

I. Brief Introduction to Radio Astronomy



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The Birth of Radio Astronomy



At this point in your student career you have undoubtedly been introduced to several science courses with some discussion of the scientific method. The scientific method has been traditionally divided up into five steps which typically go something like this.

1. Observe some aspect of the universe.
2. Invent a tentative description, a hypothesis, that is consistent with what you have observed.
3. Use the hypothesis to make predictions.
4. Test those predictions by experiments or further observations and modify the hypothesis in the light of your results.

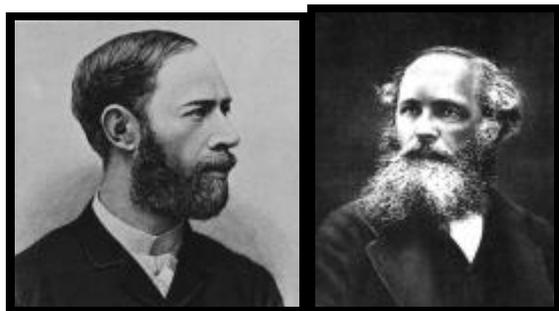
5. Repeat steps 3 and 4 until there are no discrepancies between theory and experiment and/or observation.

If that doesn't put you to sleep, then nothing will! While it's true that the process of scientific discovery can in some way be stretched and molded into the 5 steps outlined above, the true story of scientific discovery has a life of its own and defies simple categorization. Such is the story of how radio astronomy came to be.

For centuries, observations of the cosmos were confined to the optical band 0.4 – 0.7 microns. (1 micron = 10^{-6} meters) As you have learned, the optical band comprises but a tiny portion of the electromagnetic spectrum. A vast ocean of light waves rippling through the enormous expanse of the cosmos having a much longer wavelength than the optical band was yet to be discovered. This ocean of light exists in the form of radio waves (1 mm to 10 m). These radio waves had stories to tell, bizarre tales of an expanding universe, mysterious quasars, interstellar chemicals in unexpected places, white dwarfs, and black holes. Who would have suspected? We humans often believe only what we can see. Seeing is believing, but what if we had a new kind of eyes?

New Eyes for New Discoveries

In 1888 Heinrich Hertz built a device that could transmit and receive radio waves. These radio waves were polarized and could interfere just as predicted by James Clerk Maxwell's theory of electromagnetism.



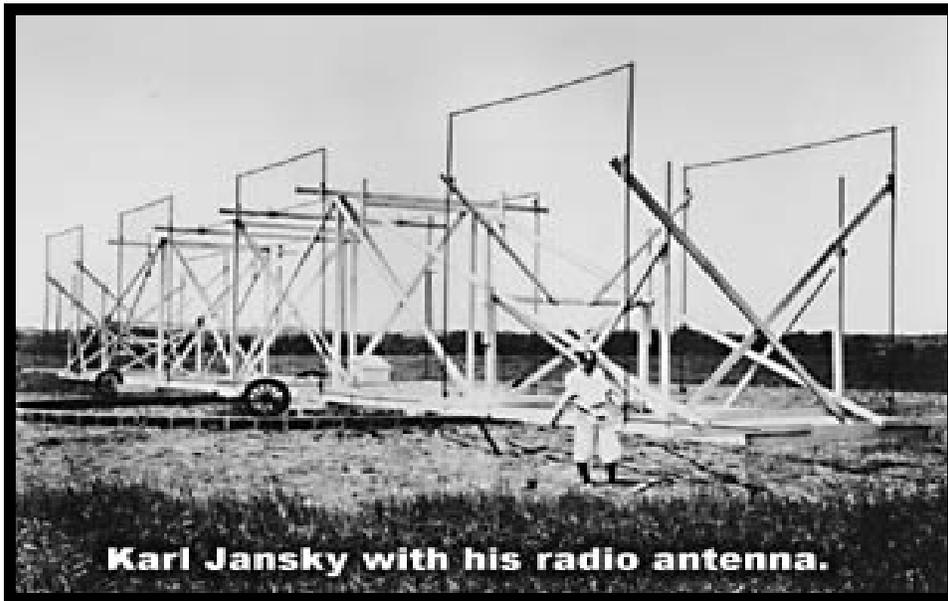
Heinrich Hertz

James Clerk Maxwell

These men saw the light and the new eyes needed to see the light was a radio antenna. Maxwell saw the light with his equations on paper and Hertz was the first to actually detect it. It couldn't have been very long before scientists thought about detecting radio waves from the Sun or other celestial bodies. The first on record to have thought about it was Thomas Alva Edison, you know, the one who invented the light bulb. You might be interested to know that his teacher the Reverend G. B. Engle thought little Thomas Edison was such an idiot that he called him "addled". Other people had the wrong idea about Edison too and mistreated him accordingly. Edison devised an experiment to measure radio waves from the Sun with steel cables wrapped around an iron core. The experiment was never carried out and it wouldn't have worked anyway. The experiment

was not very sensitive and the wavelength of radio waves it was designed to detect would have been absorbed in Earth's upper atmosphere.

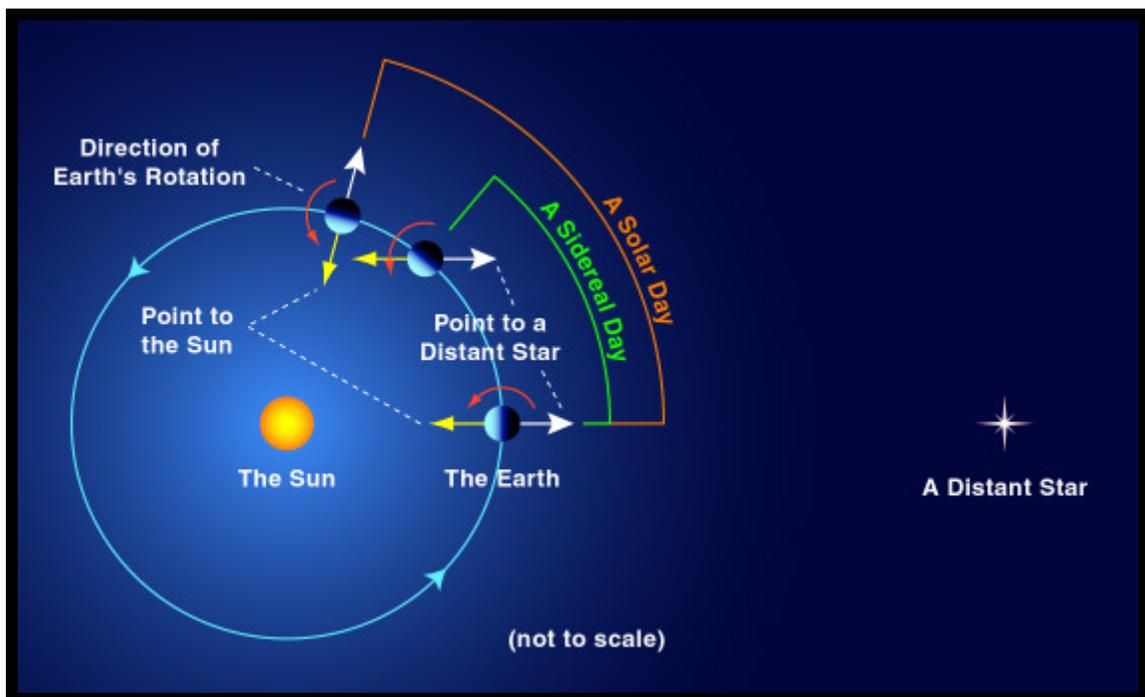
In 1931, Karl Jansky, a radio engineer working for Bell Telephone Laboratories, was assigned the task of determining the source of radio interference in Bell's transatlantic radio-telephone communications system. Radio static had proved problematic for transoceanic communications and it was Jansky's job to find out if the radio wave interference had a preferred direction, in which case they could easily tune out the interference by using directional antennas pointed away from the source of the interference. Jansky constructed an antenna to study the problem. It was a unidirectional, polarized beam antenna, 30m long by 4m high that was mounted on a circular train track so that the antenna could be rotated in azimuth (azimuth is the rotational angle along the ground.) The antenna structure rotated once every twenty minutes. It operated at a wavelength of 14.6m (20.5 MHz) and was connected to a sensitive receiver where the data obtained by the antenna was logged by a pen-and-paper recorder.



Jansky worked systematically and identified three sources of radio static: (1) static from local thunderstorms, (2) static from distant thunderstorms found to originate principally from the south, and (3) "...a steady hiss type static of unknown origin." It was this third mysterious source of static which intrigued Jansky. He had worked so systematically that he was well aware that this third source of interference was simply not a mistake or oversight. It was there but what was it? Jansky carefully studied the strange ghostly signals with all his willpower and concentration. At first he thought that his signals might be coming from the Sun. He made careful measurements of how the signal changed throughout the day and it seemed to follow a 24-hr. cycle, implying that the signals were Solar in origin. Upon closer inspection it was determined that the signals

followed a 23-hr. 56-min. sidereal cycle. These signals could not therefore be linked with the Sun. What could it be?

The answer to the riddle lay in the 4-minute time discrepancy. As the Earth revolves around the Sun it completes one additional rotation with respect to the fixed stars. The Sun rises and sets $365 \frac{1}{4}$ times per year according to someone standing on Earth's surface. There are $366 \frac{1}{4}$ **Sidereal** days in one year, each of which is 23-hr. 56-min. Can't see where the additional rotation is coming from? Imagine that the Earth didn't rotate about its own axis. Have the same side of Earth face the Sun as you revolve it once about the Sun. You'll quickly notice that the Earth's actually rotates once about its axis by virtue of having completed one revolution around the Sun. Take out two coins, a quarter for the Sun and a dime for the Earth and try it. Another way to see this is that as Earth rotates about its axis as it revolves around the Sun in such a manner that the next day arrives 4 minutes sooner than if the Earth didn't revolve around the Sun.



Sidereal and Solar Days

It was clear that the source of the mysterious steady hiss type static was associated with the fixed stars and not with our own solar system or Sun. Jansky found that the signal was strongest when his antenna pointed toward the center of our Milky Way Galaxy. This event marked the beginning of radio astronomy. It was an event of inestimable importance. Mankind saw the cosmos with his new eyes for the first time. Paradoxically, we sometimes can't see things because they're too big. Some discoveries are so important that their significance can only be understood later. The initial

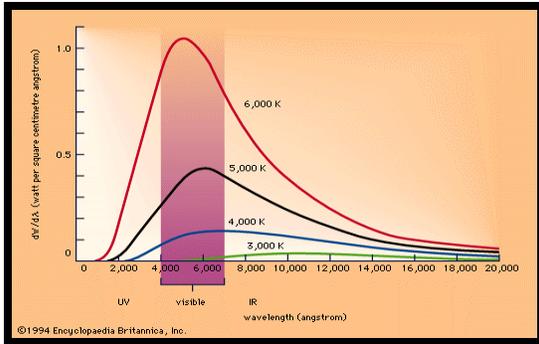
enthusiasm faded and Jansky was reassigned. The future of radio astronomy was to be developed by amateur astronomers. Etymology of the word amateur is from the Latin *amator*, meaning one who loves. We usually associate the word amateur with the negative connotation meaning one who lacks skill. This is not its original meaning. An amateur is a devotee, an admirer, someone who engages in a pursuit, study, science, or sport as a pastime rather than as a profession. Radio astronomy was to be continued by just such individuals who saw its potential. It was the good fortune of all mankind that the future of radio astronomy was to find a haven in its nascent stages with such dedicated individuals. One such amateur had an avid interest in the work of Jansky and was determined to continue exploring the vast cosmic oceans of radiation, his name was Grote Reber.



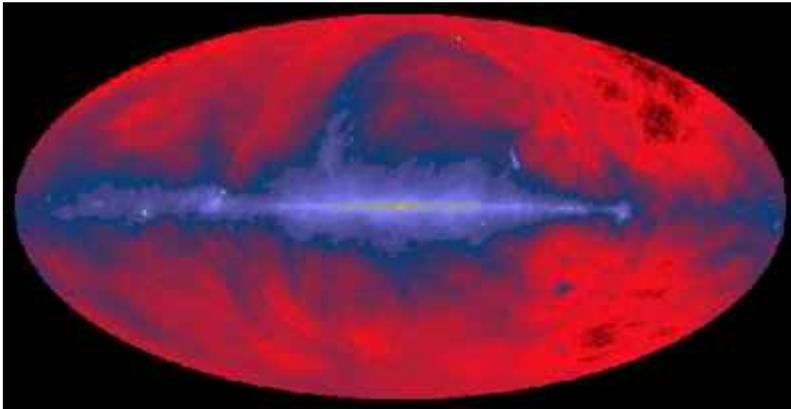
Grote Reber

In 1937, just six years after the groundbreaking discoveries of Jansky, Grote Reber constructed a parabolic-reflector antenna 9.5 m in diameter and operated it from his backyard. He built his antenna at his own expense while working for a radio company. The antenna relied on Earth's rotation to change its right ascension and was adjustable only in declination. Reber's goal was to continue where Jansky left off. He turned his antenna toward the nucleus of the Milky Way Galaxy and investigated the radio waves seen six years earlier by Jansky.

The assumption was that the radiation earlier observed by Jansky would obey **Planck's blackbody radiation law** (see the Planck blackbody frequency distribution curve). The blackbody distribution curve shows how intensity varies with wavelength for radiation emitted from an ideal **thermal** radiator. This ideal thermal radiator comes close to actual thermal bodies in most cases.



The radiation should therefore be stronger at shorter wavelengths. Reber tuned his receiver to 9.1 cm (3,000 MHz) and his first experiments failed to detect any radiation. His antenna was then adjusted to operate at a wavelength of 33 cm (910 MHz). Still no radiation detected. Undaunted he modified his receiver to pick up 1.87m (160 MHz). Almost two years after he began his experiments, Reber found the first conclusive evidence of radio emission from the Milky Way Galaxy.



Milky Way Radio Image

Reber produced the first brightness maps of the radio sky. These maps helped establish radio astronomy as a viable field of study in the minds of then contemporary astronomers. The brightest areas of the radio sky were the in the direction of the nucleus of our own Milky Way Galaxy. Reber's results demonstrated that the radiation was not stronger at the shorter wavelengths but became more intense at longer wavelengths, a trend in contradiction to Planck blackbody radiation law. The sensible conclusion to all of this is that the radiation observed by Reber and Jansky was not blackbody (thermal) radiation. Other mechanisms of radiation emission had to be at work here but what were they? This mystery remained unsolved until 1950 when Vladimir Ginzburg demonstrated that the observed increase in radiation intensity with increased wavelength could be explained by a mechanism know as **synchrotron** emissions. Synchrotron radiation is caused by high speed electrons moving at near the speed of light within the galactic magnetic fields. The magnetic field causes the electrons to spiral, traveling down a path resembling a long helix. This circular movement implies acceleration and whenever a charge is accelerated, it gives of radiation. Electrons could achieve these very high, near light velocities in cataclysmic events such as **supernovae**. At these very

high speeds, Newton's laws of motion breaks down and Einstein's theory of special relativity takes over. Because of this, it is common for scientists to refer to these high velocities as **relativistic** velocities.

Towards the end of his career, Reber made an investigation of very long radio wavelengths, 100-300 meters (1-3 MHz). These investigations were not possible in most places because the signal would be absorbed by the ionosphere. Among the few suitable places on Earth where investigations of the wavelengths could take place is Tasmania, where Reber lived out the rest of his days. Reber donated his backyard radio telescope to NRAO (National Radio Astronomy Observatory) at Green Bank, West Virginia. It was painted red, white and blue and is on display for the general public, a memorial to American ingenuity and amateurs everywhere.

The torch of radio astronomy was passed on to an unlikely place at an unlikely time. World War II ravaged Europe. The entire civilized continent lived in constant fear and anxiety over what the Nazis might do next. Despite the unceasing turmoil and tragedy enveloping the land, some astronomers were able to meet, discuss their theories, have fellowship, and turn their eyes towards the heavens to forget their terrestrial woes if only for a short time.

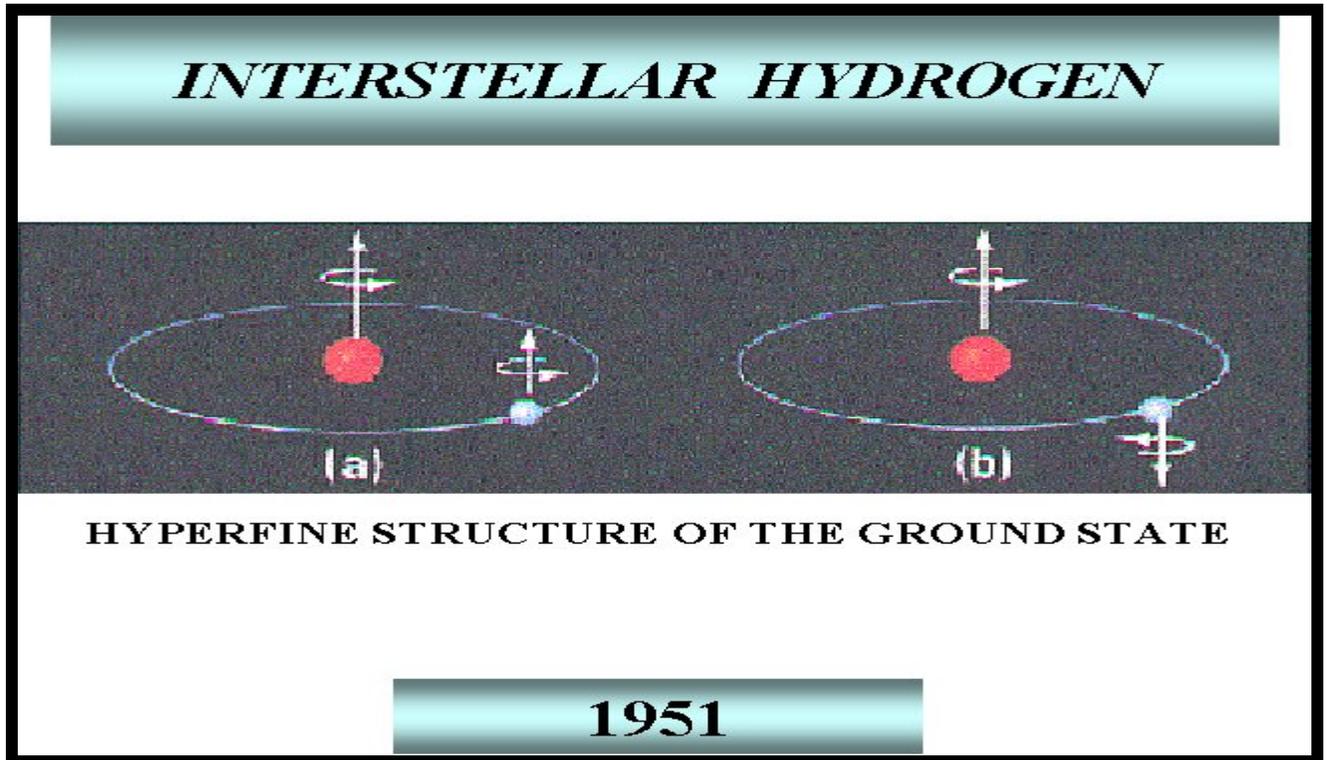
The Nazis were obsessive about censoring and regulating information inside the countries they occupied. A copy of the Astrophysical Journal managed to reach the Leiden Observatory. Inside were the groundbreaking Galactic maps and discoveries of the pioneering radio astronomers in America. In a time of little hope, this diversion was a Godsend.

Jan Oort had spent many years exploring the center of the Galaxy. (Whenever galaxy is capitalized it refers to our own Milky Way Galaxy.) His investigations were hampered by the inherent limitations of optical astronomy. On a foggy day, you can't see very far in front of you. If we were somehow able to see in radio waves, everyday would be a clear day. Jan Oort had the same problem. Intergalactic gas absorbed the visible light from the center of our Galaxy before we even had a chance of seeing it. It's as though everyday is a foggy day in our Galaxy. Jan Oort's investigations of galactic rotation met up with these difficulties. The burgeoning science of radio astronomy was the key to unlocking the mysteries hidden away in the center of the Galaxy. Jan Oort wasted no time. He set his graduate student Hendrik Christoffel van de Hulst to the task of investigating which radio frequencies one might observe were associated with the Galactic center. Since the most abundant element in the universe is hydrogen, it was suggested by van de Hulst that they examine the emission spectra of hydrogen's hyperfine structure which corresponds to a wavelength of 21 cm (1421 MHz). The hyperfine structure of hydrogen is a noticeable signature that cannot be mistaken. If the same shape of the hyperfine structure were observed at a slightly different wavelength, it's safe to conclude that it was the hydrogen hyperfine spectrum but **Doppler** shifted.

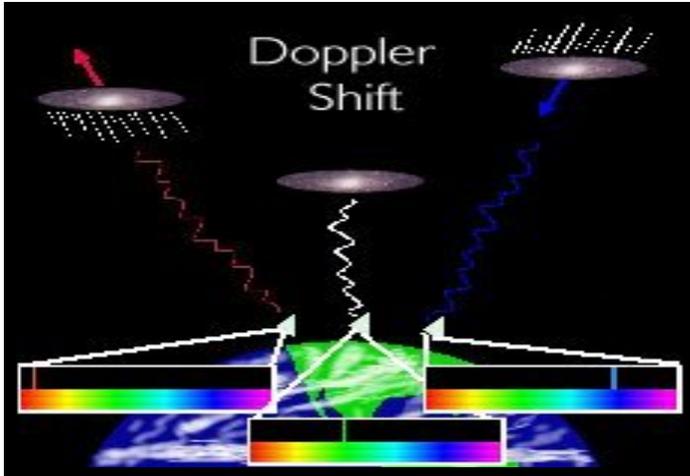
To understand the physics of what is happening here consider the frequency of the hyperfine structure of hydrogen. The hyperfine structure arises from changes of state inside the hydrogen atom from the proton and electron transitioning from a parallel to

anti-parallel arrangement. The energy difference in these two configurations, parallel and anti-parallel inside the hydrogen atom, is related to the frequency of the emission by Planck's relation. This is also called the spin-flip transition.

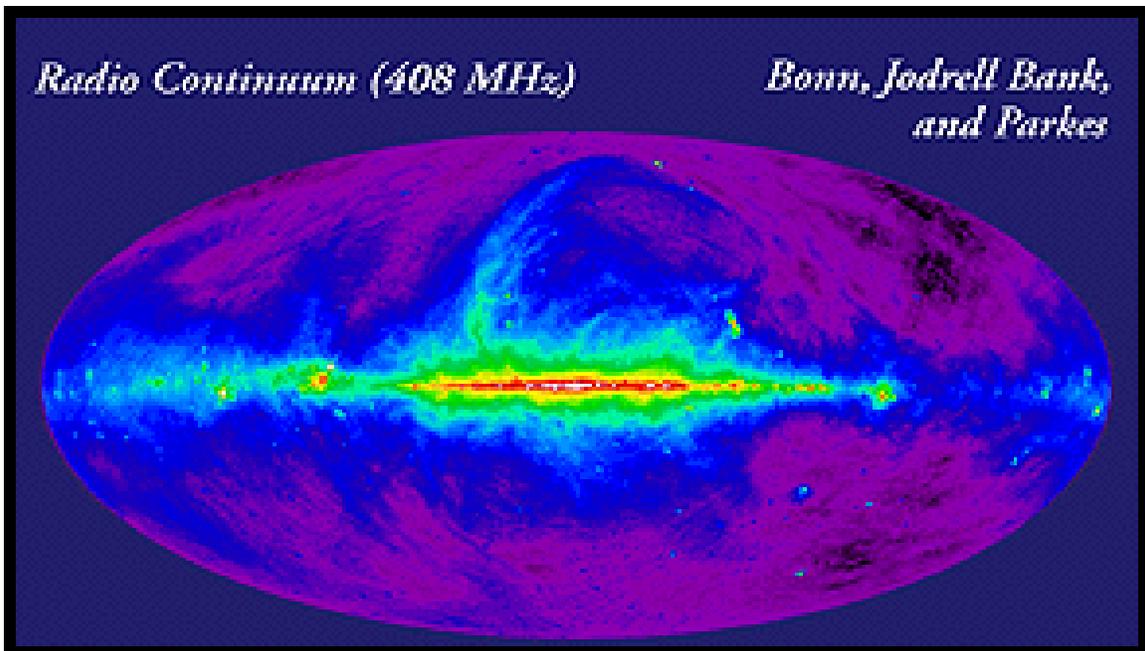
$$\text{Energy} = 6.026 \times 10^{-34} \text{ (Joules} \cdot \text{seconds)} \cdot \text{Frequency (Hz)}$$



The frequency of the radiation is 1421 Hz. If the source of the radiation is traveling toward or away from us it becomes **blue shifted** or **red shifted**. Most objects in the universe are red shifted meaning they are moving away from us. If the hydrogen is moving away from us, the wavelength will appear to be longer because the source is moving away as the waves are being made. This apparent change in wavelength, and by direct association, also the frequency, is known as the Doppler shift. It is the same phenomena observed when the pitch of a fire truck's siren changes when it approaches and recedes from an observer. The observed Doppler shift in the hyperfine structure of hydrogen makes it possible for scientists to calculate exactly how fast a galaxy or gas cloud is moving toward us or away from us.



By observing the Doppler shift in the hyperfine spectra of hydrogen, Oort and van de Hulst were able to see past the intergalactic gasses and into the core of our Galaxy. They were the first to accurately map the general features of the Milky Way Galaxy and measure its rotation, a truly monumental achievement.



Radio map of the Milky Way Galaxy