spectral lines of a binary star system. Among the broad lines that shift as the two stars orbit each other, there are narrow lines that do not move. The narrow lines are from much colder gas in the interstellar medium between us and the binary system.

The hydrogen gas is observed in a variety of states: ionized, neutral atomic and molecular forms. The ionized hydrogen emits visible light as the electrons combine with the protons to form neutral hydrogen. Both neutral atomic and molecular hydrogen emit in the radio region of the electromagnetic spectrum.

### H II Regions

The Roman numeral "I" indicates a neutral atom. A "II" represents an ionized the atom has lost one electron. Thus, a H I nebula a made of neutral atomic hydrogen, a H II nebula consists of ionized hydrogen. H II regions are hot (several thousand K) thin hydrogen emission nebulae that glow from the fluorescence of hydrogen atoms. Ultraviolet light from hot O and B stars ionizes the surrounding hydrogen gas. When the electrons recombine with the protons, they emit light mostly at visible wavelengths, and primarily at a wavelength of 656.3 nanometers, giving the hydrogen emission nebulae their characteristic red color. Since each ultraviolet photon produces a visible photon, the temperature of the stars causing the nebula to fluoresce can be estimated, even though the O and B stars are hidden inside the nebula. Fluorescent light bulbs operate on the same basic principle except they use mercury vapor to produce ultraviolet light.

\*This page was modified from Nick Strobel's Astronomy Notes: [www.astronomynotes.com](http://www.astronomynotes.com). Most of the ground-based telescope pictures here are from the Anglo-Australian Observatory: <http://www.aao.gov.au/> (AAO---used by permission).

The H II region in the Orion Nebula (below left), the fuzzy patch in the sword of the Orion constellation, is famous because it is the closest large star factory. The image to the right is close-up of the heart of the nebula and shows the four hot ``Trapezium'' stars (four O and B stars making a trapezoid figure.



The Lagoon Nebula in Sagittarius (above right) is another large H II region. The Lagoon Nebula is about 5000 light years away and spans 90 by 40 arc minutes in our sky. Converting the angular to a linear size, it is about 130 by 60 light years in extent (the Orion Nebula is only 29 by 26 light years in size). The nebula looks like a twisted, turbulent lagoon due to the complex interaction of the intense radiation from the hot stars lighting it up, the varying densities of the gas and dust, and temperature.

The Trifid Nebula (right), named because of the dust lanes that trisect the H II region behind them, is next to the Lagoon Nebula in Sagittarius. The image to the right illustrates the three types of nebulae: the red H II region behind a dark dust nebula showing the effect of the extinction of light, and a blue reflection nebula showing the preferential scattering of shorter wavelengths.



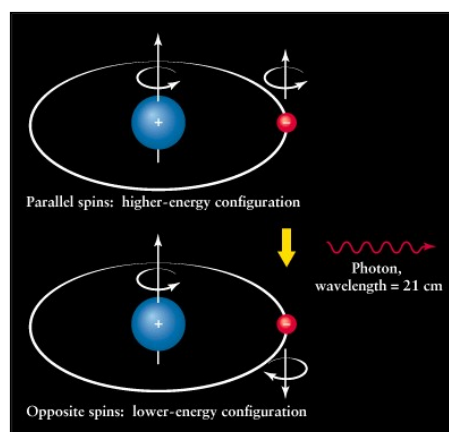
Hot, luminous O and B-type stars are found in regions of star formation because they are young and do not live long enough to move away from where they were formed. Stars form in

clusters, and where O and B stars are found, there are smaller, lower-mass stars still forming. The spectra of H II regions are much simpler than star spectra so they are easier to decipher. The composition and conditions inside the H II regions are also easier to determine and understand than for stars. So H II regions provide a valuable tool for understanding the history of star formation in a galaxy.

H II regions also provide a convenient way to map the structure of a galaxy because they are so large and luminous. In our galaxy the H II regions are distributed in a spiral pattern. The best wavelengths to use to map the distribution of hydrogen, however, are in the radio region and not the red emission line of hydrogen which is absorbed by dust. Most of the hydrogen gas is not ionized because O and B stars are rare, but radio waves pass easily through dust.

### 21-cm Line Radiation

Most of the hydrogen gas in the ISM is in cold atomic or molecular form. In 1944 Hendrik van de Hulst predicted that the cold atomic hydrogen (H I) gas should emit a particular wavelength of radio energy from a slight energy change in the hydrogen atoms at a wavelength is 21.1 centimeters (frequency = 1420.4 MHz). As a consequence, this radiation is called **21-cm line radiation**. The atomic hydrogen gas has temperatures between 100 K to about 3000 K.



Most of the hydrogen in space (far from hot O and B-type stars) is in its ground state. The electron moving around the proton can have a spin in the same direction as the proton's spin (i.e., parallel) or spin in the direct opposite direction as the proton's spin (i.e., anti-parallel). The energy state of an electron spinning anti-parallel is slightly lower than the energy state of a parallel-spin. Since atoms always want to be in the lowest energy state possible, the electron will eventually flip to the anti-parallel spin direction if it were in the parallel spin direction. The energy difference is very small, so a hydrogen atom can wait on average a few million *years* before it undergoes this transition.

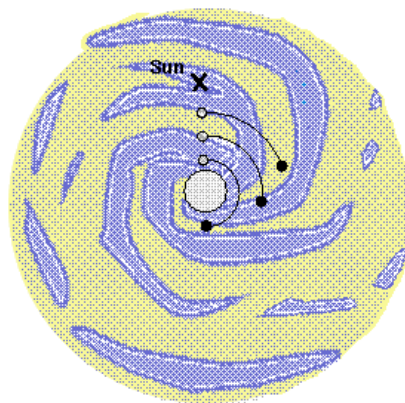
Even though this is a rare transition, the large amount of hydrogen gas means that enough hydrogen atoms are emitting the 21-cm wavelength radiation at any one given time to be easily detected with radio telescopes. The Milky Way has about 3 billion solar masses of H I gas with about 70% of it further out in the Galaxy than

the Sun. Most of the H I gas is in disk component of our galaxy and is located within 720 light years from the midplane of the disk. What's nice is that 21-cm line radiation is not blocked by dust! **The 21-cm line radiation provides the best way to map the structure of the Galaxy.**

### Using 21-cm line radiation to Map the Galaxy

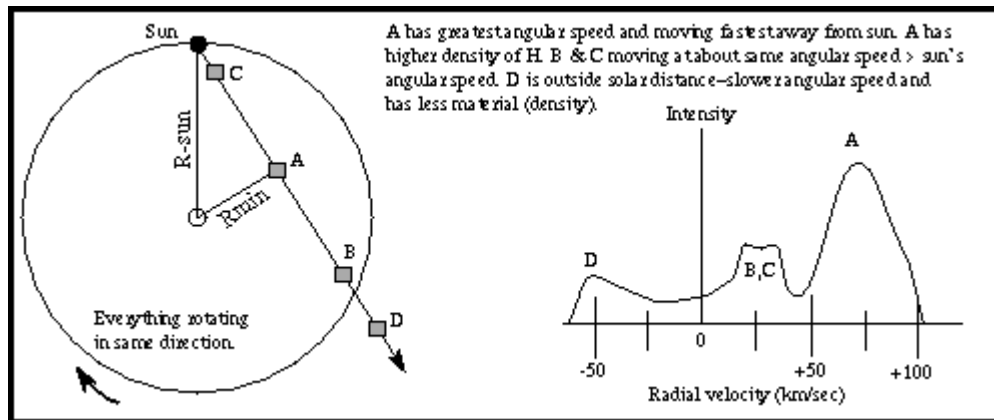
The intensity of the 21-cm emission line depends on the density of the neutral atomic hydrogen along your line of sight. Atomic hydrogen all along the line of sight will contribute to the energy received. You will need a way to determine the distance to each clump of hydrogen gas. Then when you observe the Galaxy in different directions, you can get a three-dimensional picture of the Galaxy.

The rotation curve is a plot of the orbital velocity of the clouds around the galactic center vs. their distance from the Galaxy center. "Rotation" in this context refers to the motion of the galactic disk as a whole---the disk made of stars and gas clouds appears to spin. The gas clouds are assumed to move in the plane of the disk in nearly circular orbits. *Jan Oort* found in 1927 that stars closer to the galactic center complete a greater fraction of their orbit in a given time than stars farther out from the center. This difference in the *angular* speeds of different parts of the galactic disk is called **differential rotation**. Using the rotation curve below, the Doppler-shifted radio emission can be converted into distances along different lines of sight to the hydrogen clouds.



*Differential rotation: greater angular speeds closer to the galactic center.*

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The 21-cm emission will include contributions of hydrogen at different distances from the galactic center and different Doppler shifts with respect to us. Some of the emission will be from gas clouds just inside the orbit the orbit of the Sun moving at slightly faster angular speeds than the Sun. They will have a small redshift. The part of the total emission coming from gas closest to the galactic center will have the greatest redshift because that gas is moving at the greatest angular speed. In the figure the line from the galactic center to the fast moving gas (called  $R_{min}$ ) makes a  $90^\circ$  angle with respect to our line of sight. Using trigonometry, the distance of the fast moving gas (at 'A') from the galactic center = (the Sun's distance)  $\times \sin$  [galactic longitude], where the galactic longitude is the angular separation between the cloud and the galactic center. Angle by angle, strip by strip, the rotation curve is constructed from the maximum Doppler velocity along different lines of sight.

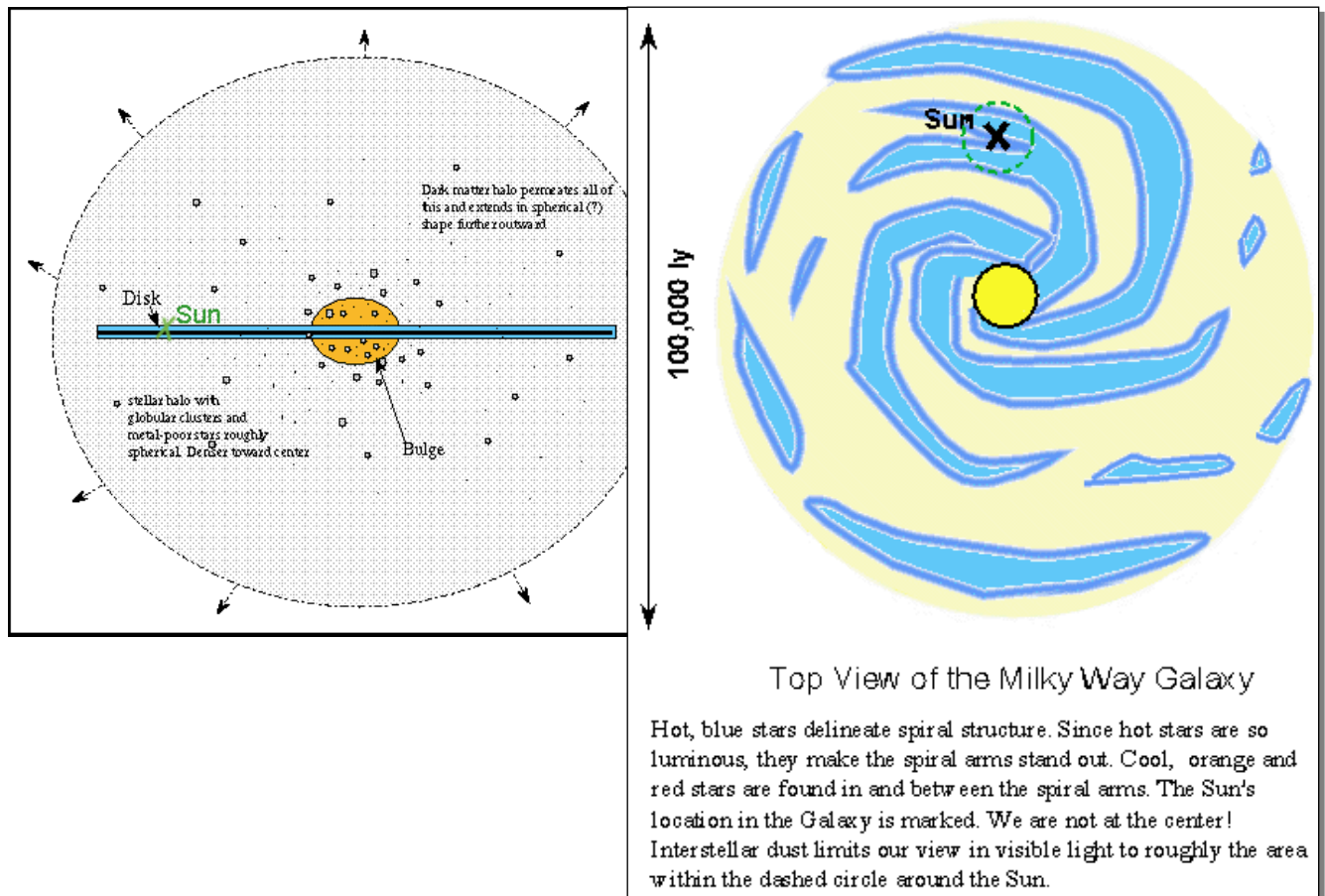
Once the rotation curve is determined, the Galaxy's structure can be mapped. The 21-cm line profile has several Doppler shifted peaks that are narrow and well-defined (figure next page). Using the known rotation curve, you can convert the Doppler speeds of the peaks to get the distance to the hydrogen producing each peak. The intensity of each peak depends on the density of the hydrogen gas cloud. The mapping surveys show that the hydrogen gas is distributed in a spiral pattern in a thin disk for almost the entire Galaxy

Finding the structure of the Milky Way is not an easy task because the solar system is stuck inside the Galaxy and we can only look in all different directions. Our situation is like having to determine the layout of your hometown from just looking out on your front porch (or back porch) and not being able to move even across the street. The fact that you see a narrow band of stars tells you that our galaxy is shaped like a thin disk. If we lived in a more spherical galaxy, the stars would be distributed more uniformly around the sky. There is a hint of a bulge in

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the direction of the Sagittarius constellation. Careful star counts and determining their distances shows hints of a spiral pattern in the disk. The interstellar dust limits our view a small section of the Galaxy. However, clear evidence of the spiral structure in the disk comes from the 21-cm line radiation.

Our galaxy, the **Milky Way**, is disk-shaped with spiral arms in the disk with an elliptical bulge in the center and a spherical halo that is denser closer to the Galaxy center. It is about 100,000 light years across and our solar system is about two-thirds of the way out from the center. For comparison, our solar system with the Oort Cloud is about 1 light year across. A view of the Galaxy as seen from above is shown below to the right. From the side the Galaxy would look very flat because most of the stars are in the disk (see the figure left below).



## The 21-cm Line: The Hydrogen 21-cm Emission Line

You can make a rough guess of the number of stars in our galaxy by dividing the Galaxy's total mass by the mass of a typical star (e.g., 1 solar mass). The result is about 200 billion stars! The actual number of stars could be several tens of billions less or more than this approximation. Recently, astronomers have discovered that most of the mass of galaxies is not in the form of stars, gas, or dust. It is made of some unknown material and is given the descriptive name "dark matter." Dark matter affects your guess of the number of stars in the galaxy! Does it increase the number or decrease it?

Our galaxy probably closely resembles the galaxy NGC 891 (below) if seen edge-on. Note the prominent dust lanes going through the disk mid-plane and how flat the galaxy is. Also notice the bulge in the middle. At the center of this galaxy as well as our own Milky Way is a giant black hole.



Name \_\_\_\_\_ Period \_\_\_\_\_ Date \_\_\_\_\_

## Worksheet on the Hydrogen 21-cm Line

1. Define the following:

- differential rotation:
- H II region:
- rotation curve:
- 21-cm line radiation:

2. What are the characteristics of the gaseous part of the ISM? Is the gas all at the same temperature and density? How do you know?

3. What are **H II regions** and how are they produced? What is going on at the atomic level?

4. Why would the presence of a H II region indicate the site of star formation?
  
  
  
  
  
  
  
  
  
  
5. How does the gas far from any star make its presence seen in the optical wavelengths and radio wavelengths?
  
  
  
  
  
  
  
  
  
  
6. How is the **21-cm line radiation** produced?
  
  
  
  
  
  
  
  
  
  
7. Why is the 21-cm line radiation so important for determining galactic structure and mass?
  
  
  
  
  
  
  
  
  
  
8. How is the 21-cm line radiation used to determine galactic structure and mass?
  
  
  
  
  
  
  
  
  
  
9. Which part of the *Galaxy* has greater angular speed? How do you determine the **rotation curve** of the *Galaxy* from the Doppler shifts of the gas?

