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Radio Astronomy
Observing the Invisible Universe

Course Guidebook

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Felix J. Lockman is the Green Bank Telescope Principal Scientist at the Green Bank Observatory, a radio astronomy observatory that is a facility of the National Science Foundation. He did his undergraduate work at Drexel University and received his Ph.D. from the University of Massachusetts Amherst. Dr. Lockman's area of research is the structure and evolution of the Milky Way and nearby galaxies, with a special emphasis on radio observations of neutral hydrogen.

After a postdoctoral fellowship at the Carnegie Institution for Science, Dr. Lockman joined the scientific staff of the National Radio Astronomy Observatory, where he worked for many years. He was a project scientist for the Green Bank Telescope during its construction phase and then moved to the Green Bank Observatory, where he was the site director for 6 years.

Dr. Lockman's research has involved studies of the ionized, neutral atomic, and molecular gas in the Milky Way and nearby galaxies. His research established the existence of an extended layer of neutral hydrogen in the

Milky Way and identified the direction in the sky with the least interstellar matter. Dr. Lockman is studying the gaseous halos of the Milky Way and Andromeda galaxies and the gas being expelled from the nucleus of our galaxy, using data from both ground-based and space observatories. He has published numerous articles in professional journals and has edited several books, including *Gaseous Halos of Galaxies* and *But It Was Fun: The First Forty Years of Radio Astronomy at Green Bank*. Dr. Lockman's 1990 review article on hydrogen in the Milky Way, coauthored with Dr. John M. Dickey of the University of Tasmania, is the most cited publication in the history of the National Radio Astronomy Observatory.

Dr. Lockman regularly lectures to diverse audiences about radio astronomy and related topics. He has been interviewed numerous times for print, radio, television, film, and online media and has given colloquia at universities and observatories around the world. Dr. Lockman appears in director Werner Herzog's film *Lo and Behold: Reveries of the Connected World* to discuss the Green Bank Observatory. In 2013, he was elected as a fellow of the American Association for the Advancement of Science in recognition of his significant studies of neutral hydrogen in our galaxy and others and for his service to U.S. radio astronomy. ■

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SCOPE

Radio Astronomy: Observing the Invisible Universe

Over thousands of years, the field of astronomy has progressed from watching the skies with our eyes to building telescopes to magnify the light and capture it on photographic film or with electronic detectors. But traditionally, astronomy always meant looking at light. We now know that visible light is just one of the channels that carries information about the universe. The accidental discovery of celestial radio waves gave us our first look into hitherto unexplored parts of the electromagnetic spectrum and inaugurated the discipline of radio astronomy.

Radio astronomy is the study of the universe through measurement of natural radio signals. Objects that emit radio waves have enormous diversity, and many of them don't emit any light. In some sense, radio astronomy is the exploration of an invisible universe—a universe that sometimes can only be detected through its radio emission.

In these 24 lectures, you will examine some of the objects that are studied by radio astronomers, explore the physical mechanisms that give rise to natural radio emission, and discover the amazing radio telescopes that have been built to measure these signals.

Along the way, you will meet some of the pioneers of radio astronomy, such as Karl Jansky, a physicist working as an electrical engineer who stumbled on extraterrestrial radio waves in 1931 and presented the astronomers of the world with a puzzle that they just couldn't solve. Then came Grote Reber, a young engineer in the days before World War II who filled a suburban lot outside Chicago with a radio dish that he designed and built himself. He was the first radio astronomer. In the decade of 1945 to 1955, using technologies developed during the war, a generation of scientists from diverse backgrounds tried to understand the mystery of this strange radio emission. In Australia, England, the Netherlands, and the United States, scientists built radio telescopes and discovered phenomena that had not ever been imagined before then.

You will be introduced to a number of radio telescopes built through the years, from rather simple dishes that would fit comfortably on a basketball court to enormous dishes the size of a football stadium. As a special feature, you will take a trip to one of the world's great radio observatories, in Green Bank, West Virginia, and encounter radio telescopes that are both of historical interest and on the cutting edge of research worldwide. You will explore the Green Bank Telescope, one of the largest movable objects on land that works to tolerances of a fraction of a millimeter.

Lectures focus on objects studied by radio astronomers, including pulsars, ionized nebulas, supernovas and their remnants, and the relic radiation from the big bang that marked the beginning of our universe. You will explore the particular technical innovations that enabled discoveries and the intellectual twists and turns that accompany research into the unknown.

The course will use radio observations of the planets—Mars, Saturn, Jupiter, Venus—to show how radio astronomy sheds new light on these familiar objects and sometimes reveals the totally unexpected. While looking at the planets, you will investigate the radio emission given off by everyday objects in the world around us and learn that if our eyes could pick up radio waves, it would never be dark.

You will learn about radio galaxies, quasars, and active galactic nuclei. These are enormously energetic phenomena triggered by black holes in the centers of galaxies whose radio emission can be seen across space at vast distances. You will explore the technique of radio interferometry, which allows signals from distant radio dishes to be combined, forming radio telescopes of unsurpassed acuity. You will also learn how radio astronomers made the unexpected discovery of a rich organic chemistry in dark interstellar clouds, with profound implications for the origin of life on Earth.

Lectures on hydrogen will recount the story of how its radio emission was predicted by a student in the Netherlands under German occupation during World War II and then detected later at Harvard and Leiden. When radio astronomers began mapping the hydrogen in galaxies, they discovered anomalies in galactic rotation that pointed toward the existence of something in galaxies besides the normal atoms that comprise human beings. You will discover how very basic measurements by radio astronomers led directly to the discovery of dark matter, a dominant substance in the universe, but one whose identification remains frustratingly elusive.

You will also learn about radio waves from unnatural sources, such as manmade transmissions, and consider whether we might someday receive signals from intelligent beings on another world, a world with their own radio astronomers studying the invisible universe. ■

LECTURE 1

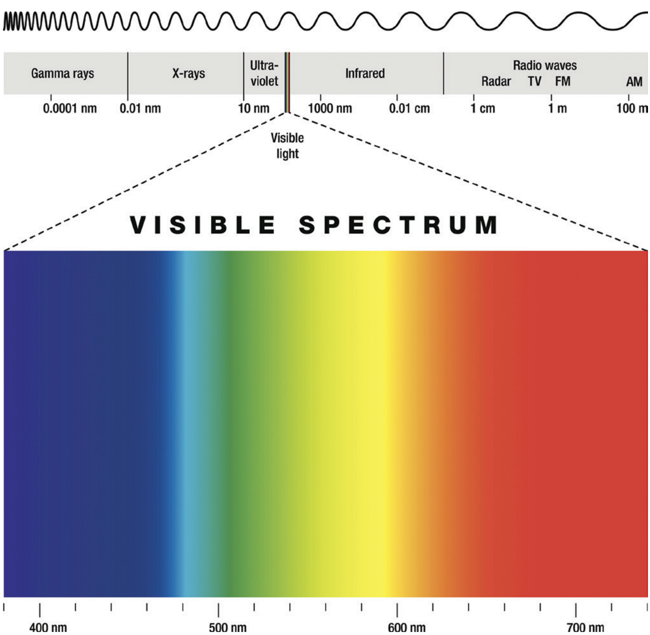
Radio Astronomy and the Invisible Universe

Astronomers have made astounding discoveries about our universe by studying the natural radio signals given off by objects in space—not only radio waves from familiar objects, such as the Sun, Moon, and planets, but also radio waves from exotic objects such as exploding stars, vast clouds of organic molecules just a few degrees warmer than absolute zero, and even radio waves from the big bang that marked the beginning of our universe. This course will sample many topics from the vast field of radio astronomy. This lecture offers an overview of radio waves and light as well as the radio telescopes that do the work of radio astronomy.

Radio Waves and Light

- Radio waves are actually a form of light. To be more precise, a radio wave is exactly the same as light, just a different color—a very different color.

- What we call light is just one part of a continuous electromagnetic spectrum distinguished by energy and wavelength. Light of different



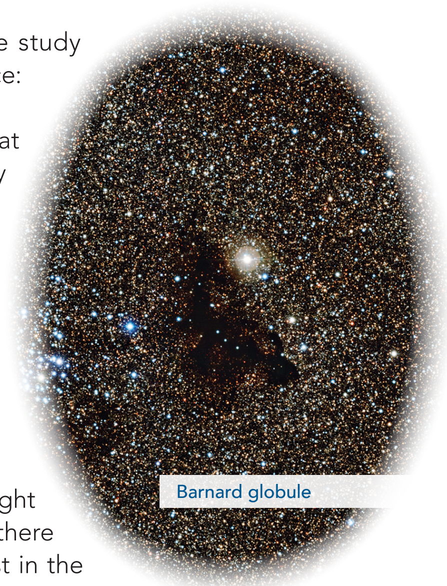
colors has different energy. For example, blue light has higher energy than yellow or red light. And red light has a longer wavelength than blue light.

- Radio waves are on the left end of the spectrum; they are the lowest-energy light with the longest wavelength. Between radio and light is the infrared—the radiation that our skin feels as heat. And higher energy than light is ultraviolet radiation, the kind of light that can give us a sunburn.

- Radio, infrared, light, and ultraviolet are all forms of electromagnetic radiation that have been given different names. X-rays are also on the spectrum, at higher energies than the ultraviolet. Gamma rays are the highest-energy light with the shortest wavelength.

- There are at least 3 reasons why we study the radio waves from objects in space:

    - There are things out there that just don't give off any light. They don't emit light or reflect light, but they do give off radio waves. If we did not receive their radio waves, we wouldn't know about them. An example is a pulsar, which is what remains behind after a massive star ends its life in an enormous explosion.



Barnard globule

    - Radio waves can go places that light cannot. In interstellar space, there are clouds of dusty gas. The dust in the interstellar clouds totally blocks the light from behind it. Clouds like this are common in the Milky Way, our home galaxy, so when we try to look through the Milky Way, the light is blocked by dust. Radio waves can pierce the dust and


Milky Way Galaxy

reveal what's behind those dark clouds. Even better, radio waves can sometimes tell us what's going on inside those clouds.

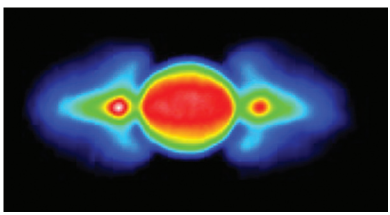
- Radio astronomy can be done from the ground—from the surface of the Earth—without the expense of going into space. The Earth's atmosphere acts as a kind of protective blanket around our planet. On clear days, the atmosphere lets the sunlight through just fine, and some light comes through even when it's cloudy. The atmosphere is pretty transparent to light. But the atmosphere is not transparent to all parts of the electromagnetic spectrum, including x-rays, gamma rays, ultraviolet, and most of the infrared. The atmosphere is transparent to radio waves, which is why we can do radio astronomy from the ground.

Jupiter

- Jupiter is a giant gas planet that is much farther from the Sun than Earth is. Here's how Jupiter looks in visible light:

- Actually, Jupiter does not give off any light itself, but it reflects sunlight, and that's what we see.

- Here's a radio image of Jupiter:



- This is what we detect with a radio telescope.

- With Jupiter, we detect something in the radio that just does not give off light, and this means that we are learning something about Jupiter that we couldn't learn from reflected sunlight alone.

- How do we make pictures from radio waves? We could display the radio data on Jupiter as a bunch of numbers. After all, that is how we detect radio waves: by measuring the output of a receiver and turning that into a number or set of numbers.

- But where possible, we like to take advantage of the power of the human eye. After all, we humans are really good at recognizing patterns in pictures. So, when possible, we turn the numbers that come out of a radio telescope into a picture of the intensity of radio waves.

- And we often color the pictures. Radio waves don't have color, but we color the radio images to make use of the power of our eyes to see patterns in color. We use an arbitrary color scale, but it helps us visualize the radio signals.

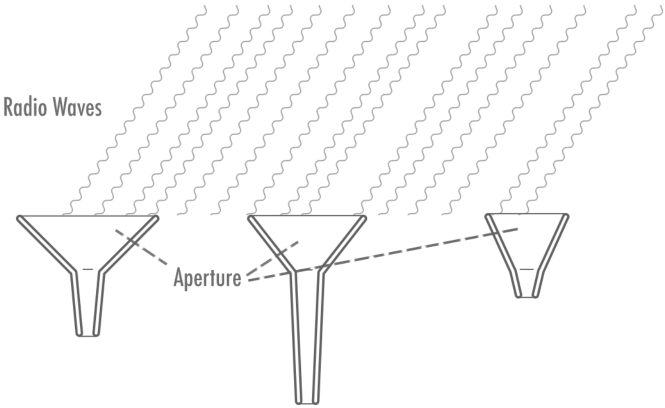
Radio Telescopes

- What does it take to capture the radio waves from galaxies exploding at the edge of the universe? Despite the fact that we are looking at some of the most energetic events in the universe, they are so extremely distant that by the time the radio waves reach Earth, the signals are extremely faint.

- From a purely abstract point of view, we can look at a telescope that collects radio waves as a funnel that just concentrates radio waves from a certain direction in the sky to a spot where we can put a receiver.

- As far as collecting radio waves, it's not the depth of the funnel or its shape that matters. The amount of radio waves we collect depends on the size of the opening, or aperture.

- We measure the intensity of radio waves as the power that passes through an aperture of 1 square meter in 1 second in a bandwidth of 1 hertz.



- We measure the intensity of radio waves in units called janskys, named after Karl G. Jansky, who first discovered radio waves from space: 1 jansky has the value of 10^{-26} watts per square meter per hertz:

  1 jansky = 0.00000000000000000000000001 watts/square meter/hertz

- That is a very small amount of energy. In modern times, we are studying objects in the universe that are measured in millijanskys and microjanskys, a million times weaker than a jansky. By comparison, a standard cell phone at a distance of about 1 kilometer puts about 5×10^{15} janskys, or 5 million billion janskys—5 million billion times stronger than the signal we'd get from a bright quasar.

- How do we detect such faint signals? We will want to have as many square meters as possible in our aperture; in other words, we want a big funnel. Also, most radio sources are fairly constant in time, so we can add up their signals over many seconds—minutes, hours, sometimes even days and months. We often also average over many hertz of bandwidth, sometimes a megahertz or more.

- All this gives us a signal that we can measure with state-of-the-art receiving systems cooled to a temperature near absolute zero. But a large aperture comes first, and modern radio telescopes have apertures of thousands of square meters.

- Most modern radio telescopes look like big dishes and are the equivalent of radio mirrors. They collect radio waves, measure them, and bring them to a focus. The telescopes also have to point at different parts of the sky to track objects as they rise and set.

- The science of radio astronomy began after World War II, when the technologies developed for the war effort were turned to peaceful uses. From 1955 to 1965, nations around the world opened radio observatories and began exploring an invisible universe through this new window.

Scientific Notation

In scientific notation, we express numbers as a power of 10, with a decimal number in front to show where within that power of 10 the number lies. Here is the decimal notation and scientific notation for several numbers:

1.0	1.0×10^{0}
100.	1.0×10^{2}
100,000.	1.0×10^{5}
311,000.	3.11×10^{5}
100.5	1.005×10^{2}
0.1	1.0×10^{-1}
0.003	3.0×10^{-3}
0.000025	2.5×10^{-5}

1 Jansky = 1.0×10^{-26} Watts / sq. meter / Hz

To put a big number into scientific notation, just shift the decimal point to the left and put as a power of 10 the number of places you've shifted it. For a number less than 1, shift to the right and put the negative of the number of places in the exponent.

For the number 311,000, the decimal point is shifted 5 places to the left, so it's written 3.11×10^{5}.

- Optical telescopes need to be away from city lights and at as high an altitude as possible to get above the clouds and to reduce the blurring of starlight by the atmosphere. That's why large optical telescopes are in domes that are sited on remote mountaintops.

- Radio observatories aren't worried about light; their enemy is interfering radio signals from manmade transmitters. That's why radio observatories are located as remotely as is practical and, where possible, on valley floors shielded by mountains. The mountains provide shielding from distant radio transmitters from TV stations, cell phone towers, and the like that could interfere with the radio signals from space.

- And although you can't see light from the stars on a cloudy night, lower-frequency radio waves can come through even overcast skies, so countries such as England, the Netherlands, France, and Germany—where there aren't many locations for good optical telescopes—built radio observatories instead.

- Radio telescopes can have a long lifetime. New discoveries are made continually, and many of the objects studied by scientists today were completely unknown when radio telescopes were first built. So, while some of the early telescopes have been dismantled, decommissioned, or used for other purposes, some are still on the front line of research.

Suggested Reading

Goddard and Milne, eds., *Parkes*.

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

Lockman, Ghigo, and Balser, eds., *But It Was Fun*, parts II and III.

Lovell, *The Story of Jodrell Bank*.

Sullivan, ed., *The Early Years of Radio Astronomy*.

Questions to Consider

Let's say that you detect an unusual radio signal from your antenna. What steps might you take to determine if it was coming from outer space, an orbiting manmade satellite, or a transmitter somewhere on the ground?

The discovery of radio waves from Jupiter made headlines in the newspapers at the time. Even today, astronomical discoveries seem to be featured more often in the media than discoveries in chemistry and physics. Why do you think this is?

LECTURE 2

Thermal Radio Emission: The Planets

For most of human history, the word "astronomy" meant looking at the sky with our eyes. As technology advanced, telescopes were invented to gather faint light from celestial objects, and then cameras came along to record the light. But still astronomers ended up looking at light—just light. By the 20th century, astronomers were generally aware that the universe might be signaling to us in other parts of the electromagnetic spectrum, but efforts in the early 1900s to detect such signals turned up nothing. Now, using telescopes that are sensitive to radio waves, not light, we can see a different universe.

How Does Nature Make Radio Waves?

- There are sources of manmade radio waves all around us: cell phones, radio and TV stations, radar from aircraft, transmissions from GPS satellites to Earth, etc. Turn on a radio and you will pick up a signal. But we are also constantly bathed in natural radio waves coming from the Earth and sky.

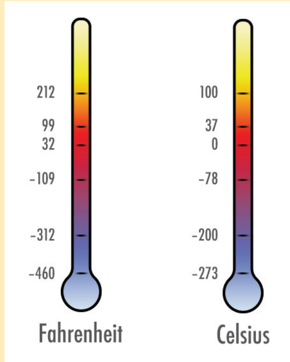
- The objects around us—the stuff of our world—do not naturally give off light. We depend on some external source of light, such as the Sun or a desk lamp, for illumination. And in that illumination, light reflects off an object, and the light is changed. When light reflects, it picks up information that allows us to distinguish a fork from our food and a friend from a foe.

- Almost every object that has a temperature above absolute zero naturally gives off radio waves. If our eyes could detect radio waves, it would never be dark.

Heat and Light

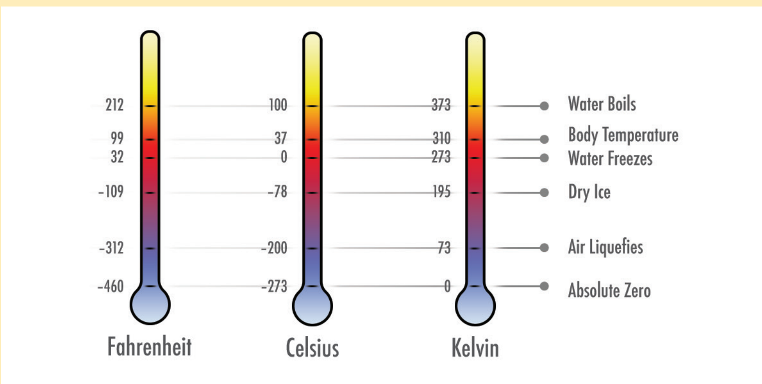
- Objects around us—our room, our bodies, the entire planet—don't give off light, but visible light is just one part of the electromagnetic spectrum, and electromagnetic radiation can be produced through

Temperature Scales

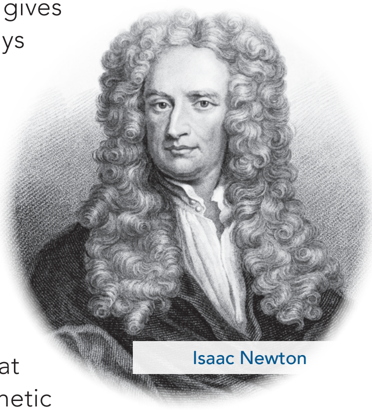


Depending on where you live, you are used to measuring temperature in either degrees Centigrade (also called Celsius) or degrees Fahrenheit. Fahrenheit is a pretty arbitrary scale but gives fine gradations. Celsius, on the other hand, is not arbitrary. The Celsius or Centigrade thermometer divides the temperature scale into 100 equal units between the freezing point and the boiling point of water. Celsius degrees are bigger than Fahrenheit degrees, so it's a coarser scale than Fahrenheit but more natural.

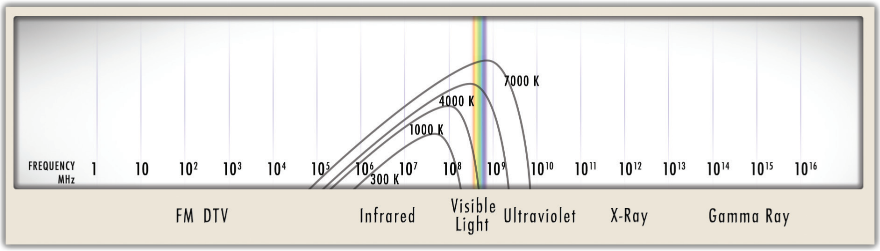
Astronomers use yet another temperature scale, called the Kelvin scale, because there is nothing special in the universe about water or its freezing point. The Kelvin scale has the same temperature intervals as Celsius, but the difference is that it starts at absolute zero—the temperature where all motion ceases. It's as cold as it can get.



heat. If you get something hot enough, it gives off light, or ultraviolet light, or even x-rays or gamma rays.


Isaac Newton

- The relationship between heat and light perplexed scientists for quite a long time. Isaac Newton, the great scientist of the late 1600s, knew that light could be made from heat, but he did not know how. It wasn't until the 20th century that a German scientist named Max Planck discovered that an object at a given temperature emits electromagnetic radiation in amounts described by this graph.

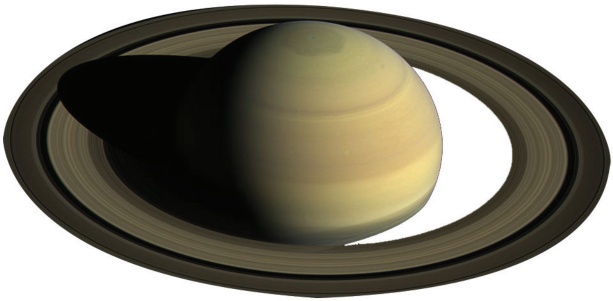


- The vertical axis is the intensity of the radiation emitted, and the horizontal axis is the part of the electromagnetic spectrum where it emits. Two things stand out: The curve has a very sharp drop-off at the higher energies, and it has a long, slow decline to longer wavelengths, or to lower energies—to the radio part of the spectrum.

- Almost every warm body—everything that has a temperature above absolute zero, such as people, rocks, and the Sun and Moon—emits radiation in a pattern that more or less follows this curve.

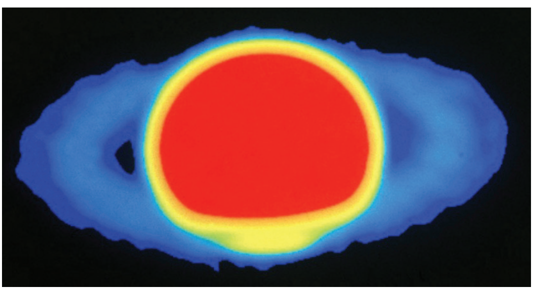
Saturn

- Saturn is one of the larger planets in the solar system. It is a gas giant planet, so what we're seeing in the following photo of Saturn in visible light is its atmosphere and clouds in its atmosphere. It's famous for its rings, which are bits of rock, ice, and dust in orbit around it. There are a number of rings separated by dark gaps.



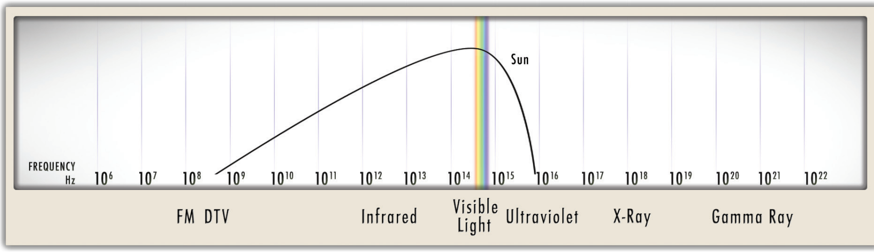
- Notice the stripes on the planet showing structure in the clouds. Also notice that the rings are about the same brightness as the planet itself.

- Now let's see how it looks to a radio telescope.



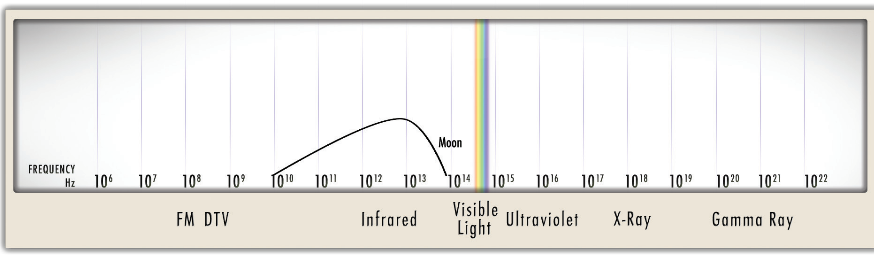
- The radio signals are colored to show their intensity. The brightest radio signals are red, and the faintest are dark blue. There is no sign of clouds or stripes. In visible light, the rings are just as bright as the planet, but in the radio image, they are much fainter. What new information are we getting from the radio image of Saturn?

- Let's look again at the radiation curves, only now we'll vary the temperature of the object. Here's what the curve looks like for a body as hot as the Sun.

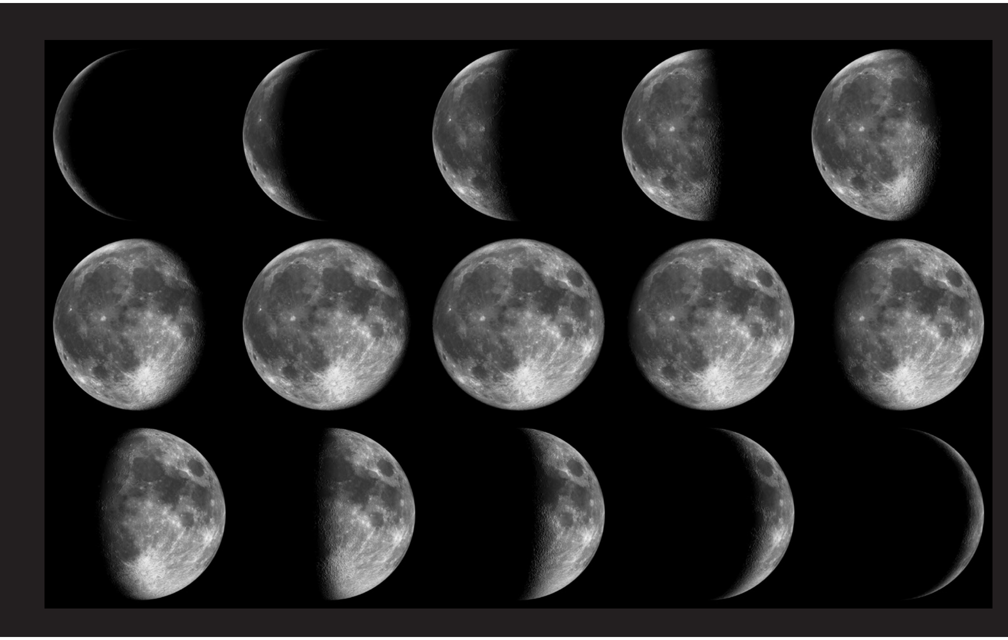


- Notice that the peak energy is emitted in the optical as light, which is where our eyes work—very convenient. But notice that the Sun gives off energy in the infrared and radio as well.

- Let's dial down the temperature to the temperature of the full Moon.

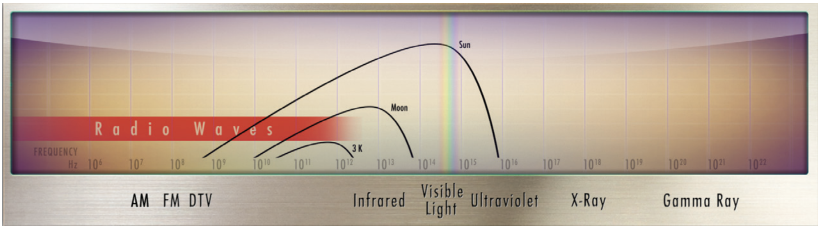


- This curve predicts that the Moon would not give off any light—which is correct. Moonlight is entirely reflected, which is why the Moon goes through phases as the Sun shines on it from different directions.

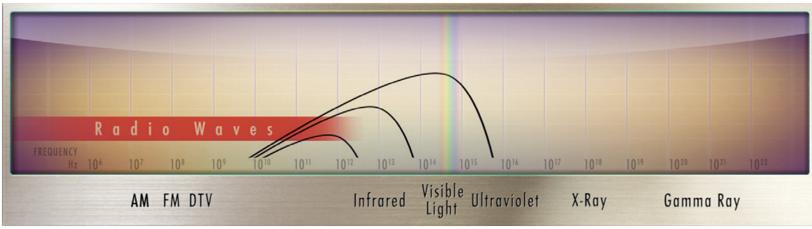


- Natural radiation from the Moon doesn't get to energies higher than the infrared, but it still emits in the radio.

- Finally, let's look at the radiation that would be emitted by a chunk of rock only a few degrees above absolute zero, which is about the coldest that things get in our universe at the current time. This feeble radiation does not even make it into the infrared, let alone give off light, but it shines in the radio.

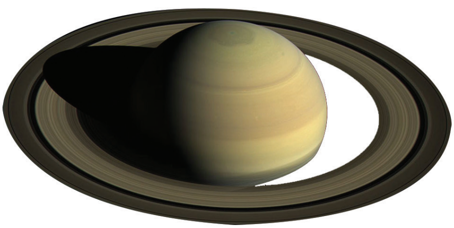


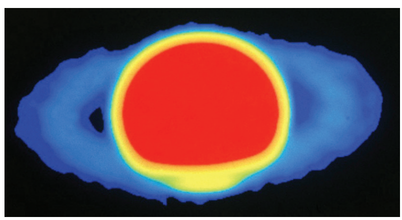
- In the following image, the 3 curves have been shifted vertically to emphasize their shape. Their shape differs only at the high-frequency end. A blackbody the temperature of the Sun extends its emission into the visible light region. But all 3 blackbodies—even the coldest—has some emission at radio energies.



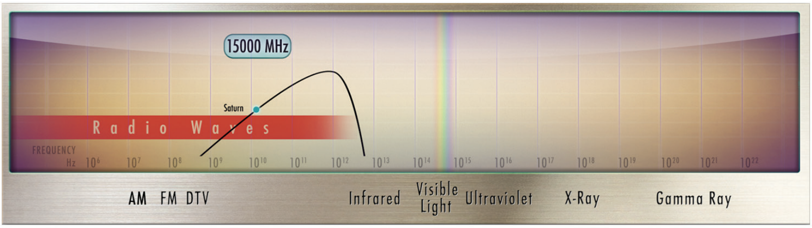
- If there is stuff in the universe that is too cold to emit light and too cold to emit in the infrared, we might still be able to detect it. That's because everything that has any temperature above absolute zero is capable of emitting radio waves. This is called thermal emission because it depends on the temperature of an object.

- The radio emission from objects at room temperature is weak, but with the right equipment, it can be detected. If you take a thing, such as a chunk of rock or a planet, and measure the intensity of its radio waves, you can get a good idea of the actual temperature of the thing—whatever it is, wherever it is.

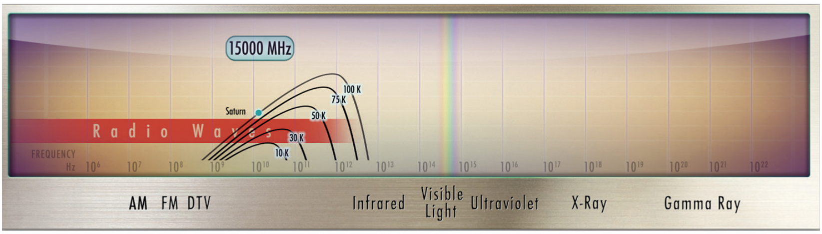




- The planet of Saturn itself has a certain radio brightness that we can measure. Let's see where it falls on the Planck curve.



- Here's our measurement of the radio emission from the body of Saturn. The measurement was made at 15,000 megahertz.



- The central part of the image has a radio brightness given by that point. A body at 100 kelvins produces just the amount of radio radiation that we have measured. We've just learned that the temperature of Saturn where the radio waves originated is 100 kelvins, or about –175° Celsius. Using naturally emitted radio waves, we've just measured Saturn's temperature from 750,000,000 miles away.

- What makes this particularly interesting is that Saturn is hotter than it should be if its only source of heat was from the Sun. Saturn must have some interior sources of heat that are trapped by the dense atmosphere.

- But our radio picture shows a planet that is hotter than its rings, while in visible light they look about the same brightness. And we don't see the fine-detailed structure in the planet's radio emission that we see in visible light.

- Part of the answer is that Saturn, at a temperature of just 100 kelvins above absolute zero, is too cold to emit light, so the light we are seeing is entirely reflected sunlight. The structure that shows up in reflected sunlight is the different reflectivity of cloud tops and wind patterns. The icy dust particles in the rings reflect sunlight just about as well as the planet, so they look bright in the photograph.

- But through radio observations, we are actually measuring electromagnetic radiation—radio waves—emitted by Saturn itself, and we can see that the rings are colder than the planet. They not only don't have internal sources of heat, but they don't have an atmosphere to keep it trapped.

- You would never guess all of this from looking at Saturn's light.

Blackbodies

- When we try to understand real objects in the real world, we often find that they're extremely complicated and difficult to analyze. So, we create a theoretical object, such as a frictionless wheel or an ideal gas—something that we can understand totally. We can then use this idealized object as a guide to the real, messy world.

- The theoretical object that Max Planck studied when he came up with his Planck curves is called a blackbody. It is an object so black that it absorbs every bit of energy that falls on it, and it is at a constant temperature, in equilibrium with its surroundings, getting neither hotter nor colder with time.

- The Planck curve, which is the relationship between the temperature of an object and the amount of radiation it emits, applies only to a perfect blackbody.


Max Planck

- In reality, there are a lot of things that behave as blackbodies, absorbing nearly all the radiation—light, radio waves, x-rays, and so on—that fall on them. A very black rock, the Moon, and even many stars are good approximations to a blackbody. The Planck curves describe the emission from these objects reasonably well.

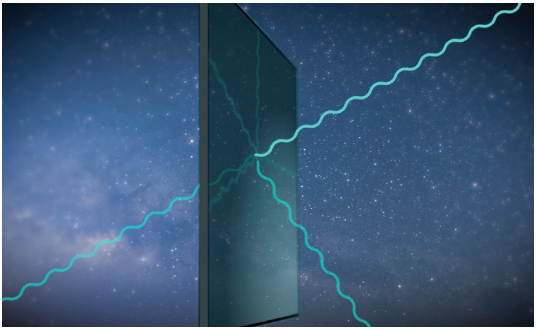
- It's only at room temperature that blackbodies appear truly black to the eye, but heat a blackbody enough and it emits light like a star. It's still a blackbody. Hot blackbodies don't look black, but they still absorb all the radiation that falls on them.

- The opposite of a blackbody is a mirror. A perfect mirror reflects every bit of the radiation that falls on it, whether light or radio waves, and does not behave as a blackbody. Because of this, a perfect mirror does not emit any electromagnetic radiation.

- Another thing that is the opposite of a blackbody is an object that is completely transparent—something that allows all the radiation that falls on it to pass through it.

- In reality, objects tend to have properties somewhere between blackbodies, perfectly transparent materials, and perfect mirrors, but there are pretty good blackbodies and pretty good mirrors as well.

- Let's consider a piece of glass. Light hitting it is partially reflected, most passes through, and a very little is absorbed. So, the glass acts a little like a blackbody, but a very bad blackbody.



- When radio waves hit the surface of something, they can be absorbed, transmitted through to the other side, or reflected—or some combination of these. When they are absorbed, the object in some way acts like a blackbody and emits radio waves, whose intensity depends on its temperature.

- Just as the metal surface of a mirror reflects light, many metals do a very good job of reflecting radio waves. Aluminum absorbs less than 0.1% of the radio waves falling on it and reflects more than 99.9%. But the fact that it absorbs anything means that it radiates slightly like a blackbody of the same temperature, just with a reduction in emission to less than 0.1% of what a true blackbody would emit. The effect is so small that for practical purposes, we can consider a sheet of aluminum as a perfect reflector of radio waves.

- The technical term for the reflectivity of an object is its albedo. It is the fraction of light (or radio waves) that's reflected from an object. A perfect mirror has an albedo of 100%; a perfect blackbody, which absorbs all electromagnetic radiation that hits it, has an albedo of zero.

- The Moon reflects only about 7% of the light that falls on it; it has an albedo of only 7%. That's about the same reflectivity as an asphalt road, and that's why the Moon acts like a pretty good approximation of a blackbody.

Suggested Reading

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

Verschuur, *The Invisible Universe*, chap. 3.

Questions to Consider

1. Both a star and its planets give off thermal radio emission: the star from its heat and the planet because it is heated by the star. What is the challenge of detecting the thermal emission from a planet around a star far from Earth?
2. We've seen a number of figures where radio waves have been turned into images so that our eyes can pick out details. What do you think should be the main considerations when making such images?

LECTURE 3

The Birth of Radio Astronomy

In this lecture, you will meet Karl Jansky, Grote Reber, and Ruby Payne-Scott—3 early pioneers of radio astronomy with 3 different trajectories to their careers. Through their stories, you will discover that radio emission from the universe gives us a glimpse into things we could not otherwise imagine.

Karl Jansky

- In 1930, the new technology of communicating by radio over large distances was just a few years old, but business was booming. A radio engineer named Karl Jansky working at Bell Telephone Laboratories was given the assignment of finding out what natural radio signals might confuse transatlantic telephone communications.

- Jansky had an antenna that could scan the horizon, looking for sources of interfering signals. The antenna and receiver worked at a low frequency by today's standards, around 20 megahertz, but it was state of the art in those days.

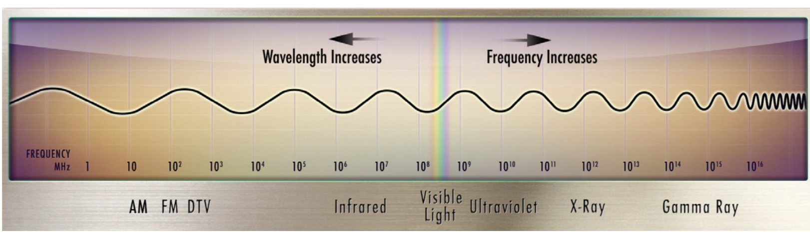
- By 1932, Jansky saw and heard a lot of radio signals from thunderstorms, both near and distant. But he also saw something else: a faint but persistent radio hiss that swept across the sky each day. After he had a year's data, he finally understood that the signals were coming from a fixed point in space outside of the solar system.

He had discovered radio waves originating from the center of the Milky Way.

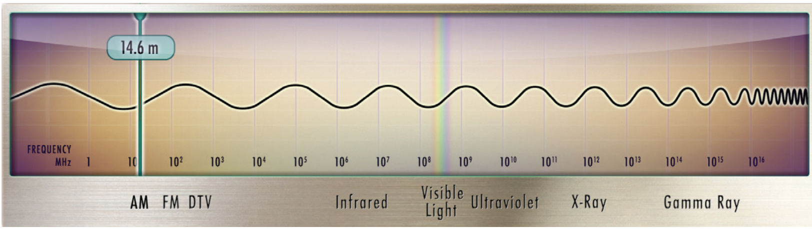
- When work on radar began in Great Britain in the 1930s, engineers knew that besides the return signal reflected off an incoming aircraft, they could also expect to get some signal in their antennas from this celestial static. They called it Jansky noise. And the unit of radio-wave intensity from astronomical objects is called the jansky.

- Jansky never did much follow-up work on his celestial static. A few scientists at other institutions made attempts to detect the radio emissions, but it was clear that progress would require large antennas, and there wasn't the enthusiasm or the funding to build them.

- On the electromagnetic spectrum, frequency increases to the right and wavelength increases to the left. The speed of light—a constant of nature—is equal to the frequency times the wavelength: $c = vl$. Low frequencies, or small frequencies, mean long wavelengths.



- We can consider radio signals as waves, and the wavelength is the distance between two peaks of the wave. Jansky made his discovery at a wavelength of 14.6 meters, or about 50 feet, so his waves are quite long. Here's where they are on the spectrum.



- A wavelength of 14.6 meters is a frequency of about 20 megahertz. Our unit of frequency is the hertz, named after German scientist Heinrich Hertz. A radio signal that has a frequency of 1 hertz means that 1 wave passes by each second.

- With frequencies, we use prefixes such as "kilo-" for 1000 times, "mega-" for 1 million times, and "giga-" or 1 billion times. A gigahertz is 1000 times a megahertz. This means that Jansky's antenna picked up waves that were passing by at 20 million times per second.

- Early radio work began in the kilohertz regime. The technology was easier at the lowest frequencies. Those waves are really long. So, as radio engineers began pushing their way to higher frequencies, they began talking about shortwave radio. By today's standards, we don't think of a wavelength of 14.6 meters as being short, but Jansky did.

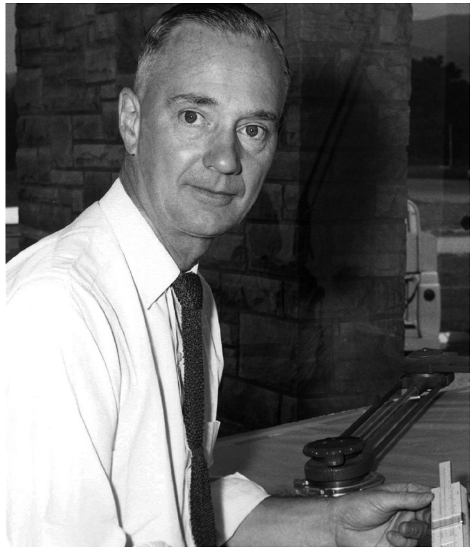
- Today, radio astronomers work at frequencies ranging from megahertz to terahertz, which is 1 million megahertz. Wavelengths can be smaller than a millimeter. The phrase "short-wave radio" is still used.

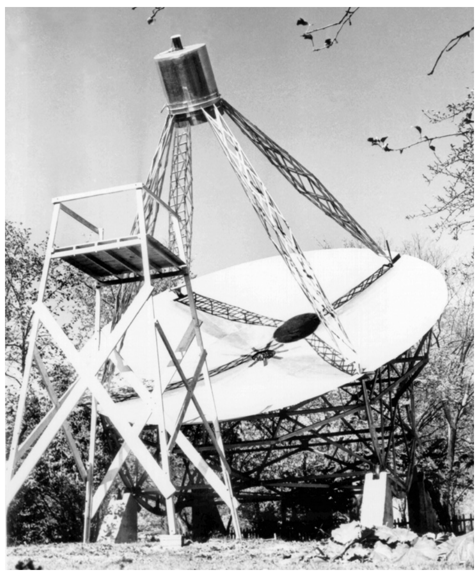
Grote Reber

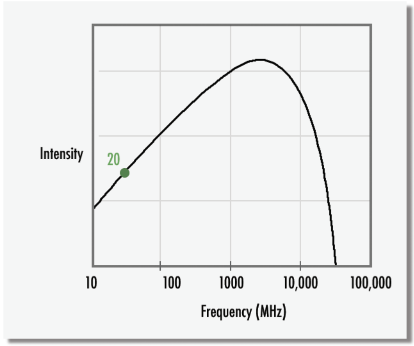
- In the mid-1930s, Grote Reber enters the story of radio astronomy as a recent college graduate with a degree in electrical engineering. He is one of the most singular scientists of the 20th century; he became the world's first radio astronomer.

- To look for the signal that Jansky saw, avid amateur radio operator Reber designed and built the first dish ever to be used for radio astronomy. He designed a dish that was 31 feet across, built it in the vacant yard next door, outfitted it with homemade receivers, and began scanning the skies.

- Reber got all of the basic design features of radio dishes just about right—with no one to guide him. Besides Reber's knowledge of how to collect and focus radio waves, he knew something else: If the radio radiation that Jansky detected came from a thermal source, then that source would emit more or less like a blackbody, following Planck's curve.



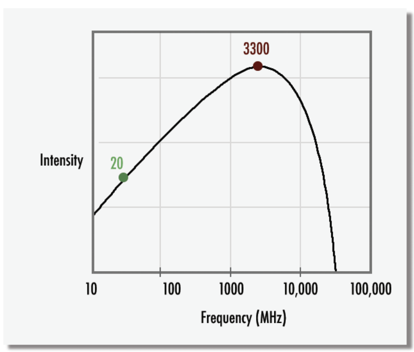




- Here is a 2-dimensional graph of the electromagnetic spectrum, with the vertical axis being intensity of radiation and the horizontal axis being frequency. Note the scale: Double the frequency and the signal gets 4 times stronger.

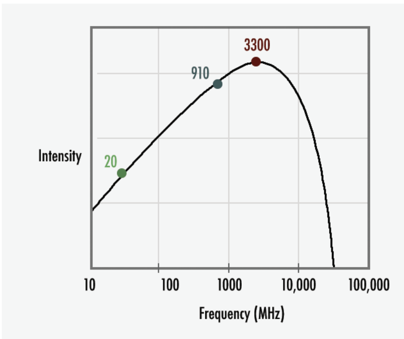
- Jansky's point is on the figure, and a Planck curve has been drawn through it for a very cold blackbody—an object at only 100 kelvins above absolute zero. For Jansky to have detected anything at his low frequency of 20 megahertz, that thing should come screaming in at higher frequencies if it is thermal emission.

- Reber knew this, so he made his first measurements in 1938 at what was then the very high frequency of 3300 megahertz, a wavelength of only 9 centimeters.



- He did not detect anything. If it was thermal emission that Jansky saw at 20 megahertz, then at 3300 megahertz it should have been more than 20,000 times stronger. But the signal was not there.

- Reber kept going. Nothing showed up at 3300 megahertz, so he tried a lower frequency, closer to the frequency where Jansky worked. He rebuilt his entire receiving system to work at 910 megahertz, and here's his second point on our chart, below.



- During late 1938, Reber scanned the skies at 910 megahertz. The result was still nothing.

- He changed his frequency again, rebuilding all of his receiving equipment. This time he dropped it to 160 megahertz. At last, he got a signal. His guess was correct: The radio emission discovered by Jansky did not follow a Planck curve, but was actually the reverse. Instead of getting stronger at higher frequencies, it was stronger at low frequencies.

- Reber used his homemade dish to map the sky and discovered that this new emission was concentrated to the Milky Way's band of bright stars. Just as Jansky had discovered, the radio signals were most intense toward the center of the Milky Way, but there were also a few hot spots whose origin was unknown.

- Here's a map that he made of the radio emission from the sky. He not only confirmed Jansky, but he also made a real radio map of part of the sky.

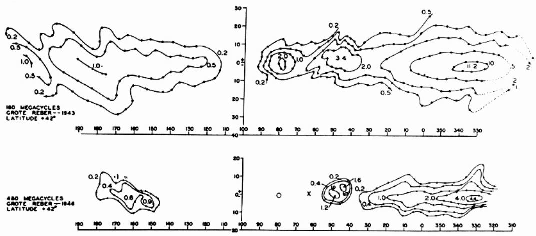
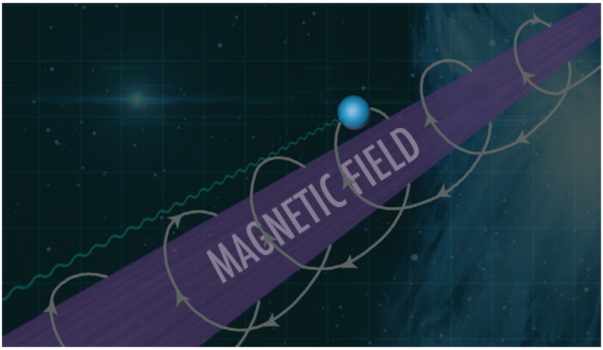


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

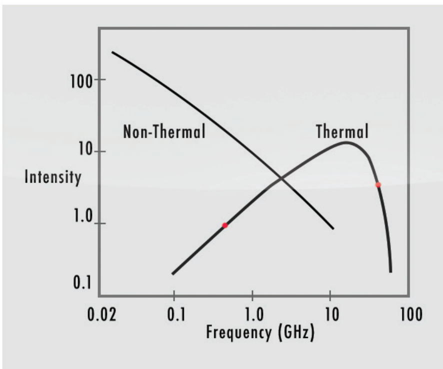
- These are 2 maps of the same regions of the sky, oriented so that the Milky Way is horizontal. The upper map is at 160 megahertz, and the lower map is at 480 megahertz. The maps show two important things: Most of the emission is confined to the plane of the Milky Way, and the emission is more extensive and brighter in the upper map (at the lower frequencies). This is exactly the opposite of what you would expect from thermal blackbody emission.

- Reber discovered that nature can produce radio waves by a process that has nothing to do with heat.

- If you take an electron traveling near the speed of light—our Milky Way Galaxy is full of electrons—and it encounters a magnetic field—our Milky Way is threaded by magnetic fields—the electrons will spiral around the field, producing electromagnetic radiation whose intensity rises to lower frequencies. That's what Jansky and Reber saw.



- Here is the expected behavior of thermal—blackbody—radiation compared with nonthermal radiation.



- The electrons and magnetic fields give off no light and are a pure discovery of radio astronomy. This discovery opened the way to an entire universe of phenomena that we are still exploring. It put radio astronomy on the map in the early 1940s.

- Nonthermal radiation is radio radiation that does not follow the spectrum of a Planck curve. A spectrum describes the intensity of electromagnetic radiation as it changes with frequency or wavelength. A Planck curve shows the spectrum of thermal blackbody radiation: It varies in a specific way with frequency.

- The spectrum of a blackbody, the Planck curve, is determined by one parameter only: temperature. The amount of radiation emitted per square meter of surface by 2 blackbodies at the same temperature is identical.

- The problem with Jansky's discovery is that his radio signals from space are so bright at megahertz frequencies that they imply temperatures of more than a billion degrees—hotter than any physical object can get without being destroyed totally. What could be producing radiation so bright, and from so much of the sky? Of course, there's no problem if the emission is nonthermal, which has nothing to do with temperature.

Ruby Payne-Scott

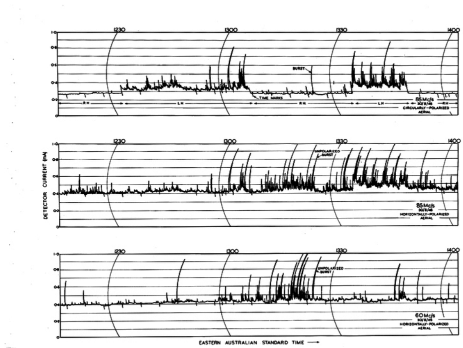
- Australian mathematical physicist Ruby Payne-Scott made radio observations of the sky in 1944. These radio-astronomical observations were not only the first made anywhere in the Southern Hemisphere, but Payne-Scott was the first woman radio astronomer anywhere in the world.


Ruby Payne-Scott

- She joined the Radiophysics Laboratory, an Australian government organization, in August 1941. She developed techniques for finding weak radio signals and created more accurate radar systems for detecting aircraft. In the late 1940s, Payne-Scott, together with her collaborator Joseph Pawsey, made groundbreaking experiments that placed Australia at the forefront of radio astronomy.

- During World War II, radar stations in England looking for German aircraft discovered that the Sun was emitting radio waves. Payne-Scott and 2 colleagues observed the Sun using a dish built for radar in October 1945 and discovered that its emission corresponded to a blackbody temperature of 15 million kelvins. Because the visible surface of the Sun is actually only 6000 kelvins, this was quite a discrepancy.

- That same measurement detected radio bursts, which are spikes of intense radio emission from the Sun, on top of the steadier signal. Here's an example of these bursts in 1948.



- By 1950, Payne-Scott had a problem. She had broken a major rule: She got married. She worked in the Radiophysics Lab, a branch of the Australian government. At that time, the Australian government policy was that a married woman could not be hired as a permanent employee.

- When the bureaucrats of the Australian government discovered Payne-Scott's marital status in 1950, she was demoted to a temporary position despite the efforts of her colleagues, who valued her contributions. She lost all of her pension benefits for the preceding 5 years. She resigned her position in 1951 to have her first child, because there were no provisions for maternity leave. That effectively ended her career in science.

- Today, the Australian government labs sponsor the Payne-Scott Awards to support researchers who have taken extended leave to care for a newborn child.

Suggested Reading

Goss, *Making Waves*.

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

Sullivan, *Cosmic Noise*, chaps. 3–7.

Sullivan, ed., *The Early Years of Radio Astronomy*.

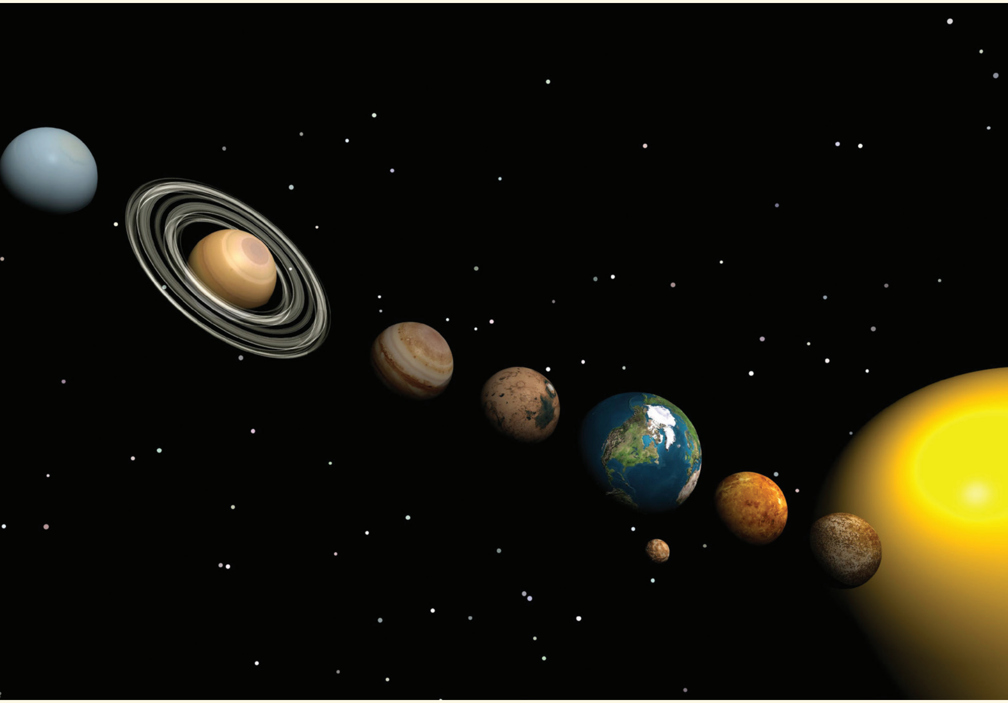
Verschuur, *The Invisible Universe*, chaps. 2 and 5.

Questions to Consider

1. If you were asked whether a cell phone emitted thermal or nonthermal radio waves, which would you choose?
2. The Earth's atmosphere ends in the ionosphere, a region of gas starting about 50 kilometers above the surface that is ionized by ultraviolet radiation from the Sun. This layer sometimes reflects low-frequency radio waves in the AM band so that they can be heard at great distances from the transmitter. So-called clear channel radio stations take advantage of this to send their signals far from their transmitters. Does this phenomenon have any implications for radio astronomy in the AM band?

LECTURE 4

The Discovery of Interstellar Hydrogen



There are now about 150 molecular species that have been detected in interstellar space through their discrete emissions at radio frequencies. We can measure their velocity using the Doppler shift and, from the intensity of their lines, determine the number of molecules in places far from the Earth. The ability to detect discrete emission lines from atoms and molecules at radio frequencies is a tool of incredible power, and astronomers use it every day.

Jan Oort

- Jan Oort of Leiden University in the Netherlands was one of the most visionary and accomplished astronomers of the 20th century. Among other things, he had worked out the rotation of the Milky Way, our home galaxy, and deduced the existence of a cloud of comets around the Sun that is now called the Oort cloud.

- Oort learned of Reber's discovery and began thinking about radio astronomy. He was keenly interested in the structure and dynamics of the Milky Way. But traditional astronomers had always been frustrated by one obstacle: They could hardly see any of the Milky Way. The problem was interstellar dust.

- From Earth, the Milky Way appears as a band of stars stretching across the sky. By 1940, astronomers had worked out that our Milky Way is a galaxy like billions of others in the universe.

- Galaxies like the Milky Way are concentrations of a few hundred billion stars held together by their mutual gravitational attraction, flattened into a disk and rotating around a common point. Here's a deep look at the central region of a nearby spiral galaxy.

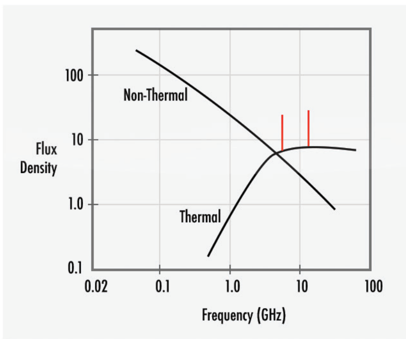
- The dark patches are clouds of gas and dust (tiny specks of matter: carbon, silicon, ice). They are less than one thousandth of a millimeter in size but are very effective at blocking starlight. From our vantage on Earth, we can see these other galaxies just fine, looking down at them from above, but because we are in the Milky Way, we can only see it edge on.

- The dark patches in the Milky Way are dust clouds, and our galaxy has so much interstellar dust that we can only see a small percentage of the stars. The dust blocks the light from the rest.

- Radio waves aren't bothered by a few specks of dust, no matter how well it blocks light, so Oort was thinking about radio astronomy as a way to see through the dust. He was particularly interested in finding a way to use radio astronomy to measure the rotation of the Milky Way.

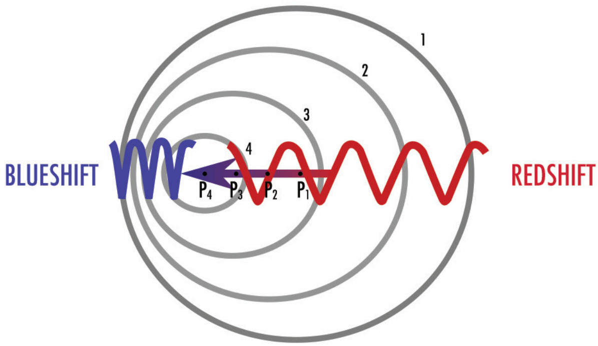
- There are 2 general kinds of electromagnetic emission: continuous in frequency and discrete. Continuous emission constitutes an unbroken continuum across a wide range of frequencies. Discrete emission occurs over a very narrow range of frequencies. All manmade sources of radio emission that are used for communication are discrete; they are confined to just a small range of frequencies.

- Here's our spectrum of thermal and nonthermal emission with a few discrete spectral sources superimposed to show how they would appear.



- The red lines represent radio emissions over a narrow range of the spectrum. On the scale of this figure, they look like simple lines. They are called spectral lines, and they are emitted by atoms and molecules. If we were to zoom in, we would see that many have a very complex structure, but they are still confined to a relatively small frequency range, so we still call them lines.

- You can do something with emission from a spectral line that you can't with the continuum: You can measure a velocity through the Doppler effect, named after Austrian physicist Christian Doppler. He noticed that waves from an approaching object would be bunched up and therefore the distance between peaks would be shorter and the frequency would be higher. Waves from a receding object would be stretched out, making them longer and at a lower frequency.



- If you know precisely what frequency a given radio emission should be when it is at rest—its so-called rest frequency—and if you can measure very precisely its observed frequency, you can calculate its velocity toward or away from you.

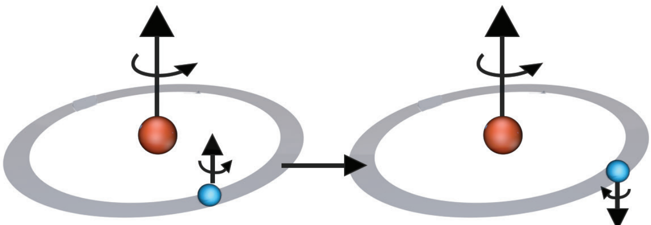
Hendrik van de Hulst

- Oort had used the Doppler shift of optical spectral lines to determine the rotation of the Milky Way in our part of the galaxy. But Oort wanted to see farther—the entire Milky Way. He learned of Reber's work and understood that radio astronomy promised a way to peer through the dust.

- Oort met with a talented Dutch student named Hendrik van de Hulst and gave him a problem: Using what was then known of the physics of atoms, what common element would produce a spectral line at radio wavelengths?

- Van de Hulst came back with an answer in 1944: hydrogen. The most common element in the universe, hydrogen—in its simplest form as individual atoms—should produce a discrete radio emission line.

- Hydrogen is composed of one electron that you can think of as being in orbit around a proton. Both the electron and proton have a property called spin. You can think of both as magnets, and spin gives them a north and south pole. It takes energy to force 2 similar magnetic poles to face each other. The same is true with hydrogen.



- Spin is quantized, so it can be either up or down. The parallel spin wants to decay into antiparallel spin, similar to how 2 magnets with their poles aligned want to flip. When it does, it will emit a photon that is at a radio frequency of 1420 megahertz and a wavelength of about 21 centimeters.

- Van de Hulst reported his results at a wartime colloquium in Leiden.

- A frequency of 1420 megahertz was within reach of the technology of the mid-1940s; after all, Reber had built a receiver to work at the higher frequency of 3300 megahertz. But the war and German occupation of the Netherlands made it impossible for Oort's group to try to detect the hydrogen emission—the spectral line with a wavelength of 21 centimeters—before 1945.

- News of van de Hulst's prediction of the possible existence of the 21-centimeter spectral line spread after the war, and scientists in the

Netherlands, Australia, and the United States started building the equipment to try to detect it.

- Van de Hulst's calculations suggested that the line could be too weak to detect, but Oort was not deterred. He was adamant that the 21-centimeter line had to be there.

Doc Ewen and Edward Purcell

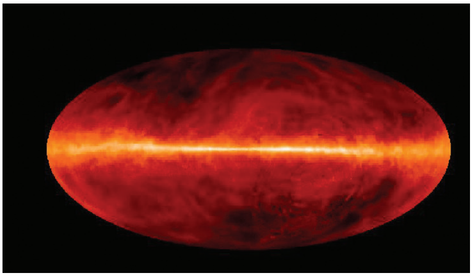
- Three teams were working independently: one led by Oort in the Netherlands, another in Australia, and a third at Harvard, consisting of Edward Purcell and his graduate student Harold Irving "Doc" Ewen. Oort's group started first, but they did not have the advantage of the enormous technical base built up in the United States and Australia during the war. The Dutch effort was also set back by a devastating fire that destroyed much of their equipment in early 1950.

- Ewen and Purcell at Harvard made the discovery in 1951. They built a horn antenna, which is simply something to catch and concentrate radio waves, exactly like a funnel.

- To their surprise, Ewen and Purcell got a signal. The radio waves from hydrogen had been found exactly at the predicted frequency, 1420 megahertz, at a wavelength of 21 centimeters. Ewen and Purcell spread the word, and within a short time the groups in the Netherlands and Australia confirmed the discovery.

- This was the first spectral line observable at radio wavelengths, and it remained the only radio line for more than a decade. Ewen and Purcell went on to other work, but Oort's group and researchers in Australia started systematic studies and began mapping the hydrogen in the Milky Way.

- Here's an image of the hydrogen emission from the Milky Way over the entire sky.



- The figure is oriented so that the Milky Way is horizontal. It's the bright band running across the center. Most of the hydrogen in our galaxy lies in a fairly thin layer held down by the gravitational attraction of the stars in the Milky Way. It's the same reason that the Earth's atmosphere hugs the surface: gravity.

- But there is also hydrogen in every direction we look. Galactic hydrogen is everywhere.

- The large loops that we see in hydrogen come from clusters of supernova stars that have exploded. The explosion blows big bubbles in interstellar gas and sweeps up shells of hydrogen.

- In addition to measuring velocity through Doppler shift, radio spectral lines give us additional information. In many cases, the strength of the emission tells us how much hydrogen there is.

- For more than a dozen years, the 21-centimeter line from hydrogen was the only spectral line known at radio wavelengths. Then, in 1963, emission lines of the molecule OH were detected at a wavelength of around 18 centimeters. They come at a shorter wavelength and a higher frequency than the 21-centimeter wavelength of the hydrogen line.

- The obvious next step is more complex molecules—combinations of atoms into larger groups. But radio astronomy took a different turn, and a detour of several years.

- Measurement of spectral lines at optical wavelengths showed that there were diatomic molecules in interstellar space—molecules made of 2 atoms. These were simple molecules, such as CH and CN. Could molecules like this have transitions in the radio, and could there be more complex molecules out there?

- Interstellar space can be a harsh environment. The Sun constantly bombards Earth with ultraviolet photons, x-rays, energetic particles—nasty stuff that is deflected by Earth's magnetic field or absorbed by our atmosphere. It would fry us otherwise.

- But the environment around Earth is sweet compared to interstellar space, where there's much more ultraviolet radiation from stars more massive than the Sun. Ultraviolet radiation is bad for the skin, and that's because it's energetic enough to break down the molecules in the cells of our skin.

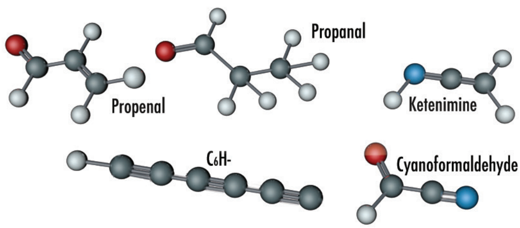
- In general, molecules are rather fragile, so the theory in the mid-1960s was that complex molecules such as water would not exist in interstellar space in any significant amounts. They would be destroyed by the general radiation field from stars. The interstellar medium should be limited to 2-atom molecules, nothing more complex.

Charles Townes

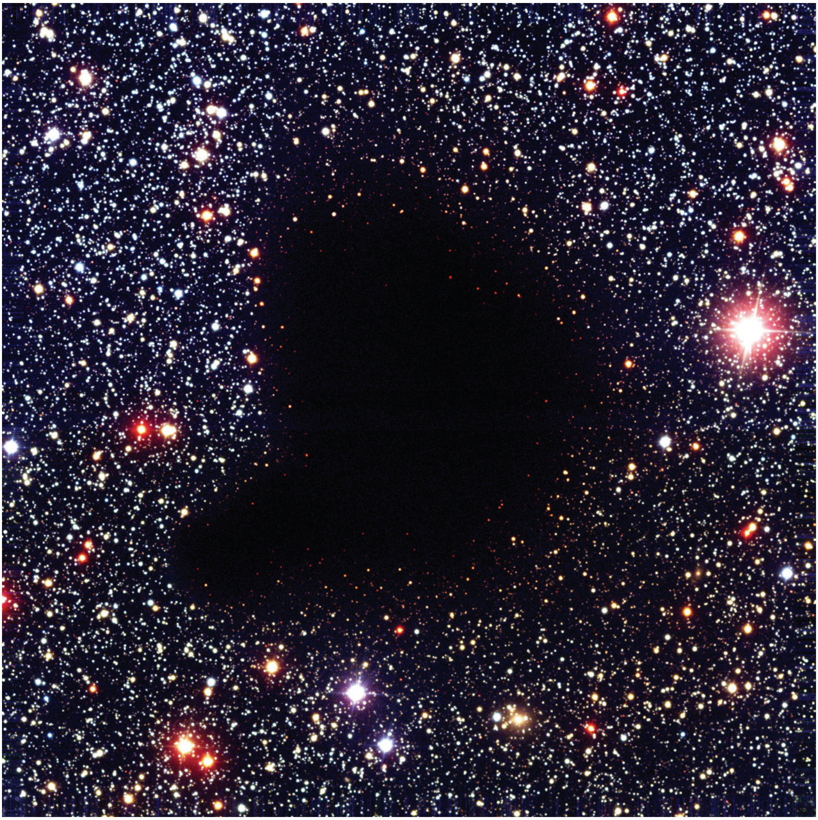
- Charles Townes, who already had a Nobel prize for work that ultimately led to the development of lasers, turned his mind to radio astronomy, using a relatively small antenna at the University of California, Berkeley's Hat Creek Radio Observatory.

- He and fellow researchers detected the telltale emission from interstellar ammonia molecules at the frequency of 22 gigahertz—that is, 22,000 megahertz—a wavelength of a little more than 1 centimeter.

- They soon added interstellar water (H_2O) to their list of detections. That opened the floodgates—carbon dioxide, formaldehyde, acetic acid, and so on. Here are models of just a few of the molecules we've discovered through their radio emission.



- The universe is much more protective of its molecules than we ever expected. We now know that dark clouds—which are found throughout the Milky Way—are excellent nurseries for the growth of complex organic interstellar molecules.



Suggested Reading

Graham-Smith, *Unseen Cosmos*, chap. 3.

Sullivan, *Cosmic Noise*, chap. 16.

Verschuur, *The Invisible Universe*, chap. 6.

van Woerden and Strom, "The Beginnings of Radio Astronomy in the Netherlands."

Questions to Consider

1. The average interstellar density of neutral atomic hydrogen near the Sun is about 1 per cubic centimeter. Outward from the Sun through the thinnest part of the Milky Way, the interstellar medium is about 100 parsecs thick, which is about 3×10^{20} centimeters. A tube 1 centimeter by 1 centimeter across would thus contain 3×10^{20} atoms of hydrogen if it stretched from the Sun straight out of the Milky Way. The Earth's atmosphere has a density of about 3×10^{19} cubic centimeters at sea level. How long would a tube have to be to contain as many atoms as our tube through the entire Milky Way?

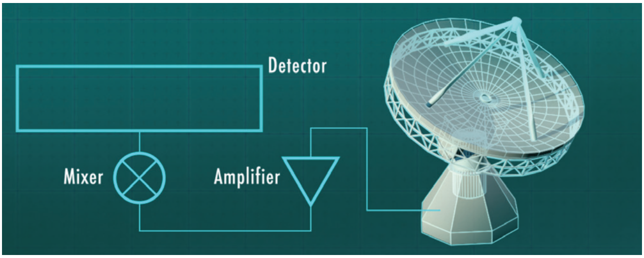
   Answer: 10 centimeters

2. If you point your radio telescope in a certain direction and see a signal, what is the easiest way to determine if it is coming from continuum emission or line emission?

LECTURE 5

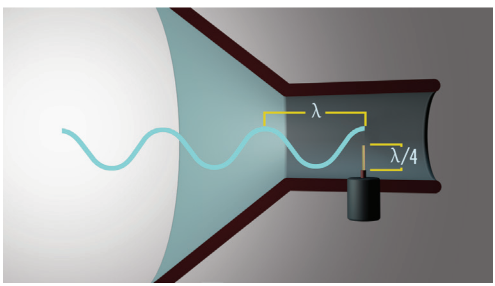
Radio Telescopes and How They Work

In this lecture, you will learn the details of how a radio telescope works. In general, a radio telescope collects radio waves from a certain direction in the sky and focuses it onto a point, where a receiver can pick up the signal. The receiver does a number of things, including amplify the signal. The signal is then passed along to systems that detect and measure it.



Radio Telescopes

- With a radio telescope, radio waves are funneled in and hit a wire in their path. The wire is not fundamentally different from wires that we see every day; its most important property is that it will carry electricity. This particular wire is called the probe because it probes the electric field.



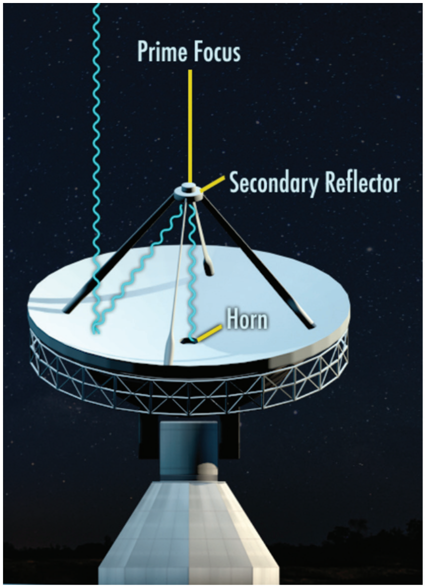
- The wire, the probe, is made of a metal such as copper or aluminum. These common metals have a lot of free electrons swimming around on their surface. Electric current is just an organized motion of these electrons.

- You push the electrons from one end of the wire, and the signal travels along as electricity. You can push electrons by hitting them with an electromagnetic wave. And when that happens, the wire has become an antenna.

- An antenna is a device that intercepts an electromagnetic wave in free space and turns it into an electric current in a wire. The antenna for the radio in your car does the same thing: It catches incoming radio waves and turns them into a current in a wire.

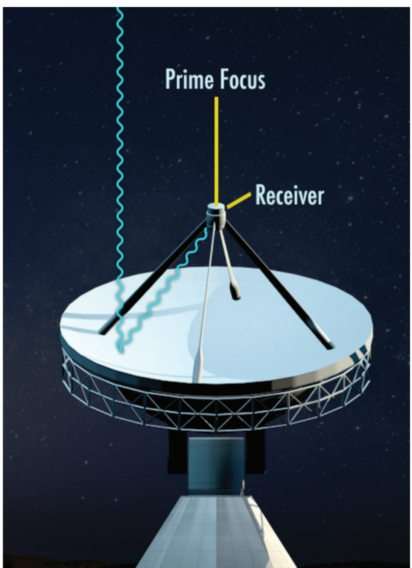
- At the heart of every radio telescope is an antenna—some bit of wire or a metal rod—that captures the incoming electromagnetic waves and puts out an electric current. The current looks like a wave running down the wire, and the amplitude, or height, of the wave is called its voltage.

- The purpose of a radio telescope dish is to capture as much radio energy as possible and focus it on that little bit of wire. For maximum efficiency, the probe should be 1/4 of the size of the wave it's going to intercept. The radio signal hits the dish and reflects up to the primary focal point, or the prime focus, where we can either catch it with an antenna or redirect it using another reflecting surface to send the signal somewhere else.



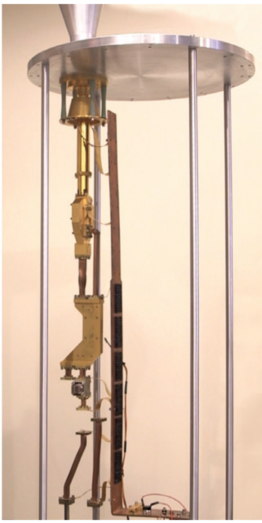
- This dish has a secondary reflector that redirects the signal down to the big horn in the middle of the dish, where the receiver sits.

- Here is a dish with the receiver at the prime focus.



- Once we have concentrated the radio power on a little antenna—which turns it into an electric current in a wire—the next thing that we do is amplify it. We feed the signal into a device that makes it stronger by many times—a thousand times—so that it turns from a faint celestial whisper into something that we can measure.

- Here's a modern receiver, inside of which the amplification and much more happens.



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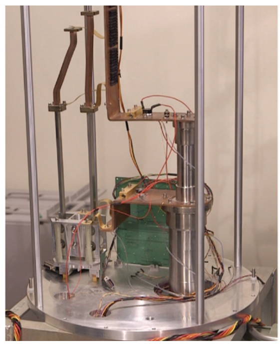


Bottom

- If you can amplify a signal by a thousand times, why go through the trouble of building this big dish with a big aperture, when you could have a smaller aperture, a much cheaper dish, and compensate for the weaker signal by adding more amplification?

- The answer goes back to thermal radiation—the radio radiation emitted by every object that acts anything like a blackbody.

- Amplifiers act somewhat like blackbodies, and this means that not only are they amplifying the incoming signal, they are simultaneously putting out their own signals—radio noise—that's indistinguishable from the radio signals coming from the antenna. And the noise gets amplified along with the signal.

- If our antenna wire does not carry electricity perfectly—if it has even the slightest resistance—it acts a little like a blackbody.

- For example, if only 1% of the astronomical signal is lost to resistance in the wire, then that same wire adds 1% blackbody noise at the temperature of the wire. The astronomical signal is lost, and it's replaced by noise. For this reason, most receivers are cooled to a few degrees above absolute zero. The colder the blackbody, the less it radiates.

- Receiver noise can swamp the celestial signals. We make great efforts to keep our receivers quiet, but nothing beats starting with the strongest astronomical signal possible, which means the biggest aperture.

- In our schematic of a radio telescope system, the receiver is always located at the focal point because even the best wires have loss and introduce noise. We want the amplification to occur as close to the antenna as possible.

- Once the radio signal has been captured by a little antenna, converted into a current, and amplified (with noise unavoidably added in the process), radio astronomers then use a technique called heterodyning, or mixing. One of the marvels of radio engineering, this process allows radio astronomers to change the frequency of the signal while preserving all of the information it contains—something that is simply impossible in other parts of the electromagnetic spectrum.

- If you own a radio, you will see that it covers a number of bands—AM, FM, maybe others. That means that the radio signals are coming through the air at frequencies such as 106.3 megahertz in the FM band or 1370 kilohertz in the AM band.

- But our radio uses heterodyning to mix those signals down into the audio range—kilohertz—where our ears work. The speakers in our radios don't know the frequency of the radio station, because by the time the radio signal gets to the speakers, it been mixed down to audio.

- We've collected the signal that passed through the aperture using the dish; focused it onto an antenna, which turned the electromagnetic radiation into current flowing down a wire; amplified the signal; and mixed it to a convenient frequency. The process of detecting the signal means converting that current running down a wire into a measurement of power. This is done with a device whose generic name is a detector.

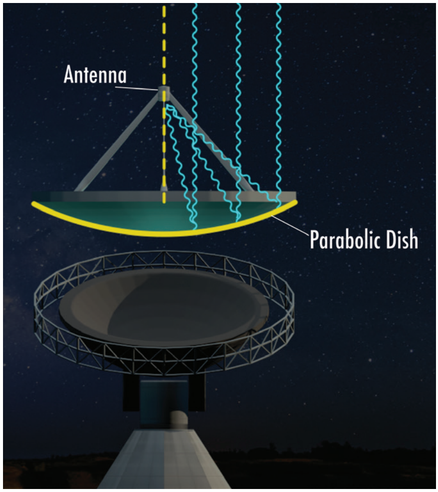
- We use various technologies to detect the power received by the telescope. A detector always averages over some band of frequencies. If we are just studying the general properties of an object emitting blackbody radiation, the band can be quite broad because the intensity of blackbody radiation does not change rapidly with frequency.

- If we are looking at detail in a spectral line, the individual bands we measure—the channels in our spectrometer—can be quite narrow. But the result is the same: We end up measuring power, and that is the voltage squared, at a particular frequency, coming from a particular direction in the sky.

- In modern times, our detectors are digital and their output goes straight into a computer, where it is stored and analyzed.

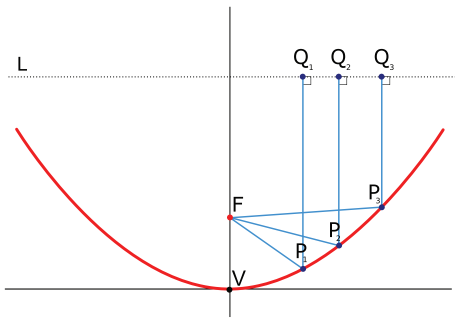
How a Dish Works

- The incoming wave that comes from the direction that we're studying is reflected and brought to a focus, where a receiver amplifies the signal, and it's sent to a detector for measurement.



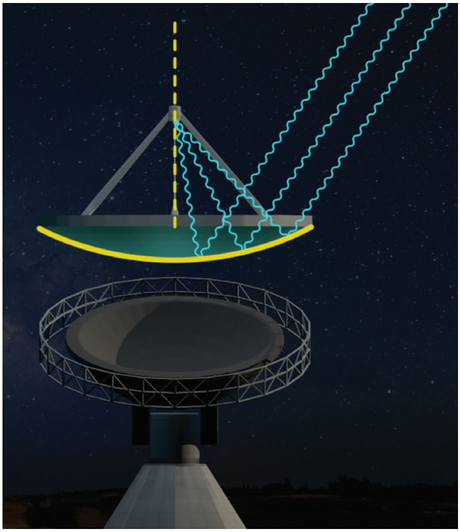
- The simplest radio dish has the shape of a parabola, which is symmetric about a central line called the vertex line. You spin this 2-dimensional curve about the vertex line to create a 3-dimensional dish called a paraboloid.

- A radio wave that comes through the aperture perpendicular to the vertex line—like the dotted line in the figure—will be reflected off the dish and all parts of it will arrive at the focus at the same time. The wave will be in focus.



- The reason this works is that it's a property of a parabola that the distance from any point on our incoming wave to the focus is the same, no matter what part of the dish it hits.

- In the drawing, the 3 parts of the wave that hit the dish at 3 different places all arrive at the focus at the same time because they all traveled the same distance. They arrive in phase with each other. The signal is concentrated. It adds, is picked up by the antenna, and is amplified by the receiver.



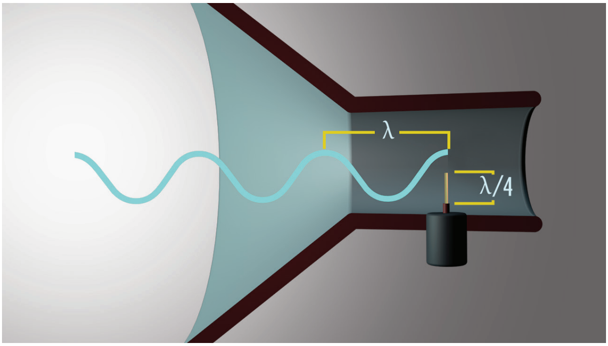
- If the wave is not perpendicular to the vertex line but is off at some angle, the right part of the wave will arrive at the focus first because it has a shorter distance to go. The left part of the wave has a longer path, so it arrives at the focus later. The two waves do not arrive in phase at the focal point.

- The word "phase" refers to a wave cycle. It's often measured in degrees, with 360° being a full cycle. We can locate position on the wave by a measure of its phase in degrees.

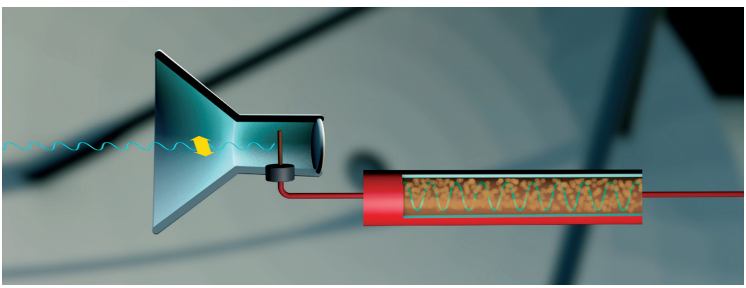
- Phase error is not absolute, but depends on the wavelength of the signal you are studying. The accuracy we require of our dish surface depends on the wavelength where we want to use it. And shorter wavelengths, meaning higher frequencies, require a more precise dish than is needed at long wavelengths.

Polarization

- The up-and-down electromagnetic wave excites up-and-down motion of electrons in our antenna wire that becomes the current we detect.



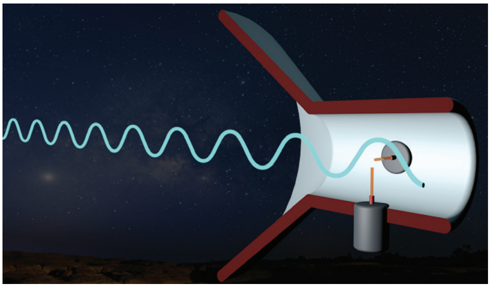
- But electromagnetic waves can have a side-to-side component as well, and if we imagine a wave coming in and out, we can see that it won't be picked up by our antenna wire, because the wire is oriented up and down.



- This property of electromagnetic waves is called polarization. The radio waves from most astronomical sources are not polarized. This means that their orientation is random, changing rapidly from horizontal to vertical to everything in between.

- Transmitters on Earth are polarized, and the antenna receives the strongest signal at one particular angle.

- A single antenna wire is sensitive to just one segment of the polarized wave and only picks up half of a randomly polarized signal. So, we have a parallel system to pick up the other half. That way, the full signal is detected. Each polarized antenna connects to its own independent set of amplifiers and detectors.



Suggested Reading

Cottrell, *Telescopes*, chap. 7.

Dunning, "Receiver Systems."

Graham-Smith, *Unseen Cosmos*, chap. 10.

Wielebinski, Junkes, and Grahl, "The Effelsberg 100-m Radio Telescope."

Questions to Consider

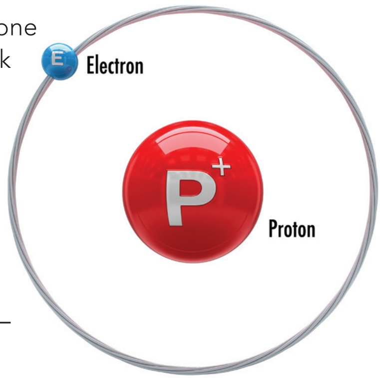
1. A radio telescope and a drawbridge are both large moving objects. What are the differences between their design properties, and what are their similarities?
2. What are some of the considerations when designing a radio receiving system for your car that don't apply to radio-astronomical receiving systems?

LECTURE 6

Mapping the Hydrogen Sky

This is the first of a 2-part lecture about hydrogen. Hydrogen is important. Everything that we see around us started out as hydrogen. Stars turn hydrogen into almost all the other elements, including carbon, oxygen, and iron. Before there were stars, planets, and galaxies, there was hydrogen. And even though a lot of hydrogen was used up to make all the other elements, there's still more hydrogen than anything else.

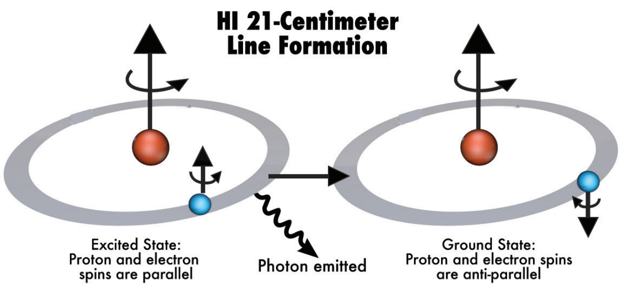
The 21-Centimeter Line



- Hydrogen is the simplest element. It has one proton and one electron, and you can think of the electron as being in orbit around the proton.

- The electron and proton have a property called spin. It's a quantized state. Spin can be either up or down. The proton and electron can have their spin aligned—called parallel—or opposite—called antiparallel.

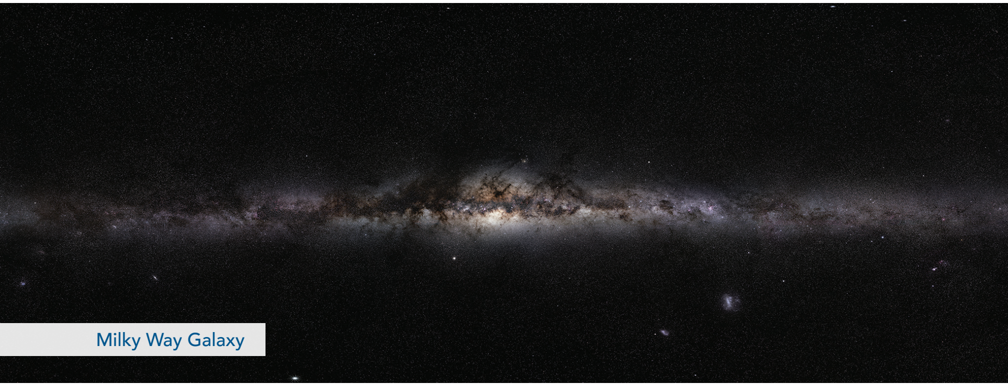
- The parallel state has higher energy; if the hydrogen atom is in that state, it will eventually decay to the antiparallel state. In the process, it will emit a photon at radio wavelengths of 21 centimeters.



- The existence of the 21-centimeter line was first discussed at a meeting in 1944 in the Netherlands. The signal was detected from interstellar space in 1951 by Edward Purcell and Harold Irving "Doc" Ewen at Harvard and, shortly afterward, by a group in the Netherlands led by Jan Oort.

- Three scientific papers reported the discovery in the same issue of the journal *Nature*: One was by Ewen and Purcell, another by Christiaan Muller and Jan Oort in the Netherlands, and a third by a group in Australia that had confirmed the detection.

- Ewen and Purcell went on to different areas of science, but the Dutch and Australians seized the opportunity and immediately began designing and building radio telescopes to exploit this amazing new tool.



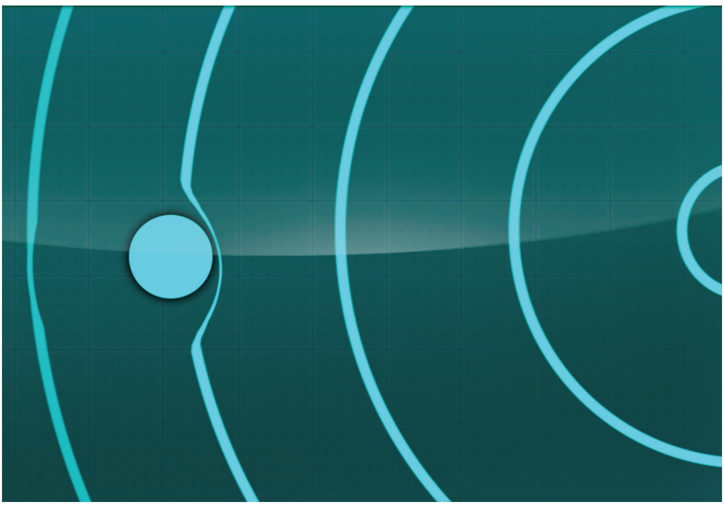
Milky Way Galaxy

- The night sky is dominated by the stars in the Milky Way, our galaxy. But our view is blocked by dust, so we can only see a small fraction of the galaxy. Radio waves promised a way to peer through the dust and, in some sense, see the entire galaxy.

- The light we see comes from stars, but the 21-centimeter line comes from interstellar gas. So, by studying radio waves, we are really learning something quite different than what the stars tell us. And as it turns out, studies of the 21-centimeter hydrogen emission from the Milky Way have revealed aspects of our galaxy that were never suspected.

- A recent map made of the 21-centimeter emission over the entire sky is available at https://www.icrar.org/hi4pi/. The data came from large radio telescopes in Australia and Germany.

- How did Jan Oort know that radio waves would not be blocked by the dense dust clouds that block light? What does it take to block a radio wave? The answer is complicated and depends a lot on what the dust is made of, but there's also a simple rule of thumb: To block a wave, it takes something larger than the wave. The wave just goes around smaller things.



- Light waves are really small—smaller than interstellar dust particles—so they're effectively blocked by dust. But to block a radio wave like the 21-centimeter line, you would need objects about a meter across. While there are some rocks in space, they're few and far between, so the 21-centimeter waves—and indeed all radio waves—just coast right through.

- If we need the large radio telescopes that we have today to do radio astronomy, how was the 21-centimeter line of hydrogen detected with Ewen and Purcell's funnel? After all, it's not much more than 1 meter across. And why did the groups in the Netherlands and Australia think that they could understand Milky Way hydrogen with their small telescopes? How could they get any signal, let alone enough to study hydrogen?

- For the answers, we need to return to our study of telescopes and develop the concept of a radio telescope beam. Every telescope has some angle on the sky over which it averages to produce its signal. This is called the beamwidth, and it is not necessarily a tiny point. It is also called the angular resolution, because if two objects are closer together in the sky than the beamwidth, they will blur into one.

- The size of the beam is proportional to the wavelength of incoming signal divided by the diameter of the aperture. A bigger dish gives us a smaller beam on the sky and a better ability to discern fine structures. A smaller wavelength also gives us a smaller beam on the sky and better resolution.

- Why did early scientists get any signal through their very modest apertures? To appreciate the answer, remember that the telescope averages all emission within the beam. If hydrogen were only in a tiny clump here and another tiny clump there, its signal would have been diluted in the enormous beams of the early telescopes and nothing would be detected.

- But in the Milky Way, hydrogen is everywhere, so there is no part of the big telescope beam that is empty. A single star can be surrounded by the darkness of night, but hydrogen clouds are lumped up against other hydrogen clouds in the Milky Way. Ewen and Purcell's tiny horn was full of hydrogen signal.

- Even with the relatively small size of the first generation of 21-centimeter telescopes, they had enough angular resolution to map the hydrogen across the sky.

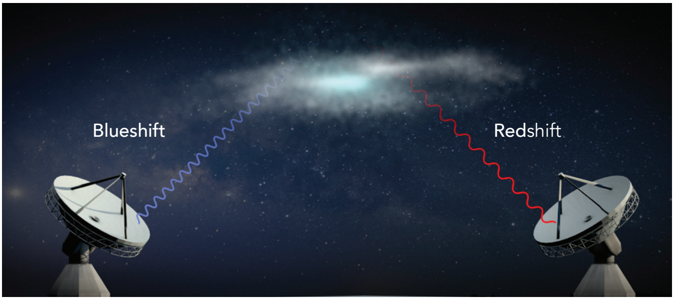
- The scientists who first started mapping the 21-centimeter line didn't know anything about how extensive the hydrogen atmosphere of the Milky Way would be. The theory said that the 21-centimeter line could not be detected. Even if it could be detected, there was no guarantee that atomic hydrogen pervaded the Milky Way. It could have been confined to a few clouds. But Oort pressed on, and his intuition was right on all counts.

- The concept of reciprocity helps us understand how radio telescopes detect the 21-centimeter line of hydrogen. It means that forward and backward are the same. In more concrete terms, it means that we can turn time backward and the system will behave in an identical way. It means that if we start having difficulty understanding our radio telescope as a receiver of radio waves, we can turn things around and consider the telescope as a transmitter. The analysis is the same.

The Doppler Effect

- All hydrogen atoms emit radiation at essentially the same frequency, and each atom emitting 21-centimeter radiation has its own Doppler shift.

- Here we have two radio telescopes looking at the same cloud of hydrogen atoms. The cloud is traveling to the left and emitting 21-centimeter radiation in all directions. Because of the Doppler effect, the telescope on the left picks up a signal that's at a shorter wavelength—a higher frequency—than the rest wavelength of hydrogen.



- The telescope on the right sees the cloud going away from it and picks up the hydrogen signal at a longer wavelength, a lower frequency than the rest frequency.

- Where optical light is concerned, a longer wavelength means redder and a shorter wavelength means bluer, so waves that have been stretched by the Doppler shift to a longer wavelength are referred to as being redshifted and waves compressed by the Doppler shift are referred to as being blueshifted.

- Redshifted means that the object is going away from us; blueshifted means coming toward. Radio waves from a cloud that's moving exactly across the line of sight are not Doppler shifted.

- The Doppler shift can be used to give us a very important piece of information about a hydrogen cloud: its velocity. The following formula describes the Doppler shift:

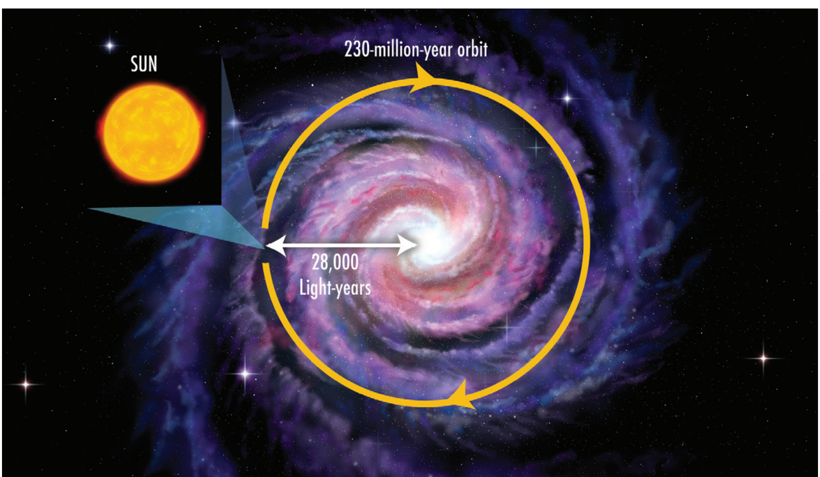
$$(n_0 - n)/n_0 = V/c$$
$$V = c(n_0 - n)/n_0$$

- In this formula, n_0 is the rest frequency, or the frequency that the 21-centimeter emission would have from an atom at rest; n is the observed frequency, or the frequency that the signal actually has; V is the velocity, and c is the speed of light. Using this equation, we can measure the velocity of a clump of hydrogen thousands of light-years away.

- The Dutch and Australian radio astronomers used their radio telescopes to measure the rotation of the entire Milky Way using the Doppler shift of the 21-centimeter line. By 1956, Oort had completed a new radio telescope with a 25-meter (82-foot) diameter at Dwingeloo on the edge of a national park. It was a telescope designed to study the 21-centimeter line. For a while, it was the largest radio telescope in the world.

Radio telescope at Dwingeloo

- The Sun goes around the center of the Milky Way at a velocity of around 250 kilometers per second.



- What we see in the 21-centimeter line is the difference between the velocity of hydrogen in different parts of the Milky Way and our own velocity.

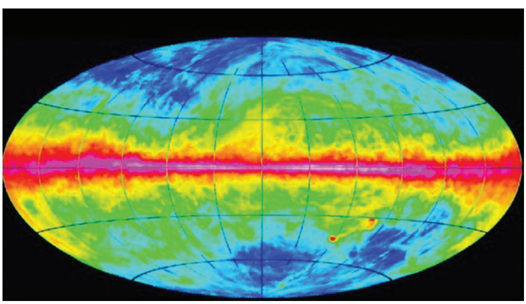
- The Milky Way does not rotate like a solid plate, whose outer parts move a lot faster than its inner parts. But even though the rim of a rotating solid plate moves faster than the center, two objects on the plate never change their distance from each other because the plate is solid.

- The Milky Way is not solid. Much of the disk has about the same rotational velocity as the Sun does. Stuff is orbiting the center at about 250 kilometers per second. But because the inner parts of the disk don't have as far to go to get around once, their orbit is smaller, and the galaxy rotates differentially.

- A problem in radio astronomy is that we have no way of knowing the distance to a cloud of gas just by measuring its hydrogen emission. It could be near or far.

- But using the velocity information from the Doppler shift of the 21-centimeter line, and a mathematical model for the differential rotation of the Milky Way, astronomers could start to assign distances to some of the 21-centimeter emission.

- Here's the sky in hydrogen from modern data.



- First, they found that the vast majority of galactic hydrogen is in a thin layer along the plane of the Milky Way. The gas is pulled down by the gravity of the stars. The layer in the inner galaxy has a thickness of just a few hundred parsecs. (A parsec is about 30 trillion kilometers; it takes light about 3.3 years to go 1 parsec.)

- They found that the hydrogen layer is only a few hundred parsecs thick over the inner 10 kiloparsecs of the Milky Way, but in the outer parts of the galaxy, this layer is warped, going up on one side and down on the other.

- To view the warp, as well as learn more about it, visit http://www.berkeley.edu/news/media/releases/2006/01/09_warp.shtml.

- Although the warp was discovered about 60 years ago, its origin is still uncertain and controversial. We now know that many galaxies have warped hydrogen in their outer parts, and the warps begin where the stellar disks start to peter out.

- We don't really understand warps, but there are some theories:

    - Warps could result from the interaction of one galaxy with another.
    - They might arise naturally as vibrations in differentially rotating stellar systems.
    - They may be caused by infall of gas onto a galaxy.

Suggested Reading

Verschuur, *The Invisible Universe*, chap. 6.

van Woerden and Strom, "The Beginnings of Radio Astronomy in the Netherlands."

Questions to Consider

1. If you could choose the first radio telescope that would measure the 21-centimeter line of hydrogen to determine the large-scale structure of the Milky Way, would you go for a big one that would give good detail or a smaller one that could map a larger area in the same time?
2. Because the Earth revolves around the Sun, at some times during the year it's going toward a particular direction of space and 6 months later it's going away from that direction. How can that effect help us differentiate between spectral lines originating from space and similar signals originating on Earth?

LECTURE 7

Tour of the Green Bank Observatory

This lecture and the next one offer an in-depth tour of the Green Bank Observatory, a radio-astronomical observatory located in West Virginia that's a facility of the U.S. National Science Foundation. This observatory was set up in the late 1950s to enable scientists to do research in radio astronomy at a time when that science was quite new. In this lecture, you will be introduced to historical radio telescopes as well as state-of-the-art radio telescopes that reside at Green Bank.

The Green Bank Observatory

- Just as optical astronomers are bedeviled by bright city lights, radio astronomy is plagued by manmade transmissions, whether deliberate or accidental, such as television towers, cell phones, and radar. So, a search was made for a site of a national radio astronomy observatory.

- The criteria included that it would have a low population density, it would be well shielded by mountains from distant transmitters, there would be enough flat land to have the facilities that would be needed for the observatory, and it would be at least 50 miles away from a city of any size.

- The Green Bank Observatory was founded in the late 1950s, and it has been flourishing ever since. The radio telescopes there have been used for research on pulsars, in the field of chemistry, to discover the black hole at the center of the Milky Way, and to discover formaldehyde, the first interstellar organic molecule.

- When the observatory was founded, a region of 13,000 square miles around it was declared the National Radio Quiet Zone. Within this area, any new fixed transmitters have to make sure that they don't interfere with activities of Green Bank. One effect of the quiet zone has been that there's a complete absence of towers on the mountains around the observatory, so there's also a complete absence of cell phone service in the area.

- At the time when the observatory was established in the late 1950s, not only was the young science of radio astronomy established at Green Bank, but also a completely new concept of an observatory—a public observatory. Unlike most optical telescopes, which are owned even today by individual institutions or consortia of institutions, the radio telescopes were going to be true public instruments available for use by qualified scientists and scheduled competitively.

The 140-Foot Telescope

- For many years, the 140-foot telescope was the premier radio telescope at Green Bank. When interstellar molecules were discovered, the telescope could easily be used to search a number of frequencies for new molecules. It detected the first interstellar organic molecule in space, formaldehyde. It was also involved in studies of radio recombination lines.

- Its position on the East Coast of the United States allowed it to work well in tandem with radio telescopes in Europe as well as radio telescopes in the western United States. It was involved in the first joint very long baseline interferometry project between the United States and the Soviet Union in 1968.

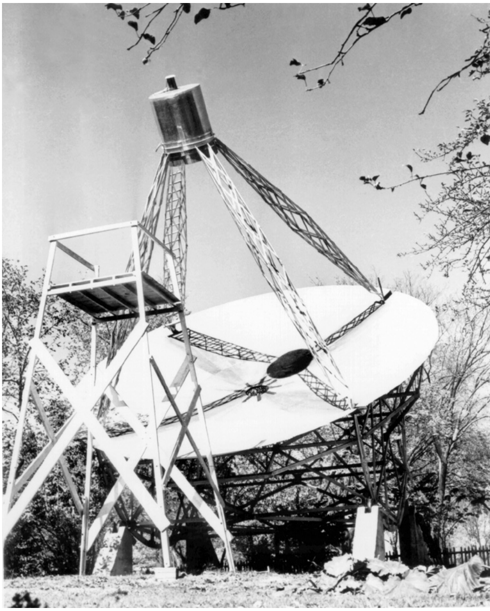
- Now that the Green Bank Telescope has come into operation, the 140-foot telescope is no longer the premier instrument. For the past few years, the 140-foot telescope has been used as a downlink for a Russian antenna, a radio telescope that is out in space.

- The Russian radio telescope combines its signals with big dishes on the ground, such as the Green Bank Telescope, to make an interferometer, a radio telescope that has the kind of angular resolution that is equal to the distance between the 2 telescopes. The 140-foot telescope picks up signals from the Russian telescope and transmits them to Russia, where they're analyzed to study quasars and regions of star formation.

- After the 140-foot telescope was taken out of general use—when the Green Bank Telescope came into use—the 140-foot telescope was used for a while for ionospheric radar studies. It's a very valuable tool to use for a number of different scientific projects even though it's no longer a dominant force in the world of radio astronomy.

The Reber Radio Telescope

- Although the Reber Radio Telescope at the Green Bank Observatory differs a little from the actual instrument that Grote Reber built in his yard in Illinois, many pieces are original. In fact, it was reassembled at the Green Bank Observatory in 1959 by Grote Reber himself.



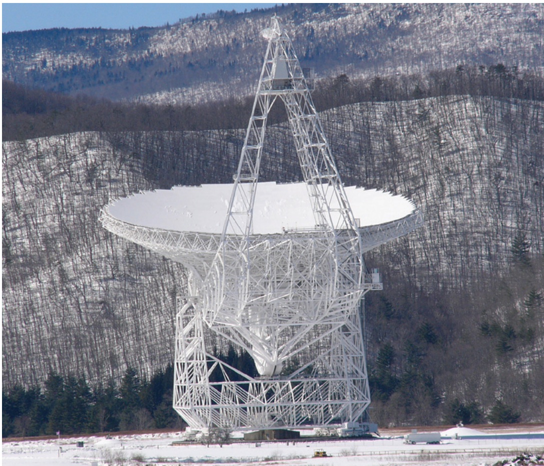
- It's amazing how many design features of modern telescopes Reber got right. He built his original telescope on his own, fresh out of college, with his own money, and in many cases using his own labor to put this dish together out of wood and metal. He decided to go with a dish, which is a great for collecting and focusing radio waves because it works over a broad range of frequencies.

At the Green Bank Observatory is a replica of Karl Jansky's antenna that is the same size and composition that he used in New Jersey to initially discover radio waves from space.

- Reber first built a receiver for 3300 megahertz and didn't detect anything. He was looking for what he thought must be thermal emission, and we now know what's coming from the sky that Karl Jansky discovered is not thermal emission. Reber built a new receiver at 910 megahertz. He didn't detect anything there either, so then he dropped down to about 150 megahertz using the same dish. And he finally got a signal.

The Green Bank Telescope

- The Green Bank Telescope operates 24/7, and at all times that it's in operation, a telescope operator is in charge of the telescope's overall security and safety. The telescope operator also turns control of the telescope over to an astronomer, who could be located in the control room at Green Bank or at a distant institution.



- Many different projects are run on the telescope each day. An astronomer could start the day observing pulsars, then switch receivers and frequencies and observe regions of star formation, then do very long baseline interferometry with a radio telescope in space, and come back in the evening to observe supernova remnants.

The Howard E. Tatel Radio Telescope

- The first radio telescope built at Green Bank was the 85-foot-diameter dish named the Howard E. Tatel Radio Telescope. Named for Howard Tatel, a talented scientist who was responsible for much of the design, Tatel tragically died before he could see his project come to fruition. The Tatel Telescope for several years was the main operating telescope at Green Bank, and it was used by a number of scientists to make some amazing discoveries in radio astronomy.

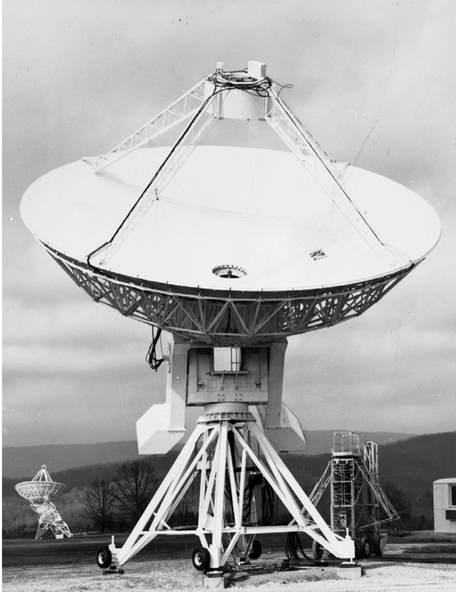
- When the Tatel Telescope was first pointed at Jupiter, it discovered that there were radiation belts, magnetic fields full of ionized particles around the planet—much like the Van Allen belts around the Earth—and that these radiation belts were giving off strong nonthermal signals.

- When the Tatel Telescope was first pointed at the radio source in the constellation Sagittarius—which we now know to be the center of the Milky Way and the radio source discovered by Janksy and studied by Reber—the Tatel Telescope's greater angular resolution enabled astronomers to see that it in fact was comprised of 5 individual sources: Sagittarius A, B, C, D, and E.

- The Tatel Telescope did the first search for intelligent life from other civilizations by looking for radio signals from several nearby stars. Researchers didn't find anything, but it was the start of an endeavor that has continued until today.

The 45-Foot Telescope

- The 45-foot radio telescope at Green Bank has a curious history because it was built not to be a resident in Green Bank but to be located 35 kilometers away to the south. With the 45-foot telescope operating together with the Tatel Telescope and a few other dishes on site, an interferometer was made that had very good angular resolution. It wasn't intended to be a major scientific instrument in its own right, but while they were testing it, researchers discovered that Sagittarius A—the radio



source that Reber and Jansky saw—was a black hole at the center of the Milky Way.

- Once that experiment was done, the 45-foot telescope was brought back to Green Bank and installed where it is today. It was then used to transmit radio signals and receive information from a Japanese radio telescope in space. Most recently, it has been outfitted with several new antennas and used to study solar radio emission.

Suggested Reading

Baars, *International Radio Telescope Projects*, chap. 1.

Drake and Sobel, *Is Anyone Out There?*, chap. 2.

Lockman, Ghigo, and Balser, eds., *But It Was Fun*.

Questions to Consider

1. There is a tension between the desire to preserve important scientific devices for historical purposes, such as radio telescopes that have made great discoveries, and the need to continually modify and modernize such devices to keep them at the forefront of research. Preservation can be inspirational but costs money that might otherwise be used to advance research. How might we balance these priorities?

2. At Green Bank, great care is taken to minimize radio interference to the radio telescopes. Almost every modern device that contains a digital computing chip emits radio emission unintentionally, and for this reason even digital cameras are restricted near the Green Bank Telescope. What other common devices might be sources of radio emission? You can discover some of these around your home by tuning an AM radio between 2 stations and holding it near various household devices such as clocks, computers, and cell phones. Did you find anything that was unexpected?

LECTURE 8

Tour of the Green Bank Telescope

The Robert C. Byrd Green Bank Telescope is a radio telescope that is designed to pick up the faintest signals from the universe. It's an enormous structure; it's as large as a football stadium, yet it can be tuned and turned to track sources as they move across the sky. In this lecture, you will learn how this beautiful and powerful telescope can be used to study some of the most distant objects in the universe.

The Green Bank Telescope

- Every radio telescope has 2 important functions: to collect the incoming radio waves and bring them to a focus, where we can put a receiver to amplify and detect the signals; and to track an object as it rises in the east and sets in the west across the sky.

- For the Green Bank Telescope, tracking is accomplished by moving along a big gear that adjusts the telescope's vertical elevation. For its azimuth, or horizontal angle, the telescope moves around on wheels on a track that can adjust its angle to the north, south, east, or west.

- When following a radio source across the sky—note that the source is not really moving but that the Earth is rotating underneath it—the telescope is moving to compensate for the Earth's rotation, and the telescope's motion is mostly imperceptible. It moves very slowly but very precisely. The Green Bank Telescope can track an object so precisely that the uncertainty is only a few arc seconds. This allows us to do work that could never have been done before with a regular telescope of this size.

- Why does the Green Bank Telescope have to be so big? The answer is that even though we're looking at some of the most energetic events in the universe—such as quasars, active galactic nuclei, and supernovas—they're so distant that by the time their radio signals reach us, they're incredibly dilute. We need a huge collecting area to be able to detect anything.

- Why does the Green Bank Telescope look so peculiar? People are used to seeing dishes that have a circular symmetry that looks like rings in a tree trunk. Instead, the Green Bank Telescope's dish looks like a clam shell.

- Conventional telescopes are symmetric, with their panels arranged like rings in a tree trunk. This brings the focal point right above the middle of the dish and requires a receiver with legs to hold it up, which blocks incoming signals.

- The Green Bank Telescope has an enormous dish: 100 meters by 110 meters, or 330 feet by 360 feet. That is more than 2 times the diameter of a symmetric dish, and it was built so that incoming radio waves bounce off the surface and can be received without any blockage.

Design Features

- There are several design features of the Green Bank Telescope that make it unique. In addition to its enormous size, there are 2 other design features of the telescope that were bold moves at the time when it was constructed.

- The first is that the surface is active. Instead of being a passive, fixed surface, the surface panels are mounted on actuators driven by motors so that they can be repositioned in real time to correct for any deformations that might be caused by gravity, wind, or thermal effects.

- The fundamental unique property of the Green Bank Telescope is its basic optical design. All the other dishes at Green Bank are circularly symmetric and have their focus in the center. The Green Bank Telescope has the focus off to one side, and that makes it asymmetric. This adds a lot of structural complexity, but in return gives us great optical simplicity and a pure beam pattern.

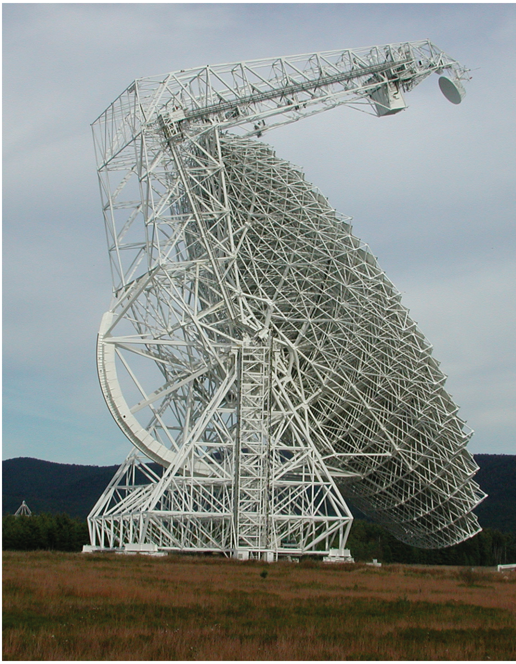
Structural Features

- To track objects as they move across the sky, the Green Bank Telescope has to move up and down in elevation, and it also has to move around in azimuth. Wheels on a track allow the telescope to make that motion. The wheels are 5 feet in diameter, and there are 16 of them. The moving weight of the telescope is about 17 million pounds, so each wheel holds more than a million pounds. In fact, it's likely that this is the greatest force a wheel has ever put on a track in human history.

- The track is quite sturdy. It is made of steel and sits on top of a concrete foundation that goes 25 feet down into bedrock. Even with the enormous weight, there's still a tendency for the track to slip slightly, so there are bolts that keep it firmly in place.

- Motors are used to drive the telescope wheels. The room on the first level of the telescope, called the server room, is completely enclosed in steel. This is where electric power is distributed to the motors to make them move the telescope.

- Radio signals get reflected by the primary mirror, which is a few acres in size, up to the secondary mirror, or subreflector, and then finally brought to a focus so that they can be collected by the feed horn



and then funneled down into the receiver. This particular feed horn works in the 21-centimeter line.

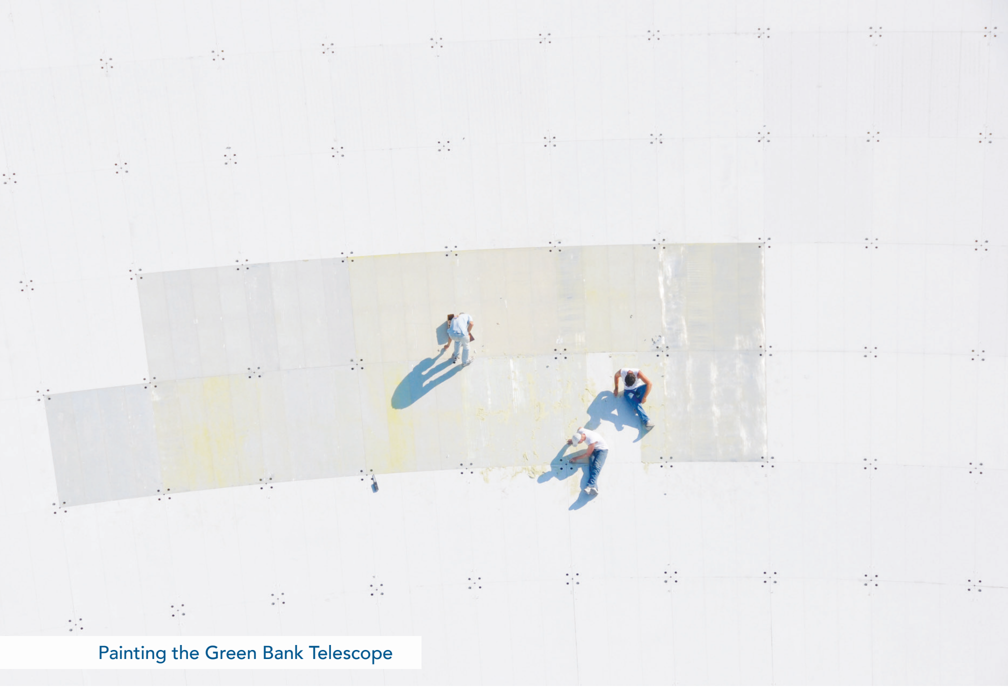
- To accommodate the various experiments that require different receivers, a number of receivers are located on the turret. In just a few moments, the turret could be moved to bring in anything we wanted to above the receiver into the focal point. The feed horns are covered by a plastic membrane that allows the radio waves to come through but keeps out snow, ice, and rain. Air is also blow-dried across the top of the membranes to keep dew and ice from forming.

- The receivers are cooled down to just a few kelvins above absolute zero, or around −450° Fahrenheit. Helium is pumped into refrigerators that keep the receivers at that temperature. We want the receivers to be at as low a temperature as possible so that they contribute the least noise possible into the system.

- The receiver room is a steel-shielded room to make sure that any interference or radio signals generated in the room don't make it out to the telescope. This is where the signals come down into the receivers and are amplified and sent by fiber back up to the lab building, where they can be analyzed. This room doesn't stay straight when the telescope is tracking a source; it can tilt at an angle. For that reason, everything in the room is bolted down.

- The Green Bank Telescope surface, which encompasses 2.3 acres, is blindingly white. The reflecting surface is covered with a special kind of white paint, and it has 2 jobs to do. First, it has to keep the telescope cool. We don't want sunlight hitting part of the dish and deforming or buckling it.

- Although the telescope looks blindingly white in the light, in the infrared it's actually black, so it radiates heat very efficiently. As a result, if there is any heating by sunlight, for example, on part of the dish, it radiates that heat away and maintains a constant surface temperature.



Painting the Green Bank Telescope

- The other thing that the white paint has to do is not reflect sunlight. In fact, this paint is very special because instead of reflecting sunlight, it scatters it in all directions. The reason that this is important is because we want to be able to observe radio emission from the Sun using the Green Bank Telescope. The sunlight that strikes the surface of the telescope amounts to about 8 megawatts, and if even a small fraction of that were reflected up, it would fry the receivers.

- The elevation gear tips the entire dish up and down. Motors engage this gear and allow us to track objects as they move across the sky. Chambers filled with concrete balance the high portions of the telescope so that it's very precisely balanced.

- Part of the elevation gear includes reinforced regions where you can place a big steel bar that will effectively pin the telescope at a certain elevation. This is used to keep the telescope safe in times of high wind or for maintenance, for example.

Questions to Consider

1. The moving weight of the Green Bank Telescope is 17 million pounds, mostly steel. What does the steel alone cost? What do you think are the major maintenance issues on structures like these?
2. What do you think might limit the possibility of building fully steerable radio telescopes larger than the Green Bank Telescope?

LECTURE 9

Hydrogen and the Structure of Galaxies

In this lecture, you will examine galaxies and see what we learn from measuring their hydrogen. Then, you will use 21-centimeter emission to weigh some galaxies, and you will discover dark matter. Finally, you will examine a relationship between hydrogen velocity and starlight that is simple to describe but whose meaning is a matter of wonder and puzzlement among astronomers today.

Galaxies

- Galaxies are self-contained systems of stars and gas held together by their own gravity. They come in all shapes and sizes. A galaxy doesn't have to contain a lot of gas, though most galaxies like the Milky Way do.
- Some galaxies have very prominent spiral arms. These galaxies are rotating and the arms are trailing, like swirls when you stir coffee in a cup. Some galaxies also have a bar, a linear feature in the stars in the center of the galaxy.

- The Andromeda Galaxy, also called M31, has about the same total mass as the Milky Way but with less gas. When we see Andromeda in the sky, it lies fairly close to the plane of the Milky Way, so there are lots of foreground stars.

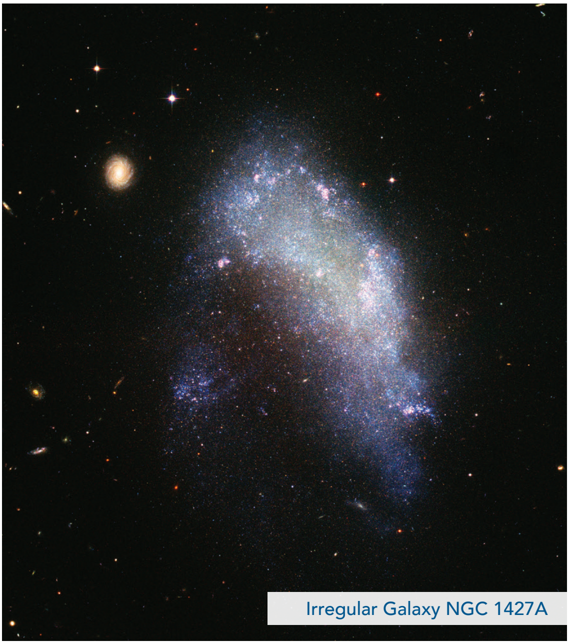
Andromeda Galaxy

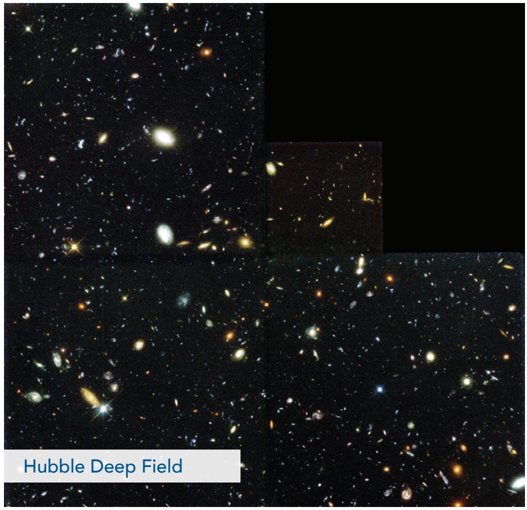
- The Milky Way and Andromeda are the biggest galaxies in what is called the Local Group. There is another spiral in the Local Group, called M33, that is considerably smaller than the Milky Way and Andromeda. There are also many dozens of smaller galaxies.

- Two other important galaxies are the Magellanic Clouds, which are only visible from Earth's Southern Hemisphere. They are relatively very close to our galaxy, and they are classified as irregular systems.

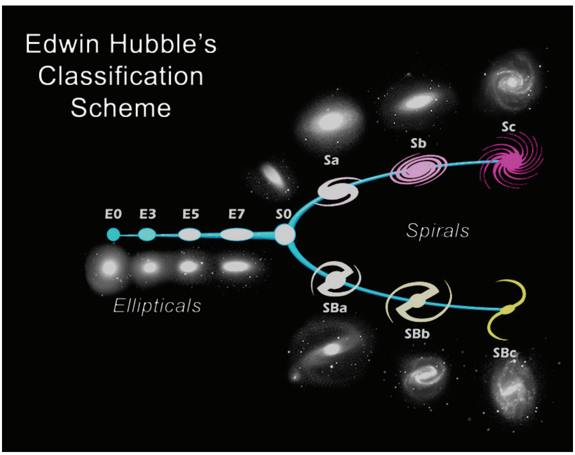
- There are also galaxies that don't look like beautiful spirals. They have a more spherical light distribution and often don't have much gas or dust.


Sombrero Galaxy


Irregular Galaxy NGC 1427A



- Astronomers of the 20th century spent a lot of time trying to understand why galaxies look the way they do. Edwin Hubble in 1926 classified them by their morphology—their visual appearance—and created this diagram. It's called the Hubble sequence.



- In one sense, this is a classification by degree of flatness. Once you get flat enough, there is lots of gas and dust, and you get spirals and maybe a bar. It's also a classification by disorder. The spiral pattern gets looser and looser going to the right, and we can imagine irregular galaxies living off the diagram to the right—galaxies that never really got organized.

- Back then, there was speculation that galaxies evolved from one type to another, but it was just speculation. Along came the radio astronomers, who found that the amount of hydrogen contained in galaxies increased roughly along the Hubble sequence, left to right. Ellipticals have very little hydrogen, spirals have a fair bit, and some irregulars are dominated by gas.

- This was an amazing discovery and indicated that the Hubble sequence is not arbitrary, but is connected to the neutral gas in a galaxy—the galaxy's atmosphere. The technical term for a galaxy's atmosphere is interstellar medium—the stuff that's in between the stars.

- There are many important differences between the Earth's atmosphere and a galaxy's interstellar medium, but one big difference is important to understand. Today's atmosphere on Earth is the product of outgassing—basically volcanic action—modified by living things over millions of years. If for some reason the Earth's atmosphere were instantly removed, it would eventually return in some form, thanks to volcanoes and evaporation from the oceans.

- But galaxies are different. There was a time when there were no stars, only gas. Stars are formed from gas, so galaxies are also formed from gas. Galaxies are formed from their own interstellar medium.

- Today in the Milky Way, several new stars and new solar systems are born every year out of the interstellar medium. Gas feeds galaxies. Supply the fuel—hydrogen—and new stars get made. Take away the interstellar medium and star formation ceases.

Measuring Hydrogen in Galaxies

- The gas of a galaxy is very important, and having a tool like the 21-centimeter line opens up new channels of our understanding. Hydrogen tells us about a galaxy's future.

- It makes sense, then, that if ellipticals are relatively devoid of hydrogen and spirals are rich in it, ellipticals won't have much star formation while spirals will have active, ongoing star formation.

- Of course, this understanding breeds a new set of questions: Have ellipticals simply run out of gas? And if so, why haven't spirals? Are galaxies stuck with the gas they had when they first formed, or is new gas coming in all the time? Why doesn't the gas in a galaxy form all its stars at once in a big flash?

- Besides looking at the hydrogen mass of galaxies, we can look at how it's distributed—the morphology of the hydrogen in galaxies. In the Andromeda Galaxy, there is a big hole in the hydrogen around the center of the galaxy. Also, the hydrogen extends way past the optical light—way past the bright galactic disk. This is a feature of spiral and irregular galaxies. (For more information and images, see http://iopscience.iop.org/article/10.1088/0004-637X/695/2/937/pdf.)

- There are 2 ways to weigh a galaxy. The first is by adding up all the stuff in a galaxy. We count the number of stars and figure out what their average mass is, so we sum that. Then, we measure the mass of the interstellar medium, and we add in dust. This can be called weighing by counting.

- When we count the mass in the Milky Way, we find that stars make up 85% of the mass and gas and dust make up another 15%. For this calculation, planets are counted with the dust. So, the total countable mass of the Milky Way is mostly stars.

- If we did this for other galaxies, the proportions would be quite different, with the elliptical galaxies being nearly totally stars and some of the small irregular galaxies nearly all gas.

- But there is a second way to weigh a galaxy that does not involve counting. We can simply measure its total gravitational force, and that will tell us the mass. We can do this courtesy of a law worked out by Johannes Kepler in the early 1600s: $M = rV^2/G$.

- This equation says that if you have something that's in a stable orbit at a distance r from a mass M, it will have a velocity squared of V^2. The quantity G is the gravitational constant, and it is a constant of nature, like the speed of light.

- Kepler's law shows the balance of the gravitational force and the rotational velocity needed to keep from falling into the mass that produces the force. Kepler's law predicts that if we know the mass, we can predict the velocity at any radius.

- Kepler's law doesn't specify what exactly is in orbit at a radius r with a velocity V. The object in orbit, or its properties, including its mass, don't matter as long as its mass is relatively small. In addition, M is the total mass interior to the distance r. It doesn't have to be concentrated at the center like the solar system is.

- Let's use Kepler's law to weigh a galaxy. (We're are not actually weighing; we're measuring the mass interior to some distance *r*.)

- The velocities from Kepler's law look a lot different for a galaxy than for the solar system. The main reason is that mass in a galaxy is distributed, not concentrated to the center. As *r* increases, more and more stars are enclosed within the distance *r*, and that changes everything. In fact, let's rewrite the law to make this explicit: Mass (interior to *r*) = rV^2/G

- The plot of velocity versus distance from the center of a galaxy is called its rotation curve, the rotational velocity of a galaxy measured at different distances from its center.

- Where there are stars and clouds of ionized gas that emit bright lines at optical wavelengths, we can measure the rotation curve using optical telescopes. But with hydrogen, we can measure the rotation curve from the Doppler shift of the 21-centimeter line, and because we have found that hydrogen often extends way outside the optical limits of a galaxy, it gives us a good way to measure the total mass of a galaxy.

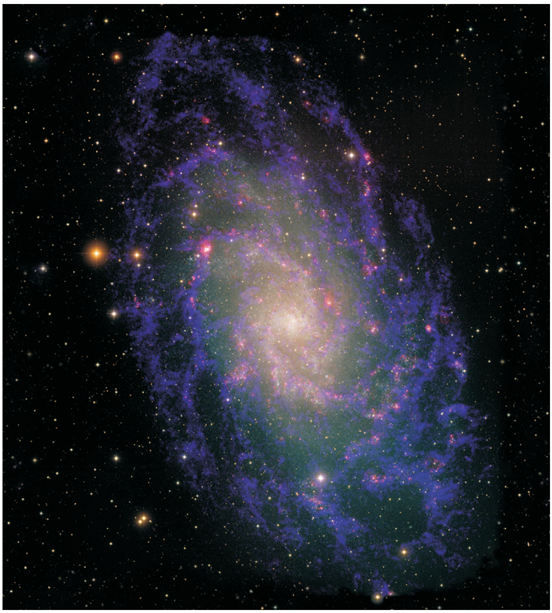
- After all, most of the matter in a galaxy is confined toward its center, so if we can measure something far enough out, we should see the velocity declining, like it does in the solar system, because the matter in a galaxy has to end somewhere—or does it?

- At first, the rotation curve for Andromeda looks like we would expect. As we go out farther from the center, more and more mass is enclosed, so the rotational velocity stays approximately constant. (View Andromeda's rotation curve at http://www.phys.ufl.edu/courses/phy3101/spring08/2006_Physics_Today_Vera_Rubin_vol59no12p8_9.pdf.)

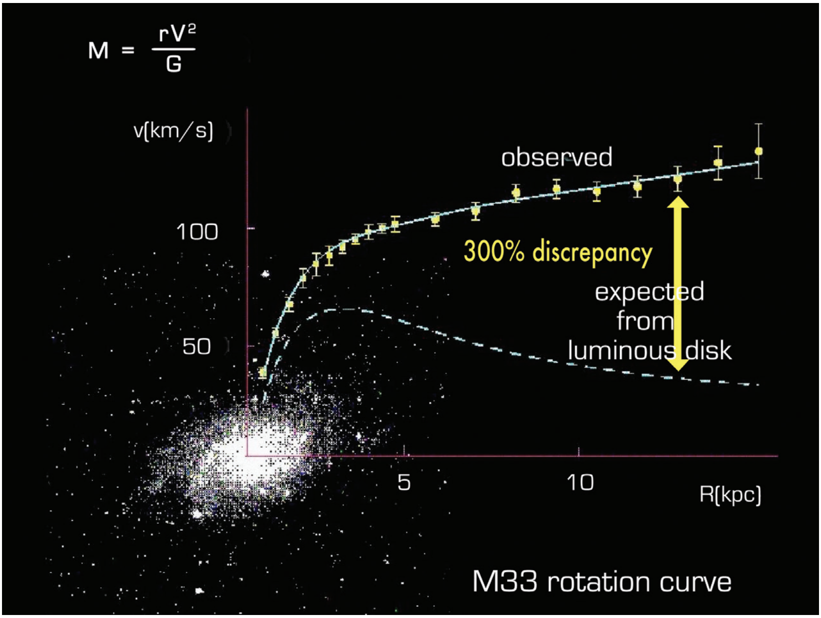
- Compare that to Kepler's curve for the solar system, where the planets contribute almost nothing to the total mass. But here's the issue: The rotation curve stays flat even when we are way past the stellar disk, when there's nothing out there to measure but hydrogen.

- There's some mass out there that's keeping the velocity high, but the mass is invisible. And it can't be hydrogen; there's not enough mass in hydrogen by a long shot.

- Let's look at the galaxy M33.



- The extensive outskirts contain nothing much but hydrogen. And here's the rotation curve.

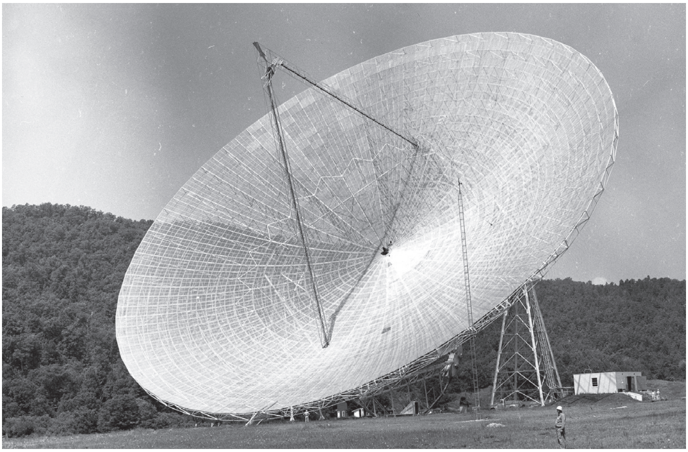


- The dashed line shows the rotation curve that we would expect from the visible matter (everything—stars, gas, and dust) alone. But the solid curve with the measured points shows what we actually measure in the 21-centimeter line. Not only does the curve not fall, but it keeps on rising out to the last measured point.

- The discrepancy in the rotation curve is enormous. In fact, it's a 300% discrepancy. Way outside the visible disk of M33 there has to be a huge amount of mass.

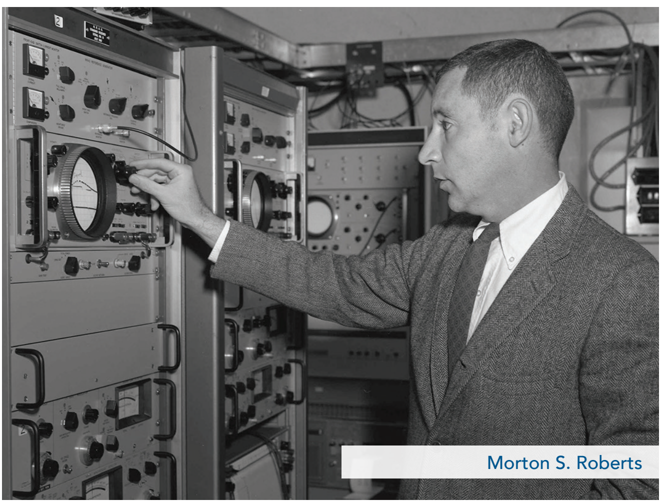
- We have just discovered dark matter.

- Radio astronomers—and one in particular, Morton S. Roberts—found this enormous discrepancy between the expected rotation curve and what was actually measured. Roberts was using the 300-foot-diameter radio telescope in Green Bank, West Virginia, to make his measurements.



- At the same time, two other scientists, Vera Rubin and Kent Ford, were making accurate measurements of the rotation curve of galaxies over the inner parts of their disks using optical lines.

- Roberts, Rubin, and Ford sometimes worked together and sometimes independently, but their discoveries made the indisputable case that there was more to galaxies than met the eye.



Morton S. Roberts

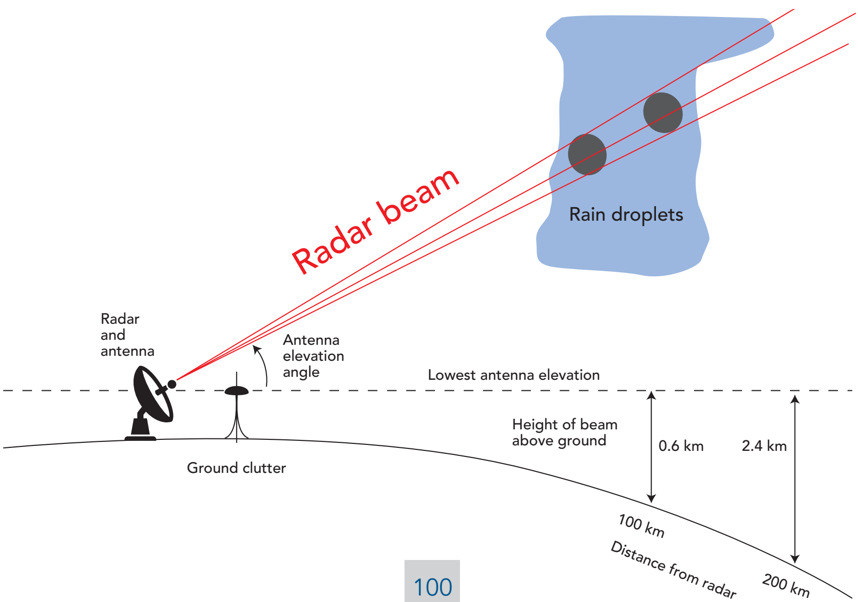
Explaining the Hydrogen

- What could explain the unexpectedly high hydrogen velocities far from a galaxy's center? Using Kepler's law, $M = rV^2/G$, we measure r and V, so there are really only 3 possibilities:

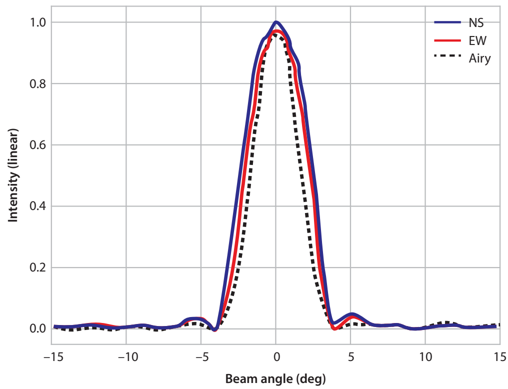
  1. Galaxies contain matter—dark matter—that does not give off detectable electromagnetic radiation but adds to the mass.
  2. The gravitational constant in Kepler's law is not a constant but changes from the inside to the outside of galaxies, or something else is wrong with our understanding of gravity on large scales.
  3. Perhaps the measurements were wrong.

- To understand this, we have to get more into the theory of how radio telescopes work and return to radio telescope beams. Radio telescopes receive waves that come from a fairly restricted direction on the sky, defined by what is called the telescope beam.

- Using the principle of reciprocity, we see that our receiving beam is just like the beam that a dish would transmit if it were used for radar.



- Besides a main beam, radio telescopes have some reception in other directions.



- Every antenna—every radio telescope—has a main lobe called the main beam, but it also has lobes off to the side. These sidelobes have several causes, but there are some that simply result from diffraction—the bending of waves by the edges of things.

- The sidelobes are weak, but they can add up to a significant fraction of the power that a radio telescope receives. As a rule of thumb, only 80% to 90% of the signal entering a receiver from a typical dish has come in through the main beam. The rest comes in through sidelobes.

- The issue of 21-centimeter emission coming into a sidelobe of the radio telescope was thought by some people to be the source of the hydrogen that Roberts was measuring far from the visible part of M31 and M33. This issue was settled when other telescopes with very different sidelobe patterns confirmed Roberts's results.

- But what about the possibility that there could be something wrong with our fundamental understanding of gravity? The idea that our theory of gravity is incomplete has captured the attention of a small group of scientists, but their work so far has not produced a convincing alternative to the concept of dark matter.

- Our new census of the Milky Way that is based on the mass in each component is that stars make up 9% of the mass, dust and gas make up 1%, and dark matter makes up 90%.

- We simply don't know what dark matter is. The best guess is that it's a subatomic particle, but nothing has been found. Except for its gravitational pull, which we measure, no other signal has been detected.

Suggested Reading

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

Sullivan, ed., *The Early Years of Radio Astronomy*.

van Woerden and Strom, "The Beginnings of Radio Astronomy in the Netherlands."

Questions to Consider

1. The average height of the space station above the surface of the Earth is about 405 kilometers. Its orbital period is 93 minutes. The gravitational constant G is 6.67×10^{-11} m^3 kg^{-1} s^{-2}. Use these numbers to calculate the mass of the Earth. Note: In Kepler's law, the distance r is the distance from the center of the system.

   Answer: 5.976×10^{24} kilograms

2. Repeat the calculation with the Moon. Use a mean distance of 385,000 kilometers and a period of 27.3 days. You will get a slightly different answer for the Earth's mass. This is because the Moon is massive enough to influence the motion of the Earth, and these two bodies actually revolve around a common center of mass.

   Answer: 6.08×10^{24} kilograms

3. Suppose that you wanted to make the Milky Way's dark matter out of giant planets like Jupiter—objects that are not massive enough to have nuclear reactions and are therefore quite cool. Jupiter has about 0.1% the mass of the Sun. If for every star in the Milky Way there is 10 times its mass in dark matter, how many Jupiters would you need for every star to account for the dark matter? Do you think that you could hide this many Jupiters in the Milky Way?

   Answer: 10,000 Jupiters per star

LECTURE 10

Pulsars: Clocks in Space

This lecture is about what you find when you look for a radio source that is twinkling. For stars, twinkling means that the light is flickering a bit and moving from side to side, and often, if you look at a star close to the horizon on a clear night, you can even see it changing colors as it dances around.

Scintillation

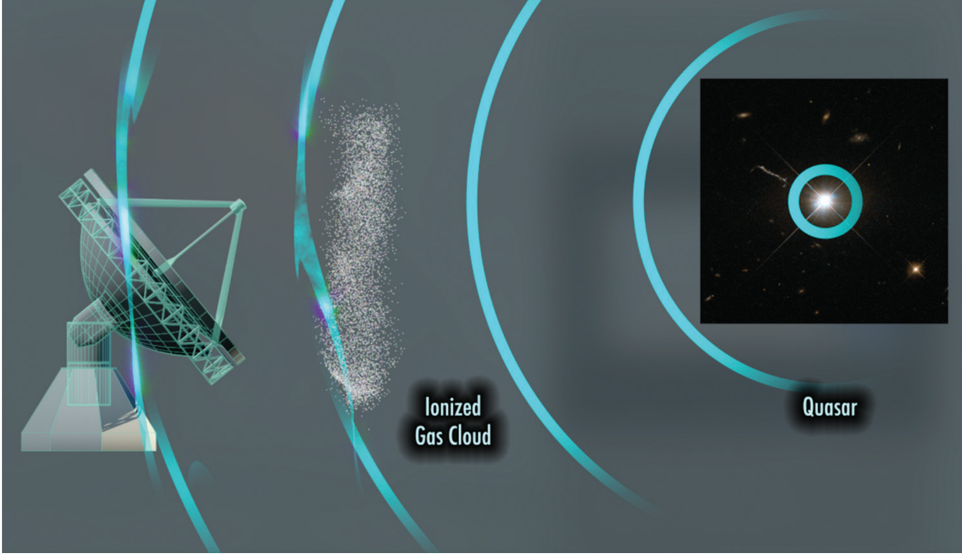
- Blobs in the Earth's turbulent atmosphere act like little lenses or prisms, and the wind blows them past the star, making the star dance and twinkle. The technical term is scintillation.

- The Moon, Sun, and planets don't scintillate, because they have too large an angular size. The light from one point of the planet scintillates, but the light from another part of the planet scintillates in a different way, and all the different scintillations add up to a fairly smooth image, though a bit fuzzy.

- It takes 2 things to make a radio source scintillate. First, the radio source has to have a small angular size. It doesn't have to be small itself, but if it is big it has to be very far away to appear small in the sky. Objects with a negligible angular size are referred to as point sources. They appear in the sky as a point without any structure. A type of radio galaxy called a quasar is very bright and very distant and can look like a point source to us.

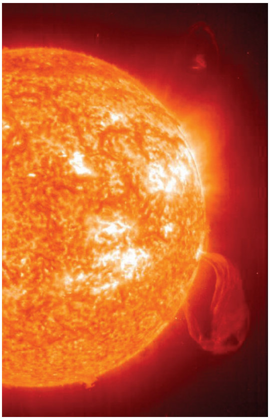
- The second thing you need to make a point source scintillate is lumps of ionized gas to refract the radio waves and bend them.

- The signal from a quasar is turned into a lumpy image, and as the ionized gas clouds move around, we alternately see bright and then faint radio emission. That's the signal of scintillation—a change in brightness with time as the radio source is focused and defocused on our telescope.



- At radio wavelengths, the strength of scintillation increases with the wavelength squared. Longer wavelengths (lower frequencies) scintillate much more than higher frequencies.

- There are many regions of ionized gas between us and a distant quasar, but close to home there's a pretty powerful lumpy ionized medium that radio waves have to traverse: the solar wind.



- The Sun is putting out ionized gas every moment, and it flows past Earth. This is the solar wind. It arises from magnetic storms on the surface of the Sun. It has lumps, and while most of the time it doesn't affect our radio measurements, at low frequencies it can make point radio sources scintillate.

Hewish's Telescope

- Antony Hewish built a telescope to discover quasars by their scintillation from blobs in the solar wind. At the time, in the mid-1960s, quasars were mysterious beasts, and they still are in many ways.

- If you're trying to understand the properties of something, you need large samples of objects or phenomena to separate the general from the particular. Hewish wanted to discover lots and lots of quasars, and in the process, he and his team discovered something else quite unexpected.

- Because the scintillation is strongest at low frequencies, Hewish designed his telescope to work around 80 megahertz, at a wavelength of 3.7 meters, just below the FM band in the United States.

- Hewish ended up covering about 4.5 acres—nearly 60 tennis courts—with his antennas. The antennas were just copper wire, strung between wooden poles.

- Hewish's graduate student, Jocelyn Bell Burnell, was involved in the construction and operation of the telescope.

- When the Hewish telescope was finished, the observations began. The data were recorded on a chart with pen and ink. Because the scintillations are rapid, the paper moved fast and the pen could record fluctuations as short as 1/10 of a second. The telescope produced 4 beams on the sky in different directions, and the data were filtered in various ways, so there were about 100 feet of chart recording that came out every day—and had to be examined every day, by hand.

The Discovery of Pulsars

- Radio telescope sidelobes can be reduced but not eliminated entirely, even from big modern dishes. The result is that radio telescopes have some sensitivity to signals coming from all directions, not just where the main beam is pointed.

- Bell Burnell and Hewish's telescope ran day and night, 7 days a week, and Bell Burnell had to sort through all that data. She discovered scintillating sources, which meant new quasars, and also lots of examples of terrestrial interference. There was also a strange faint signal—some "scruff" on the chart recordings—that didn't look like scintillation and didn't look like interference.

- After a while, Bell Burnell recognized that one particular patch of scruff had reappeared several times from about the same fixed direction in space. That was peculiar. Something was producing regular radio pulses. It didn't seem fixed to the Earth but appeared earlier each day, like something fixed to the stars.

- Could this be some signal from another civilization? They looked at it with another radio telescope at Cambridge, and after a few fumbles detected it. So, it was not being generated in their own equipment.

- Study of thousands of feet of charts showed a few other directions with pulsing radio sources. They had discovered something new: pulsars.

- They reported their results in a paper in February 1968. By late spring, more pulsars had been discovered. Pulsars were not only real, but there seemed to be quite a lot of them. But what were they?

- We now understand that a pulsar is the remnant of a massive star that exploded as a supernova at the end of its life. In order for a star to become a supernova, it has to have 8 times the mass of the Sun. These massive stars are short-lived, and upon exploding, their interior collapses and forces electrons onto protons to form neutrons, thus producing a neutron star. This ball of matter is incredibly dense—as dense as matter can get.

A cubic inch of a neutron star—about the size of a sugar cube—contains the same mass as Mount Everest.

- A neutron particle left by itself in free space decays in just a few minutes into a proton and electron, but bound up in a bundle with others, it's quite stable.
- The neutron star has a diameter of just a few kilometers. It has a mass between 1 and 2 times the mass of the Sun, so that's a lot of matter compressed into a tiny volume.
- A star has a magnetic field, just as the Earth does. That magnetic field is threaded through the interior of a star, and when the star collapses, it drags the field down with it, amplifying it enormously. We're left with a collapsed stellar core that's rotating rapidly because of conservation of angular momentum.
- Earth's north magnetic pole is not at the North Pole. It's the same for a neutron star; a neutron star's magnetic pole can be offset from its rotational pole. The magnetic field produces strong radio emission, and if the magnetic pole sweeps past us, we see it as a radio pulse. And we call it a pulsar.
- The pulses from a pulsar are extremely regular. The first pulsars that were detected had periods of about 1 second, meaning that the neutron star was spinning around about once a second. But now we have pulsars whose periods span from a few seconds to a few thousandths of a second.

- The pulsars are losing energy as they rotate, so they are slowing slightly, but very predictably. Pulsars slow down and eventually die.

- The discovery of pulsars initiated a flurry of observations around the world. Although pulsars were discovered in observations at 80 megahertz, in modern times they're most commonly observed between 300 megahertz and 3 megahertz using large single dishes.

- In a typical pulsar pulse, there's a main pulse and sometimes a secondary pulse, or interpulse. If we think about the pulsar as having 2 magnetic poles, then it makes sense that sometimes we see emission from both. The average pulse shape is very stable, but any one individual pulse may show large variations in intensity and shape from the average.

- How do pulsars produce radio radiation in narrow beams? Nearly 50 years after their discovery, there's still lots of mystery about the basic pulsar emission mechanism. The emission is certainly nonthermal. It's broadband, and its intensity increases rapidly to lower frequencies, opposite of the Planck curve—a clear sign of nonthermal emission. But what exactly makes it?

- We know that energetic particles in magnetic fields produce nonthermal emission. Pulsars have very strong magnetic fields, far in excess of anything that we could produce on Earth. All we need is particles. It's likely that charged particles from the neutron star's surface are accelerated by intense electric fields.

- Spiraling in the magnetic fields, these particles emit high-energy photons, which in turn are converted into electrons and positrons by the intense magnetic field. It is these electrons and positrons that produce the radio emission we observe. This sounds plausible, but many details still don't fit this picture.

- The first observers of pulsars discovered that the arrival time of pulses depended on the frequency that was observed. A given pulse arrived first at the higher frequencies and then progressively later at lower and lower frequencies. But all frequencies left the pulsar at the same time. The delay comes from interstellar electrons.

- Ionized gas between us and the pulsar delays the pulse arrival. The size of the delay increases as frequency decreases. This process is called dispersion. It depends on the amount of ionized gas between us and the pulsar.

- This is important for 2 reasons. First, manmade signals from Earth don't travel through the interstellar medium to reach us, so their pulses are not dispersed unless they're transmitted that way. Looking for the signature of dispersion gives us one way to discriminate between pulses from space and terrestrial interference.

- Second, the amount of dispersion gives us an estimate of the distance to the pulsar. The farther the pulsar, the more it should be dispersed. There are many uncertainties, but it's so difficult to get distances in radio astronomy that anything that gives us something even approximating a distance is grasped like a lifesaver.

Suggested Reading

Graham-Smith, *Unseen Cosmos*, chap. 6.

Hewish, "Pulsars and High Density Physics."

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

Verschuur, *The Invisible Universe*, chap. 8.

Questions to Consider

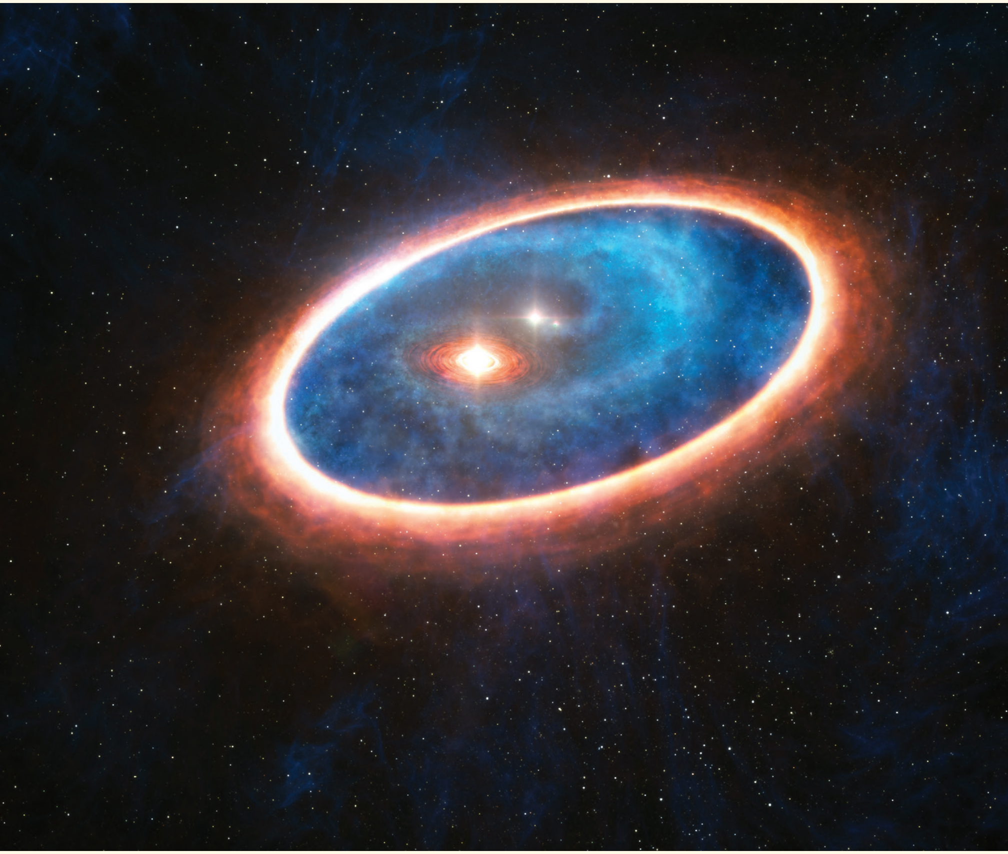
1. A pulsar has what is called a duty cycle, which is the fraction of the time, in every pulsar period, when the pulse is actually on. A typical duty cycle is less than 10%, meaning that if a pulsar has a period of 1 second, the pulse is seen for less than 0.1 seconds. What does this tell us about the size of the area on the pulsar that emits the pulse?

2. Hewish's array could produce 4 beams in different directions because the individual dipoles have a very broad beam pattern. Could you produce 4 beams in very different directions if the array were made up of dishes?

3. Besides the slowdown of a pulsar's spin because of energy loss, other factors could make a pulsar appear to slow down or even spin up. What could those be? (Answer provided in the next lecture.)

LECTURE 11

Pulsars and Gravity



In this lecture, you will learn how to use pulsars—spinning tops with the mass of the Sun that give off a radio pulse every second or so—to confirm Einstein's prediction of gravitational radiation. You will also learn how to confirm Einstein's theory by measuring a pulsar's Doppler shift.

The Doppler Shift of Pulsars

- The Doppler shift describes how a wave is stretched or compressed as the source of the wave moves toward us or away from us. A pulsar can have a Doppler shift.

- We can think of the pulses as peaks of a wave; we just don't have the rest of the wave. And those peaks will be shifted by any motion.

- We can measure a Doppler shift from a pulsar—sort of. The rub is that with atoms and molecules, we have a clearly defined rest frequency set by quantum physics. We can measure velocity directly because we know the rest frequency.

- But for a pulsar, its actual rotational period can be anything from seconds to milliseconds. All we can measure is the observed period, which is the combination of its rest period and any Doppler shift.

Measuring Doppler Shift

You can measure the Doppler shift of the ticks from any clock. To do this, find a small portable clock that gives off loud ticks. Tie it to a meter-long string and whirl it around your head.

You will hear a steady beat because the clock is not changing its distance from you, but someone standing nearby will hear the increase and decrease of the clock tick rate as the clock on the string approaches them and then recedes from them.

- The terms "period" and "frequency" describe the same thing—namely, some sort of repetitive phenomenon—but they are the inverse of each other. Something that happened 10 times a second has a frequency of 10 hertz and a period of 0.1 seconds. Something that happens every 2 seconds has a period of 2 seconds and a frequency of 1/2 hertz.

- The Doppler shift is in play for every pulsar in the sky, only we can't use it because we don't know the actual period of the pulsar. We can't use the Doppler shift unless we see the period change.

- In fact, the period we observe of every pulsar changes all the time because we're observing pulsars from a moving platform—the Earth—which spins on its axis toward the east and away from the west. So, as we observe a pulsar rising, we see that its period increases, and as it sets, its period decreases.

- The Earth also goes around the Sun at 30 kilometers per second or so. If we measure a pulsar in the spring of the year and then later in the fall, we will have seen a change in its period because of the Earth's revolution around the Sun.

- But we can correct for all of these motions and measure the Doppler shift of pulsars so precisely that we even need to make corrections to pulse arrival times because Earth's motion is influenced by the gravity of the planet Jupiter.

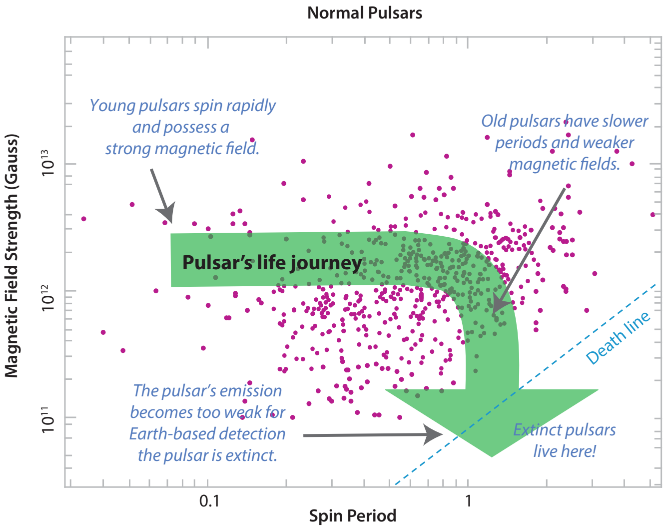
- This Doppler effect is stronger in some parts of the sky than others. Because we know the Earth's velocity very accurately, this Doppler shift can be used to locate the position of pulsars quite precisely.

How Do Pulsars Get Their Spins?

- All stars rotate. A star that goes supernova blows off its outer layers, but the inner parts collapse, preserving their angular momentum and spinning up as they fall.

- The result is a neutron star spinning quite fast. The neutron star in the Crab Nebula currently has a period of 33 milliseconds; it rotates more than 30 times each second. At its birth, it certainly had an even shorter period, around a few milliseconds.

- As pulsars age, they slow down and their magnetic field weakens and period increases. Eventually, they cease being observable as pulsars.



- Millisecond pulsars are old. They have run out of steam and dropped out of sight. But then, for some of them, an amazing thing happens: They get rejuvenated and spin up—a lot. Their magnetic field is still weak, so their radio emission is weak, but they are spinning fast.

- These pulsars were formed in a binary system, which is where a pair of stars is in mutual orbit around each other. The most massive star went supernova and became a neutron star. That neutron star did the pulsar thing, and over time, its magnetic field weakened and its rotation slowed.

- But then, as the other star evolved, it started losing matter and dumping some of the matter on the neutron star. That spun the neutron star back up, to even faster periods than it had before. It made a millisecond pulsar.

- So, a pulsar can get its spin from either its creation in a supernova explosion or by mass transfer from a companion.

- All pulsars are neutron stars. But not all neutron stars are pulsars. To be a pulsar, a neutron star has to have a magnetic field strong enough to produce radio emission, and that radio beam has to sweep across the Earth. Because the beams are relatively narrow, we probably see only 10% of the active pulsars in the Milky Way.

How Do We Measure Pulsars So Precisely?

- There is radio noise in all of our measurements, and it comes from our electronic equipment, the galactic nonthermal background, the atmosphere, and other sources. The challenge of radio astronomy is how to dig the signal out of the noise.

- But we have one important thing going for us: Noise is truly random. It fluctuates from instant to instant. If you average 2 noisy signals, the noise in one tends to cancel the noise in the other.

- The amplitude of the noise—that is, the height of the noisy signal—decreases as the square root of the number of samples that you have. If you average 4 noisy signals, the noise in the average has decreased by a factor of 2.

- We are able to detect pulsars, and almost every other signal in radio astronomy, because as we add data and average, the noise level decreases while the signal stays constant.

- We can look at the pulsar and measure the pulse and average down the noise in time, but because pulsar radio emission is broadband, we can also measure it at a number of frequencies and average over frequency as well as time.

- Because of interstellar dispersion, the pulses arrive at slightly different times at different frequencies. We have to shift the samples before adding them lest we blur out the signal. But we can measure the dispersion quite accurately, and the shift is easy.

- Using signal-averaging techniques, we can also measure the period derivative, which is the technical name for the spin-down rate, and also the dispersion measure. This allows us to predict the arrival time of pulses many months into the future.

- But how do we determine the period in the first place? One way is to average the data using a guess for the period. If we are off, the pulse is blurred because data taken at different times do not add in phase. If we are spot-on, the pulse appears at its sharpest. In detecting new pulsars and measuring their rotational periods, quite a lot of this searching goes on, and it's computationally intensive.

Confirming Einstein's Theory of Relativity

- In 1972, Joseph Taylor, a young faculty member at the University of Massachusetts in Amherst, wrote a proposal to the National Science Foundation seeking funds to search for new pulsars using Puerto Rico's Arecibo radio telescope, which is 1000 feet across and has no rival in its sensitivity to pulsars.

Arecibo telescope

- At the time of Taylor's proposal, there were about 100 known pulsars, but no pulsar had been found in a binary system. Taylor got the grant, began to buy the hardware necessary to build a digital pulsar detection system, and recruited a graduate student, Russell Hulse, as a collaborator.

- They did their search at frequencies around 400 megahertz. At every point in the sky where they took data, their programs searched more than 500,000 combinations of period, dispersion, and pulse shape seeking a detection.

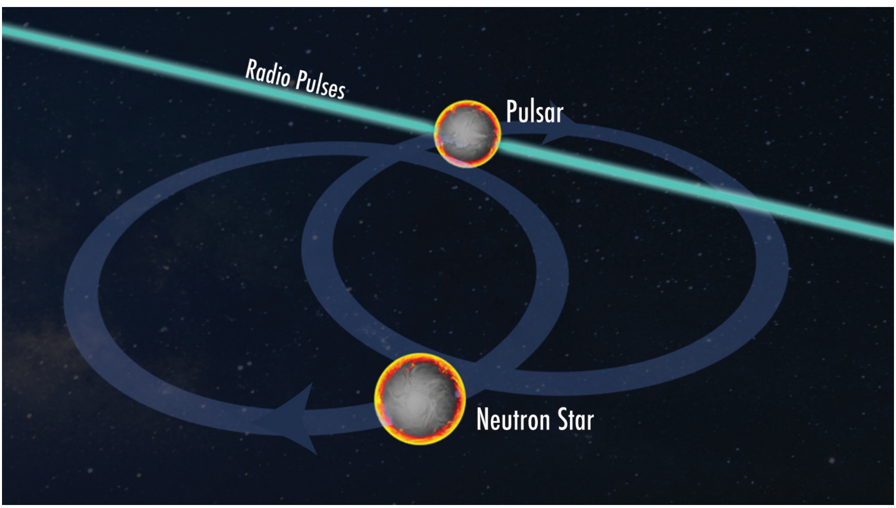
- If you take enough samples of random noise, every once in a while the noise combines to look like something real. But it's not. Given that each spot on the sky would be analyzed in half a million different ways, Hulse set his threshold for detection at 7 standard deviations. This means that a signal would have to be 7 times the expected noise level before the computer would flag it as possibly being real.

- Taylor and Hulse took their system to the Arecibo telescope and began searching the sky for new pulsars. The observations were performed on and off for more than a year. In the end, they found 40 new pulsars. One in particular caught their eye. It had a period of around 60 milliseconds, which made it the second-fastest pulsar then known, second only to the Crab pulsar.

- When Hulse reobserved this particular pulsar several times, the pulsar's period couldn't be pinned down. He set up a new data analysis scheme with faster time sampling of the incoming signal. The new data showed that this pulsar's period seemed to be changing in a regular way.

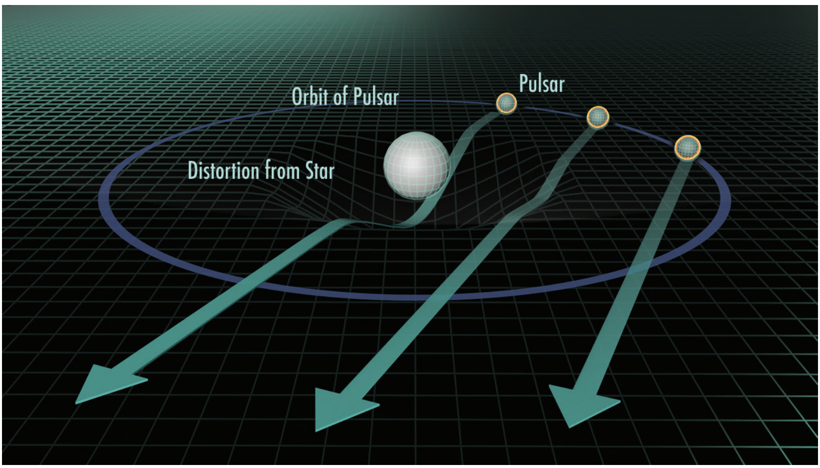
- Then, Hulse realized that the changes could arise from a changing Doppler shift of the pulsar, which meant that it must be in orbit around another star—a pulsar in a binary system.

- In short order, Joe Taylor arrived at Arecibo carrying new equipment that made study of this pulsar much easier. Here's what we now know about this amazing system.



- There are 2 neutron stars in orbit around each other. Both have about 1.4 times the mass of the Sun, and one of them is a pulsar with its radio beam intersected by Earth. They are quite close together; at their closest, they are only a few times farther apart than the Earth and Moon. They orbit around each other every 7.7 hours. That rapid orbit produces a large Doppler shift in pulse arrival times.

- In classical physics, there is nothing to keep 2 objects from orbiting each other forever. But Albert Einstein changed all that with his theory of relativity. Under this theory, space is curved around massive objects, and as they interact gravitationally, they radiate gravitational waves. Eventually, the 2 neutron stars will merge as their orbit decays through radiation of gravitational waves.



- The pulsar found by Hulse and Taylor confirmed this theory and provided direct experimental proof that changes in gravity travel at the speed of light. For this, they were both awarded the Nobel prize in Physics in 1993.

- Pulsars can be used to probe the curvature of space predicted by Einstein's theory of relativity. Every object distorts the space around it at least a little. When the pulsar is nearly exactly behind the star, its pulses have to travel an extra distance because of the distortion of space. When the pulsar is behind its companion, the pulses are delayed by the extra path they need to travel. This is a direct measurement of the curvature of space.

Suggested Reading

Graham-Smith, *Unseen Cosmos*, chap. 7.

Hulse, "The Discovery of the Binary Pulsar."

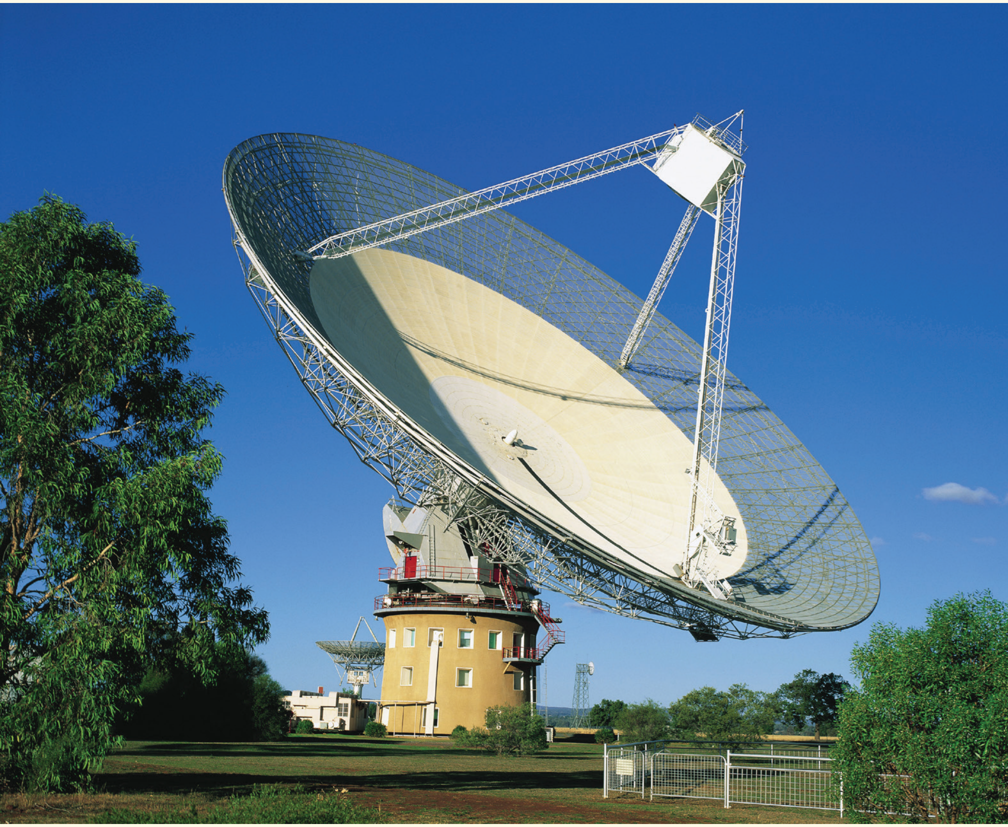
Taylor, "Binary Pulsars and Relativistic Gravity."

Questions to Consider

1. Although all frequencies of a pulsar are emitted at the same time, the arrival time of a pulse on Earth depends on frequency because of delay by interstellar electrons (the technical term is dispersion). And the delay is proportional to frequency to the −2 power; a decrease in frequency by a factor of 2 increases delay by a factor of 4. Because the interstellar medium between a pulsar and us changes as ionized clouds drift past, the dispersion changes and pulse arrival times change. How might this be detected and corrected?
2. Searches for new pulsars are typically done at frequencies below 1 gigahertz, where pulsars are brightest, but accurate timing of pulsars is done at frequencies above 1 gigahertz, even though the pulsars are weaker there. Can you understand why, in view of the previous question?
3. Because we can measure the period of a pulsar extremely accurately and we have to compensate for the Doppler shift of the period arising from the Earth's motion around the Sun, does this give us information on possible extra planets in the solar system, or even a dark companion star to the Sun?

LECTURE 12

Pulsars and the 300-Foot Telescope



In this lecture, you will learn more about pulsars and how to use the radio spectrum for earthly purposes. Then, you will discover the amazing story of a radio telescope that was created almost overnight. It made great advances in studies of pulsars, hydrogen, and the radio sky; then, more quickly than it came, it vanished overnight.

The Sound of Pulsars

- If you hooked up a speaker to the output of a radio telescope, the result would be pure static. But buried in that noise are subtle signals that can be pulled out with some signal-processing techniques.

- There are a few exceptions to the boring hiss. Jupiter's radio bursts are one exception. Another exception is the sound of pulsars. Because pulsars emit periodic bursts of intense radio emission, they can rise above the noise.

- We assume that these signals we hear come from pulsars far out in space, that they are natural and not manmade—that they're not coming from a nearby alarm clock or a malfunctioning computer. But how can we be sure?

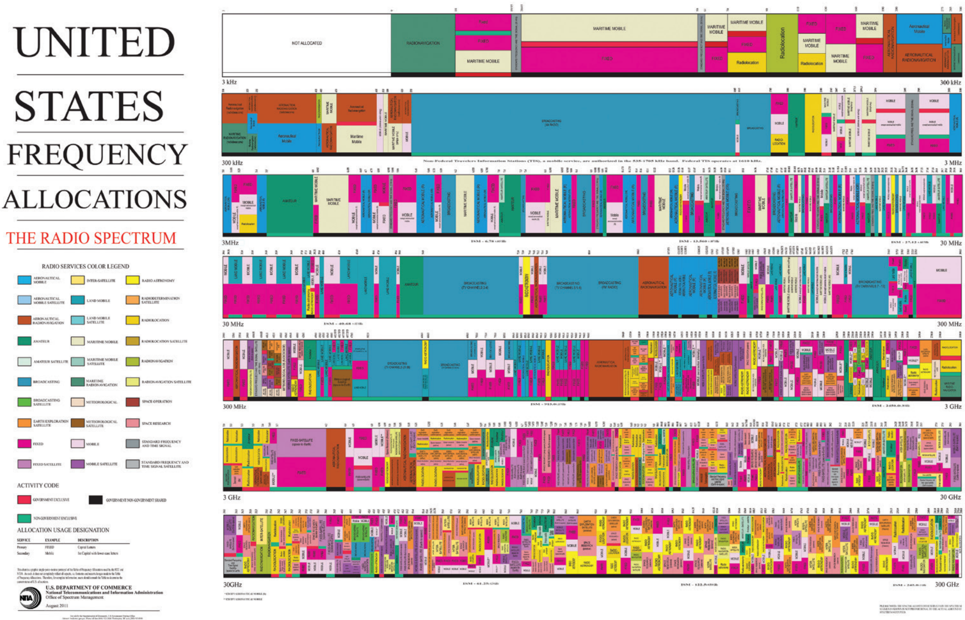
- You might say that we are pointing our telescopes at outer space, not at some transmitter on top of a tower. The signals must be coming from where we're pointing. But it turns out that this is not good enough.

- In practice, when we see a new signal, we go through a number of checks to make sure that it's coming from the sky. We point at different positions and observe at different times. We check the polarization characteristics. Manmade signals are almost always strongly polarized because they are transmitted through wires that have a preferred direction. Most celestial signals are not strongly polarized. We are always suspicious because there are transmitters all over the place.

Transmitters and Telecommunications

- The radio spectrum is a finite resource. In the United States, the spectrum is divided up among competing interests by the Federal Communications Commission and the National Telecommunications and Information Administration. They're the referees, and the stakes are billions of dollars.

- This chart shows how the radio spectrum below 300 gigahertz is allocated.



- The 2 radio astronomy allocations are around 10.7 gigahertz and around 15.4 gigahertz. There are allocations for radiolocation, which is radar, mobile transmitters, radio navigation—another type of radar—and so on.

- The frequencies allocated for radio astronomy are not supposed to be used for transmitters. Radio astronomy shares its frequencies with passive space research and passive exploration satellites, both of which are pretty good neighbors. But the 15.4-gigahertz radio astronomy allocation is adjacent to radar, and the 10.7-gigahertz allocation is adjacent to a satellite downlink.

- A problem is that the power in a real signal doesn't fall to zero at the edges of the band the way the allocation chart would make it seem, and radio astronomy receivers are very sensitive. A little bit of transmission just out of the band and radio astronomy is toast. In reality, instead of neat boxes, there are fuzzy regions of frequency without distinct borders.

- There's increasing use of satellites for communication of all sorts of information. There are plans underway to mass-produce vast numbers of small satellites. There will be hundreds and even thousands of these in orbit to provide services such as global wireless broadband. At their frequencies, we will never again be able to detect radio signals from the universe.

- All of this is perfectly legal. The electromagnetic spectrum is a shared resource, and radio astronomy does not have claim to anything except the few bands that are specifically protected.

- This is just a small fraction of the transmitters out there. Our civilization depends on use of radio transmitters. But at the same time, there aren't very good controls on actual transmitters. Transmitters can be messy and spew power outside their specified band; they can malfunction disastrously, and there's no real mechanism for stopping a rogue system.

The 300-Foot Telescope

- You might think that we would get some benefit by putting our radio telescopes in space, but once we leave Earth, we lose the protection of mountains and are exposed to transmitters from an entire continent.

- The Green Bank Observatory has special protection because it's surrounded by 2 radio quiet zones: the National Radio Quiet Zone, which protects from new fixed transmitters, and a smaller zone established by the state of West Virginia, which has stronger protection. Nothing else like these exists in North America.

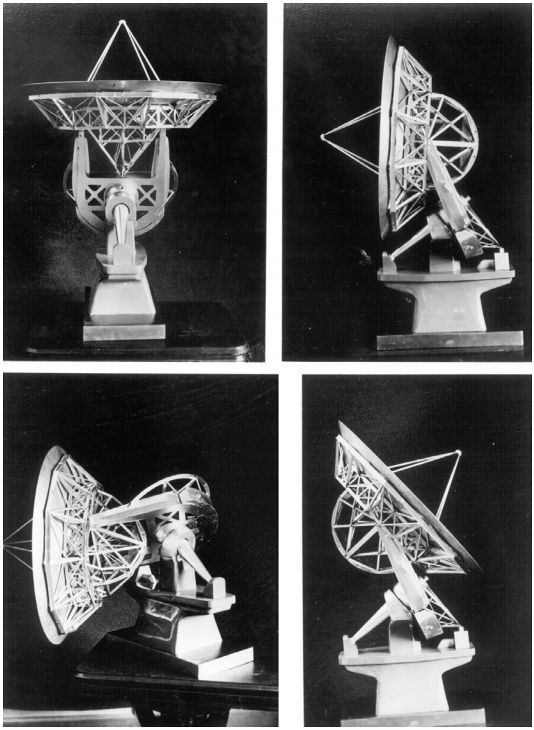
- The quiet zones were established in the late 1950s, when the Green Bank Observatory was founded as the National Radio Astronomy

Observatory. The observatory would be a national facility and not the province of any particular university or group of scientists. It would provide state-of-the-art telescopes for use by any competent researcher.

- A site for the new radio observatory was chosen in a remote valley in Green Bank, West Virginia, far removed from cities and industrial activities that might produce harmful radio interference and shielded by mountains.

- The National Radio Astronomy Observatory was dedicated in 1956, and work began immediately on an 85-foot diameter radio telescope—relatively small, but it was a start.

- The centerpiece of the observatory was to be a dish 140 feet in diameter, fully steerable to track objects across the sky, with a surface that was of unprecedented accuracy for a dish that size.



- The centerpiece of the 140-foot telescope's design is the polar shaft. This enormous piece of steel points toward the North Pole. As an object in the sky is tracked, the polar shaft rotates slowly to follow it. This design had been used for all large optical telescopes but never on something as huge as the 140-foot telescope. The massive polar shaft rests on a large bearing, which had to be fabricated quite precisely, with a mirror finish.

- The project was being managed from Washington and New York, and there were problems early on. In fact, the design that was initially proposed proved almost impossible to actually build. By 1960, the 140-foot telescope construction was in serious trouble and work had come to a halt.

- This left the scientists at Green Bank stranded without a major telescope. In fact, astronomers everywhere in the nation didn't have a functioning National Radio Astronomy Observatory that they could use.

- The small group of scientists at Green Bank took it upon themselves to turn this situation around. As an interim measure, they proposed to build a completely different radio telescope in Green Bank. This would not be a general-purpose instrument but would have quite limited capabilities. But for what it could do, it would be the best in the world.

- The telescope would be built quickly to get the observatory functioning as a national facility. And it would have to be inexpensive. The Green Bank astronomers designed the 300-foot telescope.

- The telescope dish was supported by 2 towers that were fixed to the ground. The dish could be tilted north or south but could not track east or west. This cut the costs way down but meant that the only time any particular object could be observed was when it passed through the meridian—the north-south line on the sky.

- The surface was not solid, but mesh. A mesh surface is cheap and light, but it limits the frequency range of the dish. For the 300-foot telescope, some convenient mesh was available in the form of chicken wire. With holes of about 1 centimeter in size, it would be a dandy reflector of waves in the 21-centimeter line.

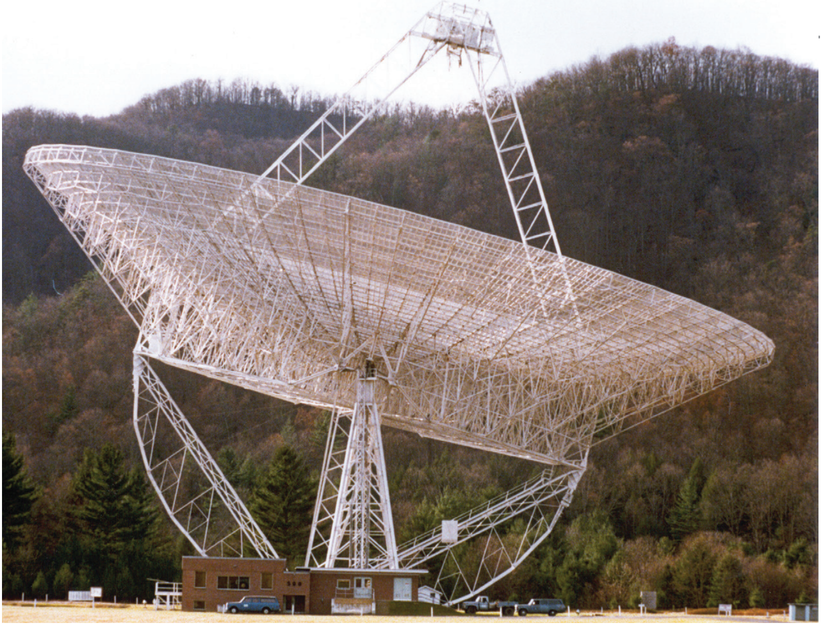
- The telescope was low to the ground. Keeping it low limits the force of the wind, making the entire structure lighter and cheaper. But this restricts the area of the sky that the telescope could access. Something had to rise to about 30° above the horizon to be visible to the 300-foot telescope.

- Because it only tips up and down and not side to side, you can support the receiver with just 2 legs and a few cables.

- The Green Bank staff did not think that they were building a telescope for the ages. Their goal was to get something going quickly that could be used by scientists as soon as possible. They thought that once the 140-foot telescope was finished, the 300-foot telescope could be retired. They thought that its lifetime might be 5 or 6 years.

- There's nothing wrong with a mesh surface for a dish, but the particular mesh used on the 300-foot telescope was not sturdy enough for the job. Some of it was damaged during installation. And more of it was deformed by an ice storm. By 1966, the surface was in bad shape, with ripples that were large enough to produce sidelobes on the telescope beam.

- The observatory tried to straighten the mesh. They rolled over it with a small steamroller. That didn't work, so eventually the entire surface was replaced with perforated panels—a great improvement in performance. It was also outfitted with new receiver support legs and a receiver mount that could be moved east-west, allowing some limited tracking of objects.



- By this time, the 300-foot was 10 years old. Because of advances in technology—and, as importantly, advances in science—the 300-foot telescope continued to be in high demand even after the 140-foot telescope came into operation in 1965.

- In the meantime, pulsars had been discovered, and it was the perfect telescope for studying pulsars. It was the telescope used to discover the first new pulsars after the original ones found by Antony Hewish and Jocelyn Bell Burnell, and it was the telescope that discovered the pulsar in the Crab Nebula.

- It was also perfectly suited for measuring the 21-centimeter line from hydrogen in galaxies. It measured extended rotation curves of galaxies, making the case for dark matter.

- It was used for most of the observations that determined the Tully-Fisher relationship that gives us a strange link between the dark matter in a galaxy and its visible matter. The 300-foot telescope had state-of-the-art electronics and was a workhorse for large-area sky surveys.

- In November 1988, while in routine operations on a cool, windless night, the 300-foot telescope collapsed completely. No one was hurt, but the telescope was a total loss.

- A formal investigation later concluded that the cause of the collapse was the failure of a single piece of steel due to progressive metal fatigue. The piece was located where it could not be inspected, and it is possible that the fatal fracture actually began during construction 27 years earlier.

- The 300-foot telescope has now been replaced by the larger, more accurate, fully steerable Green Bank Telescope, which is making discoveries in areas not even conceived of in 1960. It's a worthy successor to this late, great telescope.

Suggested Reading

Ekers, Cullers, Billingham, and Scheffer, eds., *SETI 2020*, sections 5.6 and 6.5.

Lockman, Ghigo, and Balser, eds., *But It Was Fun*, part II.

Questions to Consider

1. Because the radio spectrum is a shared resource, can you think of ways that we might still use it for radio astronomy without greatly inconveniencing other radio services?
2. What is the moral (if any) that you personally draw from the story of the 300-foot telescope?

LECTURE 13

The Big Bang: The Oldest Radio Waves

This lecture is about the radio signals from the big bang. These radio waves are very old. They're the oldest electromagnetic radiation in the universe. These old radio waves tell a story from a time when the universe was very young and very simple.

Radio Noise

- Objects in our world constantly emit radio waves—it's thermal emission of radio waves. This means that our radio receivers are always putting out some sort of signal, even if nothing is coming in from the antenna.

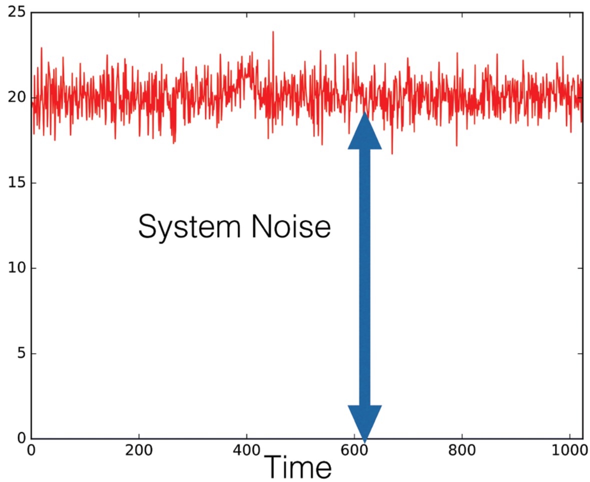
- Consider a camera. If you block the lens with something at room temperature—such as your hand—there will be no picture, because nothing in the camera gives off light.

- On the other hand, if you block the input to a radio telescope receiver, the receiver would see blackbody emission from whatever was blocking it. If the object was at room temperature, around 300 kelvins, the radio emission would be quite bright. Objects at 300 kelvins don't give off visible light, but they do emit radio waves.

- Sources of radio emission—radio noise—that we have to contend with in our radio telescopes include noise from the receiver, antenna and horn, dish, ground, atmosphere, and unrelated celestial emission.

- The signals that we're trying to detect usually sit on top of a sea of unrelated emission. For this reason, radio-astronomical measurements are almost always differential, which means that we're almost always looking at the difference of signals rather than the absolute signal.

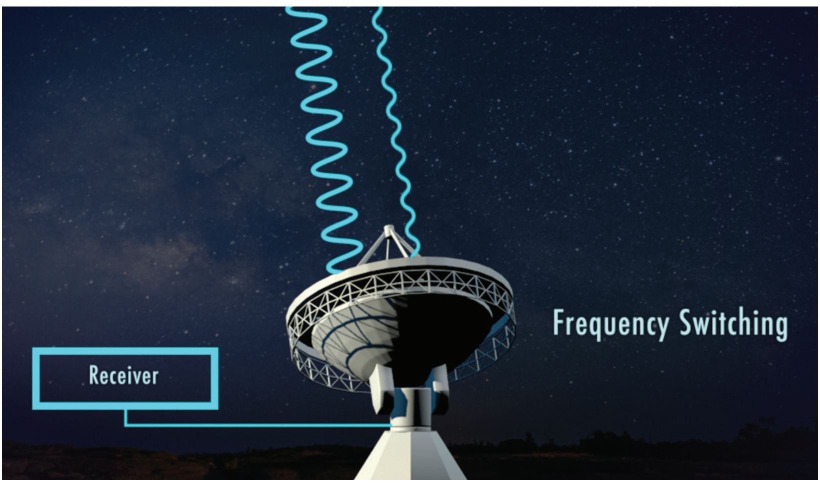
- Observations of pulsars give a great example. The pulse sits atop a large amount of radio emission—the so-called system noise, which comes from the receiver, atmosphere, ground, and so on. Usually, our signals of interest are much less than 1% of the total system noise.



- Everything except the pulsar is fairly constant with time. Therefore, we can just take the average intensity over the entire pulse period and subtract it from all the data to eliminate the radio signals that aren't of interest. This is called time switching, because we are making a comparison between signals that arrive at a different time—pulse on compared to pulse off.

- This technique can't be used for most celestial radio sources because they're pretty constant in time, but we can always do what is called position switching, where we compare the radio emission in one direction with what we get when we point the telescope in another, nearby direction. If we switch quickly enough, the receiver noise, atmosphere noise, and so on will remain constant and our difference will reflect the different radio emission that comes in from the 2 parts of the sky.

- Another technique is frequency switching. If you are looking at a spectral line that covers a small range of frequencies, you can compare the signal at the frequency of the line with what the telescope receives at adjacent frequencies. The difference between them, in theory, should leave you only with the line emission.



- If you are switching in time, position, or frequency, you don't have to know what the different parts of the system are doing. You don't have to know the atmosphere, receiver, ground, etc., very well because their emission all cancels out.

- There's another comparison that can be done: load switching, where we are switching the receiver between a dish looking at the sky and some source of radio noise located just in front of the receiver. The load—that is, the noise source—should be a blackbody whose temperature we can measure precisely. If we can look at a few different temperature loads, we can determine the noise that the receiver adds to the system.

- With the switch pointed at the load, we have the radio emission from the receiver plus the blackbody emission of the load. With the switch thrown toward the antenna, we have the same emission from the receiver, but instead of the load, we have something from the antenna, sky—everything else.

- We can compare what's coming in through the telescope to what comes from the load and say that the telescope gives us a certain antenna temperature. In other words, the radio emission from everything in front of the receiver can be related to one number: the temperature of a blackbody that would have given the same amount of signal.

- This is one reason why it's very convenient for radio astronomers to pretend that the signals we observe come from thermal objects—blackbodies—even if they don't.

- The intensity of radio spectral lines is usually given in units of temperature—antenna temperature or a related temperature. It is the temperature that a blackbody would have if it were producing the identical amount of emission as the spectral line does at that frequency.

- In the same way, we can describe the receiver noise as having a certain antenna temperature. This is the temperature that a blackbody would have to supply the same amount of radio emission, or radio noise, as the receiver does.

- In many instances, the antenna temperature is very close to the physical temperature of an object, or it's easily related to it, so it's not just an arbitrary intensity scale.

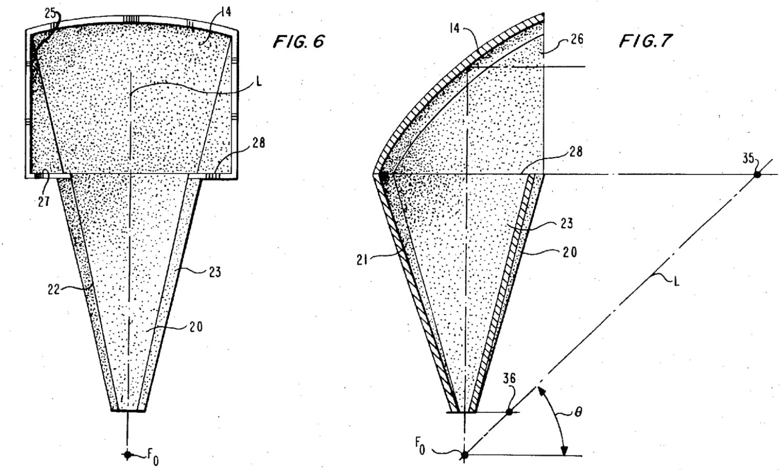
- The system temperature is the amount of noise in our radio telescope system added by everything but what we want to look at in the sky. It is an amount of noise expressed as the temperature that a blackbody would have to produce that amount of noise.

The Cosmic Microwave Background

- In 1964 at Bell Telephone Laboratories in Holmdel, New Jersey, there was a very peculiar looking antenna, called a horn reflector, that no one was using because the project that it was built for—Project Echo, a very early attempt to communicate over long distances by way of a satellite in orbit—had come to an end.

- Horns funnel the radio waves down to the point where an antenna probe can pick them up. Horns have simple beam patterns. They don't have many sidelobes because there is no blockage. And they don't have legs holding up the receiver in front of them, so the telescope beam is quite clean.

- Most radio telescope dishes are based on the parabola, which is symmetric around a central line and brings incoming plane waves to a single focus. Receivers often have a small horn to collect the signal and couple it to the antenna. The horn reflector design uses just a portion of a parabolic surface, and instead of a small horn in front of the receiver, it extends the horn and makes it part of the structure.



- At the Bell Labs facility in 1964, Arno Penzias and Robert Wilson were young scientists interested in making very precise radio-astronomical measurements. Wilson, in particular, wanted to see if there was a faint radio halo around the Milky Way that might have been unintentionally removed in position-switched observations.

- They had a new load that they could use—a cold load. Penzias designed it. It's called a cold load because it uses liquid helium to produce very cold blackbody emission. Liquid helium boils at a temperature of about 4 kelvins, and they calculated that because of heat leakage into the load, it would appear to their receiver as a blackbody at about 5 kelvins. So, the load would give 5 kelvins.

- What did they expect when they switched from the load to the antenna? The atmosphere would give about 2.5 kelvins, and there might be 1 kelvin from losses in the antenna itself. At their frequency of 4 gigahertz, any galactic synchrotron emission should have faded to below 1/10th of a kelvin, and from the ground or other sources, they expected less than 1/10th of a kelvin of radio noise. The antenna plus atmosphere, and so on, should be around 4 kelvins—20% cooler than the 5-kelvin load.

- They flung the switch to the cold load and measured the output of the receiver; then, they flung the switch to the antenna. The antenna was not cooler than the load. It was hotter than the load.

- Any kind of error with the load would have increased the noise coming out of it and made the antenna seem cooler than the load. But they got the opposite result. The antenna, and whatever was coming into the antenna, was hotter than they expected. It was not a huge difference, but it was a difference, and it was different in a way that was not easy to explain.

- Penzias and Wilson had detected a completely new source of radio emission that came from all directions in the sky. They estimated a temperature of 3.5 ± 1 kelvins. It's the remnant of the big bang that marked the origin of the universe.

- They published their findings in a short paper in *The Astrophysical Journal*. This radiation is now generally referred to as the cosmic microwave background. It's also often called relic radiation because it is the relic of the big bang.

- In the first few sentences of their paper, they made the key points:

    - It's isotropic, meaning that it comes from all parts of the sky. So, it's not just part of the Milky Way.

    - It's unpolarized. Emission from a blackbody has no preferential polarization, unlike synchrotron emission or manmade transmissions.

    - It's free from seasonal variations. This makes it unlikely that it came from any particular object, which would rise and set at different times throughout the year.

- Meanwhile, a group at Princeton University was working on the problem of the origin of the universe. They were led by Robert Dicke, who came up with the idea of switching a receiver between the antenna and a load. The technique is often called Dicke switching.

- While Penzias and Wilson were still scratching their heads over their result, Dicke had a group at Princeton building a small horn antenna to work at a 3-centimeter wavelength to try and detect the signal. The groups learned of each other's work, got together, and 2 short papers were published in *The Astrophysical Journal*: one from Penzias and Wilson reporting their detection and the other from Dicke and collaborators reporting the interpretation that it was blackbody radiation from the big bang.

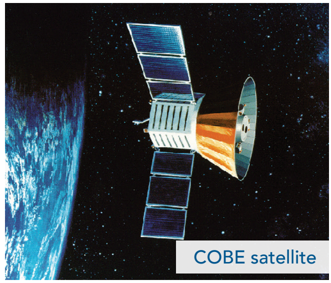
- A few Soviet scientists were also hot on the trail of the background radiation, and in retrospect, the radiation had shown up indirectly in the excitation of molecules observed at optical wavelengths.

- When the Princeton group finished their antenna and measured the radiation, they got 3 ± 0.5 kelvins, in agreement with the Penzias and Wilson result of 3.5 ± 1 kelvins. And because the Princeton group worked around 10 gigahertz while the Bell Labs group worked at 4 gigahertz, the agreement meant that the spectrum was thermal blackbody emission.

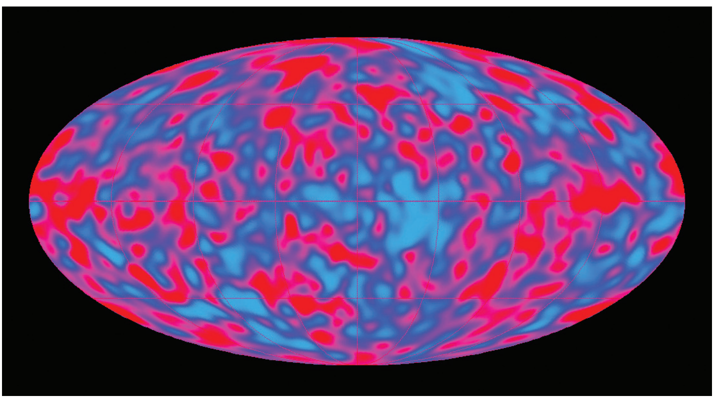
- For their discovery, Penzias and Wilson were awarded the Nobel prize in physics in 1978. The discovery of thermal radio emission from all parts of the sky pretty much clinched the big bang as our theory of the origin of the universe. The radiation has been measured quite a bit since then and has passed every test.

- The COBE (Cosmic Background Explorer) satellite, launched in late 1989, measured the blackbody spectrum of the background radiation quite precisely and searched for fluctuations across the sky. Although the background radiation looked uniform across the sky when observed with the Bell Labs horn reflector antenna, it has to have structure at some level.

- This is because at the time that the radiation was created, the universe was already beginning to get lumpy. Gravity was drawing some regions together, and those slight density fluctuations should have left a mark on the radiation. Those density fluctuations later grew into galaxy clusters and into all the structures that we see around us. If we could measure their imprint on the cosmic background radiation, we'd be seeing the earliest-possible signs of structure in the universe.


COBE satellite

- COBE showed the blobby structure of the universe that evolved into all the amazing things that we see today. The structures have been analyzed extensively, and it turns out that they don't make sense unless the universe is dominated by dark matter.



- Work on the microwave background continues today. From the remnant radiation of the big bang, we know the age of the universe: 13.799 billion years, with an uncertainty of only 38 million years—an accuracy of 99.5%.

Suggested Reading

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

Mather, "From the Big Bang to the Noble Prize and Beyond."

Mather and Boslough, *The Very First Light*.

Smoot, "Cosmic Microwave Background Radiation Anisotropies."

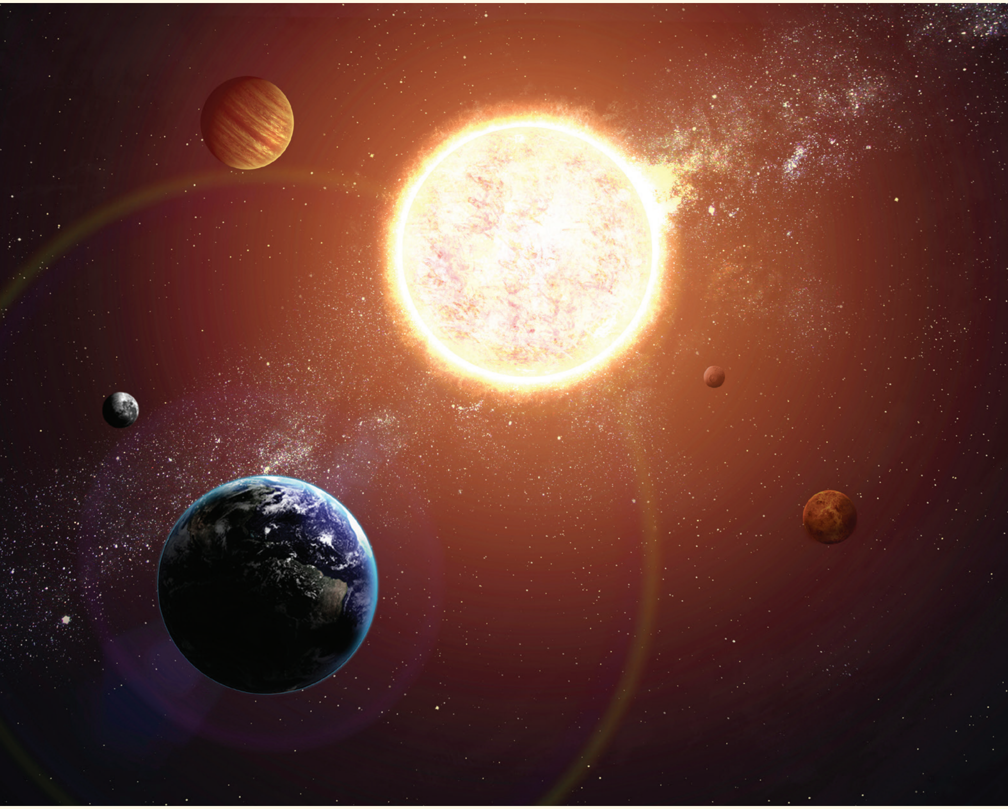
Wilson, "The Cosmic Microwave Background Radiation."

Questions to Consider

1. Is it possible for something in interstellar space that is bathed by the radiation from the big bang, a 3-kelvin blackbody, to be cooler than 3 kelvins?
2. When we look back in space and time to a time when the universe was smaller than it currently is, do you think that the radiation from the big bang was hotter than 3 kelvins?

LECTURE 14

H II Regions and the Birth of Stars



This lecture is about really massive stars—stars that are at least 10 times more massive than the Sun. Radio astronomy gives us powerful tools to understand how these stars are formed, how they influence their surroundings, and how they shape the future evolution of the galaxies where they live.

H II Regions

- Stars like our Sun have long, peaceful lives, measured in billions of years. But stars that are 10 times the mass of the Sun, or even larger, take a different route. They consume their nuclear fuel in times measured in millions of years, not billions of years.

- And they burn hot. Their surface temperatures are so hot that they produce enormous amounts of ultraviolet radiation. And they end their lives in a supernova explosion.

- Astronomers classify stars using an ancient and arcane scheme in which stars like this are called B stars or, if they're really massive, O stars. If you hear about an OB star, you know that it's hot and it's going to end its life in a bang.

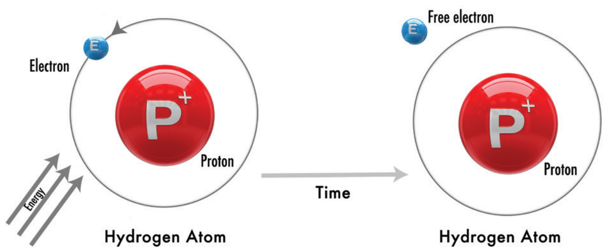
- Stars are formed in dense clouds of interstellar gas. We don't understand all the factors that go into star formation. But when stars begin to form in a dense cloud of interstellar gas, only a small part of the cloud gets turned into stars. There is lots of gas left over. A gas cloud typically turns only a few percent of its mass into stars.


Jewel Box Cluster

- Massive stars also don't form as solitary entities. They form in clusters, and clusters have mostly small stars, like the Sun or smaller. But for every hundred small stars that form, a massive star is also born.

- Stars like the Sun have a very modest effect on their surroundings. But massive stars put out enormous amounts of ultraviolet radiation that eat into the gas cloud where they were born. This radiation is energetic enough to destroy any molecules in the area and ionize all the hydrogen.

- This means that our neutral atomic hydrogen atoms—an electron and a proton—get disrupted entirely. The electron gets ripped from the proton, and they go their separate ways. That's what it means to ionize the gas: to strip the electrons from the atoms.



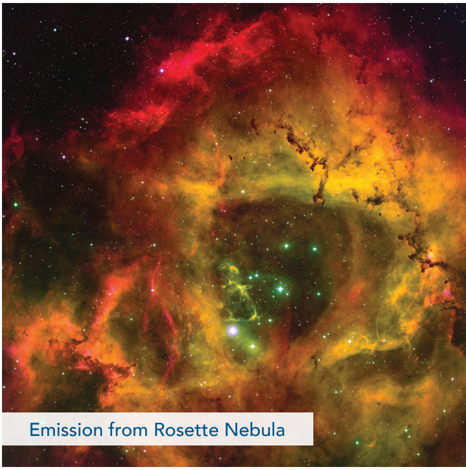
- The result is that the massive stars create an ionized plasma around them. A plasma is the state of matter where electrons are separated from their atomic nuclei. These plasmas are quite hot. The interstellar plasmas in star-forming regions around massive stars are typically about 10,000 kelvins.

- Imagine that hydrogen atoms have been broken up and become a swarm of electrons and protons. The heavier elements also get some of their electrons stripped from them.

- Interstellar gas clouds that are fully ionized are called H II regions. Neutral hydrogen is denoted H I, and ionized hydrogen is denoted H II.

- H II regions are among the most beautiful objects in the sky. The ionized gas gives off lots of light.

Gum 15 star-formation region



Emission from Rosette Nebula

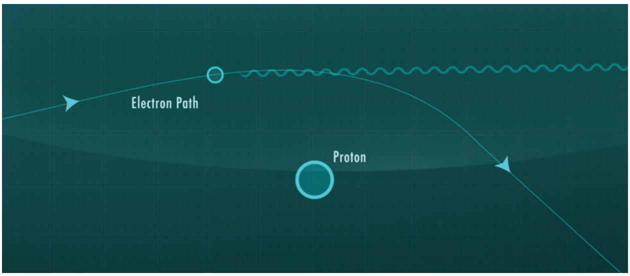
- You will see dark dust clouds in most H II regions. Those clouds contain gas that's dense and cold and has not yet been ionized and disrupted by the ultraviolet radiation.

- Because the massive stars that create H II regions live such short lives, H II regions generally mark the places in galaxies where stars are currently being formed.

- Previously in this course, you have learned about broadband thermal radio emission from blackbodies. You have also learned about the narrowband 21-centimeter spectral line of hydrogen. H II regions make both broadband and narrowband radio radiation, but of a different kind.

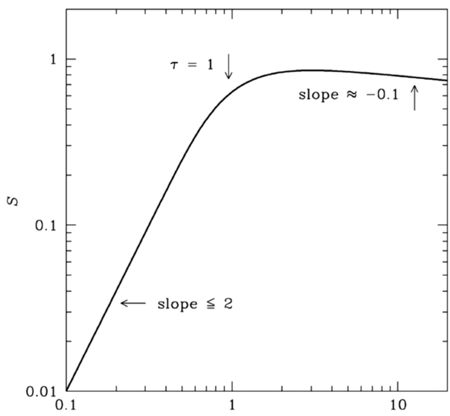
- Here's what's happening inside that plasma—inside the H II region. Electrons and protons are zipping around. Because they have opposite charge, they feel the force from each other, and when they pass, the electrons are deflected slightly. Whenever you accelerate an electron—and bending the path of an electron is an acceleration—it produces electromagnetic radiation.

- When the electron path bends as it encounters a proton, it emits radiation. It's called free-free radiation because it's made by a free electron and a free proton. And both remain free after their interaction. The proton is almost 2000 times more massive than the electron, so it just sort of sits there while the electron zips around.



- This process works both ways. Electrons can also absorb radiation, increasing their energy. When a low-frequency radio wave is produced in an H II region, it doesn't get far before it's reabsorbed by another electron passing by a proton.

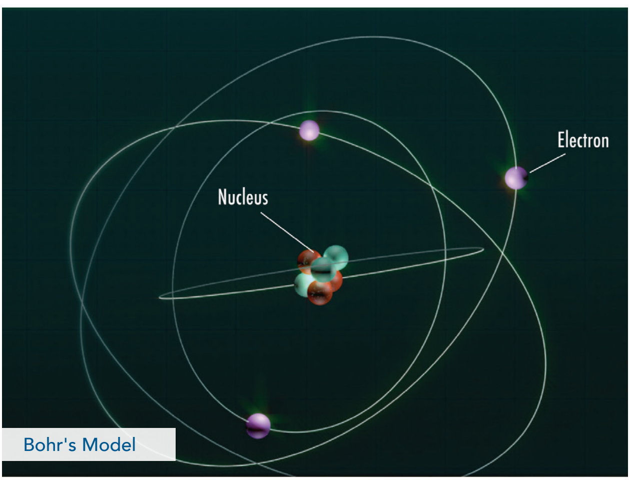
- Low-energy radio waves can be emitted by a very slight acceleration of an electron, and the radiation is absorbed so efficiently that at low frequencies, an H II region can be a good approximation to a blackbody.



- But to produce and absorb higher-frequency radio photons—higher-energy radio waves—you need a closer interaction between an electron and a proton, and these interactions are rarer. As a result, there is always a frequency where the H II region stops acting like a blackbody and its spectrum changes character. The broadband spectrum of an H II region is very characteristic of emission from ionized gas.

- H II regions also make spectral lines.

- About 100 years ago, Danish physicist Niels Bohr worked out a way to pull together a lot of disconnected measurements into a simple model for atoms. In the Bohr model, you can think about an atom as a miniature solar system with the nucleus in the center, like the Sun, and electrons in orbit about it.



Bohr's Model

- In the Bohr atom, the electron is not allowed be just any distance from the nucleus. Its allowed orbits are quantized; only certain orbits are permitted. The electron can only occupy specific locations, or specific energies. This idea that nature on the smallest scales is not continuous but is quantized was introduced in 1913.

- The Bohr model was a triumph of science, and the dawn of the quantum age. Bohr showed that a multitude of diverse data could be explained by a simple model of the atom with quantized electron orbits.

- Lines were produced when the electron jumped between quantum orbits. The frequency of any spectral line emitted by ionized hydrogen could be determined by 2 numbers: the quantum number of the level where the electron started and the quantum number where it ended up.

- Inside H II regions, a negatively charged electron will occasionally hook up with a positively charged proton and recombine, with the electron cascading from one quantized state to another as it falls toward the ground state. In its cascade, it emits specific frequencies of radiation.

- Many of these frequencies are radio frequencies. Because the emission lines are given off as the electron and proton recombine into hydrogen, they are called recombination lines.

- About 100 years ago, every physicist knew that an electron transition from quantum level 100 to level 99, for example, would produce a photon at radio wavelengths. These radio recombination lines are such a natural consequence of the Bohr atom that they have to be out there—right?

- But there were 2 problems. The first has to do with the size of a hydrogen atom when its electron is in those high quantum states. Theoretically, there are an infinite number of quantum levels that could be occupied by an electron. But a hydrogen atom in a high quantum state is really big. A hydrogen atom with its electron sitting in the 200th quantum level could be seen through a microscope. Something like this could never exist on Earth, where it would quickly be torn apart by collisions. It might not exist even in the near-vacuum of space.

- Here's the second problem. In 1944, when Hendrik van de Hulst was asked by the Dutch astronomer Jan Oort to think about possible spectral lines at radio wavelengths, he considered the emission from high quantum levels predicted by the Bohr model. But he calculated that there would be a problem.

- The electron is so weakly bound to the proton at quantum level 100 that another passing electron would easily perturb it. This would have the effect of smearing out the 100 quantum level. Instead of discrete quantum levels, with their crisp spectral lines, the atom would be a mess and the electron's emitted frequencies would be spread out enormously—the spectral lines would be broadened out of existence.

- So, van de Hulst suggested that neutral hydrogen would be a better candidate for a radio line. He predicted the 21-centimeter hydrogen line but thought that radio recombination lines wouldn't be observable. Other scientists in following years came to a similar conclusion, so there was no attempt by astronomers to look for radio recombination lines in space.

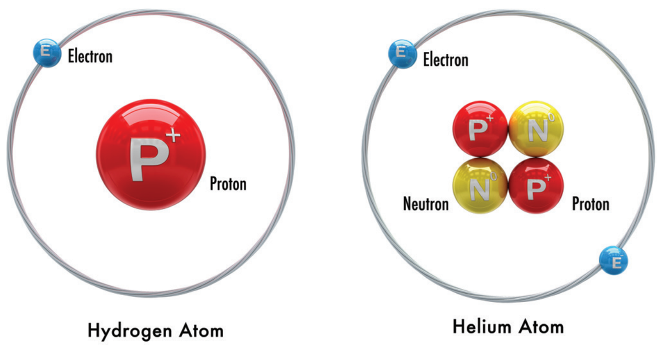
- Then, in 1959, Soviet scientist Nikolai Kardashev published a paper that reached a different conclusion. He proposed that radio recombination lines would not be smeared out by collisions but could be detected from H II regions.

- This paper attracted the interest of scientists in the Soviet Union and Germany. After several unsuccessful attempts, a detection was announced at an international conference in 1964 by 2 groups from the Soviet Union, but the data were not totally convincing.

- Work by the Soviet scientists motivated others to look, and in the next year, recombination lines were detected with telescopes at many observatories around the world. Radio astronomers use radio recombination lines for star formation and to measure helium and temperature.

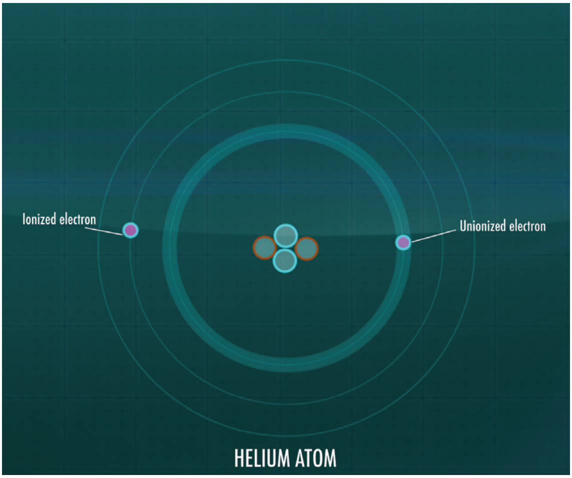
Star Formation, Helium, and Temperature

- Helium is the second most abundant element in the universe. For every 10 hydrogen atoms, there's 1 helium atom. Helium is a more complicated atom than hydrogen.



- Helium has 2 protons and 2 neutrons in its nucleus, and 2 electrons. It takes a more energetic ultraviolet photon to ionize helium than to ionize hydrogen, but there are plenty of those photons around massive stars, so here's what happens: A photon hits helium, ejecting one of its electrons. Eventually, an electron sees this ionized nucleus and recombines, falling into one of the high quantum states and emitting helium recombination lines.

- But the incoming electron doesn't feel the full force of the 2 helium protons, because of shielding by the electron that didn't get ionized.



- So, the quantum states of singly ionized helium are nearly identical to those of hydrogen, shifted just a bit because the helium nucleus is more massive than hydrogen.

- It was not very long into the history of radio astronomy before free-free continuum emission from H II regions began to be measured around the sky. Astronomers in the Netherlands discovered a number of H II regions that are completely invisible in the optical. A similar effort went on in Australia.

- Radio recombination lines took these studies to a new level. Using the Doppler shift of recombination lines, it became possible to measure the velocity of H II regions all across the Milky Way and chart where the massive stars were forming.

- Radio recombination lines also allow us to measure the amount of helium in H II regions. This is important because theories about the evolution of the universe make very specific predictions about the amount of helium that should be around today. So, it's important to know the amount of helium in interstellar space and see if it varies from place to place. Today, there's no evidence for variations in the amount of helium in our galaxy.

- The exact strength of a radio recombination line is related to the temperature of the H II region. We can use this property to study how the temperature in H II regions changes from place to place in the Milky Way. This is important because the thermostat that regulates the temperature of an H II region is the amount of elements it contains that are heavier than hydrogen and helium—elements such as oxygen.

- Quantum transitions in oxygen are extremely efficient at turning thermal energy into photons that then escape the nebula. They turn heat into light—mostly infrared light—that gets past the dust and gets out. So, H II regions are heated by hot stars but are cooled by emission from oxygen. The more oxygen, the cooler the H II region should be.

- Unlike helium, which was created in the big bang, carbon, oxygen, and all the heavier elements were created in stars and blasted into interstellar space through stellar winds or supernovas. These elements then mix in the interstellar medium with hydrogen and helium to form the next generation of stars.

- The amount of heavy elements at any location in the Milky Way is related to what star formation has been doing for the last few billion years. The latest evidence is that H II region temperatures change systematically from place to place in our galaxy, and this implies that the distribution of metals around the galaxy may be irregular.

Suggested Reading

Lockman, Ghigo, and Balser, eds., *But It Was Fun*, part III.3.

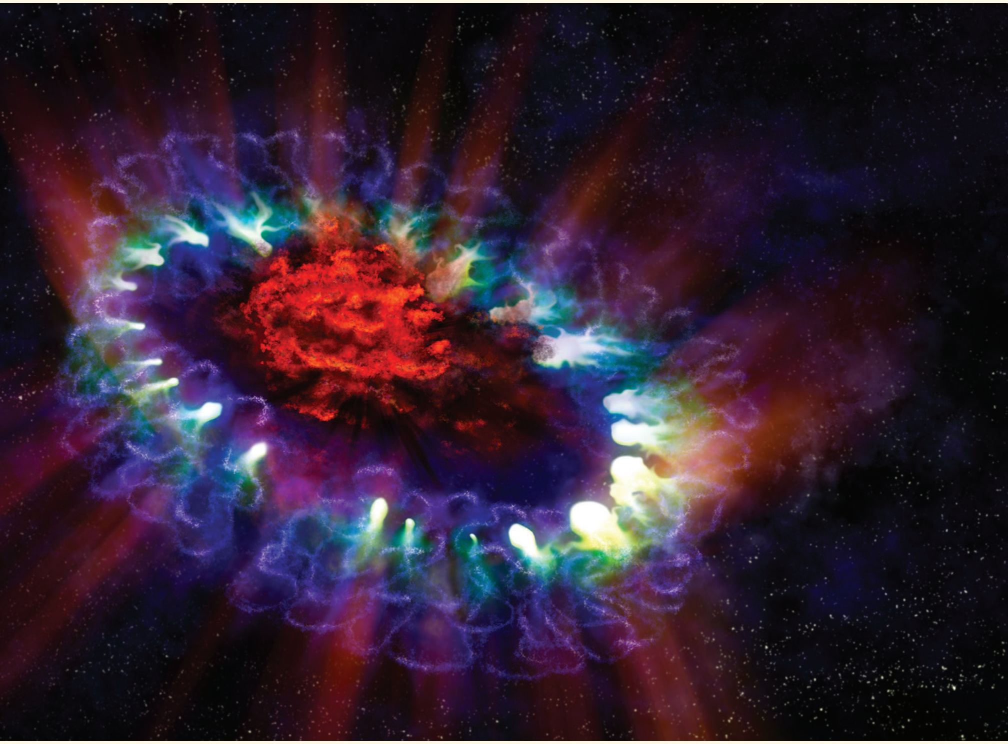
Verschuur, *The Invisible Universe*, chap. 4.

Questions to Consider

1. Let's say that in the Milky Way, new stars are being formed at the rate of about 2 per year and that the Milky way has about 200,000,000,000 stars. From this, can you determine the age of the Milky Way? How does this compare with the age from other methods? What might be wrong with the assumptions that went into your calculations?
2. The pressure in the interstellar medium is the product of the density times the temperature. When a massive star is formed, it quickly ionizes most of the gas in its vicinity and increases the gas temperature from, for example, 10 kelvins to 10,000 kelvins. What effect would that have on its surroundings?
3. There is neutral hydrogen in almost all areas of the Milky Way, but bright regions of ionized gas are confined to the vicinity of young massive stars. Through radio recombination lines, we can trace the velocity of H II regions throughout the Milky Way. What extra information does this give us that we can't get from neutral hydrogen?

LECTURE 15

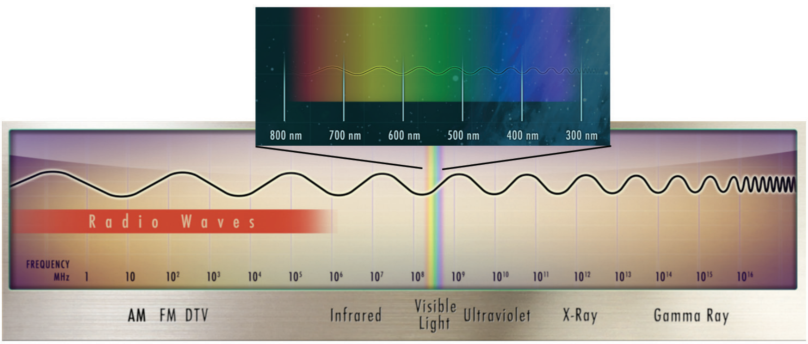
Supernovas and the Death of Stars



Massive stars are incredible. They blaze their way through the interstellar medium in life, and in death they create an enormous explosion that can alter the very evolution of their host galaxy. This lecture is about the death of massive stars and their imprint on the universe. Supernovas are probably the most important thing after gravity in determining the nature of the universe around us. Without supernovas, there would be no solid planets, no organic chemistry, no life.

Supernovas

- In 1930, the year before Karl Jansky began measuring radio waves from space, astronomers pretty much only knew a tiny part of the electromagnetic spectrum: optical wavelengths. The optical part of the spectrum spans only about 300 nanometers to about 800 nanometers.



- Then, in 1931, Karl Jansky discovered radio waves from space with wavelengths 10 million times longer than light waves. He broke the barrier that confined astronomers to peering at the universe through a small optical window. Radio wavelengths range from several meters to 1 millimeter, a factor of several thousand in frequency and energy, a much broader range for discovery than the optical.

- But when Jansky and then Grote Reber found bright radio signals at very low frequencies, scientists interpreted the cosmic static in terms of what they were familiar with—thermal emission of the kind that produces optical light.

- Scientists theorized about making radio waves from some sort of super H II region, or very hot dust. Their attempts were unsuccessful. Most astronomers just ignored the radio results.

- The main problem was that new physics was involved—an understanding of processes in nature that no one had ever confronted before. And massive stars are at the heart of it. For most of their lives, massive stars are perfect thermal sources, putting out ultraviolet radiation that creates H II regions.

- But when they end their lives, their physics changes completely. The remnant of a supernova radiates nonthermal emission from charged particles and magnetic fields. A supernova leaves a pulsar, a nonthermal radio source. And supernovas create the cosmic rays that pervade the galaxy and emit most of the radio signal that Jansky and Reber saw.

- For more information about Reber's work, visit the following link (see especially figure 4): http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1944ApJ...100..279R&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf.

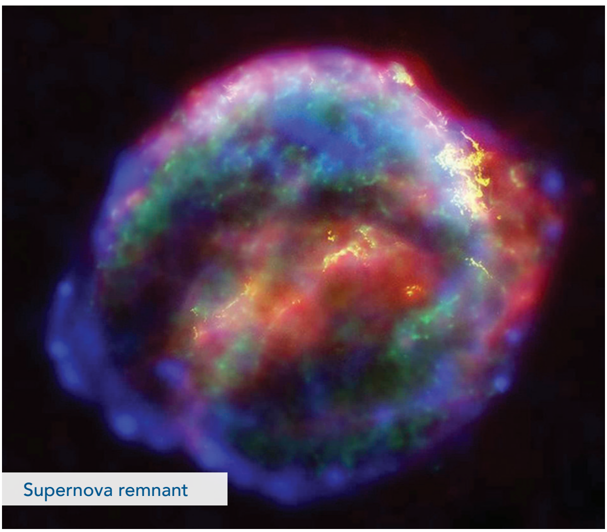
- Reber was probably seeing several different things. First, there was a broad source of emission much larger than the beam, quite extended on the sky. But there were also what looked like discrete radio sources that were smaller than his beam. What could be making the radio noise, and what could those discrete sources be?

- It took a while to answer these questions, and progress required building radio telescopes with better angular resolution. But one of

Reber's discrete sources is a radio galaxy that's quite distant, and the other is a supernova remnant in the Milky Way. The supernova remnant is the brightest radio source in the constellation Cassiopeia, so it is called Cassiopeia A.

Supernova Remnants

- A supernova remnant is what's left over after a massive star has gone supernova. Toward the end of a massive star's life, it becomes increasingly unstable and, finally, in the matter of a few moments, its core collapses and produces an enormous release of energy that blasts the outer layers of the star out into space. At its peak energy, it outshines 10 billion stars like the Sun. It can be brighter than the rest of its galaxy and can be seen at great distances.



Supernova remnant

- The stellar debris is hurled outward at tens of thousands of kilometers a second, a few percent of the speed of light. This material hurtles through interstellar space, producing shocks in the interstellar gas.

- The interstellar magnetic field is compressed around the expanding shell, and high-energy electrons hit the magnetic fields, producing synchrotron radiation. This nonthermal emission is very bright at low radio frequencies.

- The remnant of the star's core—the core of the massive star that exploded—is left behind as a neutron star, or even a black hole. Every pulsar had its birth in an event like this.

- Before radio astronomy, there were only 2 known supernova remnants: the Crab Nebula and Kepler's remnant. We now know of several hundred supernova remnants in the Milky Way and more in nearby galaxies.

- In 1948, British astronomers Martin Ryle and Francis Graham-Smith studied the radio source in the constellation Cassiopeia that was detected by Grote Reber and localized the emission to a small patch of the sky where there wasn't any evidence of an unusual source of light. So, there were radio waves without much light.

- Soon, radio emission was detected that was associated with known supernova remnants like the Crab Nebula, so scientists knew what they were looking at: supernova remnants. What they didn't understand was the physical process that made the radio emission, and that problem was solved when Iosif Shklovsky proposed synchrotron radiation as the mechanism.

When Will We See the Next Supernova in the Milky Way?

We have a good idea of the number of massive stars in the Milky Way, and we know about how long they live. We expect there to be a supernova in our home galaxy, the Milky Way, at least once every 50 years. The last recorded supernova in the Milky Way was in 1604, so we are about 350 years overdue for a visible supernova in the Milky Way.

Why Should We Care about Supernovas and Their Remnants?

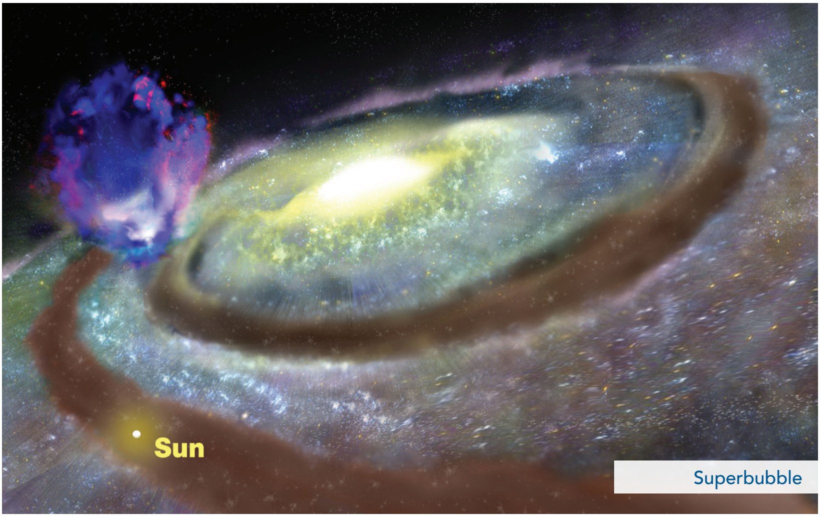
- Nearly all the elements except hydrogen and helium are created through fusion reactions in stars. Some elements are created only in the massive stars that go supernova, and some elements are created only in the supernova itself.

- Although some heavy atoms are made in supernova explosions, it takes the supernova remnants to spread them through the galaxy so that when new stars are formed—like the Sun 6 billion years ago—there's lots of carbon and iron and silicon around to make rocky planets full of water and life. The remnants spread the atoms about. It would do us no good if the elements formed by nuclear fusion just clung together in a big lump somewhere.

- Stars form in clusters, and clusters can have a lot of stars. So, instead of a solitary supernova, there will be a series of supernovas going off one by one, over millions of years, in more or less the same spot. The first supernova plows into whatever interstellar gas is hanging around, but the later remnants are expanding into a void created by the early ones. It can be an enormous space. They can expand and expand.

- Collective action of multiple supernovas can blow superbubbles in the interstellar medium. Scientists working with the Green Bank Telescope discovered a truly enormous superbubble rising out of the disk of the Milky Way.

- This towering inferno sits over one of the most active star-forming regions in the Milky Way and must have taken 30 million years and several generations of supernovas to form. When its top finally comes crashing down, it will distribute newly made heavy elements over the inner part of the Milky Way.



Superbubble

- But there are even bigger structures created by supernovas. In fact, if enough supernovas explode, they can blow the top off a galaxy. In the center of the following galaxy, so many massive stars are blowing up that their collective energy is creating an enormous wind, ejecting lots of gas into intergalactic space.

M82 starburst

- Large correlated explosions could clean a galaxy of all its gas, choking off future star formation. That's a real threat for small galaxies. Small galaxies don't have a lot of mass, so they don't generate a lot of gravitational force to hold down their interstellar gas. If a small galaxy makes stars and they begin to go supernova, those stars could blow away all remaining gas, ending star formation forever. The first generation of stars could be the last generation.

- Supernovas make pulsars.

- If a supernova goes off too close to a planet, it can sterilize the planet, wiping out whatever life there was.

- By moving lots of gas around and sending shock waves through gas clouds, supernova remnants can trigger the formation of new stars, yet by injecting energy into interstellar gas, supernova remnants keep our galaxy stirred up so that the gas doesn't collapse all at once into stars. The turbulence from previous generations of stars can regulate star formation today.

- We suspect that a supernova was involved with our solar system early on, because we find some meteors with evidence of radioactive elements that must have been deposited in the solar system from a nearby supernova when the Sun was young.

- Supernovas and their remnants can reshape galaxies and determine their future evolution. They are central to many astronomical processes.

- Supernova remnants make cosmic rays, which are not rays but bits of atoms that have been accelerated to extremely high energies. They permeate space. They are the nuclei of atoms of normal elements that have been stripped of some of their electrons and accelerated to enormous speeds.

- When cosmic rays hit the atmosphere, they create showers of secondary particles. Dozens of cosmic rays pass through our bodies each second.

- Cosmic rays may be responsible for life on Earth. Cosmic rays pervade the galaxy and cause ionization in interstellar clouds that would otherwise be entirely neutral. In other words, these energetic particles penetrate gas clouds and kick electrons off atoms, leaving charged ions behind. The ionization from cosmic rays is not large, but it's enough to trigger chemical reactions that may be necessary to grow organic molecules, like the kind that are involved in life on Earth.

- At the time of Jansky's discovery, the scientists studying cosmic rays were only aware of the heavy cosmic-ray ions that made it to the Earth's atmosphere. These move too slowly to produce synchrotron radio emission.

- But there are also high-speed cosmic-ray electrons. These hit the galactic magnetic field and, through the synchrotron process, emit low-frequency radio waves. This understanding eventually unified 2 different areas of science—cosmic-ray studies and radio astronomy—and they both have their origin in supernovas.

Suggested Reading

Binney, *Astrophysics.*

Plait, *Death from the Skies*, chap. 3.

Sullivan, *Cosmic Noise*, chap. 15.

Verschuur, *The Invisible Universe*, chap. 4.

Questions to Consider

1. What kind of radio telescope would you design to detect the very early signals from a supernova, or other objects that might make a brief, bright radio "flash" from an unknown direction on the sky?
2. Because the interstellar medium is concentrated to the plane of the Milky Way, a supernova that goes off a bit above the plane of the Milky Way would find itself expanding into a medium that was increasingly more dense below it and increasingly less dense above it. How would that affect the evolution of the supernova remnant?
3. Young massive stars heat the dust in their vicinity, and this is visible in the infrared and short radio wavelengths. Young massive stars also quickly go supernova, producing cosmic rays that make diffuse synchrotron radiation. Would you expect to see a galaxy-wide connection between infrared radiation and synchrotron radiation?
4. A series of supernovas can build up a shell of neutral gas that they've swept up during their expansion through the interstellar medium. What do you think is the ultimate fate of these shells?

LECTURE 16

Radio Stars and Early Interferometers

This lecture is about radio stars. The first thing that you need to know is that they aren't stars. They are galaxies. But nobody knew this for a while, and it took some work to figure it out. In this lecture, you will also learn about early interferometers, which are a type of radio telescope.

Interferometers

- In the years immediately after World War II, groups in Australia and the United Kingdom that had been involved in radar work turned their attention to radio studies of the sky. Some studied the Sun, but others went after the mysterious cosmic static found by Karl Jansky and mapped by Grote Reber.

- They quickly understood that there were 3 kinds of radio sources: a broad, general band of emission coincident with the Milky Way; discrete sources concentrated to the Milky Way disk; and discrete sources that seemed to be found in all directions.

- The fact that these discrete radio sources appeared to have a uniform distribution around the sky and not be concentrated to the Milky Way disk meant that they were either quite close to us, like the nearby stars, or very far out of the Milky Way, like galaxies. They came to be called radio stars.

- It was known from studies of the Sun that stars could have storms that created some nonthermal radio signals, so it all sort of made sense. Perhaps there was a type of star that had lots of storms and was bright in the radio.

- All that scientists needed to do was be able to identify a few radio sources with a few stars that could be observed optically. The problem would be solved.

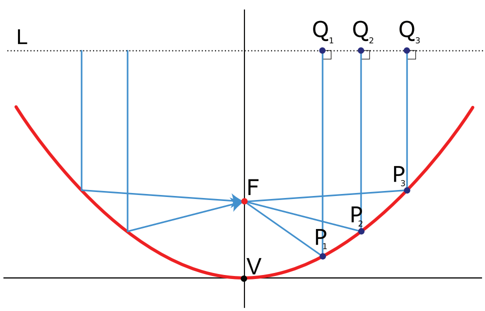
- And that was the difficulty. The early radio telescopes had such poor angular resolution that they couldn't localize the radio sources. They needed more angular resolution, and the solution lay in an arrangement of radio telescopes called an interferometer.

- Radio waves hitting distant parts of a radio telescope dish arrive in phase at the focus if the waves come from a small angle around the vertex line of the dish—the line of symmetry of the parabola.

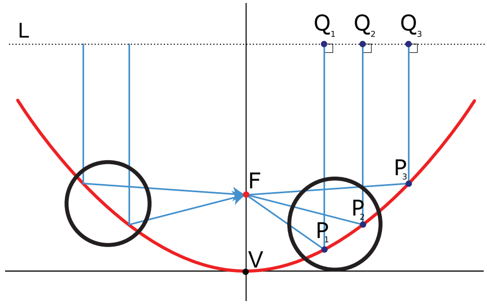
- The radio telescope beam size—that is, the angle on the sky that accepts radio waves—is proportional to the wavelength divided by the diameter of the dish times some scaling factor. If you want the angle in degrees, the factor is about 60: beam width = 60*l*/*D*, where *l* is wavelength and *D* is diameter.

- In the years after World War II, better angular resolution was needed to pinpoint the location of these radio sources.

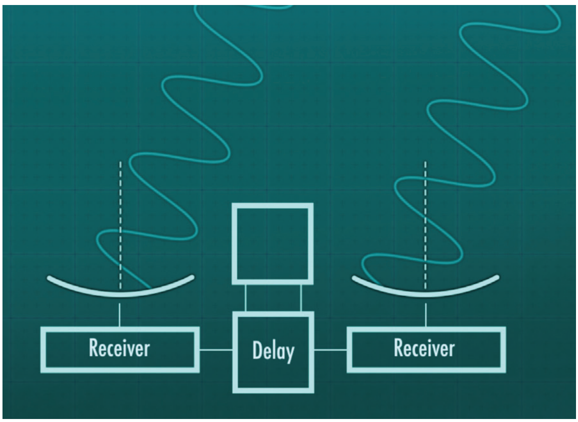
- Our antennas convert radio waves into an electric current in a wire. That electric current contains all of the original information in the wave—not only the amplitude of the wave, but also the phase.



- In a single dish, it's the dish shape that governs the distance between the reflecting surface and the focus. Let's break our big dish into 2 smaller dishes.



- Then, let's give each of our small dishes its own receiver and pipe the signal to a central location where the 2 signals can be combined. The result is an interferometer.



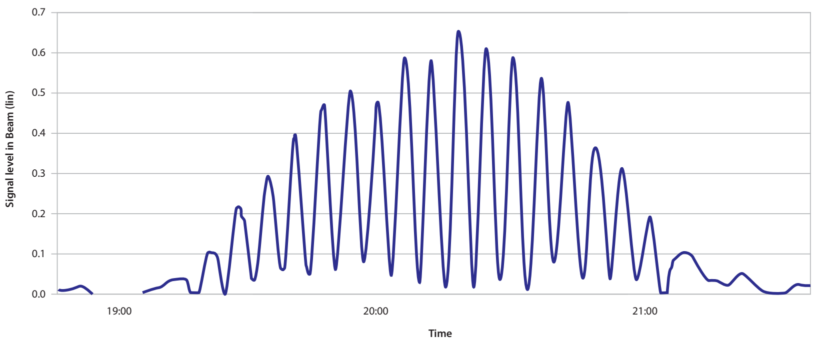
- In this drawing, the signal arrives first at the dish on the right. But we can put some delay in the system—extra wire, perhaps—so that the waves arrive in phase at the combiner.

- Let's use the principle of reciprocity to think about this system a bit more easily. We imagine 2 dishes, pointed straight up for simplicity, each transmitting a signal.

- The signals will arrive in phase at a point directly perpendicular to the line joining the 2 antennas. At some offset angle, the signals will cancel; then, as the offset increases, the signals combine in phase again. So, we have a main beam and sidelobes, just like a single dish.

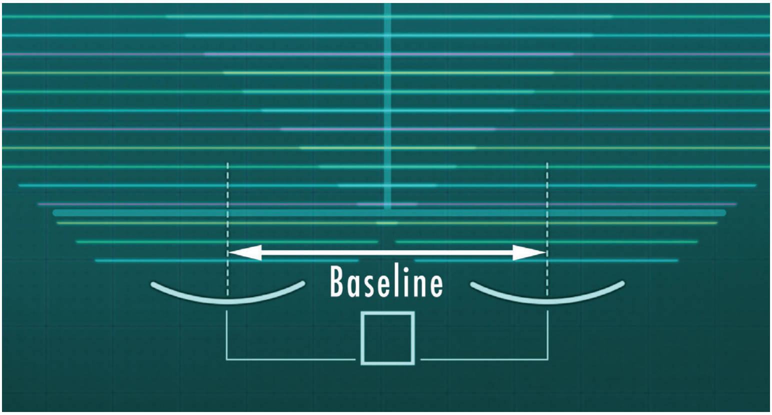
- Thinking of our interferometer as a transmitter, we have a comb of main lobe and sidelobes across the sky.

- Now let's turn the system around and think of it as a receiver. If we keep our telescope pointed straight up, radio sources that drift across the sky because of the Earth's rotation will pass through the sidelobes and main beam of our interferometer and we'll get a signal called a fringe pattern, which is characteristic of interferometers.



- A dish only focuses waves to a point if its surface is accurate to a small fraction of a wavelength. With an interferometer, we have to keep the tolerances on the entire signal path just as tight. If the wires that connect the 2 antennas are not the same length, then the signal won't add in phase.

- But the result is that the interferometer beam on the sky—just like a single dish—covers an angle proportional to the wavelength divided by the diameter, but for an interferometer, instead of the dish diameter, it's the distance between the 2 antennas, called the baseline.



- There are practical and financial limits to a dish size, so for high angular resolution, we use an interferometer.

- If beam size is proportional to wavelength divided by the diameter or divided by baseline length, you could get a small beam by shrinking the wavelength—simply observing at high frequency—rather than going for a big baseline or large dish.

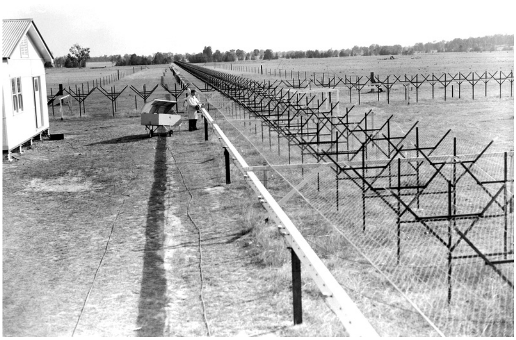
- For a given dish, higher frequencies give smaller beams. But these radio stars are nonthermal sources; their intensity is dropping rapidly at increasing frequency. At higher frequencies, you simply run out of signal.

- Also, in the years we're discussing, radio receiver technology was not advanced at higher frequencies. They did not have modern low-noise amplifiers. In modern times, we use both single dishes and interferometers at all radio wavelengths. But the radio star pioneers looked at frequencies where the radio stars were strong—low frequencies, meaning long wavelengths—and built interferometers.

Radio Stars

- After World War II, technology and science were moving rapidly. Nobody had much money to work with, but at the low frequencies where they were operating, the equipment was relatively inexpensive, and the radio sources were bright. The worldwide leaders in radio interferometry were in Australia and in England at the University of Manchester and at the University of Cambridge.

- In Australia, Bernard Mills built a cross antenna—the Mills cross.



- Meanwhile, in England, the group at Cambridge led by Martin Ryle was making some very clever technical innovations that would lead to modern-day interferometers capable of making very precise measurements. They built an interferometer with a baseline of half a mile and then extended it to a mile.

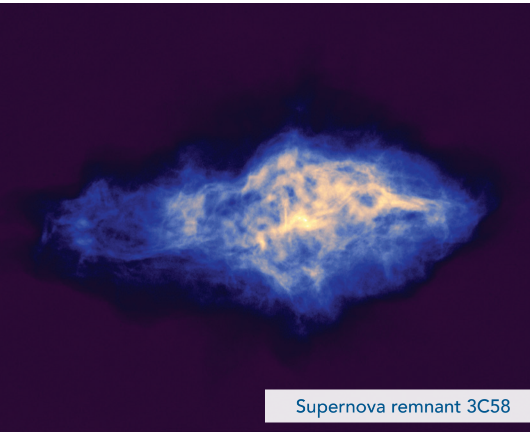
Half-mile telescope

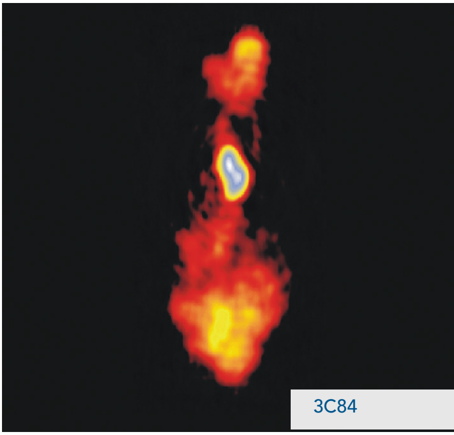
- The energetic group at the University of Manchester was pushing radio-linked interferometers to ever-longer baselines, up to 100 kilometers.

- The groups were discovering that the sources of astronomical radio emission could be divided into 3 general categories. First was a broad region of emission concentrated to the plane of the Milky Way. This we now know comes from cosmic rays and magnetic fields in the galaxy.

- Second were extended radio sources with sizes of many arc minutes, in some cases as large as a degree. These seemed also concentrated to the galactic plane. Many were identified with supernova remnants.

- Third were the radio stars. These had a uniform distribution on the sky and had a very small angular size. Because the radio stars did not seem to show a concentration to the Milky Way disk, they were either quite nearby or very far away.


Supernova remnant 3C58


3C84

- Higher-angular-resolution measurements of the brighter radio stars showed that some coincided with distant galaxies. But what really flummoxed everyone was how strong the radio emission from these distant galaxies was. In normal life, closer things are generally brighter than distant things. But the closest big galaxy, Andromeda, has modest radio emission compared to those distant galaxies. And the same goes for the Milky Way.


Andromeda Galaxy

- The same is true of M33, another nearby neighbor. The radio galaxies were a million times stronger than normal galaxies at radio wavelengths.

- Why were the distant galaxies radio-bright and the nearby ones radio-faint? This went against all reason. Moreover, as the angular size of some of these radio stars began to be measured, some of them appeared to be much smaller than the galaxies that contained them.

- Furthermore, there was inconsistency and confusion between results of the various groups. Some of the problems were caused by the complicated beams of the interferometers, with their multiple sidelobes. With only a few baselines, several weak radio sources sitting in sidelobes could be mistaken for a bright source in the main beam.

- These technical issues played out against major scientific issues as well. If the radio stars were truly distant objects, powered by some unknown energy source, then they should tell us something about the nature of the universe. Was it evolving or in a steady state? There was a debate.

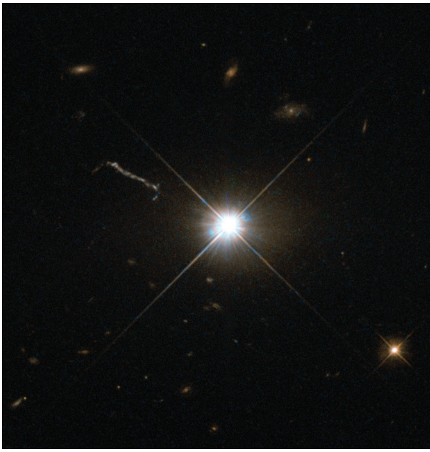
- As more and more radio stars were identified with galaxies—or at least with objects that might be distant galaxies—puzzles about their properties grew. Some of the sources appeared to have 2 components, like 2 spots of emission on the sky.

- These unidentified radio sources did not have any spectral lines at radio wavelengths, so it was not possible to determine a Doppler shift from the radio data alone. For this reason, there was cooperation between radio and optical astronomers to use large optical telescopes to try to pin down the identification of radio sources.

- Normal galaxies have lots of spectral lines at optical wavelengths—lines from different elements, such as hydrogen, oxygen, and magnesium. It was the measurement of the Doppler shift of these optical lines from normal galaxies that led Edwin Hubble to discover the expansion of the universe.

- So, if a radio source could be associated with an object that had optical lines, its Doppler shift could be measured, and this would give an estimate of its distance. The results were mixed.

- Then, in 1962 and 1963, astronomers at the Mount Wilson and Palomar Observatories identified radio sources that were coincident with things that looked like stars—bright, point-like objects. But they certainly were not stars. They had Doppler shifts that put them very far away, and that meant that they were incredibly bright. They were called quasi-stellar objects, or quasars. No one had a clue what they were.



- We now know that quasars are not some distant, weird phenomenon but are part of a continuum of processes that include the object at the center of the Milky Way, the central regions of normal galaxies, radio galaxies, and quasars.
- And we have an energy source—black holes. At the heart of all radio galaxies and quasars, there's a giant black hole spewing out matter in 2 jets that head out into intergalactic space.

Suggested Reading

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

Ryle, "Radio Telescopes of Large Resolving Power."

Sullivan, *Cosmic Noise*, chap. 14.

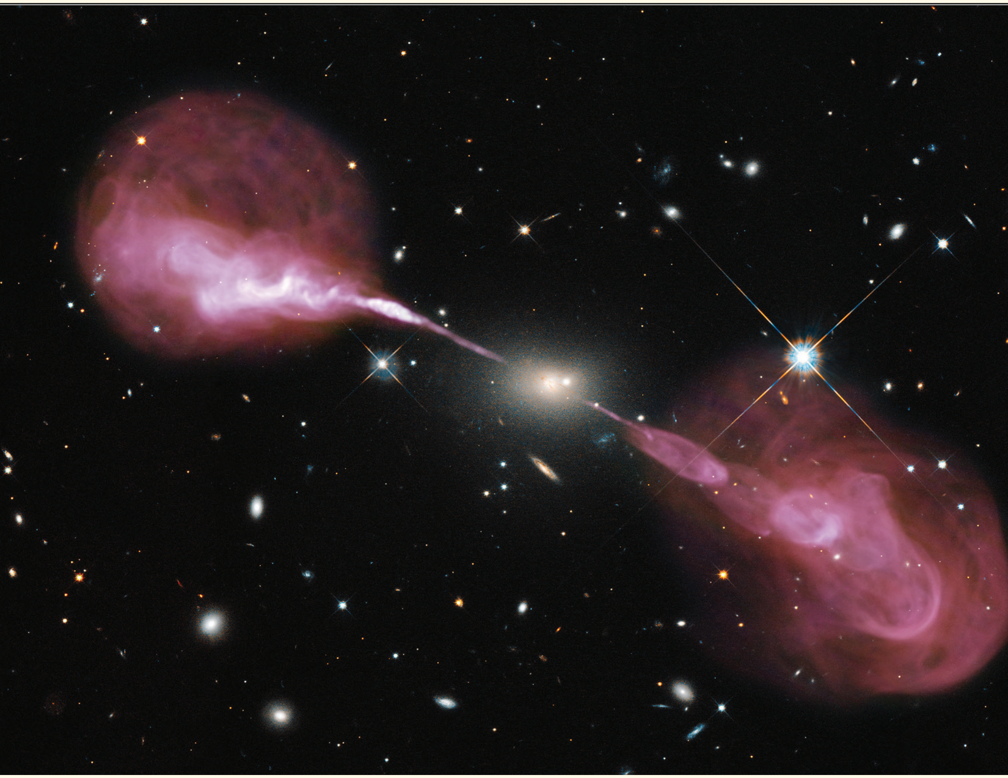
Sullivan, ed., *The Early Years of Radio Astronomy*.

Questions to Consider

1. Supernova remnants are bright sources of nonthermal emission. They arise from short-lived massive stars that have recently been formed from the interstellar medium. Given what you know about the location of the interstellar medium in the Milky Way, what can the location of a nonthermal radio source tell us about its likelihood of being a supernova remnant and not a distant galaxy?
2. The brightest radio source in the constellation Cassiopeia is a supernova remnant, Cassiopeia A. The brightest source in the constellation Virgo is a radio galaxy, Virgo A. The brightest source in the constellation Orion is an H II region, Orion A. What does this tell you about what it takes to be a bright radio source as seen from Earth?

LECTURE 17

Radio Source Counts



This lecture continues our exploration of radio stars, which are actually radio galaxies, quasars, and active galactic nuclei—anything but stars. The theme of this lecture is that there are many galaxies that are undergoing, or have undergone, some very energetic events in their past.

Radio Surveys

- Since the middle of the 20th century, there has been a major effort by astronomers to understand radio stars, the most luminous objects in the universe—objects that give off strong nonthermal radio emission and that are distributed uniformly across the sky.

- But what are they? And how are they powered? These questions drove astronomical research in several directions. One important direction was toward surveys, studies of large areas of the sky to simply discover radio sources, measure their brightness, determine their positions, and provide the basic roadmap for further investigations.

- Surveys provide large samples of objects so that we can do some statistics, and they always turn up new, interesting things. Surveys give us the basic maps of the sky.

- One of those surveys is the Third Cambridge Catalogue of Radio Sources, called the 3C survey. It was published in 1959 and revised several times, first in 1962. The 3C survey was made using an interferometer located outside of Cambridge, England, and contains about 500 radio sources.

- At the time that the 3C survey was made, there were major uncertainties about the basic properties of our universe. Was it infinite or finite? Did it begin in a bang, or was it in a steady state? If it went bang once and expanded, would it turn around in a big crunch?

- The 3C survey produced a catalog of the brightest small radio sources in the northern sky. The sources were no more than a few arc minutes across. Because the 3C was done at the relatively low frequency of 178 megahertz, its sources are dominated by nonthermal emission, and the vast majority are extragalactic, meaning that they are not part of the Milky Way. They are very far away.


Radio night sky over Green Bank

- This is an alternative sky—not the sky that we see with our eyes or with powerful optical telescopes, but a radio universe. And when this image was made, in the late-1980s, we really didn't understand what these objects were. We still don't fully understand them, but we've made a lot of progress and cleared away a lot of confusion, and learned a lot about the universe in the process.

- By the late 1980s, it was generally accepted that all the point-like radio sources in this figure—and there are hundreds and hundreds of them—are at large distances from Earth, way outside of our Milky Way Galaxy. This must mean that they are extremely luminous. And many, if not most, were associated with galaxies, especially with the nucleus of a galaxy, the very central part.

- This survey was made at 5 gigahertz, a frequency about 30 times higher than the 3C survey. The measurements were done in the mid-1980s, 25 years after the 3C, using the 300-foot telescope at Green Bank. This survey is more sensitive than the 3C and has been processed so that extended sources are removed. It still has a few ghostly images of supernova remnants and H II regions.

- Every little dot that looks like it might be real is actually real. There are a thousand real radio sources in this map. And the deeper you look, the more sensitivity and angular resolution that you can bring to your observations, and the more of these radio sources get detected.

Flux Density

- The intensity of radio emission from an object can be related to the intensity of a blackbody at some temperature through Planck's law. This temperature, the brightness temperature, is often very close to the physical temperature of an object if the emission is thermal, and it can vary from point to point across an object. Brightness temperature is an intrinsic property of a radio source.

- This is different than the antenna temperature, which is the temperature of a blackbody placed in front of a telescope's antenna that gives off the same amount of radio signal as we receive from an object in space. The antenna temperature is the brightness temperature of the radio sky averaged over the main beam. But the antenna temperature depends greatly on the size of the dish.

- The flux density of a radio source is proportional to the average brightness of the source times its angular size. It doesn't depend on antenna beam size.

Small, bright

Big, dim

- The flux density tells us a lot about the energy that reaches Earth from a radio source, but it also leaves out information. You can get the same flux density from a small, bright source as from a large, dim source. You can also have the same flux density from a nearby radio source that's intrinsically dim and a distant source that's intrinsically bright. Flux density measures the signal that actually gets to Earth.

- If we have 2 identical radio sources but one has twice the distance as the other, its flux density will be down by a factor of 4. This is the inverse square law: The power we receive from something depends on the inverse of its distance squared.

- Flux density is easy to measure. For every radio telescope, there's a single number that converts antenna temperature to flux density at a particular frequency. Flux density is measured in units named after Karl Jansky: the jansky.

- Can we use radio sources to understand the universe, even if we don't fully understand the radio sources themselves? Are the faint radio sources faint because they have an intrinsically low luminosity, or are they faint because they are more distant?

- From the inverse square law, we know that the flux density decreases as the inverse square of the distance. So, if all the radio sources have the same intrinsic luminosity, then the nearby sources would be bright and the distant ones would be faint.

- But we should see many more faint sources than bright sources—faint because they are distant, and many more because the survey area encompasses more space the farther out you go.

- In fact, a distribution like this produces a very specific relationship between how bright a source appears to be—that is, its flux density—and the number of radio sources with that same flux density. There would be a few bright objects—bright because they are close to us—and a lot more distant faint sources.

- You don't even have to assume that all the sources are identical to get a lot of information. You could have a distribution of luminosities. In that case, if you saw a faint radio source, you would not know if it was near or far. But that can be taken into account in the analysis.

- When we look for fainter and fainter sources, if we see fewer and fewer of them, instead of more and more, that would tell us that somewhere out there—out there in the distance—space was getting empty.

- But there's a complication. As you look out to greater distances, you are looking back in time. So, the radio source counts are measuring several things at once.

- For things inside the Milky Way, the look-back time is maybe 100,000 years at most. But when we look to distant regions of space, we are looking back potentially billions of years. Look far enough back and you look back to a time when galaxies like ours were young.

- Today, the Milky Way is more than 13 billion years old. Suppose that when galaxies were young, less than half the age of the Milky Way, every galaxy had an outburst of radio emission. Let's call this galactic adolescence. Let's say that at the tender age of 6 billion years, give or take a billion years, galaxies go wild and start putting out enormous amounts of energy. And let's say that the phase is mercifully short. If that happened, how would the universe look?

- When the Milky Way had its outburst at the age of 6 billion years, that would have happened more than 7 billion years ago. This is the same for nearby galaxies. Galaxies near us are all about the same age as the Milky Way, give or take a billion years. So, locally, things would now be calm, because the action was far in the past. But as we looked out deeper and deeper into space—further and further back in time—there would be a point in space and time where galaxies would light up.

- This is what astronomers found when they analyzed the source counts. As they made surveys with more and more sensitivity, they found that there weren't the large number of very faint radio sources you'd expect from a uniform universe. The source counts of faint radio sources came up short, meaning that there was a time when these extremely luminous radio sources were common. But before that time, there weren't many of them.

- The greatest number of bright radio sources occurred about 6 billion years after the big bang, more than 7 billion years ago. Everything didn't light up at once, and the sources have a spread in luminosity, but there was an early time in our universe when there

Can we look out at great distances and not be looking far into the past?

Nope. Electromagnetic radiation travels at the speed of light, so distance is time. There's no way of knowing what's happening way out there right now. We've got to wait for the signal to arrive. It'll be just a few billion years.

weren't many luminous radio sources and then a time when there were lots of them.

- When this discovery was made, it sparked a fierce debate, because it implied that the universe was not in a steady state but was evolving. And the universe was not only evolving, but it was evolving through stages.
- Just as there aren't many bright radio sources in the early days of the universe, there're aren't many bright radio sources in our own times. In general, these amazing radio sources are a phase that the universe went through, and by and large that phase is now past.

Active Galaxies

- The study of radio source counts has led us to a dramatic realization: a picture of an evolving universe that was quite a bit different in the past than it is today. But what are these radio sources? What supplies all that energy that makes them so bright over such a great distance?
- All bright radio sources are associated with galaxies. They arise in galaxies, and they are powered by black holes. Galaxies are at the heart of it.
- About the time that radio astronomy got started, in the 1940s, astronomers were discovering that there were lots of galaxies that were just a little bit peculiar, including radio galaxies, giant radio sources in elliptical galaxies, radio-loud quasars and radio-quiet quasars, Seyfert galaxies, blazars, liners, and starbursts—and who knows what else.
- This profusion of active galaxies has hit radio astronomers in an interesting way. Many of these peculiar galaxies are not strong radio sources, but that does not mean that they have no radio emission.

They have radio emission; it's just intrinsically fainter than the radio galaxies, by a lot.

- As radio astronomers detected and counted ever-fainter sources, besides finding distant radio galaxies, they started turning up Seyfert galaxies, starburst galaxies, and other sources that are intrinsically fainter but much closer. It makes the source count interpretation difficult and often contentious.

- The early results still stand: There was a time when the universe made luminous radio galaxies, and that time is mostly past—but we're now seeing lots more than that.

- What do we now know about all these different kinds of active galaxies? We think that some of the extragalactic radio sources—the radio galaxies, some quasars, blazars, and so on—are actually one phenomenon viewed from different perspectives and probably different stages of development. We think that they are all driven by extremely massive black holes at the center of galaxies.

- At the same time, there seems to be 2 possible sources for activity in galaxies. Some galaxies are undergoing extreme bursts of star formation. They're called starburst galaxies. They are making new stars at a rate hundreds of times that of the Milky Way.

- Star formation produces massive stars, which produce supernovas and supernova remnants, making cosmic rays and nonthermal radio emission as well as light and x-rays. Make enough massive stars and soon enough you light up the neighborhood.

- Some data just don't fit the simple models. But between massive black holes and starbursts, we understand that galaxies can have different evolutionary tracks and histories. At some stages, they can produce very energetic events—events that we try to understand through analysis of radio emission and surveys of radio sources across the sky.

Suggested Reading

Graham-Smith, *Unseen Cosmos*, chap. 8.

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

Sullivan, ed., *The Early Years of Radio Astronomy*.

Questions to Consider

1. Radar is an active area of research used for study of objects in the solar system. The flux density of an object decreases as the inverse square of its distance. What law would there be for the return radar signal's intensity transmitted from Earth as the distance of the reflecting object changes? (One way to think about this is to imagine a radio telescope that receives a signal from a point source and then retransmits it back to that source.)
2. In this lecture, we imagined that all extragalactic radio sources had the same intrinsic luminosity so that there was a direct relationship between the observed flux density of an object and its distance. Suppose that the radio sources had a spread in intrinsic luminosity of a factor of 2 around the average. How would that change the relationship between numbers at a given flux density and their distance?
3. Suppose that as all galaxies evolved, their radio emission grew brighter so that the younger ones were intrinsically faint and the older ones were intrinsically bright. What would that look like to us on Earth?

LECTURE 18

Active Galactic Nuclei and the VLA

In this lecture, you will learn about galaxies with what are called active galactic nuclei that produce radio sources that stretch far beyond the stars of the host galaxy. You will also learn about the Very Large Array (VLA). Other interferometers around the world operate on the same principles as the VLA, but in many ways, the VLA is the premier instrument of its kind.

Active Galactic Nuclei

- After the discovery of a sky full of nonthermal radio sources, astronomers were in a quandary. Some of these sources were apparently at an enormous distance, and they appeared to be associated with galaxies or with quasi-stellar objects that might be the bright cores of galaxies—quasars—but the energy source was unknown.
- One approach to understanding them was to survey the sky to evermore sensitive levels to count the radio sources and learn something about their distribution in space and time.
- Another approach was to try to match individual radio sources with objects that could be seen with traditional telescopes. This was also fruitful, and showed that there were galaxies with what are called active galactic nuclei that produced radio sources with extended lobes of radio emission stretching far beyond the stars of the host galaxy.
- When a radio source could be associated with a galaxy, it is also possible to get the distance to the source from the Doppler shift of spectral lines in the galaxy.
- So, the bright extragalactic radio sources were shown to be tied to galaxies. Where did all of that energy come from? And were the lower-energy active galactic nuclei simply radio galaxies or quasars on smaller and less energetic scales? If radio telescopes could be

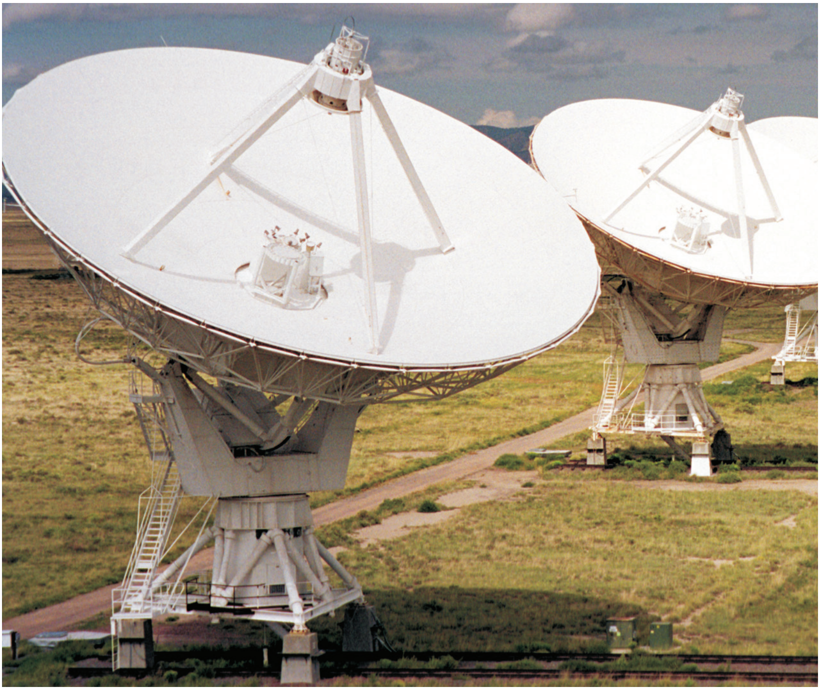
made sensitive enough and with high enough angular resolution, would all active galactic nuclei look the same?

- These specific astronomical questions spurred the development of an entire generation of radio interferometers—radio telescope arrays—whose prime objective was to untangle the energetic extragalactic radio sources. The telescopes would have other uses, but the thrust from the scientific community was active galactic nuclei.

The Very Large Array

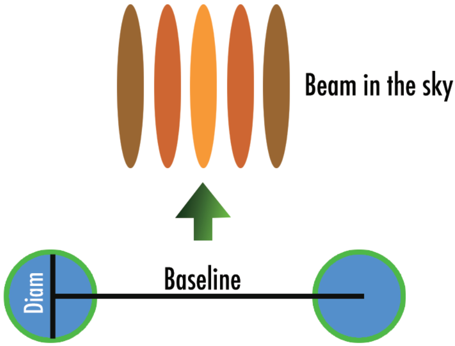
- The VLA uses 27 antennas spread out in a Y formation on an ancient dry lake bed in central New Mexico. The antennas sit on concrete pads but can be moved on railroad tracks into different locations along the Y. At its most extended, it covers an area larger than the Washington DC beltway. The longest baselines are 35 kilometers. When the VLA is in an extended configuration, its antennas stretch out of sight.

- Each antenna has a set of receivers that can cover frequencies between about 1 gigahertz and 50 gigahertz, as well as a few lower-frequency bands.

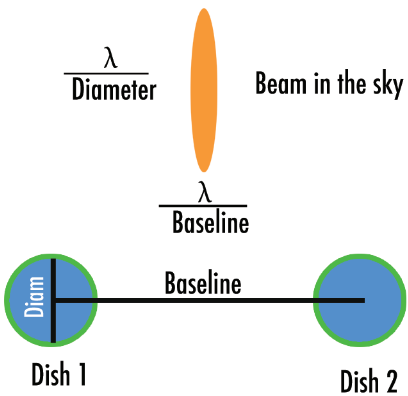


- There are several receivers housed in a structure at the secondary focus. The incoming radiation is reflected off the dish, then re-reflected from the secondary reflector, and finally focused on a receiver. By changing the position of the secondary reflector, the signal can be steered from one receiver to the next to observe at different frequencies.

- With interferometers in general, if you add the signals from a pair of dishes, you can get a beam pattern on the sky whose size in one direction is set by the angular resolution of the dishes and in the other direction by the spacing between the dishes. And you get a comb of lobes across the sky—a main beam, and sidelobes.



- What an interferometer measures at any instant is the sum of the total power that comes in through all of those beams.



- The size of the beam and the sidelobes on the sky is set by the wavelength of the radio emission (noted by the Greek symbol λ) divided by either the dish diameter or the spacing between dishes (the baseline).

- Because radio emission could come to the receiver through any of the sidelobes, sometimes it's difficult to sort out what's going on. Early radio surveys, including the first version of the 3C, had problems with what's called lobe ambiguities.

- But we can make things a lot better by adding just a few more dishes to our array and by taking advantage of a great tool that nature offers us.

- As the Earth rotates, the baseline of an interferometer also rotates, so the beam pattern on the sky is not fixed, but rotates around. It changes in angle on the sky.

- As the Earth rotates, a baseline can also change its length. The baseline is not simply the spacing between the dishes; it's the spacing between the dishes as seen by the radio source.

- So, when looking straight up, the baseline is just the distance. But when looking off to the side—for example, looking at a radio source as it is rising above the horizon—the baseline is foreshortened, and it's equivalent to having the dishes closer together. So, the baseline shrinks as we point our telescopes at angles away from straight overhead.

- In practice, this means that we don't have to build an interferometer with all orientations of the baseline covered and with a total range of baseline distances; we can let Earth's rotation do some of the heavy work.

- When the VLA is in its most compact configuration, the longest baseline is about 1 kilometer. The radio source that the array is observing sees that the spacing of some of the antennas is foreshortened. That's a good example of how the actual baseline length depends on the angle of the radio source, which changes as the source moves across the sky.

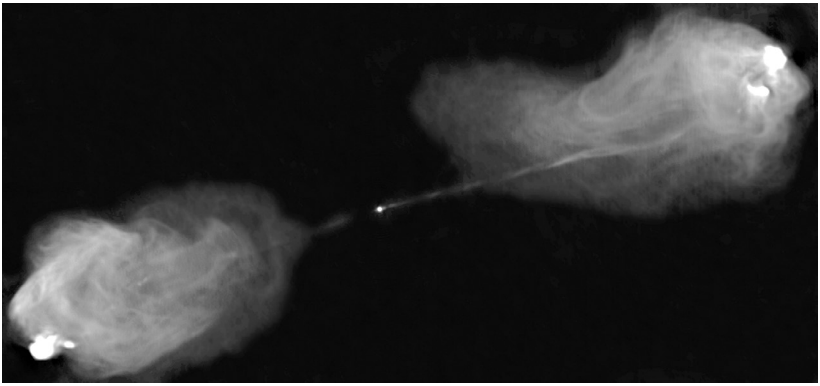
- Every antenna of the VLA makes an interferometer pair with every other antenna, with its own baseline at a specific length and angle. This produces baselines of all different lengths and, just as importantly, lots of different orientations.

- Each baseline produces its own beam and sidelobes on the sky, and the varying angles and varying lengths give quite a range of information about the source being observed. You end up with a fairly clean beam pattern even with a simple snapshot using the VLA.

- As the Earth rotates, the VLA is also rotating. After 8 hours, its individual antennas have swept out a big circular-like aperture filled with baselines. The technical term for this is aperture synthesis, or making a large telescope aperture from pairs of small antennas. The result is a very clean main beam with low sidelobes.

Cygnus A

- Some of the finest images to come out of the VLA—like this image of Cygnus A, or 3C405—use data from 4 array configurations, from the most compact to the most extended, to capture the source structure on all scales.

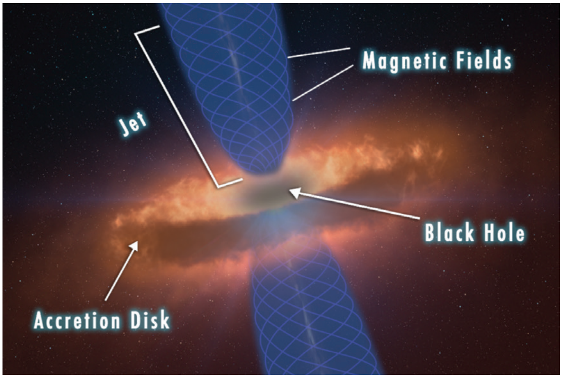


- Because Cygnus A is extremely bright and relatively nearby, we can see it in detail. It has the 4 parts of a classic radio double:

  1. A radio spot on the nucleus of the host galaxy
  2. One or more long, narrow jets emanating from the nucleus
  3. Hot spots at the ends of the jets
  4. Broad lobes of radio emission where the material that hits the hot spots flows back toward the galaxy.

- The existence of jets in Cygnus A was predicted before the jets were observed. When Martin Ryle and his colleagues analyzed their map in 1965, they just saw 2 lobes, not all the detail. But the lobes were far from the parent galaxy. They realized that the lobes were radiating so much energy that if they had been shot from the parent galaxy, they would have radiated it all away before reaching their present location. The lobes had to be supplied with energy by something like a jet from the galaxy—a jet that could transport energy without radiating it away.

- In the 1990s, Megan Urry, now at Yale University, and Paolo Padovani, now at the European Southern Observatory, proposed a scheme to unify the different types of active galactic nuclei.



- This drawing shows what we think is happening. The central engine is a black hole—a supermassive black hole—surrounded by a disk of gas that has been attracted by the gravitational force of the black hole. It's called an accretion disk.

- The accretion disk is threaded with a strong magnetic field, and somehow that field and the black hole launch one or more jets out of the nucleus, carrying magnetic fields and particles at enormous speeds. The jets from Cygnus A are moving at half the speed of light.

- The jets plow through the elliptical galaxy, creating a tunnel that carries the magnetic field and particles far outside the galaxy. Eventually, the jets hit intergalactic gas and are brought to a halt. Like a snowplow, the jets plow ahead, sweeping up gas before them until they pile up enough material to bring them to a halt.

- When this happens, jet material splashes back toward the galaxy and spreads out, forming the large radio lobes. A key feature of the jets is that they propagate great distances without losing much of their energy, so when they hit the wall, quite a lot of energy is released.

Suggested Reading

Blundell, *Black Holes*, chap. 8.

Graham-Smith, *Unseen Cosmos*, chap. 5.

Verschuur, *The Invisible Universe*, chaps. 10, 11, and 12.

Questions to Consider

1. The resolution of an interferometer pair goes as wavelength divided by baseline length. We want to observe over as large a band of frequencies as possible to increase sensitivity, but that means that the wavelength at one end of our frequency band is somewhat different than the wavelength at the other end. Does this affect the data? (Yes, it can blur the images and is called bandwidth smearing.)
2. To make a bright active galactic nucleus requires both a massive black hole and a source of matter falling into it to feed the jets. Can you think of circumstances that would make bright active galactic nuclei less common today than in earlier times, even though almost every galaxy still has a massive black hole at its nucleus?

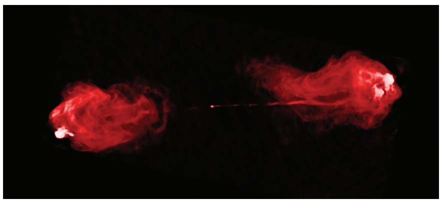
LECTURE 19

A Telescope as Big as the Earth

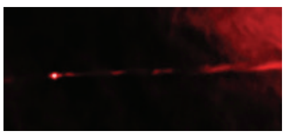
Jets dump energy into lobes on the outskirts of radio galaxies. But what's happening in the center near the black hole? How are the jets made, and where do they come from? The Very Large Array is not sufficient to answer these questions. It does not have enough angular resolution. To see into the vicinity of black holes in radio galaxies, we need a bigger radio telescope—a radio telescope as big as the Earth, which is the subject of this lecture.

Very Long Baseline Interferometry

- The extragalactic radio source Cygnus A is shown here in an image that combines the radio emission and starlight.



- Let's look more closely at the Cygnus A jet.

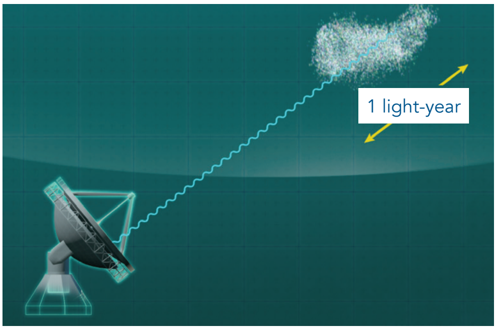


- Not much structure is visible in the jet. In fact, the angular resolution of these observations is not good enough to discern any detail about the jets or the radio source in the core. The picture's too blurry.

- The angular resolution of this VLA map is about half an arc second, and that translates to about 500 parsecs at the distance of Cygnus A. A parsec is about the distance from the Sun to the next nearest star. Light takes about 3.25 years to travel a parsec, so a parsec is about 3¼ light-years. Apparently, the jets and the core are smaller than 500 parsecs.

- There are other clues about their size. First, there are estimates that the jets are traveling at half the speed of light. That's fast, and it implies that they should be moving by 1 parsec in just a few years. If we could get the angular resolution of a parsec, perhaps we could actually watch the jets move.

- There's another line of thought. Some active galactic nuclei change their visible brightness and radio emission on time scales of months to years. That means that the source of the emission can't be bigger than a few light-years across.



- Let's say that we have a blob of plasma that lights up all at once and begins sending out radio waves. If it's 1 light-year across, it still takes an entire year for the signal from the back to reach us after the signal from the front arrives.

- So, we would see a pulse on a time scale of a year. We could put an upper limit of 1 light-year on the size of the emitting source. It could be smaller if the emission didn't happen all at once, but not larger. A larger object couldn't make such a short pulse. It's an upper limit.

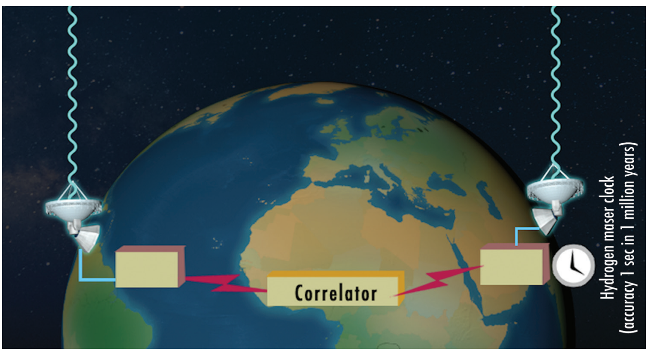
- And that's what we see in some active galactic nuclei. We see fluctuations in radio brightness on time scales of a year. One light-year is about 1/3 of a parsec. So, it seems that we need angular resolution that gives us 1 parsec or better at the distance of Cygnus A.

- To get a resolution of 1 parsec at the distance of Cygnus A, we need an angular resolution of about a milli–arc second, or one thousandth of an arc second.

- At a wavelength of 6 centimeters, this requires a baseline that is 350 times longer than the longest VLA baseline. This needs a baseline that's more than 12,000 kilometers long. That's the diameter of the Earth.

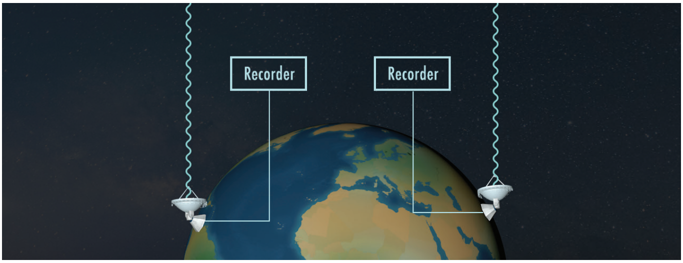
- We can make an interferometer with a baseline that stretches from one side of the Earth to another. It's called very long baseline interferometry (VLBI).

- We have 2 radio telescopes on different sides of the Earth. They each receive a signal from a distant object, and the signals are combined in a correlator. The result is a telescope as big as the Earth.



The Early Days of VLBI

- So far, we have been discussing connected interferometer pairs, where the 2 dishes are connected to the correlator by a wire, fiber, radio transmitter, or something similar. In the late 1960s, groups first in Canada and then throughout the world developed a technique for creating an interferometer from 2 antennas that were not connected.



- Instead of connecting the signals to a correlator, we simply record them on tape. The tapes are then shipped through the mail to a central location, where they are played back into the correlator some time later. The signal is preserved perfectly on the tape, and the correlation can be done at any time.

- The ability to record the VLBI data has always been a challenge. For VLBI experiments, you have to record hundreds of millions of numbers every second. This has always strained the limits of recording technology and continues to be an issue today.

- In the early days of VLBI, radio astronomers would arrive at remote telescopes with carloads of tapes and balky electronics and struggle with basic logistics. The data rate was so large that it would fill up a tape the size of a large pizza in 5 minutes. Then there'd be the rush to mount another tape to keep the experiment going.

- Thankfully, those days have past. Today, VLBI measurements use disk storage—the kind of disks that are found in many computers.

- While the recording medium is always a challenge, an equally important consideration is that for the VLBI technique to work, you have to be able to synchronize the 2 signals at playback time. And that requires a very accurate time stamp be put on the data at each telescope.

- For this reason, every VLBI system has a highly accurate time standard at every antenna, a time standard that is colloquially called an atomic clock. These clocks use the emission from quantized states of an atom to produce a very precise frequency, which can then drive a precise clock, which can be used to time-stamp the incoming radio wave for correlation later.

- In modern times, it's routine to capture radio signals using isolated ratio telescopes scattered across the world and reconstruct a virtual antenna by combining their signals.

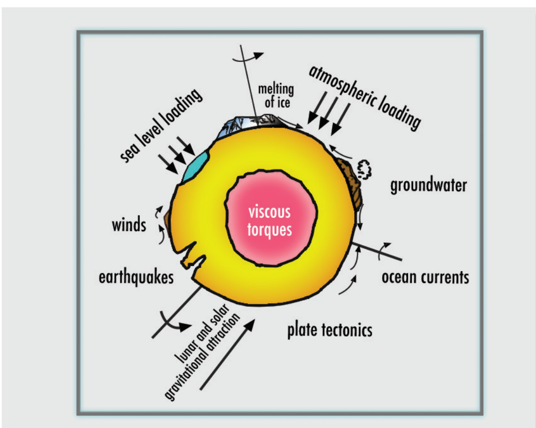
- In the United States, the National Science Foundation funded construction of the Very Long Baseline Array (VLBA), which has 10 25-meter antennas spread from Hawaii to the Virgin Islands.

- Tape was originally used to transport the signals and play them back into the correlator in New Mexico. But they've since switched to high-density disks. For some measurements where extra sensitivity is needed, other telescopes, such as the Green Bank Telescope, are added to the array.

Location and Timekeeping with VLBI

- To correlate the signals properly, we need to know the position of the antennas quite accurately. In fact, some early VLBI measurements showed that there were errors in official maps. By observing astronomical sources, we learn about the location of the antennas on Earth.

- The correlation process has to account for the Earth's rotation; after all, it's the Earth's rotation that makes stars rise and set. VLBI measurements produce extremely accurate information on the Earth's rotation, the wobble of the North Pole, and so on. There are many factors that influence the rotation of Earth.



- So, the entire astronomical observational process can be reversed. We take a set of quasars with well-known positions and use them to determine the exact parameters of the rotation of the Earth.

- In the United States, the U.S. Naval Observatory is responsible for providing information on Earth's rotation and polar motion for accurate timekeeping, and they have long recognized the importance of very long baseline interferometry to their mission.

- The Naval Observatory regularly measures the apparent location of a set of reference quasars and uses this information to determine the precise rotation of the Earth. They also feed this information into the global positioning system (GPS). VLBI techniques tell us what time it is.

- Knowing the precise location of an object fixed to the Earth, such as an antenna, can also be used to tell us when that piece of Earth has moved. The crust of Earth is a dynamic system, with plate tectonics and earthquakes constantly rearranging the surface.

- There are areas rebounding from the weight of glaciers during the last ice age and other areas where volcanism causes ground height changes. Some VLBI arrays are dedicated to studying the Earth's crustal motions.

- It may be possible before too long to measure antenna locations with errors of only a few millimeters.

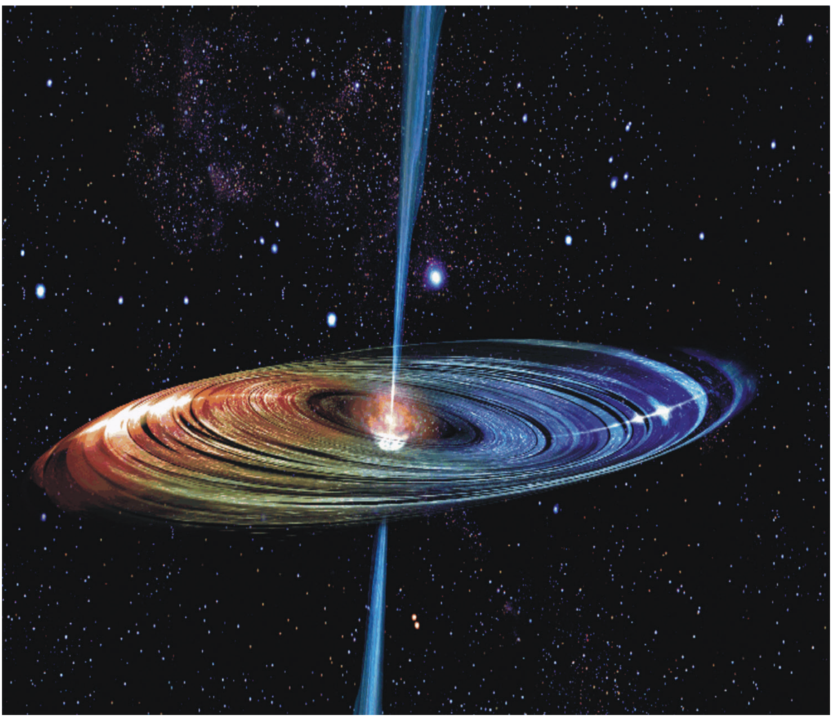
Accretion Disks and Jets

- To make any progress in understanding the inner structure of active galactic nuclei, we need an angular resolution of about one thousandth of an arc second, a milli–arc second. With a lot of work and advances in technology and with new telescopes, that resolution has been achieved.

- A great discovery in recent years is that most galaxies like the Milky Way, and probably all large galaxies, have a very massive black hole at their center. Black holes are collections of matter so concentrated that their gravitational force keeps even light from escaping.

- We really don't know how these massive black holes came to occupy the very centers of galaxies, but somehow the formation of the black holes and the formation of the galaxy itself seem to be linked.

- Matter that comes near to the black hole doesn't plunge right in. It settles into a disk, an accretion disk, which gets its name because it's the last stop for matter on its journey to being accreted by the black hole.



- The vicinity of black holes is a fairly violent place, but within the accretion disk, there are regions hospitable to molecules such as water. And indeed water is found there.

- Water molecules can emit very bright radio spectral lines through a process called maser emission. A maser is the radio equivalent of a laser. Maser emission from interstellar water has a frequency of 22 gigahertz, and the luminosity of water masers can be enormous. We can detect them at great distances from us.

- So, we have clouds of water vapor emitting bright radio lines in an accretion disk rotating around a black hole, and we can use them to weigh the black hole. We can use the velocities of the masers to weigh the black hole, the same way we can use the velocities of the planets to weigh the Sun—through Kepler's law.

- By watching individual maser spots move as they rotate around in the accretion disk, we can also determine the distance to the galaxy using just a little geometry. This is important because most ways of measuring distances to galaxies rely on indirect methods, such as the brightness of certain stars. With VLBI and water masers, you get distance from velocity and angle.

- Using long baseline interferometry, we can look down at the base of radio jets and watch individual jet blobs emerge. While we now have several promising models for how the jets are actually formed when material from the accretion disk hits the black hole, the full story still eludes us. It is very likely that magnetic fields in the accretion disk become tangled and transfer energy perpendicular to the disk, launching jets.

Suggested Reading

Blundell, *Black Holes*, chap. 7.

Cottrell, *Telescopes*, chap. 7.

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

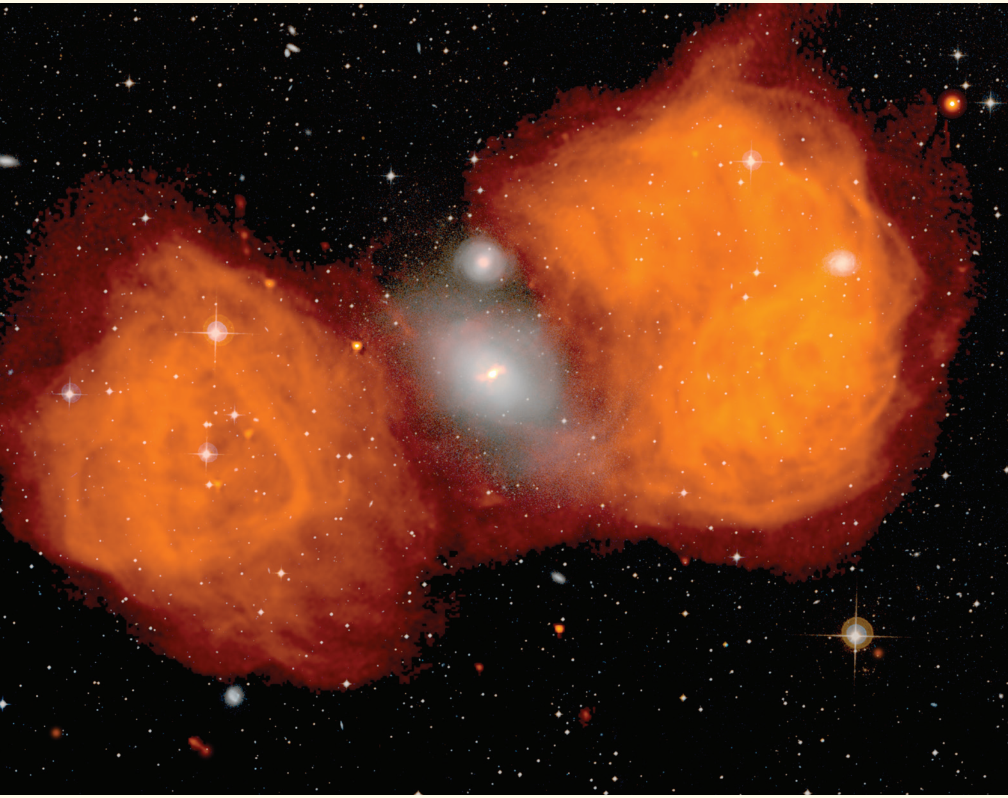
Lockman, Ghigo, and Balser, eds., *But It Was Fun*, parts III.3, IV.9, and IV.10.

Questions to Consider

1. If a small country wanted to become involved with radio astronomy, it might build and operate a telescope of the 25-meter class for very long baseline interferometry. Why might that be of importance to the world's science?
2. If most galaxies have black holes in the center and galaxies regularly merge or capture smaller galaxies, might we expect to see a galaxy somewhere that has 2 supermassive black holes possibly driving 2 pairs of radio jets?
3. The video lecture showed a movie of the changes in the radio emission from 3C274 over fairly short times. Would this be a good object to use as a calibrator for geodetic very long baseline interferometry studies? If not, what sort of radio source would make an ideal calibrator?

LECTURE 20

Galaxies and Their Gas



In this lecture, you will learn about the relationship between galaxies and their gas. And at the heart of this is a very deep question: What exactly is a galaxy?

Island Universes

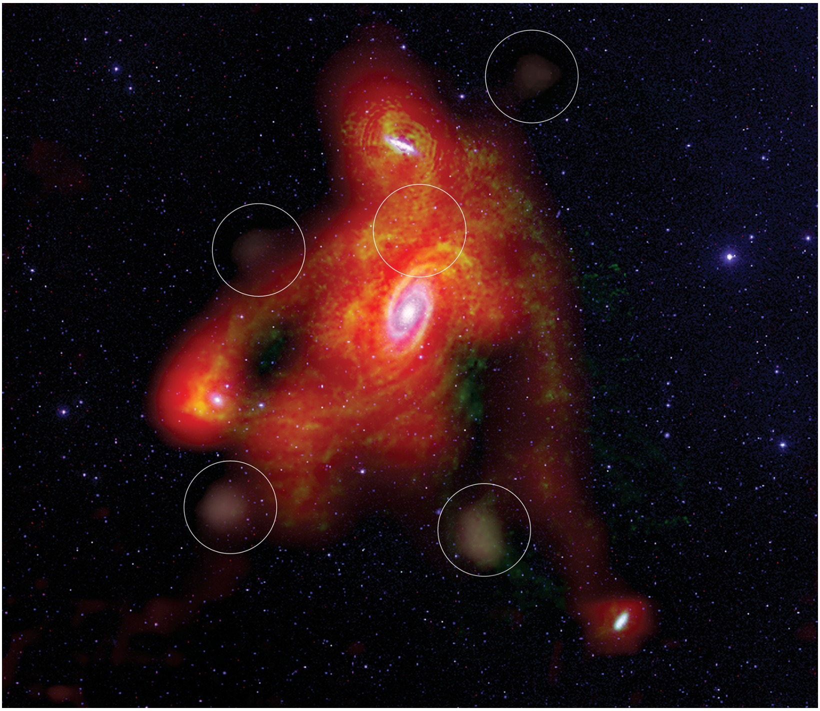
- About a hundred years ago, astronomers were beginning to understand that the fuzzy patches they saw all over the sky were actually independent stellar systems, such as the Milky Way.

- At that time, astronomer Heber Doust Curtis used the phrase "island universes." Galaxies come in different sizes and shapes, but they seem to be self-contained. They're held together by their own gravity and with the help of gravity from lots of dark matter. They have reasonably distinct edges.

- Galaxies also are often found in groups or clusters that can contain anywhere from a handful to thousands of other galaxies. The Milky Way is part of what is called the Local Group, which also includes Andromeda and M33. There are also many smaller systems, such as the Magellanic Clouds.

- Another group that is not too far away from our own, M81, has spiral and irregular galaxies.

- But when astronomers measured the 21-centimeter radio emission from hydrogen in the group, they saw quite a different scene.



- The galaxies are connected by streams of neutral hydrogen. These galaxies are interacting with each other and ripping out their gas.
- Some of that gas has fallen into the galaxy at the top of the image, causing a burst of star formation. And the supernovas from this starburst are forming a powerful wind from the center of that galaxy, blasting out into space.
- In the last few decades, astronomers have come to understand that instead of being isolated island universes, galaxies often have strong

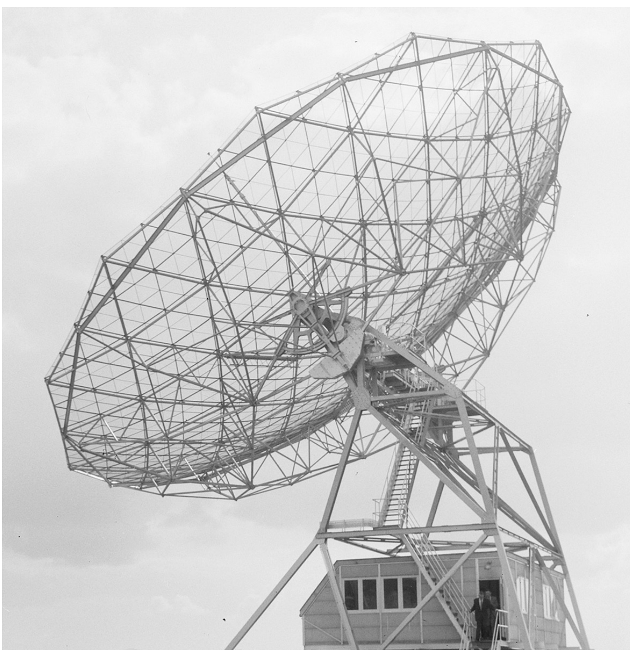
interactions with their environment. In fact, it's likely that these interactions are not a secondary feature in the life of galaxies, but are the key to their basic structure and appearance.

- At the same time, we now recognize that the process of galaxy formation is not something that happened in the distant past, but is going on today, and we are learning to observe it at work, close up, in the Milky Way.

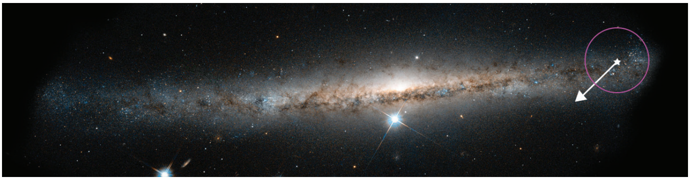
The Smith Cloud

- A 25-meter-diameter radio telescope at Dwingeloo in the Netherlands went into operation in 1956. At that time, it was the largest radio telescope in the world.

- Under the leadership of Professor Jan Oort, Dutch astronomers began a major effort to understand the distribution of neutral hydrogen in the Milky Way.



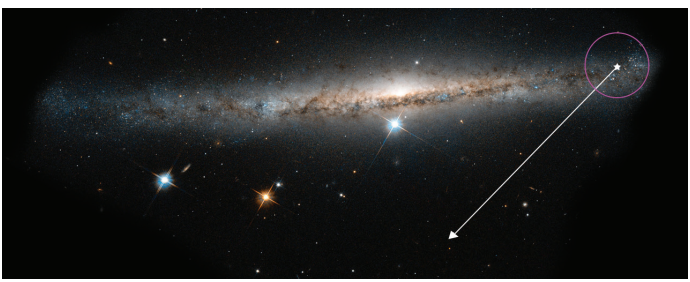
- In the early 1960s, Gail Smith was a young American graduate student in astronomy at Leiden University in the Netherlands. Her advisor turned her loose on 21-centimeter data obtained with the Dwingeloo telescope, and she focused on a hydrogen cloud with an unusual velocity.



- If we look out at some angle from the Milky Way disk, everything we see is nearby. That's what it means to be in a disk. For example, if we look outward along the angle of the arrow, we'll see mostly what's in the circle. Beyond the circle, we've left the disk of the Milky Way and are heading into the wild blue yonder.

- Gas nearby us rotates around the center of the galaxy the same way we do, so we won't see a large Doppler shift from gas within the circle.

- Smith found a cloud of hydrogen that was somewhat away from the galactic plane and had a high velocity.

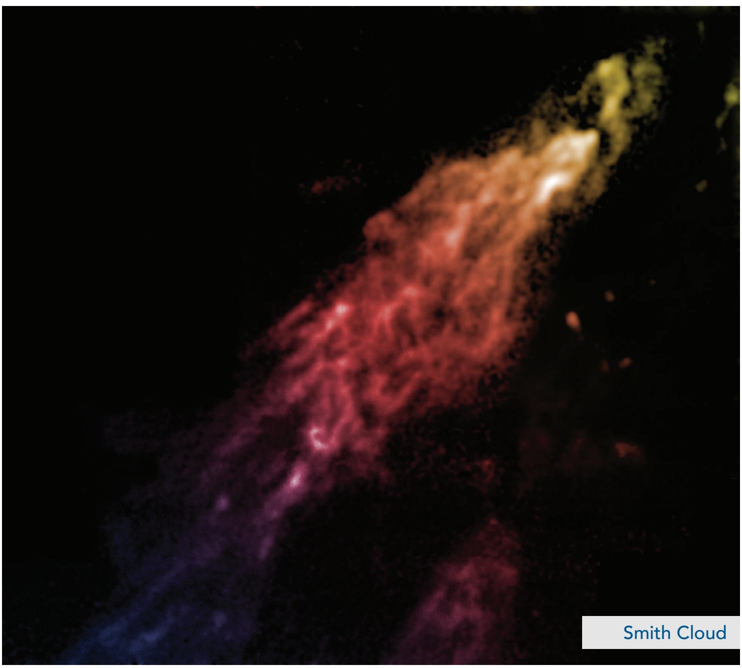


- It was somewhere along this direction, but where? It was a puzzle.

- Smith published a paper with her findings. She showed a 21-centimeter spectrum, confirming that this cloud was separated from the more normal Milky Way hydrogen. She also published maps of the hydrogen at a few velocities. They showed a rather extended blob sitting off by itself, without much detail.

- Smith considered a few possibilities. The cloud could be part of a supernova shell, or part of a spiral arm, or it might be an interloper—something that was actually outside the Milky Way but just happened to be only 15° from the galactic plane and only 100 kilometers per second different from galactic velocities. The cloud wasn't visible in photographs of that part of the sky. It was all hydrogen.

- Smith published her paper in 1963 and a few years later left astronomy. No one really followed up on her discovery.



Smith Cloud

- Smith found hydrogen 21-centimeter emission from a cloud whose velocity wasn't consistent with galactic rotation. The Smith Cloud has high velocity.

- Oort and colleagues found that high-velocity 21-centimeter hydrogen emission was quite common around the sky. And in the following years, astronomers discovered more and more high-velocity clouds whose relationship to the Milky Way was totally unknown.

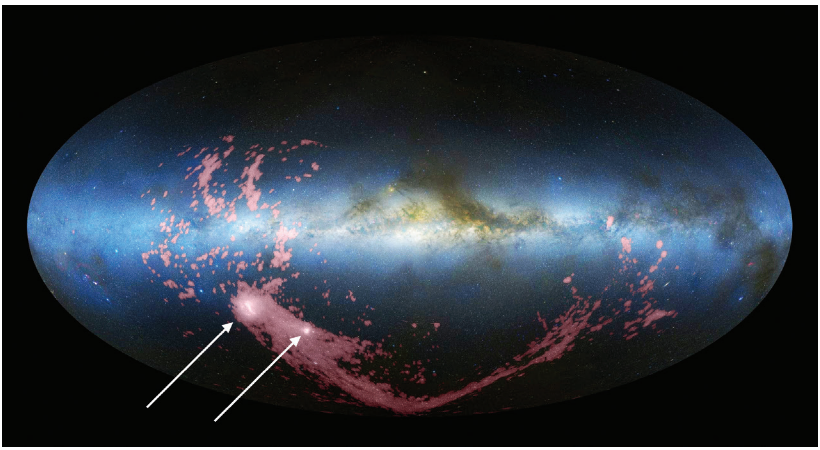
- For decades, the key problem was that there was no good measurement of the distance to any of the clouds. That meant that their mass and size were completely unknown: Were they mere wisps of gas nearby us or distant gigantic structures? One thing for sure was that high-velocity clouds had no stars. They weren't galaxies.

The Magellanic Stream

- The Magellanic Clouds are 2 small galaxies named after the European explorer Ferdinand Magellan, though they were well known to other cultures long before Magellan's epic voyage around the globe. The Magellanic Clouds are dwarf galaxies with only a few percent the mass of the Milky Way. You can only see them from the southern sky.

- The Magellanic Clouds orbit around each other. Their mutual interaction and encounter with the Milky Way has somehow pulled an enormous mass of gas out of the clouds like a contrail that stretches nearly 200° across the sky. And it doesn't have any stars.

- The Magellanic Stream is a hydrogen stream that extends from the Magellanic Clouds. Even though the Magellanic Stream arises from galaxies with only a few percent the total mass of the Milky Way, the stream has an enormous amount of gas, about 10% of the entire gas mass of the Milky Way. And this gas is going to eventually be incorporated into the Milky Way, where it can be used to make new stars.



- There are many questions about the Magellanic Stream, but at least we know where it came from—it was originally gas in the Magellanic Clouds—and we know where it's going—eventually, it will fall onto the Milky Way.

- But what about all other high-velocity clouds? Where do they come from, and where are they going?

- The Local Group is held together by mutual gravitational attraction and is dominated by 2 large galaxies: the Milky Way and Andromeda. There's also a moderate-sized galaxy, M33, and a number of smaller dwarf galaxies. The Magellanic Clouds are by the Milky Way.

- How far away are the high-velocity hydrogen clouds that we see in the sky? Are they near the Milky Way, or are they floating in the Local Group, or are they even farther out?

Dark Matter and Hydrogen Clouds

- Astronomers studying the distribution and velocity of hydrogen in galaxies discovered that the hydrogen was experiencing quite a bit more gravitational force than could be accounted for by the visible mass in the galaxies. There was more gravity than could be produced by the stars, gas, and dust.

- The mass of galaxies is dominated by dark matter. Surprisingly, we know quite a lot about dark matter, considering that the only way that dark matter is detected is through its gravity.

- We know that over the age of the universe, dark matter clumped into clumps the size of galaxies—some very big clumps, many smaller clumps—and it dragged gas along with it.

- We also know that the clumps didn't form very quickly; otherwise galaxies would be older than they are. And the clumps can't form too slowly; otherwise we wouldn't have any galaxies even today.

- The fact that dark matter doesn't seem to interact with normal matter also limits its properties. So, although we've never detected dark matter directly, there isn't a lot of wiggle room in its main properties.

- Theoreticians who simulate the evolution of the universe have produced images that show nothing but dark matter—dark matter that we expect to find around a galaxy like the Milky Way. The Milky Way sits in the large, fuzzy object in the center, in a dark matter halo. And there are many, many smaller dark matter blobs surrounding the central halo—almost innumerable smaller sub-halos of dark matter.

- If this is in any way even in the ballpark of the truth, then the Milky Way must be surrounded by thousands of dark matter clumps, many of which have the mass of small galaxies.

- What is a galaxy? Can a galaxy be a galaxy if it doesn't have any stars? No, because we basically define a galaxy as something that has stars and dark matter.

- The theoretical simulations of the structure of dark matter halos imply that there are many possibilities for dark galaxies. A dark galaxy would be a halo of dark matter without any stars.

- Do such things exist? And if they exist, how could we find them? Perhaps their gravity might attract some hydrogen that could be seen in the 21-centimeter line. Could the high-velocity hydrogen clouds that we see around the Milky Way be dark matter blobs that picked up a little hydrogen?

- This very interesting question has driven a lot of research in radio astronomy. There were 2 breakthroughs. First, astronomers were able to measure the distance to a few of these high-velocity clouds and found that they were relatively close, at only about 10 kiloparsecs from the Sun—definitely not far out in the Local Group. Second, a system of high-velocity hydrogen clouds was discovered around the Andromeda Galaxy.

- It seems that spiral galaxies can have hydrogen clouds around them. Some of these clouds have more than a million solar masses of hydrogen. What are they?

- This brings us back to the cloud discovered by Gail Smith. She published her paper in 1963. Over the next 40 years, the paper was mentioned only a few dozen times. As interstellar objects go, the Smith Cloud was pretty obscure. There were many high-velocity clouds in the sky. Why should the Smith Cloud be important?

- In the 2000s, several scientists thought that the Smith Cloud might be extremely important, so they used the Green Bank Telescope to measure its hydrogen at high sensitivity and resolution. Instead of a shapeless blob, they saw a dynamic structure looking like a comet pointed toward the galactic plane.

- At about the same time, other astronomers determined the distance to the Smith Cloud. For the first time, we understood that it contained several million solar masses of gas and was plunging toward the Milky Way, heading for a collision in about 30 million years.

- If you could see the Smith Cloud with your eyes, it would arch across the sky. But it doesn't have a single star that we know of, and it hardly emits any light—just a feeble few photons from some ionized gas.

- In 30 million years, we expect the Smith cloud to plunge into the Milky Way, bringing with it more than a million solar masses of fresh gas to fuel future star formation.

- The idea that the Milky Way is an "island universe" is not correct. We are pulling in stuff all the time. And we're not just pulling in gas. There's lots of evidence that the Milky Way is also swallowing small galaxies—more or less normal galaxies with their stars and dark matter.

- It's a good thing that the Milky Way is continually replenishing its gas, because otherwise it would have run out of material to make new stars a billion years ago.

- So, we're being replenished by things like the Smith Cloud. But what exactly is the Smith Cloud? Where did it come from? Does it contain dark matter? Is it one of the dark galaxies whose existence is implied by the theoretical calculations? Are there any dark galaxies?

- These questions have been the focus of research at a number of observatories. And while we don't have the answers today, some ongoing research revolves around finding these answers.

Suggested Reading

Drake and Sobel, *Is Anyone Out There?*, chap. 4.

Verschuur, *The Invisible Universe*, chap. 6.

Questions to Consider

1. How would you define and measure the size of a galaxy if it does not have a sharp edge?
2. Can you think of a way to detect a dark galaxy? It would have only gravity, and no normal matter.
3. It is possible that the large dark matter halo of the Milky Way overlaps with the dark matter halo of the Andromeda Galaxy. How might that affect their properties in the future?

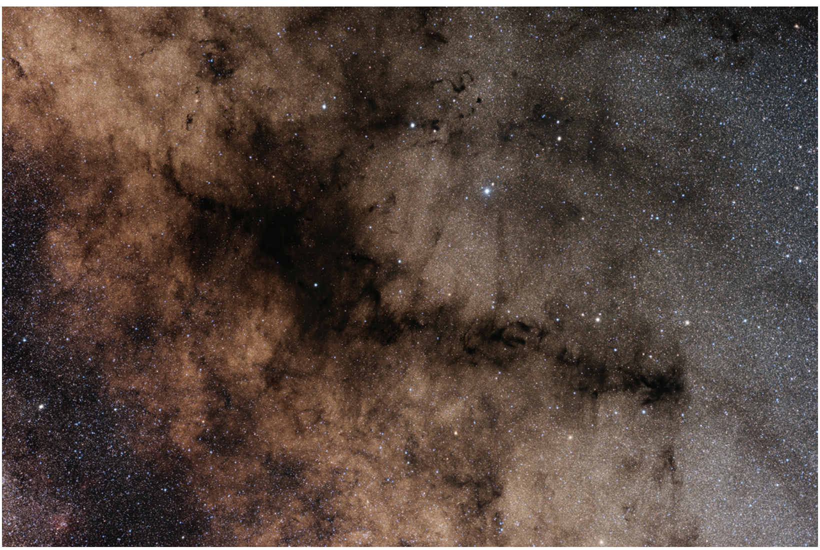
LECTURE 21

Interstellar Molecular Clouds

Spiral galaxies are so called because the brightest sources of light in these galaxies lie in a spiral pattern that trails behind the galaxy's rotation. These bright areas are regions of star formation—H II regions—glowing concentrations of ionized gas, ionized by ultraviolet radiation from young massive stars. In the star-forming regions of galaxies, the dark dust clouds are also arranged in spirals. In these dark dust clouds, new stars are formed. But the clouds are so dusty that they are opaque to visible light. We can't see what's happening inside. This sounds like a job for radio astronomy—which has transformed our understanding of star formation.

Dark Clouds

- The process of making a star begins in a dark cloud, where the densities get high enough that gravity overcomes forces such as pressure and turbulence and gas forms clumps that collapse to make new stars and new solar systems.



- Dark clouds are defined observationally, meaning that we observe that in certain directions there is a void in the star field caused by clouds of dust in the interstellar medium—not a general haze of dust, but a confined region of dust.

- In 1962, astronomer Beverly Lynds published a catalog of dark clouds that she identified in photographs of the part of the sky that's visible from the Northern Hemisphere. The Lynds catalog of dark clouds has become the go-to source for studies of dense gas clouds near the Sun—gas clouds that might be in the process of forming stars.

- Dark clouds are especially common around H II regions. The minute that a massive star is formed, it begins to ionize the gas around it. It heats the gas, and the gas glows. The star makes an H II region. But there can be a lot of dense, dark gas left over. When the dark gas lies in front of the H II region, we can see it clearly. In some cases, stars are still being made in that dense gas.

- The gas that constitutes a kind of atmosphere of the Milky Way and similar galaxies contains dust. The dust is microscopic bits of matter. The dust and gas are pretty tightly coupled so that when the gas density gets high, so does the density of dust.

- Dark clouds are defined by an absence of background starlight. But that's not a lot to go on if we want to understand why these are the cradle of star formation. What's going on inside that dusty veil?

- The method of identifying dark clouds by their blockage of background starlight only works for nearby clouds. For example, a single dark cloud will block our view of other dark clouds behind it. This means that most of Lynds's clouds have to be within a few kiloparsecs of the Sun. Also, a very distant dark cloud, even on a clear line of sight, would have lots of foreground stars in front of it and could be difficult to see.

- Lynds's catalog was published in 1962. At that time, the only tool that radio astronomy could bring to bear on dark clouds was the 21-centimeter hydrogen line. But that changed rapidly. In 1963, the hydroxyl (OH) molecule was detected by astronomers at MIT in absorption against the supernova remnant Cassiopeia A.

- Every atom and molecule has distinct quantum states of rotation, vibration, excitation, and so on. Those quantum states and the frequencies of photons they emit when making the transition from one to another are determined by the specific molecular structure.

- For simple systems, such as excited hydrogen, it's easy to determine the expected frequencies of the radio recombination lines. But determining the spectral-line frequencies appropriate for molecules is often extremely difficult and requires a combination of theoretical calculations, laboratory studies, and astronomical measurements.

- The astronomers at MIT were able to detect the OH molecule because its frequencies had been measured in a lab. They knew where to look—what specific frequencies to examine—out of all of the electromagnetic spectrum.

- A few years later, in 1968, Charles Townes, who invented the maser and won the Nobel Prize for it, used a small radio telescope at the University of California, Berkeley, with some colleagues to discover emission from interstellar ammonia and, soon after, interstellar water vapor.

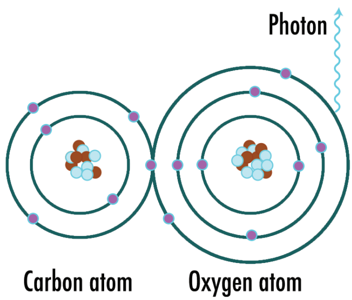
- The prevailing theories of the day said that nothing more complicated than diatomic molecules—molecules with only 2 atoms, such as OH—could survive in the extreme environment of interstellar space. But the prevailing theories had just been overturned.

- This was the turning point. If molecules as complex as water and ammonia could be found interstellar space, what else was out there?

Molecular Clouds

- In the late 1960s and throughout the 1970s, radio telescopes designed for completely different purposes were turned to interstellar molecular spectroscopy. In 1969, interstellar formaldehyde was discovered using the 140-foot telescope in Green Bank.

- In 1970, interstellar carbon monoxide (CO) was discovered by Arno Penzias and Robert Wilson, who won the Nobel Prize for their discovery of the big bang radiation. This gas is deadly on Earth but a treasure in space. It changed our understanding of star formation.



- Penzias and Wilson detected emission from the lowest rotational state of CO. This rotational transition produces an emission line at 115 gigahertz, a wavelength of 2.6 millimeters. It's become an extremely important tool in studying star formation.

- CO is important because it's a rugged molecule that can survive in a range of interstellar densities. We see it pretty much wherever there are dust clouds. CO emission is also fairly bright and easy to detect.

- There's another advantage. Because the CO emission is at a short wavelength and the beam size of a telescope goes as wavelength over diameter, you get good angular resolution on CO with even relatively small dishes. And as a spectral line, its Doppler shift carries information on the gas velocity.

- As astronomers began to grapple with interstellar molecules, they found a new world opening up. There were molecules everywhere, especially OH and CO. CO remains the primary measure of molecular cloud mass throughout most of the Milky Way.

- Before the detection of all these molecules, astronomers called dark clouds "dark clouds" because they blocked starlight. But by 1970, these objects had picked up a new name: molecular clouds, because the gas inside them was predominantly in molecular form, not broken into individual atoms.

- In H II regions, where the ultraviolet radiation is strong, we measure ionized hydrogen. In the general interstellar medium, where the radiation field is weaker but still strong enough to break molecular bonds, we measure atoms—the 21-centimeter line from neutral atomic hydrogen. And in molecular clouds, we measure carbon and oxygen. What happened to the hydrogen?

- In molecular clouds, the dominant matter is still hydrogen, and it's in molecular form. Two hydrogen atoms make molecular hydrogen. But molecular hydrogen does not have any quantum states that emit or absorb at radio wavelengths. There are some states in the infrared and ultraviolet, but these are of limited use for most molecular clouds, so we're basically blind to molecular hydrogen in dark clouds.

- Instead of molecular hydrogen, we have surrogates: OH, CO, ammonia, water, formaldehyde, and other molecules. This means that we are one step removed from tracing the mass in dark clouds. Although the other molecules give us lots of information about temperature, density, and chemical evolution in ways that signals from pure molecular hydrogen could not, it would be much simpler for us if molecular hydrogen had a transition in the radio like the 21-centimeter line of neutral hydrogen.

- Most molecular gas lies between us and the galactic center, and so do most regions of star formation. This suggests that it's mainly the amount of molecular gas that determines the amount of star formation.

Giant Molecular Clouds

- The fact that a modest-sized telescope could do world-class research at millimeter wavelengths was proved by a generation of telescopes run by small groups at university observatories. They made incredible strides in our understanding of star formation.

- What did this first generation of millimeter-wave radio telescopes tell us? With radio observations of CO, a new class of objects was discovered: giant molecular clouds. It's in giant molecular clouds that almost all of the star formation in the Milky Way occurs. They have masses from 100,000 to several million times the mass of the Sun. If you could turn a giant molecular cloud into stars, it would make more than 100,000 solar systems like ours.

- In addition to carbon monoxide, which helps us identify giant molecular clouds and their properties, there are other molecules with transitions at radio wavelengths that are sensitive to specific physical attributes of molecular clouds. Ammonia is a good diagnostic of temperature and density. Hydrogen cyanide picks out the densest gas. Silicon monoxide can be used to identify shocks.

- Star clusters form in giant molecular clouds, which are dense enough that they are held together by their own gravity. What keeps them from collapsing entirely? There must be a regulating mechanism that allows some star formation but on the whole keeps most of the cloud as gas.

- We have good ideas but lots of work to do. It's possible that giant molecular clouds are assembled from smaller clouds as they pass through the spiral arms of a galaxy. The giant clouds are then broken up by energy from the stars they've formed, and the clouds dissipate to reform once again 100 million years later in passage through another spiral arm.

Suggested Reading

Gordon, *Recollections of "Tucson Operations."*

Kellermann and Sheets, eds., *Serendipitous Discoveries in Radio Astronomy*.

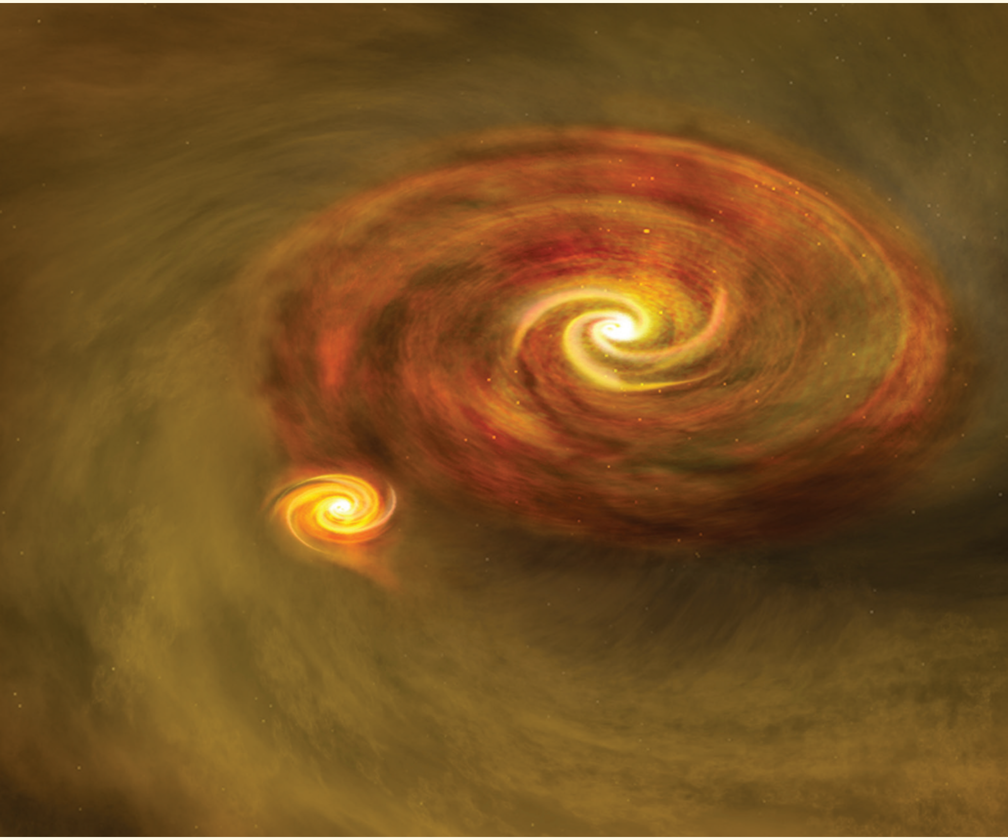
Verschuur, *The Invisible Universe*, chap. 7.

Questions to Consider

1. The dark molecular clouds in the Milky Way lie in a thin layer and are quite patchy compared to the neutral hydrogen layer. As a result, the sky above and below the plane of the Milky Way is relatively clear and we can see light from distant galaxies. There must be solar systems like ours that are embedded in dusty molecular clouds. How would the universe look to their astronomers?
2. Before astronomers understood that there was an interstellar medium, some suggested that dark clouds were real holes in the distribution of stars. What observation could show that this idea was incorrect?

LECTURE 22

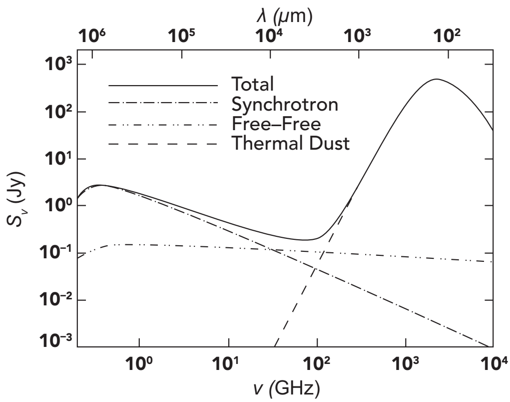
Star Formation and ALMA



New stars are forming in the Milky Way every year. To make progress in understanding star formation, we had to be able to measure molecular line emission from dark clouds. And to be able to measure the molecular line emission, we had to make major progress in several technical areas of radio science.

Working at Millimeter Wavelengths

- Synchrotron radiation from cosmic rays hitting magnetic fields, and from active galactic nuclei, is strongest at low frequencies and dominates the flux density of a spiral galaxy below a few gigahertz.



- At frequencies of a few tens of gigahertz, thermal emission begins to be important. This is free-free emission from interaction of electrons and protons in ionized gas in H II regions.

- At much higher frequencies, typically above 100 gigahertz, the dominant emission is thermal radiation from interstellar dust. This is basically blackbody emission described by a Planck function.

- Other objects that you've learned about fall in these 3 general categories. Pulsars and supernova remnants follow the general trend of nonthermal emission; the Moon and planets follow the emission from dust.

- The 21-centimeter line from neutral atomic hydrogen appears at 1.4 gigahertz, which was easily detectable with the equipment available in 1950. Interstellar hydroxyl, the next molecule to be detected, is rather close to the frequency of hydrogen. Its wavelength is 18 centimeters.

- Then came the radio recombination lines. These are scattered everywhere throughout the radio spectrum but were first detected and exploited in the 1 to 20 gigahertz range.

- Ammonia and water were detected in 1968 at around 20 gigahertz. Formaldehyde came next in 1969. The first formaldehyde transition to be discovered was around 5 gigahertz, which is a wavelength of 6 centimeters.

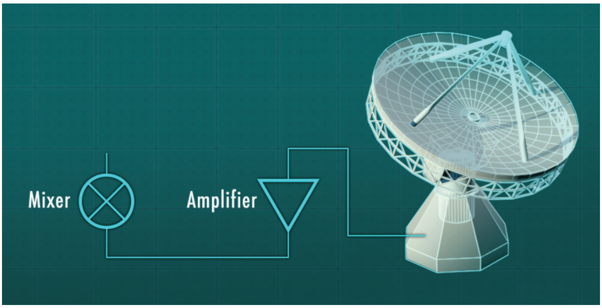
- During this era, several other molecules were detected through their radio emission. Carbon monoxide (CO) was detected in 1970 at a frequency of 115 gigahertz, or a wavelength of 2.6 millimeters. CO has many other transitions, all at higher frequencies.

- All of a sudden, the frequencies of interest jumped from those of ammonia and water, around 20 gigahertz, to 115 gigahertz, a factor of 5 higher. This created some technical problems.

- To focus the shorter wavelengths, a dish needs a very accurate surface. Spectral lines such as hydrogen, at a wavelength of 21 centimeters, are easily reflected and focused with rather crude surfaces. You can live with random surface deviations of a centimeter or so and still focus 21-centimeter waves. But dishes need to have much more accurate surfaces to focus millimeter waves.

- This affects telescope design profoundly. The telescope beam size, which tells us how clearly we can distinguish 2 nearby objects, is proportional to the wavelength divided by the dish diameter. Huge dishes, with a big diameter, aren't necessary to get good angular resolution at such small wavelengths.

- The push into millimeter wavelengths also challenged the limits of receiver technology. To make a long story short, at first there were no amplifiers.



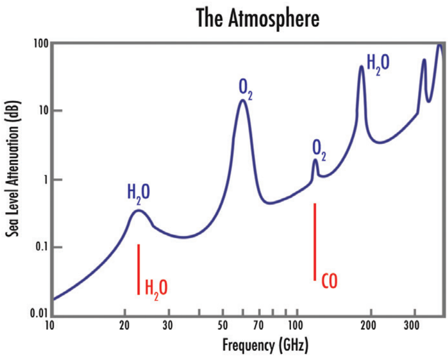
- Our fundamental radio-astronomical system consists of a dish that concentrates the incoming signals and converts them from an electromagnetic wave in free space into an electric current in a wire. This current then almost immediately goes through one or more amplifiers to boost the signal.

- Following amplification, the signal goes into a mixer, where it is converted to another frequency—usually a lower frequency—for further processing. This conversion is called the heterodyne process, or mixing, and the device that does it is called a mixer.

- Roughly, the higher the frequency, the more difficult it is to build amplifiers that actually amplify the signal without contributing excessive noise. Amplification at 100 megahertz is easy; amplification at 100 gigahertz is more difficult.

- Technology has caught up with the need for amplifiers at millimeter wavelengths, and they're now used at frequencies up to about 150 gigahertz—but not beyond that. At higher frequencies, the signal still goes straight into a mixer.

- Then there's the atmosphere. Less air means less absorption. At radio wavelengths, when something absorbs, it also emits noise. At frequencies below a few gigahertz, the atmosphere absorbs less than 1% of the incoming signal and, as a result, usually adds less than 3 kelvins to the system temperature; 3 kelvins is 1% of an atmosphere that has a temperature of 300 kelvins.



- But atmospheric attenuation changes with frequency because common substances, such as oxygen and water vapor, have quantum states that can absorb strongly at radio wavelengths.

- At millimeter wavelengths, you always have to deal with the atmosphere. Radio astronomers working at long wavelengths could use their telescopes 24/7, pretty much regardless of the weather. But once you begin working at the short centimeter and millimeter wavelengths, the weather will sometimes shut you down.

- There are other technical considerations that can make work at millimeter wavelengths difficult; in general, the bandwidths are large and the data rates are high.

The 36-Foot Telescope

- When Frank Drake and Frank Low, astronomers at Green Bank, convinced the observatory to build a 36-foot telescope that would work at millimeter wavelengths, it was placed near an existing optical observatory on Kitt Peak, a desert mountain southwest of Tucson, Arizona—high and dry.

- The 36-foot telescope was designed in the early 1960s to observe the planets and whatever else might be interesting at millimeter wavelengths. It didn't have the best surface and had rather large sidelobes from its gravitational and thermal distortions.

- Nonetheless, because the 36-foot telescope was there and accessible to scientists, it was used to discover the emission from CO in 1970 as well as dozens of other interstellar molecules. It pioneered the field of millimeter-wave spectroscopy.

- Modern millimeter-wave radio telescopes are better in every way than the old 36-foot telescope, but because it was in the right place at the right time, was available for use by any scientist, and had good enough performance, it made great discoveries. And those discoveries gave us the tools to begin to unravel the mysteries of star formation.

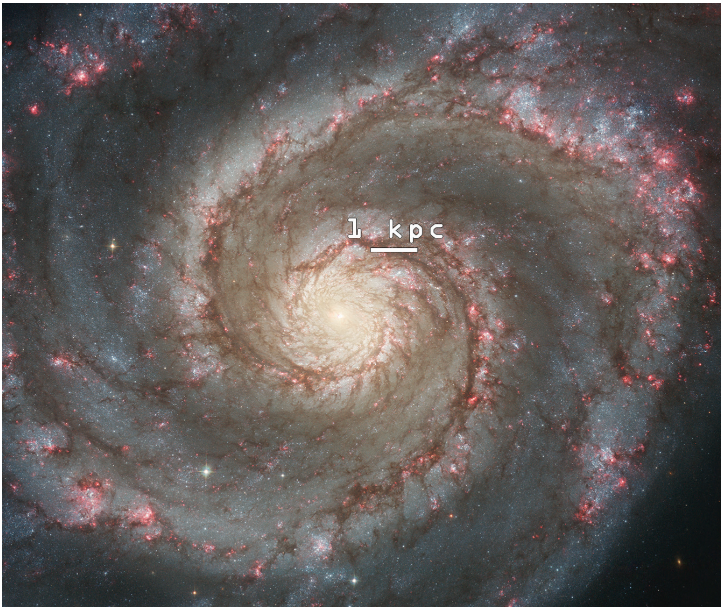
Star Formation

- Star formation is a tough problem. For one thing, it's pretty clear that there are environmental influences on star formation that operate on all size scales, from the galactic scale—10 to hundreds of kiloparsecs—to the scale of a solar system—a few thousandths of a parsec.

- This is a galaxy with beautiful spiral arms. It's called M51, or the Whirlpool Galaxy. It has dark dust lanes and H II regions. It also has a companion galaxy, which is the fuzzy blob off to the right. The passage of the small companion perturbed the bigger galaxy and probably produced the beautiful spiral pattern.

- This galaxy is only a third the size of the Milky Way, but its star-formation rate is higher. For its size, it's making more new stars each year than the Milky Way. The interaction with the companion created fairly intense spiral arms, and that boosted the overall star-formation rate. This is a great example of how something on the scale of an entire galaxy can affect star formation.

- Then there's the scale of the spiral arms of galaxies. Most new stars in galaxies like the Milky Way are formed from molecular clouds concentrated in spiral arms. Here, the relevant size scale is about a kiloparsec.



- Gas circulating around a spiral galaxy gets concentrated in the spiral arms. Giant molecular clouds are assembled, and they begin forming new stars. The new stars pop out downstream of the spiral arms.

- Within the spiral arms, star formation takes place in giant molecular clouds. The relevant length scale for giant molecular clouds is about 100 parsecs (a tenth of a kiloparsec) or less.

- Within giant molecular clouds, there are regions of enhanced density called cloud cores. These cores contain just a small percentage of the overall cloud mass, but it's in the cores that the action happens. The size scale of cores is about a parsec or less. The densest cores are most likely to be making new stars.

- The dust clouds in the galaxy M51 are stringy, not round. Part of this is the differential rotation of the galaxy. The inner parts go around more frequently than the outer parts. That tends to stretch structures into filaments.

- Then there's the spiral pattern. Gas flows into the spiral arms, and clouds collide and accumulate along the arc of the arms.

- Filaments can be produced in several ways. When gas clouds collide, they can form sheets, and when sheets collide, they form filaments.

- There are also theoretical reasons based on computer modeling of collapsing clouds for expecting gas clouds to preferentially collapse into filamentary shapes.

- It's only in the last few years that astronomers have realized the importance of filaments to star formation, and there's a tremendous amount that we don't understand. But within molecular cloud filaments, clumps form, and that begins the star-making process.

- Most of the gas in giant molecular clouds is moving supersonically, and this keeps the clouds stirred up. Turbulence is what keeps giant molecular clouds from collapsing entirely to make new stars. It's the regulator.

- But still, there are regions within giant molecular clouds where the turbulence must dissipate, where gas flows into filaments, and within the filaments, clumps form that can coalesce and collapse into stars and clusters of stars.

ALMA

- A number of radio interferometers have been designed to work at wavelengths in the millimeter range. For example, the Atacama Large Millimeter/submillimeter Array (ALMA) sits in the Atacama Desert of northern Chile and has more than 60 dishes. It's a joint project of Asian, European, and North American institutions. Early science operations began in 2014, and it's scheduled to be completed by 2020. It is already transforming our understanding of star formation.

- The observatory is located at an altitude of 5000 meters, which is more than 16,000 feet above sea level. It's high above much of the atmosphere in one of the driest locations on Earth. The core of the array consists of 54 dishes, each 12 meters in diameter, of 2 different designs. Like the Very Large Array, the location of the antennas can be reconfigured.

- Using ALMA, astronomers can measure spectral lines from molecules and thermal emission from dust with unprecedented sensitivity and angular resolution. ALMA has receivers covering the 3-millimeter band at 100 gigahertz all the way up to a frequency of 950 gigahertz, which is a wavelength of less than half a millimeter.

- ALMA is beginning to let us see new stars in the making. And just as exciting, we can also see young solar systems being made.

- A star forms when a gas clump collapses to densities so high and temperatures so hot—just from the heat of compressing gas—that nuclear reactions can begin at the core of the cloud. This is what makes a star.

- At the same time, the collapsing gas cloud settles into a rotating disk, and planets begin to condense out and grow. That's how the solar system and all of our planets were made.

- A lump of gas always has some rotation. It condenses out of a swirling, turbulent cloud, so it would be unbelievable if it had no residual rotation. When it begins to collapse under its own gravity, the rotation can support a disk, but it collapses fully at the poles. Finally, the densest part forms a star surrounded by a disk of dust and gas, which begins to form planets.

- For the first time, we're now able to see this in some detail in other systems and watch the process unfold. The initial results are stunning.

- Our understanding of star formation—which began with dark clouds and moved rapidly into giant molecular clouds and millimeter-wave radio astronomy—has now reached another plateau. Expect more discoveries every day.

Suggested Reading

Baars, *International Radio Telescope Projects*, chap. 6.

Verschuur, *The Invisible Universe*, chap. 7.

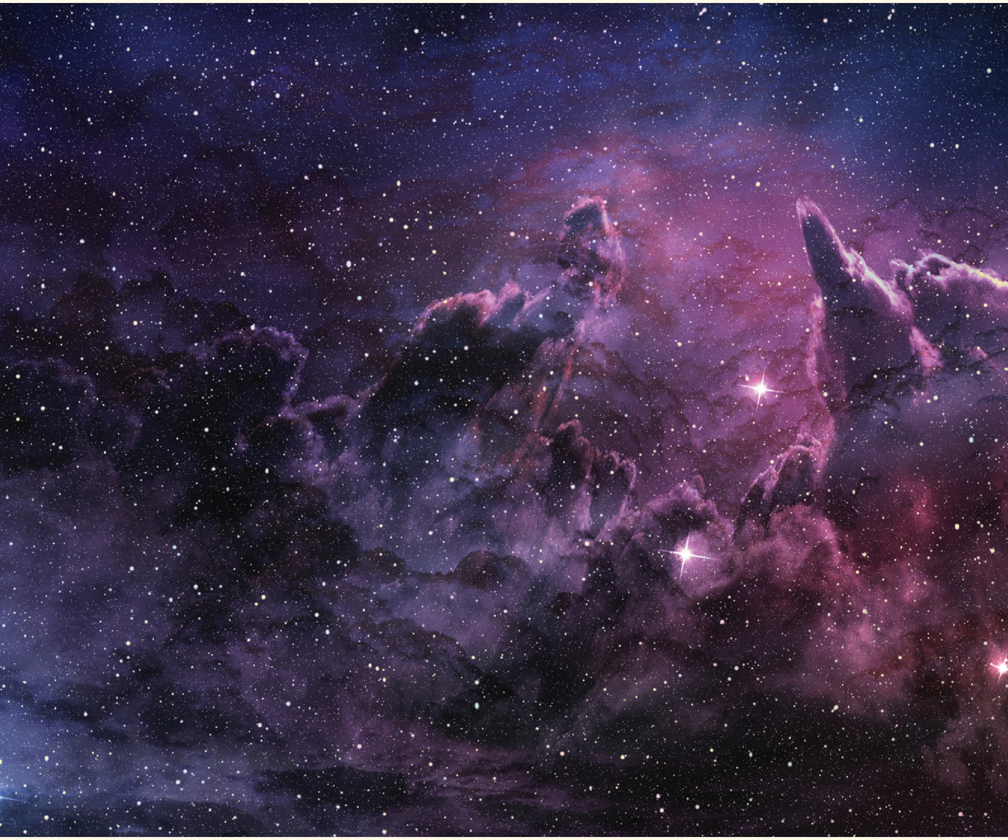
Wielebinski, Junkes, and Grahl, "The Effelsberg 100-m Radio Telescope."

Questions to Consider

1. Interstellar molecular clouds have a range of densities and sizes, and within clouds there can be quite a variety of structures in the gas. The internal structure of a cloud clearly has something to do with whether it forms one star or more. Can you think of ways that the structure of a cloud, or the way it forms stars, might produce the binary stars that are so common?
2. A star-forming cloud holds itself together by its own gravity, but when the stars light up, their radiation drives away the remaining gas. What might this do to the group of stars left behind? Remember that only a fraction of the cloud mass is turned into stars.

LECTURE 23

Interstellar Chemistry and Life



The past few lectures have gone from the scale of a galaxy to the scale of a star. This lecture will zoom in even further—to a star-forming region containing a protostar that has already begun disrupting its gas cloud and cloud cores that haven't yet made a star. This lecture will begin by examining the composition of a cloud core.

Interstellar Chemistry

- Imagine that a molecular cloud core would look like a dark cloud if we could see it. What would it contain? It would contain hydrogen, the most abundant element in the universe. It would have quite a bit of hydrogen, and it would also contain helium.

- But in the cold, dark interior of this cloud, there would be very little atomic hydrogen—nothing to give off the 21-centimeter line. All the atomic hydrogen would be bound up in molecular form as molecular hydrogen. So, we would have molecular hydrogen and neutral atomic helium.

- Helium is a noble gas. It doesn't like to form molecules. It remains as solitary atoms. There's no interstellar chemistry involving helium, so although it's plentiful, it's basically uninteresting.

- Neither molecular hydrogen nor atomic helium gives off radio emission, so we have to measure them at other wavelengths, such as the infrared or optical.

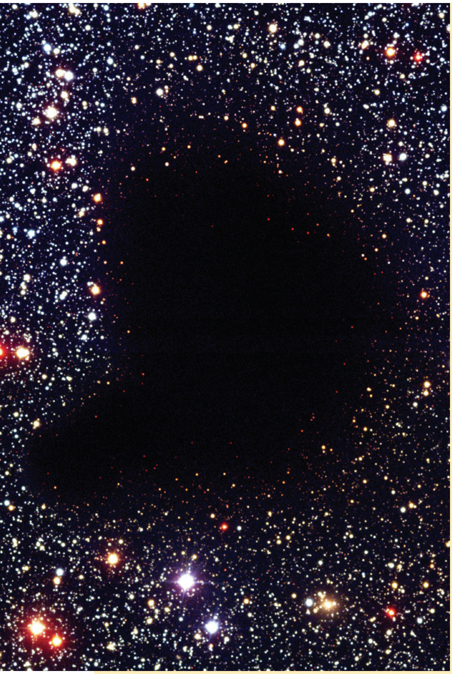
- Considering that helium does not form molecules, hydrogen will play a big part in interstellar chemistry.

- Next, we'd find some simple molecules. They're the result of chemistry in interstellar space. Chemistry is the scientific field that studies the properties of atoms as they interact with each other to form molecules and the interaction between molecules.

- To our list, we add hydroxyl (OH) and carbon monoxide (CO), simple molecules with 2 atoms. Both are widespread in the dusty regions of the interstellar medium. They're formed from the more abundant atoms: hydrogen, oxygen, and carbon.

- Now to more complex molecules, all detected by their radio spectral lines. Water in interstellar space is often locked up in grains, but in the vapor form, it can produce powerful radio lines. Formaldehyde is also fairly common, about as common as OH and CO. Ammonia is found in dense star-forming regions.

- And onward to more complex molecules. The next 8 molecules have from 5 to 10 atoms.



H	Hydrogen (atomic)
H_2	Hydrogen (molecular)
He	Helium
OH	Hydroxyl
CO	Carbon monoxide
H_2O	Water
H_2CO	Formaldehyde
NH_3	Ammonia
$HCOOH$	Formic acid
CH_3OH	Methanol
CH_2CHCN	Vinyl cyanide
$HOCH_2CH_2OH$	Ethylene glycol
CH_3CO_2H	Acetic acid
CH_3CH_2OH	Ethyl alcohol
CH_2OHCHO	Glycolaldehyde
C_6H^-	

1. Formic acid is the substance that causes stinging nettles to sting. It's also found in certain insects and in ants.
2. Methanol, also known as methyl alcohol or wood alcohol, is highly toxic when ingested.
3. Another toxic substance in interstellar space is vinyl cyanide. When it burns, it makes cyanide gas.
4. Ethylene glycol is the key ingredient in automobile antifreeze. It's sweet tasting but toxic.
5. Acetic acid diluted 10 to 1 with water makes vinegar. It tastes sour, but it's not deadly.
6. Ethyl alcohol is the alcohol that's found in beer, wine, and whiskey.
7. Glycolaldehyde is a molecule related to sugar.
8. C_6H^- is a linear molecule with 6 carbons in a row and a hydrogen at the end with an extra electron. But it's nearly pure carbon.

- Interstellar chemistry is dominated by the carbon chemical bond. The chemical processes in interstellar clouds favor formation of carbon-based molecules over any other kind. The result is a profusion of chemicals similar to those that occur naturally on Earth.

- Historically, these chemical compounds have been called organic because they've long been associated with life. Some scientists have speculated that silicon atoms might be the basis for a complex chemistry and even some kind of life. But although silicon forms many molecules with interesting structures, no atom can match the complexity and diversity of carbon-based compounds.

- Interstellar chemistry is now a vital branch of astronomical studies. New molecules are being discovered regularly through their radio spectral lines. It's often very difficult to predict the radio frequencies of some of the more complex molecules, but work is underway in laboratories around the world. We're regularly discovering more and more complex molecules. The count is now nearing 200.

The 3 Branches of Interstellar Molecular Studies

- The study of interstellar molecules in space has 3 main branches. The first branch is occupied by people who call themselves chemists, or astrochemists. They are interested in chemistry in space and what it can tell us about the nature of the chemical bond.

- Chemistry on Earth is dominated by reactions in liquids, but in interstellar space, there are no liquids. The pressure is too low; liquids would boil away.

- Chemistry in space takes place in gas at extremely low temperatures—just 10° to 100° above absolute zero. And it occurs at extremely low densities by terrestrial standards, with a little bit of ionization from cosmic rays thrown in to boot.

- In interstellar space, a molecule may wander about for an entire day before it collides with another molecule. The chemical reactions can also take, for example, 100,000 years to reach equilibrium. There is quite a number of possible reactions.

- There's also a significant amount of interstellar chemistry that occurs on the surface of interstellar dust. In fact, the very basic reaction of putting 2 hydrogen atoms together to make molecular hydrogen appears to be impossible except on the surface of a dust grain. The grain acts as a catalyst. Larger organic molecules may require grain chemistry as well.

- Astrochemistry is an exciting field of science. It's giving new insights into fundamental chemical processes.

- The second group of scientists who are interested in radio emission from interstellar molecules use the molecules to get information about something else. For example, molecules can be used to trace the distribution of star-forming clouds in the Milky Way.

- For this group of astronomers, molecular lines are tools, and depending on the job of interest, they choose one tool or another. The simplest interstellar molecules, such as OH and CO, are very good at locating cool, dusty clouds. More complex molecules are found only in the densest regions.

- There's a new tool in molecular astronomy that we may be close to discovering. And if we get it, it will revolutionize our ability to understand star formation. It all rests on the fact that interstellar chemistry is a dynamic process—specifically, the chemical structure of molecular clouds changes with time.

- The new astronomical tool is called a chemical clock, and it would enable us to look at a cloud and tell its age. With this tool, we might be able to know where the cloud was formed and maybe how close it is to making stars.

- Today, we're taking our first steps in this direction. And it might not work. Interstellar conditions may be so variable that a cloud can't evolve chemically for 100,000 years without being hit by a shock wave or a blast of ultraviolet photons that changes the environmental conditions totally. But this technique might be useful in some clouds, at least some of the time.

- The third branch of interstellar molecular studies is populated by scientists who stare at the table of organic molecules and wonder about how life on Earth began. We know that the Earth was formed in a dusty disk around the Sun. And the disk was probably full of molecules dominated by the carbon atom—organic molecules.

- The simple sugar glycolaldehyde has been detected in interstellar space. There are certainly even more complex molecules waiting to be discovered. Perhaps they were present in the protoplanetary disk. Perhaps they were amino acids. Amino acids are the building blocks of proteins. There have been searches for the radio emission from a simple interstellar amino acid, but it has not been detected yet.

- How high does the interstellar molecular complexity go—proteins, or perhaps interstellar DNA?

- The discovery that there was a rich chemistry in the star-forming regions of the Milky Way, and that the chemistry was organic, has profound implications.

- If planets are formed in this rich soup of organic molecules, then perhaps life does not have to start from scratch on each planet. We could think of the planets as they form being seeded by organic molecules from space, or after they are formed being seeded by comets crashing into the baby Earth carrying a cargo of organic molecules.

- Life on Earth could have gotten a considerable head start with the help of the interstellar molecules formed over millions of years in a molecular cloud.

- But it's an enormous jump to go from interstellar grains to the lump of rock that we call Earth. And there's an enormous gap between interstellar glycolaldehyde and biological life.

- Astronomers are working on the question of life from both ends. From the molecular end, they're looking at certain peculiarities of biological chemistry and asking if there is an interstellar connection. From the other end, they're looking for evidence of extraterrestrial civilizations.

Suggested Reading

Drake and Sobel, *Is Anyone Out There?*

Ekers, Cullers, Billingham, and Scheffer, eds., *SETI 2020.*

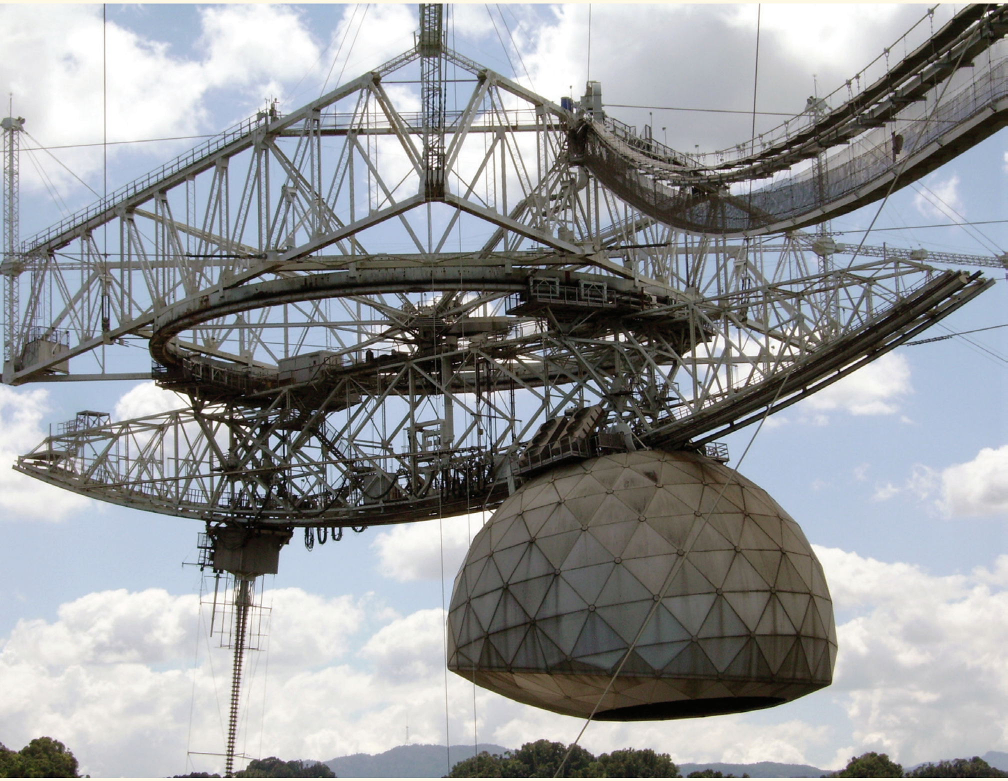
Verschuur, *The Invisible Universe*, chap. 7.

Questions to Consider

1. Chemistry laboratories on Earth work mostly at the pressure and temperature of our atmosphere. What might we be able to learn about basic chemistry from the interstellar medium?
2. What would be the prime conditions on a planet that could encourage the development of life? What kinds of intelligent life might not be interested in communicating by radio?
3. We've discussed how a pulse from a pulsar, which is emitted at all frequencies instantaneously, arrives first on Earth at higher frequencies and then later at lower frequencies because of dispersion by interstellar electrons. Does this phenomenon have any implications for our ability to communicate over interstellar distances?

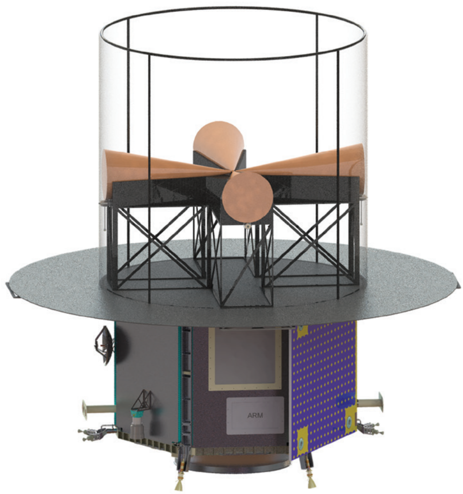
LECTURE 24

The Future of Radio Astronomy



There are big questions that radio astronomy can help us answer: How and when were galaxies assembled? How do we get stars and planets from a molecular cloud? Is there a limit to the complexity of interstellar organic chemistry? Did life begin in space? What is dark matter? How does gravity work? This final lecture is about the future of radio astronomy. You will discover new radio telescopes and research areas that are unfolding.

Radio Telescopes in Space



- There is a proposal to send a small radio telescope into orbit around the Moon to make radio observations using the Moon as a shield. The project is the Dark Ages Radio Explorer (DARE). It would operate in the 40 to 120 megahertz range, looking for signals from extremely redshifted hydrogen—hydrogen heated by the first generation of stars that were formed in the universe, just a few hundred million years after the big bang. DARE would only be used when it was behind the Moon. It's just an idea for now, but it may be funded in a few years.

- One reason to send a radio telescope into space is to get really long baselines for very long baseline interferometry (VLBI). The angular resolution of an interferometer is determined by the baseline length, and going into space can give baselines longer than you could ever achieve on Earth.

- The first radio telescope designed for space VLBI was a Japanese mission called HALCA, which was launched in the late 1990s. It was an 8-meter-diameter dish that worked in 2 bands, at 1.6 gigahertz and 5 gigahertz. It was in operation from 1997 to 2003. Its orbit was highly elliptical, ranging from about 500 kilometers to more than 21,000 kilometers from Earth. In combination with large dishes on the ground, HALCA observed maser emission from the hydroxyl molecule and studied the structure of quasars.

- The follow-up to HALCA has been a Russian radio telescope called RadioAstron, which was launched in 2011 on an orbit that takes it from about 10,000 kilometers above the Earth to almost the distance of the Moon, about 350,000 kilometers. RadioAstron is doing VLBI and has shattered the limit of the Earth's diameter. The dish has a novel design: It was folded up to fit atop the rocket and then unfolded like a flower once it got to space.

- RadioAstron works as one element of an interferometer with ground-based telescopes. Its scientific program includes studies of active galactic nuclei and pulsars at extremely high angular resolution.

- But RadioAstron also illustrates the current limits of space. This is a major scientific instrument, but the dish is only 10 meters across.

That's quite small for a modern radio telescope, yet RadioAstron is the largest telescope of any kind now in space.

- It's expensive to put a large object into space. A telescope in space does not have to fight the forces of gravity or deal with wind and rain, but that's not nearly compensation enough for the cost of lift-off and operations, or for hardening it against the harsh space environment, with its cosmic rays, solar flares, and extremes of temperature.

- The only way that RadioAstron, with its 10-meter dish, or HALCA before it, could get significant science done is in combination with very large ground-based radio telescopes such as the Green Bank Telescope and Arecibo. They supply most of the signal.

- The ultimate solution to terrestrial interference is a radio observatory on the far side of the Moon. There have been discussions about the location and operations of such an observatory, but anything concrete is quite a number of years away.

Radio Telescopes on Earth

- Meanwhile, on Earth, new radio telescopes are being planned and built. We're entering a new era in high-frequency radio astronomy—wavelengths of millimeters or less. This research is being transformed daily by a new telescope, the Atacama Large Millimeter/submillimeter Array (ALMA), which has already produced mind-boggling results on star formation and planet formation.


ALMA

- Another telescope that is just beginning observations at millimeter wavelengths is called the Large Millimeter Telescope (LMT), a 50-meter-diameter dish that is a joint project of the Mexican National Institute of Astrophysics, Optics, and Electronics and the University of Massachusetts.

- NOEMA, an expansion of an existing millimeter-wave array in France, is a joint French-German partnership.

NOEMA

- In China, the dust is just settling on construction of what will be the largest radio telescope in the world when it begins operations. It's called the Five-Hundred-Meter Aperture Spherical Telescope (FAST). Like Arecibo, it's built in a limestone sinkhole and its surface is spherical and attached to cables, but FAST is much bigger. FAST will be fantastic for studying the 21-centimeter hydrogen line and pulsars. It will mark China as a major world power in radio astronomy.

- In western Canada, another radio telescope is slated to begin observations soon. It's called CHIME. This telescope, located outside Penticton in British Columbia, has a set of fixed cylindrical parabolas that can observe the same part of the sky over and over, day after day. It's designed to measure faint, highly redshifted 21-centimeter line emission but will also be used for studies of pulsars and fast radio bursts.

- Another radio telescope—long in the planning—is finally getting off the ground. More than 20 years ago, a group of scientists had an idea for a really big radio telescope. Its collecting area would be 1 square kilometer. That kind of area can't be achieved with a monolithic structure. It would be an array—maybe several arrays.

- Thus, the Square Kilometre Array (SKA) project was born. The SKA is an international collaboration involving partners from the Netherlands, Great Britain, China, Italy, India, Canada, Australia, South Africa, and others, though not the United States. The SKA will consist of several sets of telescopes. The design is still being decided, but it will be located at 2 sites: one in western Australia and one in a desert region of South Africa. At both locations, there are precursor arrays under construction.

- At first, the SKA will work only at frequencies below a few gigahertz, but there are plans for eventual expansion to higher frequencies. Key science projects for the SKA include detection of hydrogen from extremely distant galaxies and understanding cosmic magnetism. If the plan comes to fruition, it will be the world's largest radio telescope by far. It will also be wonderful for studying pulsars.

The Search for Life on Other Planets

- On Earth, we produce a lot of radio noise—a lot of radio emission. If there's intelligent life on planets around other stars, they might be just as noisy. Perhaps we could eavesdrop.

- There are currently programs on several radio telescopes to systematically search for radio emissions from extraterrestrial intelligent beings. These searches will certainly continue in the future, despite the fact that it's almost impossible to guess their chances of success.

- We know that there are more planets in the Milky Way than stars. And most of them are billions of years older than Earth. If life were common, then almost everyone else has a billion-year head start. Where are they?

- Maybe they were wiped out by a supernova, which could sterilize all the planets in a large volume. Supernovas were much more common billions of years ago, when most of the stars in the Milky Way were formed. So, maybe it's only relatively recently that our neighborhood has been calm enough to permit life to develop to the point of inventing radios.

- In another few generations, we may have learned enough to be able to predict when the Earth might be in danger from the hijinks of our surroundings, such as supernovas, gamma-ray bursts, and fast radio bursts. We might even be able to engineer a shield to protect us, given enough warning.

- Maybe conditions for sustaining advanced life in the Milky Way weren't good until fairly recently—on a galactic scale. Maybe everyone else had a head start of only a few hundred million years, not a few billion.

- There are other hazards. Radio astronomers are involved in discovering all of the rocks that might threaten Earth. For this purpose, the Green Bank Telescope is used as the receiving element for transmitters from NASA's Goldstone facility in California and the Arecibo observatory. The goal is to learn enough about the shape and size of asteroids to predict their orbit.

- If a large asteroid hit Earth, it could easily reset the clock of civilization. So, maybe intelligent life has to progress to the point where it can do a little space engineering and avoid being snuffed out by explosions and falling rocks. Only then might it be able to send signals into space for a sustained time.

- And there are numerous problems that we're bringing on ourselves in maintaining the quality of our own planet's environment. We have to start turning that around right now.

- The bottom line is that we probably need at least another hundred years of progress before we can be sure that we humans have arrived on the galactic scene as a sustainable intelligent species with something to say to the neighbors.

The Future of Scientific Research

- As we make progress in understanding the universe and how to make life on Earth thrive in the universe, we're also making progress in democratizing scientific research.

- In recent years, there has been a major shift in the attitude of the scientific community, particularly in radio astronomy, toward the nature of scientific research.

- You don't have to have a Ph.D. to do quality scientific research. Of course, there are problems in the field of radio astronomy that require lots of education, skill, and training in physics and math at the highest levels, but there are research areas where the main attributes for success are a clear head, persistence, focus, and curiosity.

- In modern times, there are many programs—such as the Pulsar Search Collaboratory, a joint project between West Virginia University and the Green Bank Observatory—that give undergraduates and even high school students a true research experience.

- About 200 years ago, astronomical research was largely the domain of wealthy amateurs or institutions, and even today, most of the large optical telescopes available to U.S. astronomers are owned by consortia of a few institutions. Access is limited.

- The big U.S. radio telescopes, however, are publicly owned and are available without charge for use by any qualified scientist. The best ideas compete for access. This merit-based system opens up use of world-class facilities to all scientists and not just those at the wealthy institutions.

Suggested Reading

Ekers, Cullers, Billingham, and Scheffer, eds., *SETI 2020*.

Graham-Smith, *Unseen Cosmos*, chap. 11.

Plait, *Death from the Skies*.

Verschuur, *The Invisible Universe*, chap. 15.

Questions to Consider

1. One completely plausible explanation for the absence of evidence of other intelligent civilizations in the Milky Way is that civilizations reach a point at which they turn inward rather than reach out to the stars. The emperor of China in the early 1400s created an enormous fleet of ships that sailed from China all the way to East Africa, exploring and exacting tribute. But his successor decommissioned the fleet and banned oceanic commerce, and that remained that country's policy for hundreds of years. It has been said that the invention of smartphones marks the beginning of humanity's turn inward. What do you think?
2. So far, fast radio bursts have not been detected at any other part of the electromagnetic spectrum except the radio. How might we design experiments to see if they emit at other wavelengths?
3. Planetary protection is a balance between the expense of guarding against unlikely events—for example, a large meteor impact—versus the catastrophic consequences of the event—no agriculture for 100 years. How should we decide to allocate resources to guard against these possibilities?

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