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Basics of Radio Astronomy
for the
Goldstone-Apple Valley
Radio Telescope

April 1998

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for the
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Prepared by

Diane Fisher Miller

Advanced Mission Operations Section

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Document Log

Basics of Radio Astronomy Learner's Workbook

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D-13835, Preliminary	3/3/97	Preliminary "Beta" release of document.
D-13835, Final	4/17/98	Final release of document. Adds discussions of superposition, interference, and diffraction in Chapter 4.

Preface

In a collaborative effort, the Science and Technology Center (in Apple Valley, California), the Apple Valley Unified School District, the Jet Propulsion Laboratory, and NASA have converted a 34-meter antenna at NASA's Deep Space Network's Goldstone Complex into a unique interactive research and teaching instrument available to classrooms throughout the United States, via the Internet. The Science and Technology Center is a branch of the Lewis Center for Educational Research.

The Goldstone-Apple Valley Radio Telescope (GAVRT) is located in a remote area of the Mojave Desert, 40 miles north of Barstow, California. The antenna, identified as DSS-12, is a 34-meter diameter dish, 11 times the diameter of a ten-foot microwave dish used for satellite television reception. DSS-12 has been used by NASA to communicate with robotic space probes for more than thirty years. In 1994, when NASA decided to decommission DSS-12 from its operational network, a group of professional scientists, educators, engineers, and several community volunteers envisioned a use for this antenna and began work on what has become the GAVRT Project.

The GAVRT Project is jointly managed by the Science and Technology Center and the DSN Science Office, Telecommunications and Mission Operations Directorate, at the Jet Propulsion Laboratory.

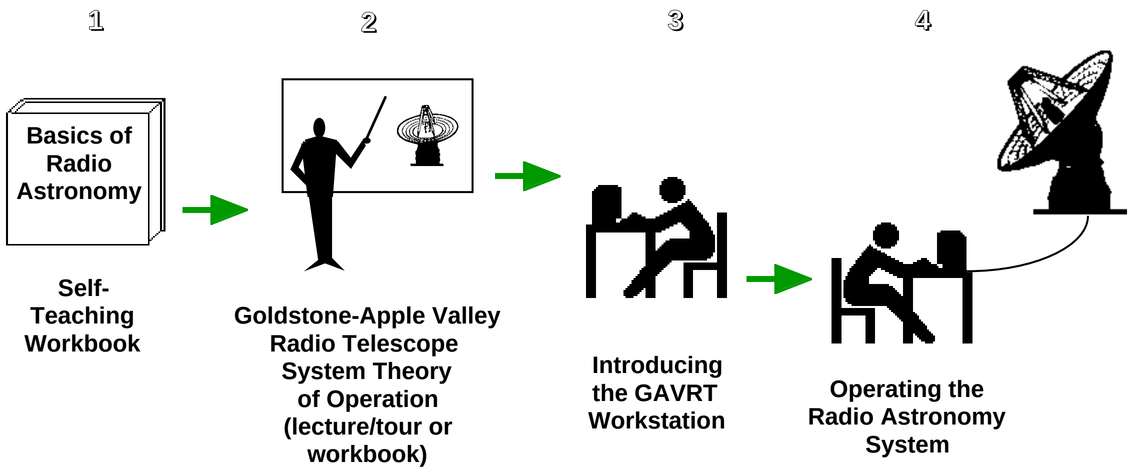
This workbook was developed as part of the training of teachers and volunteers who will be operating the telescope. The students plan observations and operate the telescope from the Apple Valley location using Sun workstations. In addition, students and teachers in potentially 10,000 classrooms across the country will be able to register with the center’s Web site and operate the telescope from their own classrooms.

Introduction

This module is the first in a sequence to prepare volunteers and teachers at the Apple Valley Science and Technology Center (AVSTC) to operate the Goldstone-Apple Valley Radio Telescope (GAVRT). It covers the basic science concepts that will not only be used in operating the telescope, but that will make the experience meaningful and provide a foundation for interpreting results.

The next module in the sequence introduces the GAVRT system itself. Following that is a hands-on introduction to the UNIX workstation to be used to operate the GAVRT, and finally instruction on the GAVRT software.

Steps in the GAVRT Operations Training Sequence



Acknowledgements

Many people contributed to this workbook. The first problem we faced was to decide which of the overwhelming number of astronomy topics we should cover and at what depth in order to prepare GAVRT operators for the radio astronomy projects they would likely be performing. George Stephan generated this initial list of topics, giving us a concrete foundation on which to begin to build. Thanks to the subject matter experts in radio astronomy, general astronomy, and physics who patiently reviewed the first several drafts and took time to explain some complex subjects in plain English for use in this workbook. These kind reviewers are Dr. M.J. Mahoney, Roger Linfield, David Doody, and Dr. Kevin Miller (who also loaned the project several most valuable books from his personal library). Special credit goes to Dr. Steve Levin, who took responsibility for making sure the topics covered were the right ones and that no known inaccuracies or ambiguities remained. Other reviewers who contributed suggestions for clarity and completeness were Ben Toyoshima, Steve Licata, Kevin Williams, and George Stephan.

Assumptions and Disclaimers

This training module assumes you have an understanding of high-school-level chemistry, physics, and algebra. It also assumes you have familiarity with or access to other materials on general astronomy concepts, since the focus here is on those aspects of astronomy that relate most specifically to radio astronomy.

This workbook does not purport to cover its selected topics in depth, but simply to introduce them and provide some context within the overall disciplines of astronomy in general and radio astronomy in particular. It does not cover radio telescope technology, nor details of radio astronomy data analysis.

Learning Strategy

As a participant, you study this workbook by yourself. It includes both learning materials and evaluation tools. The chapters are designed to be studied in the order presented, since some concepts developed in later chapters depend on concepts introduced in earlier ones. It doesn't matter how long it takes you to complete it. What is important is that you accomplish all the learning objectives.

The frequent “Recap” (for recapitulation) sections at the end of each short module will help you reinforce key points and evaluate your progress. They require you to fill in blanks. Please do so either mentally or jot your answers on paper. Answers from the text are shown at the bottom of each Recap. In addition, “For Further Study” boxes appear throughout this workbook suggesting references that expand on many of the topics introduced. See “References and Further Reading” on Page 85 for complete citations of these sources.

After you complete the workbook, you will be asked to complete a self-administered quiz (fill in the blanks) covering all the objectives of the learning module and then send it to the GAVRT Training Engineer. It is okay to refer to the workbook in completing the final quiz. A score of at least 90% is expected to indicate readiness for the next module in the GAVRT operations readiness training sequence.

Help with Abbreviations and Units of Measure

This workbook uses standard abbreviations for units of measure. Units of measure are listed below. Refer to the Glossary in Appendix A for further help. As is the case when you are studying any subject, you should also have a good English dictionary at hand.

k	(with a unit of measure) kilo (10^3, or thousand)
M	(with a unit of measure) Mega (10^6, or million)
G	(with a unit of measure) Giga (10^9, or billion; in countries using the metric system outside the USA, a billion is 10^{12}. Giga, however, is always 10^9.)
T	(with a unit of measure) Tera (10^{12}, or a million million)
P	(with a unit of measure) Peta (10^{15})
E	(with a unit of measure) Exa (10^{18})
Hz	Hertz
K	Kelvin
m	meter (USA spelling; elsewhere, metre)
nm	nanometer (10^{-9} meter)

Chapter 1

Overview: Discovering an Invisible Universe

Objectives: Upon completion of this chapter, you will be able to describe the general principles upon which radio telescopes work.

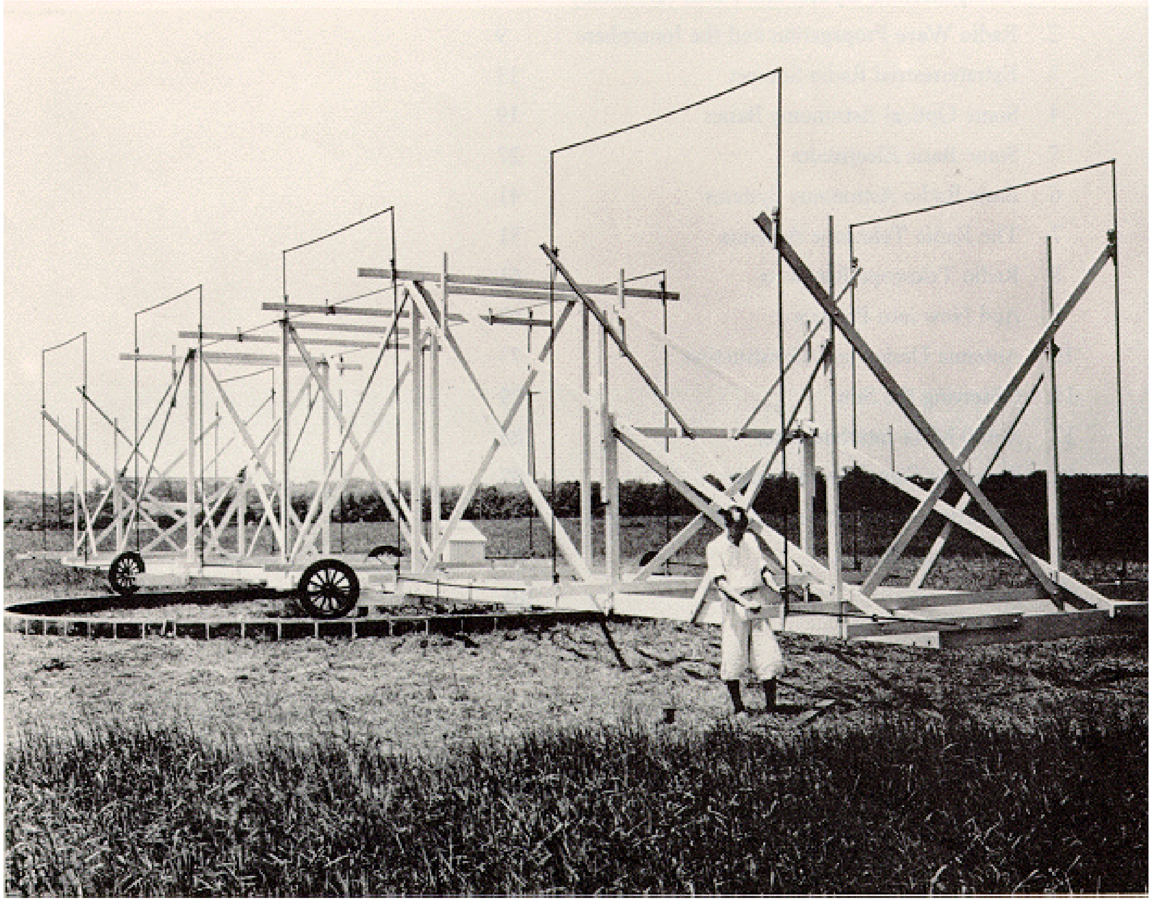
Before 1931, to study astronomy meant to study the objects visible in the night sky. Indeed, most people probably still think that's what astronomers do—wait until dark and look at the sky using their naked eyes, binoculars, and optical telescopes, small and large. Before 1931, we had no idea that there was any other way to observe the universe beyond our atmosphere.

In 1931, we did know about the electromagnetic spectrum. We knew that visible light included only a small range of wavelengths and frequencies of energy. We knew about wavelengths shorter than visible light—Wilhelm Röntgen had built a machine that produced x-rays in 1895. We knew of a range of wavelengths longer than visible light (infrared), which in some circumstances is felt as heat. We even knew about radio frequency (RF) radiation, and had been developing radio, television, and telephone technology since Heinrich Hertz first produced radio waves of a few centimeters long in 1888. But, in 1931, no one knew that RF radiation is also emitted by billions of extraterrestrial sources, nor that some of these frequencies pass through Earth's atmosphere right into our domain on the ground.

All we needed to detect this radiation was a new kind of "eyes."

Jansky's Experiment

As often happens in science, RF radiation from outer space was first discovered while someone was looking for something else. Karl G. Jansky (1905-1950) worked as a radio engineer at the Bell Telephone Laboratories in Holmdel, New Jersey. In 1931, he was assigned to study radio frequency interference from thunderstorms in order to help Bell design an antenna that would minimize static when beaming radio-telephone signals across the ocean. He built an awkward looking contraption that looked more like a wooden merry-go-round than like any modern-day antenna, much less a radio telescope. It was tuned to respond to radiation at a wavelength of 14.6 meters and rotated in a complete circle on old Ford tires every 20 minutes. The antenna was connected to a receiver and the antenna's output was recorded on a strip-chart recorder.



Jansky's Antenna that First Detected Extraterrestrial RF Radiation

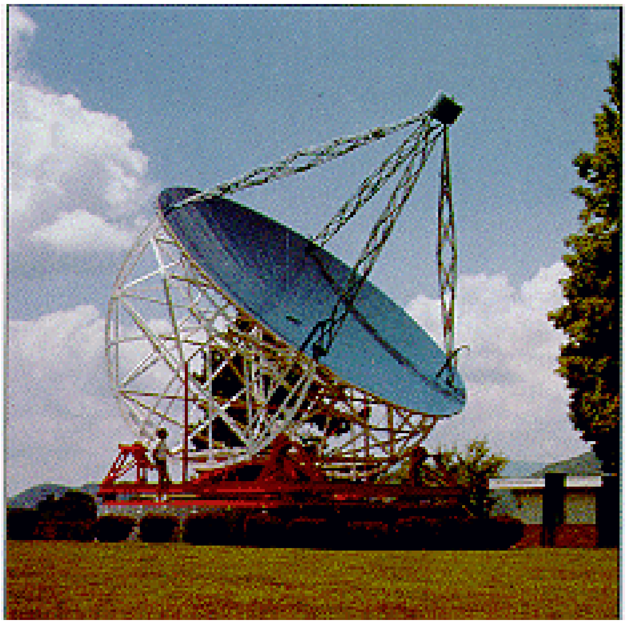
He was able to attribute some of the static (a term used by radio engineers for noise produced by unmodulated RF radiation) to thunderstorms nearby and some of it to thunderstorms farther away, but some of it he couldn't place. He called it " . . . a steady hiss type static of unknown origin."

As his antenna rotated, he found that the direction from which this unknown static originated changed gradually, going through almost a complete circle in 24 hours. No astronomer himself, it took him a while to surmise that the static must be of extraterrestrial origin, since it seemed to be correlated with the rotation of Earth.

He at first thought the source was the sun. However, he observed that the radiation peaked about 4 minutes earlier each day. He knew that Earth, in one complete orbit around the sun, necessarily makes one more revolution on its axis *with respect to the sun* than the approximately 365 revolutions Earth has made about its own axis. Thus, with respect to the stars, a year is actually one day longer than the number of sunrises or sunsets observed on Earth. So, the rotation period of Earth with respect to the stars (known to astronomers as a sidereal day) is about 4 minutes shorter than a solar day (the rotation period of Earth with respect to the sun). Jansky therefore concluded that the source of this radiation must be much farther away than the sun. With further investigation, he identified the source as the Milky Way and, in 1933, published his findings.

Reber’s Prototype Radio Telescope

Despite the implications of Jansky’s work, both on the design of radio receivers, as well as for radio astronomy, no one paid much attention at first. Then, in 1937, Grote Reber, another radio engineer, picked up on Jansky’s discoveries and built the prototype for the modern radio telescope in his back yard in Wheaton, Illinois. He started out looking for radiation at shorter wavelengths, thinking these wavelengths would be stronger and easier to detect. He didn’t have much luck, however, and ended up modifying his antenna to detect radiation at a wavelength of 1.87 meters (about the height of a human), where he found strong emissions along the plane of the Milky Way.



Reber’s Radio Telescope

Reber continued his investigations during the early 40s, and in 1944 published the first radio frequency sky maps. Up until the end of World War II, he was the lone radio astronomer in the world. Meanwhile, British radar operators during the war had detected radio emissions from the Sun. After the war, radio astronomy developed rapidly, and has become of vital importance in our observation and study of the universe.

So What’s a Radio Telescope?

RF waves that can penetrate Earth’s atmosphere range from wavelengths of a few millimeters to nearly 100 meters. Although these wavelengths have no discernable effect on the human eye or photographic plates, they do induce a very weak electric current in a conductor such as an antenna. Most radio telescope antennas are parabolic (dish-shaped) reflectors that can be pointed toward any part of the sky. They gather up the radiation and reflect it to a central focus, where the radiation is concentrated. The weak current at the focus can then be amplified by a radio receiver so it is strong enough to measure and record. See the discussion of Reflection in Chapter 4 for more about RF antennas.

Electronic filters in the receiver can be tuned to amplify one range (or “band”) of frequencies at a time. Or, using sophisticated data processing techniques, thousands of separate narrow frequency bands can be detected. Thus, we can find out what frequencies are present in the RF radiation and what their relative strengths are. As we will see later, the frequencies and their relative powers and polarization give us many clues about the RF sources we are studying.

The intensity (or strength) of RF energy reaching Earth is small compared with the radiation received in the visible range. Thus, a radio telescope must have a large “collecting area,” or antenna, in order to be useful. Using two or more radio telescopes together (called arraying) and combining the signals they simultaneously receive from the same source allows astronomers to discern more detail and thus more accurately pinpoint the source of the radiation. This ability depends on a technique called radio interferometry. When signals from two or more telescopes are properly combined, the telescopes can effectively act as small pieces of a single huge telescope.

A large array of telescopes designed specifically to operate as an array is the Very Large Array (VLA) near Socorro, New Mexico. Other radio observatories in geographically distant locations are designed as Very Long Baseline Interferometric (VLBI) stations and are arrayed in varying configurations to create very long baseline arrays (VLBA). NASA now has four VLBI tracking stations to support orbiting satellites that will extend the interferometry baselines beyond the diameter of Earth.

Since the GAVRT currently operates as a single aperture radio telescope, we will not further discuss interferometry here.

What’s the GAVRT?

The technical details about the GAVRT telescope will be presented in the GAVRT system course in the planned training sequence. However, here’s a thumbnail sketch.

GAVRT is a Cassegrain radio telescope (explained in Chapter 4) located at Goldstone, California, with an aperture of 34 meters and an hour-angle/declination mounting and tracking system (explained in Chapter 7). It has S-band and X-band solid-state, low-noise amplifiers and receivers. Previously part of the National Aeronautics and Space Administration’s (NASA’s) Deep Space Network (DSN), and known as Deep Space Station (DSS)-12, or “Echo,” it was originally built as a 26-meter antenna in 1960 to serve with NASA’s Echo project, an experiment that transmitted voice communications coast-to-coast by bouncing the signals off the surface of a passive balloon-type satellite. In 1979, its aperture was enlarged to 34 meters, and the height of its mounting was increased to accommodate the larger aperture. It has since provided crucial support to many deep-space missions, including Voyager in the outer solar system, Magellan at Venus, and others. In 1996, after retiring DSS-12 from the DSN, NASA turned it over to AVSTC (associated with the Apple Valley, California, School District) to operate as a radio telescope. AVSTC plans to make the telescope available over the internet to classrooms across the country for radio astronomy student observations. NASA still retains ownership, however, and responsibility for maintenance.

Recap

1. Because the static Jansky observed peaked 4 minutes earlier each day, he concluded that the source could NOT be ______ __________.
2. Radio frequency waves induce a _____________ in a conductor such as an antenna.
3. The proportion of RF energy received on Earth is __________ compared with the amount received in the visible range.
4. The GAVRT was formerly a part of NASA's ___________ __________ ________________ of antennas supporting planetary missions.

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1. the sun 2. current 3. small 4. Deep Space Network (DSN)

For Further Study

- *History and principles of radio telescopes*: Kaufmann, 114-116; Morrison et al., 165.
- *Radio Interferometry*: Morrison et al., 165.

Chapter 2

The Properties of Electromagnetic Radiation

Objectives: When you have completed this chapter, you will be able to define the term "electromagnetic spectrum," explain the relationship between frequency and wavelength, and give the relationship between energy received and distance from the source. You will be able to describe the limits of the "S-band" and "X-band" of the electromagnetic spectrum. You will be able to describe wave polarization.

What is Electromagnetic Radiation?

Field is a physics term for a region that is under the influence of some force that can act on matter within that region. For example, the Sun produces a gravitational field that attracts the planets in the solar system and thus influences their orbits.

Stationary electric charges produce electric fields, whereas moving electric charges produce both electric and magnetic fields. Regularly repeating changes in these fields produce what we call electromagnetic radiation. Electromagnetic radiation transports energy from point to point. This radiation propagates (moves) through space at 299,792 km per second (about 186,000 miles per second). That is, it travels at the speed of light. Indeed light is just one form of electromagnetic radiation.

Some other forms of electromagnetic radiation are X-rays, microwaves, infrared radiation, AM and FM radio waves, and ultraviolet radiation. The properties of electromagnetic radiation depend strongly on its frequency. Frequency is the rate at which the radiating electromagnetic field is oscillating. Frequencies of electromagnetic radiation are given in Hertz (Hz), named for Heinrich Hertz (1857-1894), the first person to generate radio waves. One Hertz is one cycle per second.

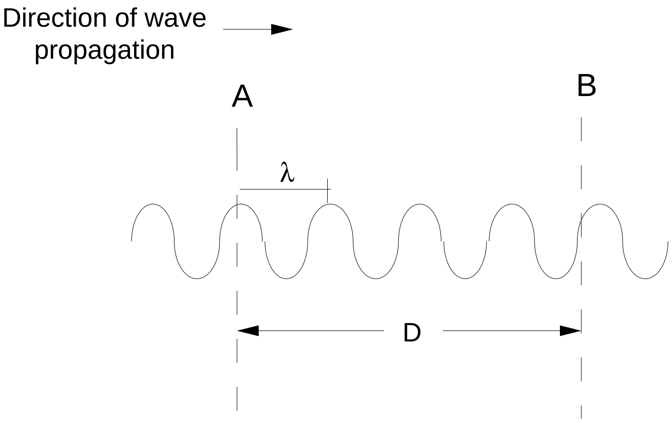
Frequency and Wavelength

As the radiation propagates at a given frequency, it has an associated wavelength— that is, the distance between successive crests or successive troughs. Wavelengths are generally given in meters (or some decimal fraction of a meter) or Angstroms (Å, 10^{-10} meter).

Since all electromagnetic radiation travels at the same speed (in a vacuum), the number of crests (or troughs) passing a given point in space in a given unit of time (say, one second), varies with the wavelength. For example, 10 waves of wavelength 10 meters will pass by a point in the same length of time it would take 1 wave of wavelength 100 meters. Since all forms of electromagnetic energy travel at the speed of light, the wavelength equals the speed of light divided by the frequency of oscillation (moving from crest to crest or trough to trough).

In the drawing below, electromagnetic waves are passing point B, moving to the right at the speed of light (usually represented as *c*, and given in km/sec). If we measure to the left of B a distance D equal to the distance light travels in one second (2.997 x 10^5 km), we arrive at point A along the wave train that will just pass point B after a period of 1 second (moving left to right). The frequency *f* of the wave train—that is, the number of waves between A and B—times the length of each, λ, equals the distance D traveled in one second.

Relationship of Wavelength and Frequency of Electromagnetic Waves



Since we talk about the frequency of electromagnetic radiation in terms of oscillations per second and the speed of light in terms of distance travelled per second, we can say

$$\textbf{Speed of light} = \textbf{Wavelength} \times \textbf{Frequency}$$

$$\textbf{Wavelength} = \frac{\textbf{Speed of light}}{\textbf{Frequency}}$$

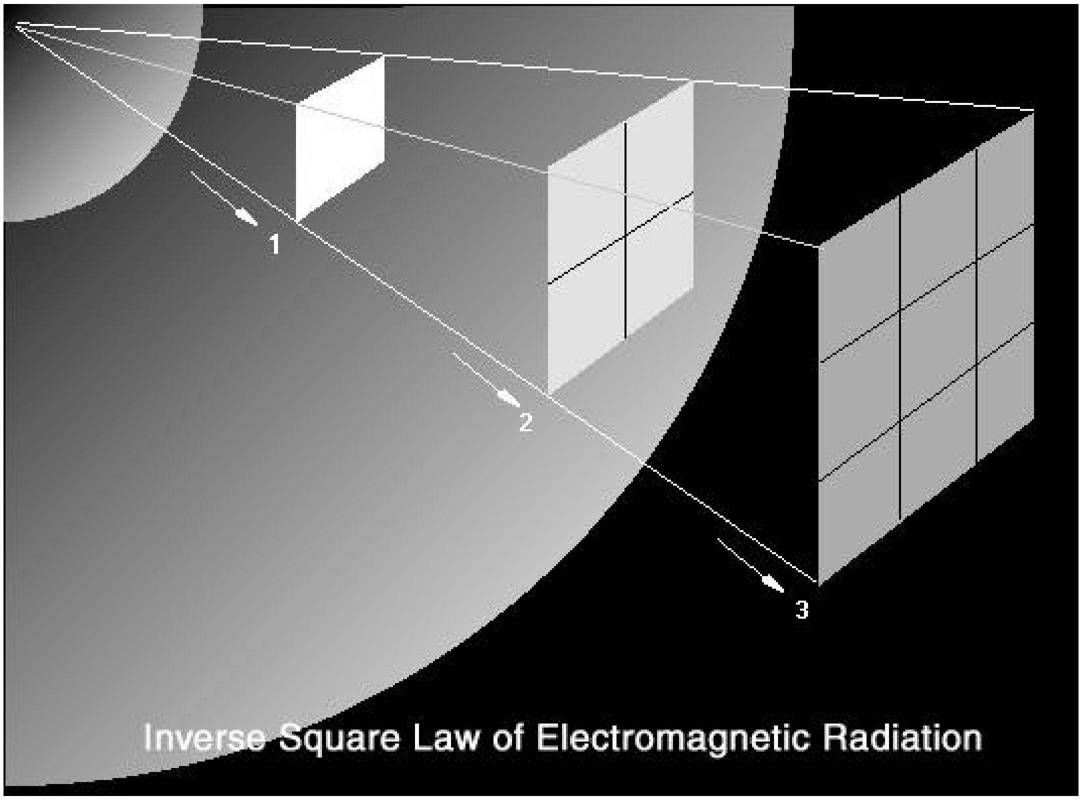
$$\textbf{Frequency} = \frac{\textbf{Speed of light}}{\textbf{Wavelength}}$$

or

$$c = \lambda f$$

Inverse-Square Law of Propagation

As electromagnetic radiation leaves its source, it spreads out, traveling in straight lines, as if it were covering the surface of an ever expanding sphere. This area increases proportionally to the square of the distance the radiation has traveled. In other words, the area of this expanding sphere is calculated as $4\pi R^2$, where R is the distance the radiation has travelled, that is, the radius of the expanding sphere. This relationship is known as the *inverse-square law* of (electromagnetic) propagation. It accounts for loss of signal strength over space, called space loss. For example, Saturn is approximately 10 times farther from the sun than is Earth. (Earth to sun distance is defined as one astronomical unit, AU). By the time the sun's radiation reaches Saturn, it is spread over 100 times the area it covers at one AU. Thus, Saturn receives only 1/100th the solar energy flux (that is, energy per unit area) that Earth receives.



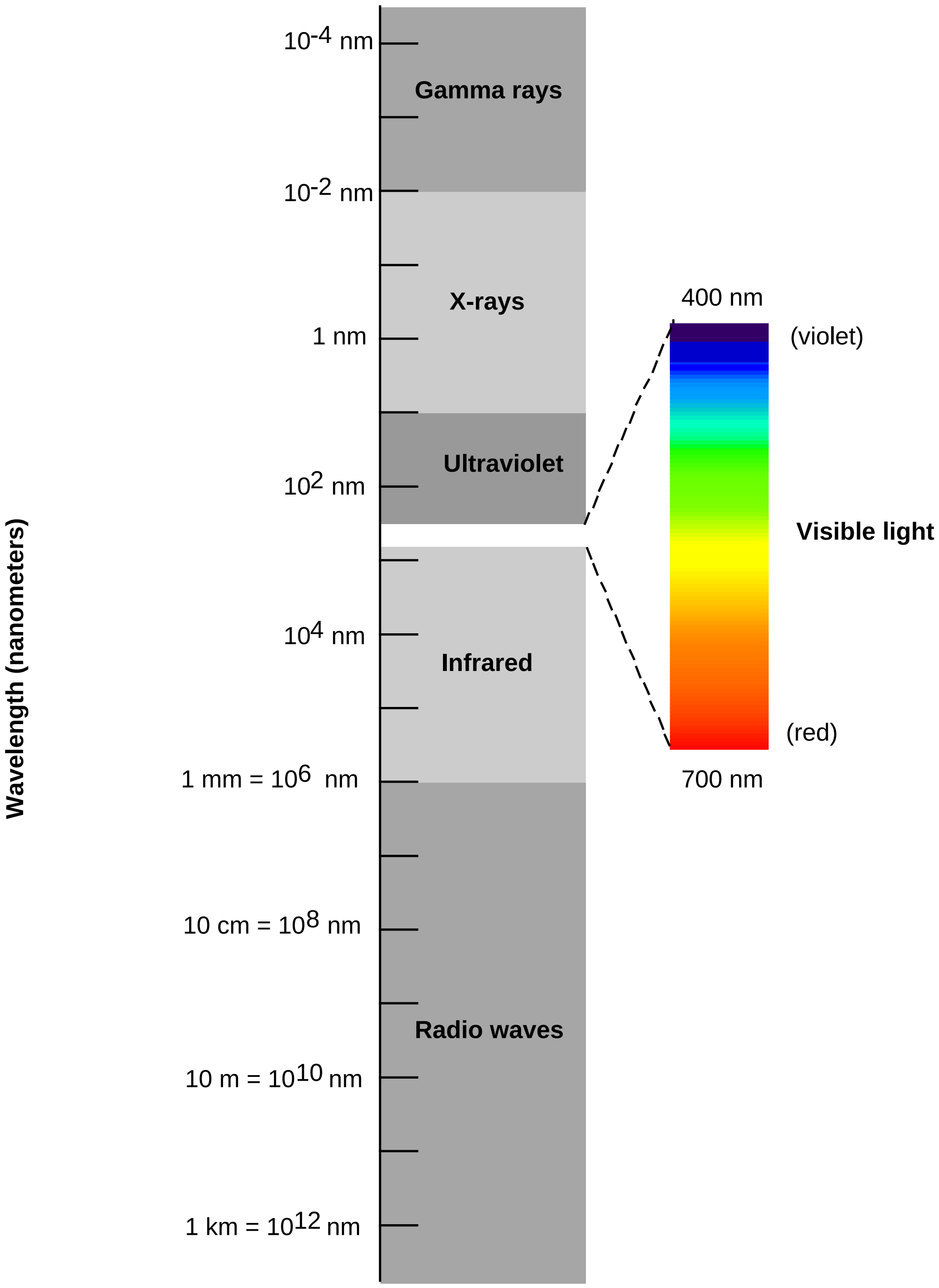
The inverse-square law is significant to the exploration of the universe. It means that the concentration of electromagnetic radiation decreases very rapidly with increasing distance from the emitter. Whether the emitter is a spacecraft with a low-power transmitter, an extremely powerful star, or a radio galaxy, because of the great distances and the small area that Earth covers on the huge imaginary sphere formed by the radius of the expanding energy, it will deliver only a small amount of energy to a detector on Earth.

The Electromagnetic Spectrum

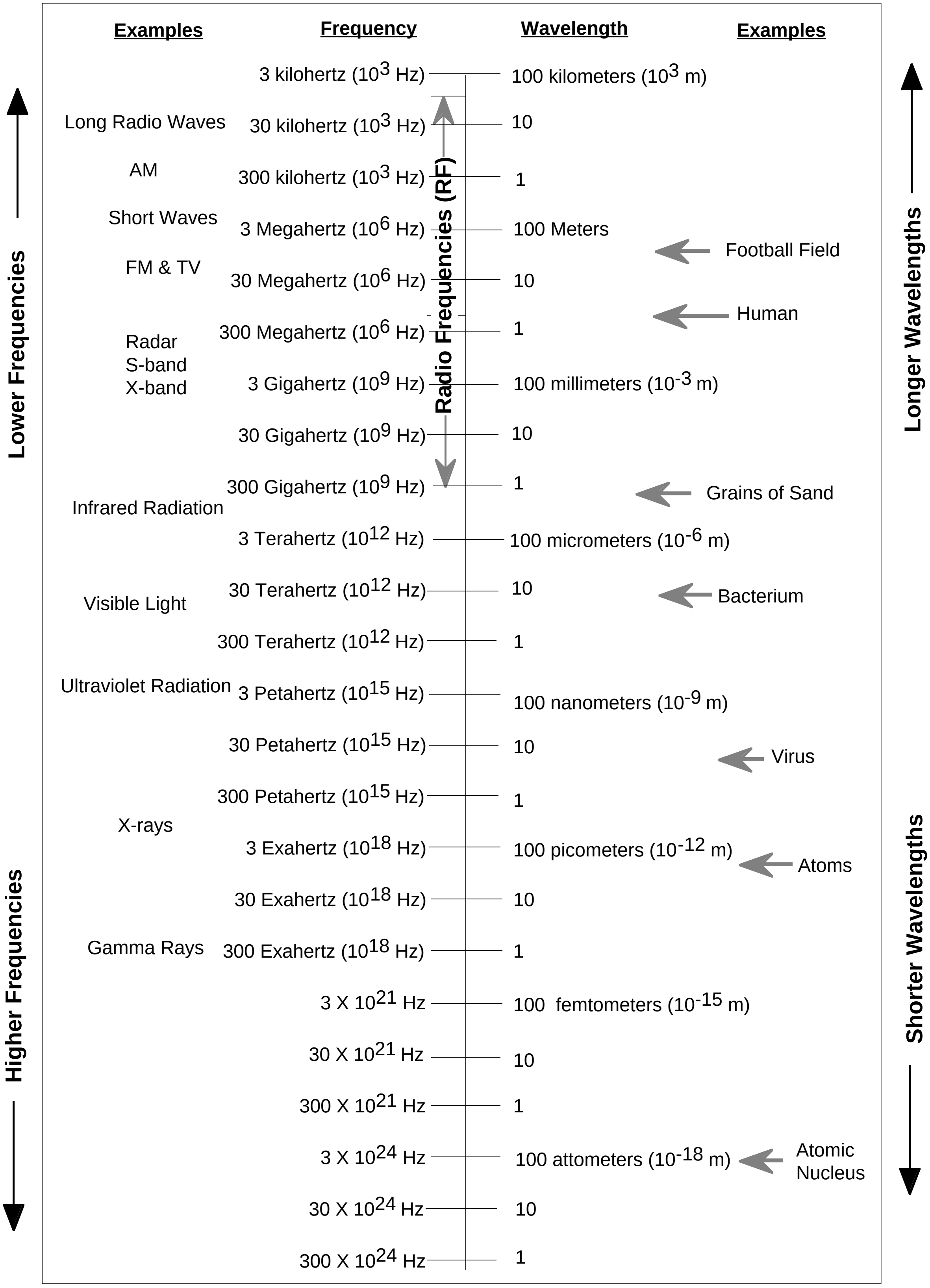
Light is electromagnetic radiation at those frequencies to which human eyes (and those of most other sighted species) happen to be sensitive. But the electromagnetic spectrum has no upper or lower limit of frequencies. It certainly has a much broader range of frequencies than the human eye can detect. In order of increasing frequency (and decreasing wavelength), the electromagnetic spectrum includes radio frequency (RF), infrared (IR, meaning “below red”), visible light, ultraviolet (UV, meaning “above violet”), X-rays, and gamma rays. These designations describe only different frequencies of the same phenomenon: electromagnetic radiation.

The frequencies shown in the following two diagrams are within range of those generated by common sources and observable using common detectors. Ranges such as microwaves, infrared, etc., overlap. They are categorized in spectrum charts by the artificial techniques we use to produce them.

Electromagnetic Spectrum: Visible light only a fraction of the spectrum



The Electromagnetic Spectrum: Wavelength/frequency chart



Examples	Frequency	Wavelength	Examples
	3 kilohertz (10^3 Hz)	100 kilometers (10^3 m)	
Long Radio Waves	30 kilohertz (10^3 Hz)	10	
AM	300 kilohertz (10^3 Hz)	1	
Short Waves	3 Megahertz (10^6 Hz)	100 Meters	Football Field
FM & TV	30 Megahertz (10^6 Hz)	10	
Radar S-band X-band	300 Megahertz (10^6 Hz)	1	Human
	3 Gigahertz (10^9 Hz)	100 millimeters (10^{-3} m)	
	30 Gigahertz (10^9 Hz)	10	
Infrared Radiation	300 Gigahertz (10^9 Hz)	1	Grains of Sand
	3 Terahertz (10^{12} Hz)	100 micrometers (10^{-6} m)	
Visible Light	30 Terahertz (10^{12} Hz)	10	Bacterium
	300 Terahertz (10^{12} Hz)	1	
Ultraviolet Radiation	3 Petahertz (10^{15} Hz)	100 nanometers (10^{-9} m)	
	30 Petahertz (10^{15} Hz)	10	Virus
	300 Petahertz (10^{15} Hz)	1	
X-rays	3 Exahertz (10^{18} Hz)	100 picometers (10^{-12} m)	Atoms
	30 Exahertz (10^{18} Hz)	10	
Gamma Rays	300 Exahertz (10^{18} Hz)	1	
	3 X 10^{21} Hz	100 femtometers (10^{-15} m)	
	30 X 10^{21} Hz	10	
	300 X 10^{21} Hz	1	
	3 X 10^{24} Hz	100 attometers (10^{-18} m)	Atomic Nucleus
	30 X 10^{24} Hz	10	
	300 X 10^{24} Hz	1	

Electromagnetic radiation with frequencies between about 5 kHz and 300 GHz is referred to as radio frequency (RF) radiation. Radio frequencies are divided into ranges called “bands,” such as “S-band,” “X-band,” etc. Radio telescopes can be tuned to listen for frequencies within certain bands.

Band	**Range of Wavelengths (cm)**	**Frequency (GHz)**
L	30 -15	1 - 2
S	15 - 7.5	2 - 4
C	7.5 - 3.75	4 - 8
X	3.75 - 2.4	8 - 12
K	2.4 - 0.75	12 - 40

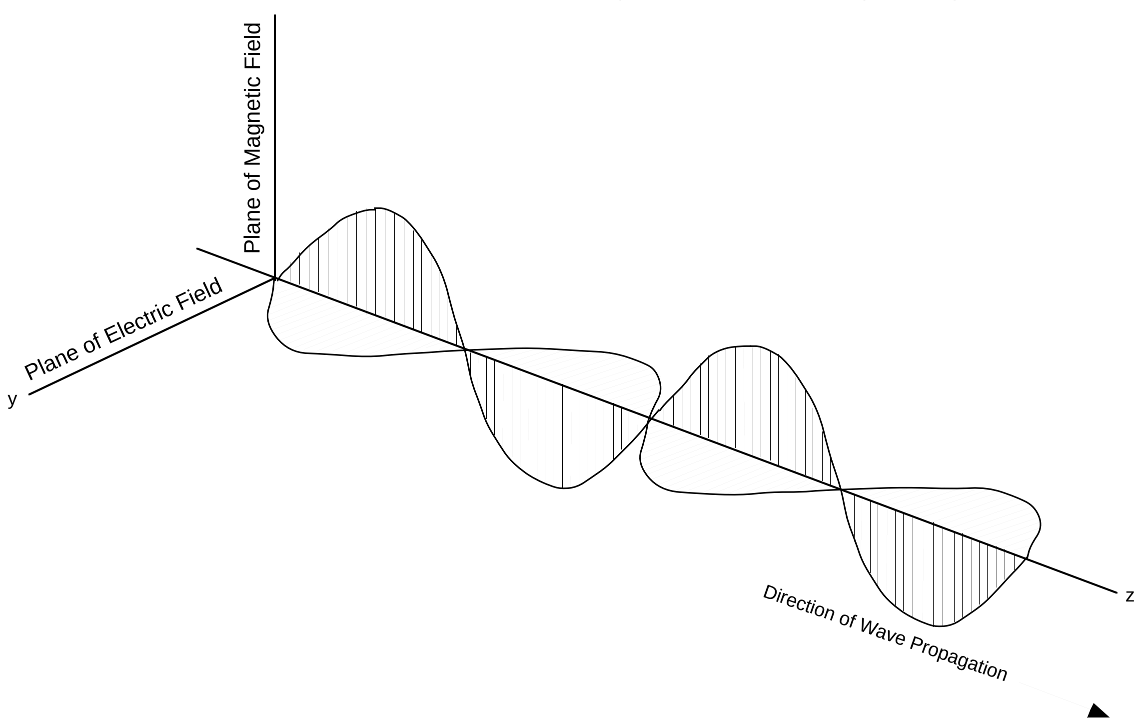
Note: Band definitions vary slightly among different sources. These are ballpark values.

The GAVRT can observe S-band and X-band frequencies. Much of radio astronomy involves studies of radiation well above these frequencies.

Wave Polarization

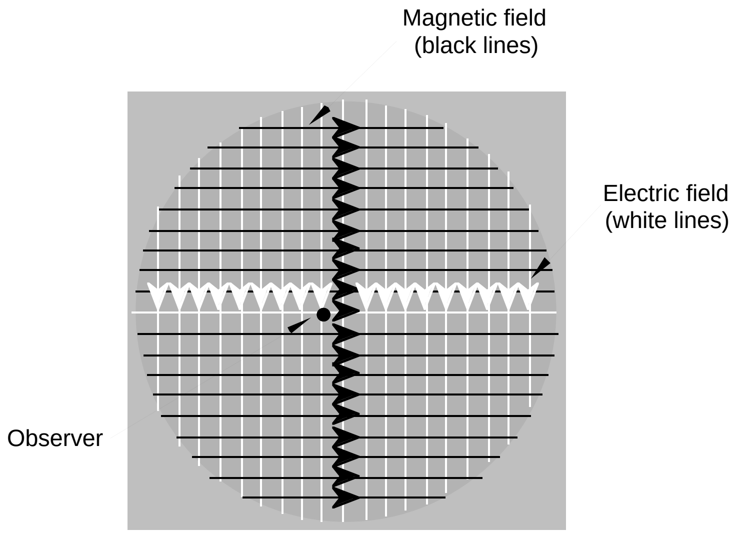
If electromagnetic waves meet no barriers as they travel through an idealized empty space, they travel in straight lines. As mentioned at the beginning of this chapter, stationary electric charges produce electric fields, and moving electric charges produce magnetic fields. Thus, there are two components to an electromagnetic wave—the electric field and the magnetic field. In free space, the directions of the fields are at right angles to the direction of the propagation of the wave.

Electric and Magnetic Fields at Right Angles

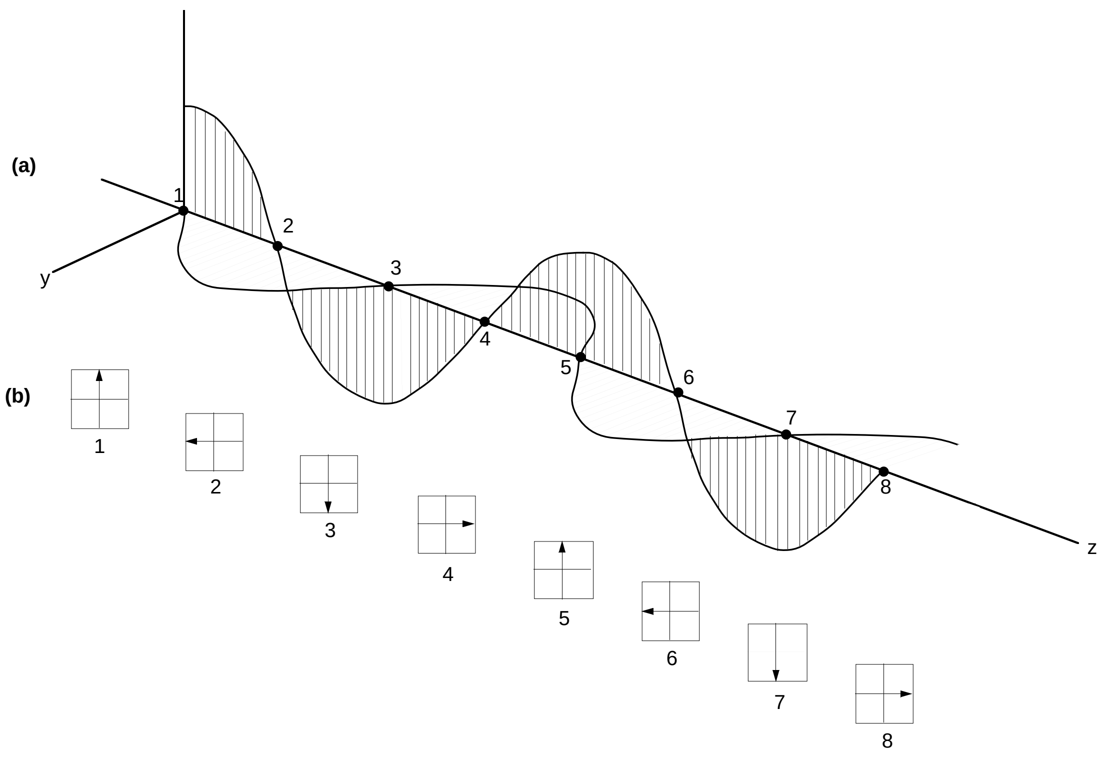


The drawing below shows part of a wavefront as it would appear to an observer at the point indicated in the drawing. The wave is moving directly out of the page. One-half a period later, the observer will see a similar field pattern, except that the directions of both the electric and the magnetic fields will be reversed.

Instantaneous View of Electromagnetic Wave
(wave is moving directly out of the page)



The magnetic field is called the *magnetic vector*, and the electric field is called the *electric vector*. A vector field has both a magnitude and a direction at any given point in space. The *polarization* of electromagnetic waves is defined as the direction of the electric vector. If the electric vector moves at a constant angle with respect to the horizon, the waves are said to be *linearly polarized*. In radio wave transmission, if the polarization is parallel to Earth's surface, the wave is said to be *horizontally polarized*. If the wave is radiated in a vertical plane, it is said to be *vertically polarized*. Waves may also be *circularly polarized*, whereby the angle of the electric (or magnetic) vector rotates around an (imaginary) line traveling in the direction of the propagation of the wave. The rotation may be either to the right or left.



Circular Polarization (see text)

Radio frequency radiation from extraterrestrial sources may be linearly or circularly polarized, or anything in between, or unpolarized. The polarization of the waves gives astronomers additional information about their source.

Recap

1. Electromagnetic radiation is produced by regularly repeating changes in ___________ and _____________ fields.
2. _______________ is the distance between two successive wave crests.
3. The shorter the wavelength, the ___________ the frequency.
4. The amount of energy propagated from a source decreases proportionally to the ___________ of the distance from the source.
5. The range of frequencies in the electromagnetic spectrum that are just below (lower in frequency than) the visible range is called ____________.
6. Radio wavelengths are in the (longest/shortest) ___________ range of the electromagnetic spectrum.
7. In the visible light range, the __________ end of the spectrum has higher frequencies than the ________ end of the spectrum.
8. The linear polarization of an electromagnetic wave is defined by the direction of its ______________ vector.
9. The GAVRT can observe S- and X-band radio waves, which includes frequencies of ____ to ____ and ____ to _____ GHz, respectively.

1. electric, magnetic 2. wavelength 3. higher 4. square 5. infrared 6. longest
7. blue, red 8. electric 9. 2-4, 8-12

For Further Study

- *Nature of electromagnetic radiation*: Kaufmann, 80-84.
- *Inverse-square law of electromagnetic propagation*: Kaufmann, 342-343.
- *Polarization of electromagnetic waves:* Wynn-Williams, 68, 74, 105-109.

Chapter 3

The Mechanisms of Electromagnetic Emissions

Objectives: Upon completion of this chapter, you will be able to describe the difference between thermal and non-thermal radiation and give some examples of each. You will be able to distinguish between thermal and non-thermal radiation curves. You will be able to describe the significance of the 21-cm hydrogen line in radio astronomy.

If the material in this chapter is unfamiliar to you, do not be discouraged if you don't understand everything the first time through. Some of these concepts are a little complicated and few non-scientists have much awareness of them. However, having some familiarity with them will make your radio astronomy activities much more interesting and meaningful.

What causes electromagnetic radiation to be emitted at different frequencies? Fortunately for us, these frequency differences, along with a few other properties we can observe, give us a lot of information about the source of the radiation, as well as the media through which it has traveled.

Electromagnetic radiation is produced by either thermal mechanisms or non-thermal mechanisms.

Examples of thermal radiation include

- Continuous spectrum emissions related to the temperature of the object or material.
- Specific frequency emissions from neutral hydrogen and other atoms and molecules.

Examples of non-thermal mechanisms include

- Emissions due to synchrotron radiation.
- Amplified emissions due to astrophysical masers.

Thermal Radiation

Did you know that any object that contains any heat energy at all emits radiation? When you're camping, if you put a large rock in your campfire for a while, then pull it out, the rock will emit the energy it has absorbed as radiation, which you can feel as heat if you hold your hand a few inches away. Physicists would call the rock a "blackbody" because it absorbs all the energy that reaches it, and then emits the energy at all frequencies (although not equally) at the same rate it absorbs energy.

All the matter in the known universe behaves this way.

Some astronomical objects emit mostly infrared radiation, others mostly visible light, others mostly ultraviolet radiation. The single most important property of objects that determines the radiation they emit is *temperature*.

In solids, the molecules and atoms are vibrating continuously. In a gas, the molecules are really zooming around, continuously bumping into each other. Whatever the amount of molecular motion occurring in matter, the speed is related to the temperature. The hotter the material, the faster its molecules are vibrating or moving.

Electromagnetic radiation is produced whenever electric charges accelerate—that is, when they change either the speed or direction of their movement. In a hot object, the molecules are continuously vibrating (if a solid) or bumping into each other (if a liquid or gas), sending each other off in different directions and at different speeds. Each of these collisions produces electromagnetic radiation at frequencies all across the electromagnetic spectrum. However, the amount of radiation emitted at each frequency (or frequency band) depends on the temperature of the material producing the radiation.

It turns out that the shorter the wavelength (and higher the frequency), the more energy the radiation carries. When you are out in the sun on a hot day and your skin starts to feel hot, that heat is not what you need to worry about if you get sunburned easily. Most of the heat you feel is the result of infrared radiation striking the surface of your skin. However, it is the higher frequency—thus higher energy—ultraviolet radiation penetrating the skin's surface that stimulates the deeper layers to produce the melanin that gives fair complected folks the nice tan—or bad sunburn. X-rays, at still higher frequencies, have enough energy to pass right through skin and other soft tissues. That is how bone and soft tissues of varying densities can be revealed by the x-ray imaging techniques used by medicine.

Any matter that is heated above absolute zero generates electromagnetic energy. The intensity of the emission and the distribution of frequencies on the electromagnetic spectrum depend upon the temperature of the emitting matter. In theory, it is possible to detect electromagnetic energy from any object in the universe. Visible stars radiate a great deal of electromagnetic energy. Much of that energy has to be in the visible part of the spectrum—otherwise they would not be visible stars! Part of the energy has to be in the microwave (short wave radio) part of the spectrum, and that is the part astronomers study using radio telescopes.

Blackbody Characteristics

Blackbodies thus have three characteristics:

1. A blackbody with a temperature higher than absolute zero emits some energy at all wavelengths.
2. A blackbody at higher temperature emits more energy at all wavelengths than does a cooler one.
3. The higher the temperature, the shorter the wavelength at which the maximum energy is emitted.

To illustrate, at a low temperature setting, a burner on an electric stove emits infrared radiation, which is transferred to other objects (such as pots and food) as heat. At a higher temperature, it also emits red light (lower frequency end of visible light range). If the electrical circuit could deliver enough energy, as the temperature increased further, the burner would turn yellow, or even blue-white.

The sun and other stars may, for most purposes, be considered blackbodies. So we can estimate temperatures of these objects based on the frequencies of radiation they emit—in other words, according to their electromagnetic spectra.

For radiation produced by thermal mechanisms, the following table gives samples of wavelength ranges, the temperatures of the matter emitting in that range, and some example sources of such thermal radiation.

Type of Radiation	**Wavelength Range (nanometers [10^{-9} m])**	**Radiated by Objects at this Temperature**	**Typical Sources**
Gamma rays	Less than 0.01	More than 10^8 K	Few astronomical sources this hot; some gamma rays produced in nuclear reactions
X-rays	0.01 - 20	10^6 - 10^8 K	Gas in clusters of galaxies; supernova remnants, solar corona
Ultraviolet	20 - 400	10^5 - 10^6 K	Supernova remnants, very hot stars
Visible	400 - 700	10^3 - 10^5 K	Exterior of stars
Infrared	10^3 - 10^6	10 - 10^3 K	Cool clouds of dust and gas; planets, satellites
Radio	More than 10^6	Less than 10 K	Dark dust clouds

The hotter the object, the shorter is the wavelength of the radiation it emits. Actually, at hotter temperatures, more energy is emitted at all wavelengths. But the peak amount of energy is radiated at shorter wavelengths for higher temperatures. This relationship is known as *Wien's Law.*

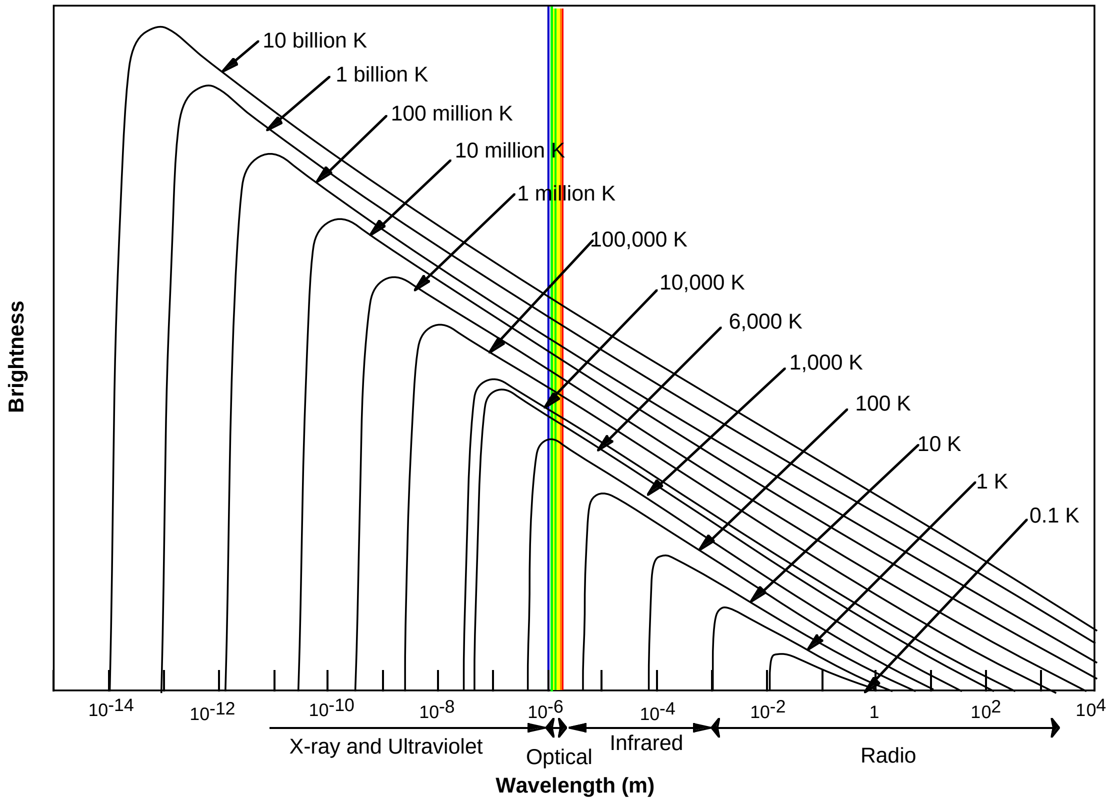
A beam of electromagnetic radiation can be regarded as a stream of tiny packets of energy called photons. *Planck's Law* states that the energy carried by a photon is directly proportional to its frequency. To arrive at the exact energy value, the frequency is multiplied by Planck's Constant, which has been found experimentally to be 6.625 x 10^{-27} erg sec. (The erg is a unit of energy.)

If we sum up the contributions from all parts of the electromagnetic spectrum, we obtain the total energy emitted by a blackbody over all wavelengths. That total energy, emitted per second per square meter by a blackbody at a given temperature is proportional to the fourth power of its absolute temperature. This relationship is known as the *Stefan-Boltzmann Law*. If the sun, for example, were twice as hot as it is and the same size, that is, if its temperature were 11,600 K, it would radiate 2^4, or 16, times more energy than it does now.

The *flux density* of the radiation is defined as the energy received per unit area per unit of frequency bandwidth. Astronomers also consider the radiation's *brightness*, which is a more mathematically precise calculation of the energy received per unit area, for a particular frequency bandwidth, and also taking into consideration the angle of incidence on the measuring surface and the solid angle of sky subtended by the source. The brightness of radiation received (at all frequencies) is thus related to temperature of the emitting object and the wavelength of the received radiation.

The variation of brightness with frequency is called the *brightness spectrum*. The *spectral power* is the energy observed per unit of time for a specific frequency bandwidth.

A plot of a brightness spectrum shows the brightness of the radiation received from a source as it varies by frequency and wavelength. In the plot below, the brightness of blackbodies at various temperatures is plotted on the vertical scale and wavelengths are plotted on the horizontal scale.



Brightness of Electromagnetic Radiation at Different Wavelengths for Blackbody Objects at Various Temperatures

The main thing to notice about these plots is that the curves never cross each other. Therefore, at any frequency, there is only one temperature for each brightness. So, if you can measure the brightness of the energy at a given frequency, you know the temperature of the emitting object!

Despite their temperatures, not all visible stars are good radio frequency emitters. We can detect stars at radio frequencies only

if they emit by non-thermal mechanisms (described next), or if they are in our solar system (that is, our sun), or

if there is gas beyond the star which is emitting (for example, a stellar wind).

As it turns out, the hottest and brightest stars emit more energy at frequencies above the visible range than below it. Such stars are known for their x-ray and atomic particle radiation. However, intense thermal generators such as our own sun emit enough energy in the radio frequencies to make them good candidates for radio astronomy studies. The Milky Way galaxy emits both thermal and non-thermal radio energy, giving radio astronomers a rich variety of data to ponder.

Our observations of radiation of thermal origin have two characteristics that help distinguish it from other types of radiation. Thermal radiation reproduces on a loudspeaker as pure static hiss, and the energy of radiation of thermal origin usually increases with frequency.

Continuum Emissions from Ionized Gas

Thermal blackbody radiation is also emitted by gases. Plasmas are ionized gases and are considered to be a fourth state of matter, after the solid, liquid, and gaseous states. As a matter of fact, plasmas are the most common form of matter in the known universe (constituting up to 99% of it!) since they occur inside stars and in the interstellar gas. However, naturally occurring plasmas are relatively rare on Earth primarily because temperatures are seldom high enough to produce the necessary degree of ionization. The flash of a lightning bolt and the glow of the aurora borealis are examples of plasmas. But immediately beyond Earth’s atmosphere is the plasma comprising the Van Allen radiation belts and the solar wind.

An atom in a gas becomes ionized when another atom bombards it with sufficient energy to knock out an electron, thus leaving a positively charged ion and a negatively charged electron. Once separated, the charged particles tend to recombine with their opposites at a rate dependent on the density of the electrons. As the electron and ion accelerate toward one another, the electron emits electromagnetic energy. Again, the kinetic energy of the colliding atoms tends to separate them into electron and positive ion, making the process continue indefinitely. The gas will always have some proportion of neutral to ionized atoms.

As the charged particles move around, they can generate local concentrations of positive or negative charge, which gives rise to electric and magnetic fields. These fields affect the motion of other charged particles far away. Thus, elements of the ionized gas exert a force on one another even at large distances. An ionized gas becomes a plasma when enough of the atoms are ionized so that the gas exhibits collective behavior.

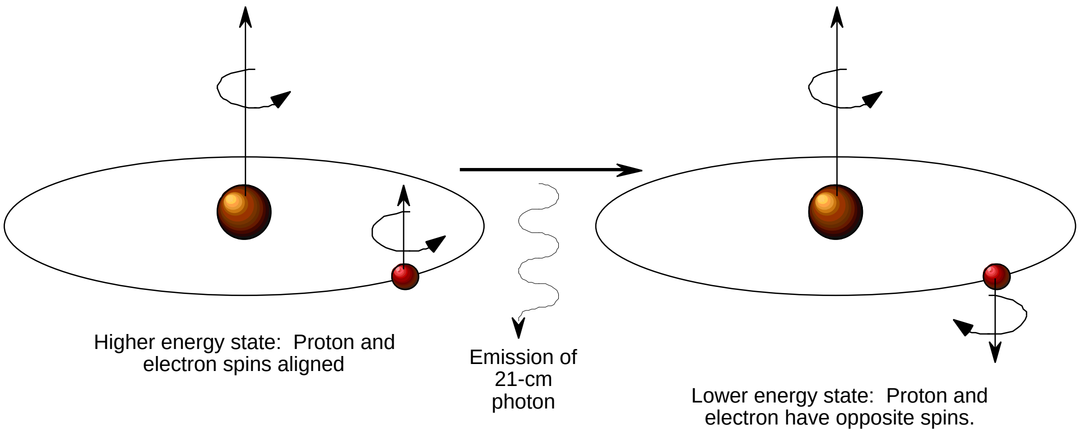
Whenever a vast quantity of free and oppositely charged ions coexist in a relatively small space, the combination of their reactions can add up to intense, continuous, wideband radio frequency radiation. Such conditions prevail around stars, nebulae, clusters of stars, and even planets—Jupiter being at least one we know of.

Spectral Line Emissions from Atoms and Molecules

While the mechanism behind thermal-related energy emissions from ionized gases involves electrons becoming detached from atoms, line emissions from neutral hydrogen and other atoms and molecules involves the electrons changing energy states within the atom, emitting a photon of energy at a wavelength characteristic of that atom. Thus, this radiation mechanism is called line emission, since the wavelength of each atom occupies a discrete “line” on the electromagnetic spectrum.

In the case of neutral (not ionized) hydrogen atoms, in their lower energy (ground) state, the proton and the electron spin in opposite directions. If the hydrogen atom acquires a slight amount of energy by colliding with another atom or electron, the spins of the proton and electron in the hydrogen atom can align, leaving the atom in a slightly excited state. If the atom then loses that amount of energy, it returns to its ground state. The amount of energy lost is that associated with a photon of 21.11 cm wavelength (frequency 1428 MHz).

Formation of the 21-cm Line of Neutral Hydrogen



Hydrogen is the key element in the universe. Since it is the main constituent of interstellar gas, we often characterize a region of interstellar space as to whether its hydrogen is neutral, in which case we call it an H I region, or ionized, in which case we call it an H II region.

Some researchers involved in the search for extra-terrestrial intelligence (see Chapter 8) have reasoned that another intelligent species might use this universal 21-cm wavelength line emission by neutral hydrogen to encode a message; thus these searchers have tuned their antennas specifically to detect modulations to this wavelength. But, perhaps more usefully, observations of this wavelength have given us much information about the interstellar medium and locations and extent of cold interstellar gas.

Recap

1. An object that absorbs and re-emits all energy that hits it without any reflections is a __________________.
2. The blackbody radiation from a hot object is (bluer/redder) __________________. than the blackbody radiation from a cooler object.
3. The hotter the object, the _______________ the wavelength of the peak range of blackbody radiation emitted.
4. Planck’s Law states that the amount of energy carried by a photon is directly proportional to its ___________________.
5. The total amount of energy at all wavelengths emitted by a blackbody, per square meter per second, is proportional to the ____________ power of the its absolute temperature.
6. A plot of a brightness spectrum displays the brightness of radiation received from a source at various ______________ or ___________________.
7. Electromagnetic radiation from blackbodies, ionized gas, and line emissions from atoms and molecules can all be generated by ________________ mechanisms.
8. Hot, ionized gases are called ______________.
9. Wavelengths of 21.11 cm are associated with line emissions from ________________ _______________.
10. Because blackbody curves do not cross, if you know the brightness of a blackbody at a given frequency, you also know its _________________.

1. blackbody 2. bluer 3. shorter 4 frequency 5. fourth 6. wavelengths, frequencies 7. thermal 8. plasmas 9. neutral hydrogen 10. temperature

For Further Study

- *Thermal radiation:* Kaufmann, 84-89.
- *Wien’s Law and Stefan-Boltzmann Law:* Kaufmann, 87-88, 197; Wynn-Williams, 28, App. G and H.
- *Planck’s constant*: Wynn-Williams, 12.
- *Plasmas:* Wynn-Williams, 43-54.
- *Spectral line emissions:* Kaufmann, 90-96; Morrison et al., 112-120.
- *21-cm emission line from neutral hydrogen:* Kaufmann, 460; Wynn-Williams, 30-42.

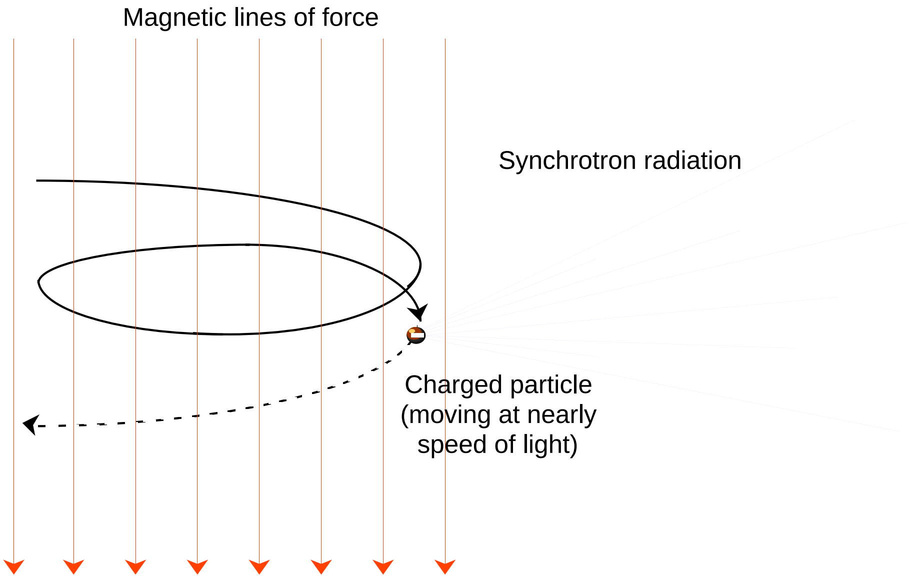
Non-thermal Mechanisms

Radiation is also produced by mechanisms unrelated to the temperature of object (that is, thermal radiation). Here we discuss some examples of non-thermal radiation.

Synchrotron Radiation

Notwithstanding the vast number of sources of thermal emissions, much of the radiation from our own galaxy, particularly the background radiation first discovered by Jansky, and most of that from other galaxies is of non-thermal origin. The major mechanism behind this type of radiation has nothing to do with temperature, but rather with the effect of charged particles interacting with magnetic fields. When a charged particle enters a magnetic field, the field compels it to move in a circular or spiral path around the magnetic lines of force. The particle is thus accelerated and radiates energy. Under non-relativistic conditions (that is, when particle velocities are well-below the speed of light), this *cyclotron radiation* is not strong enough to have much astronomical importance. However, when the speed of the particle reaches nearly the speed of light, it emits a much stronger form of cyclotron radiation called *synchrotron radiation*.

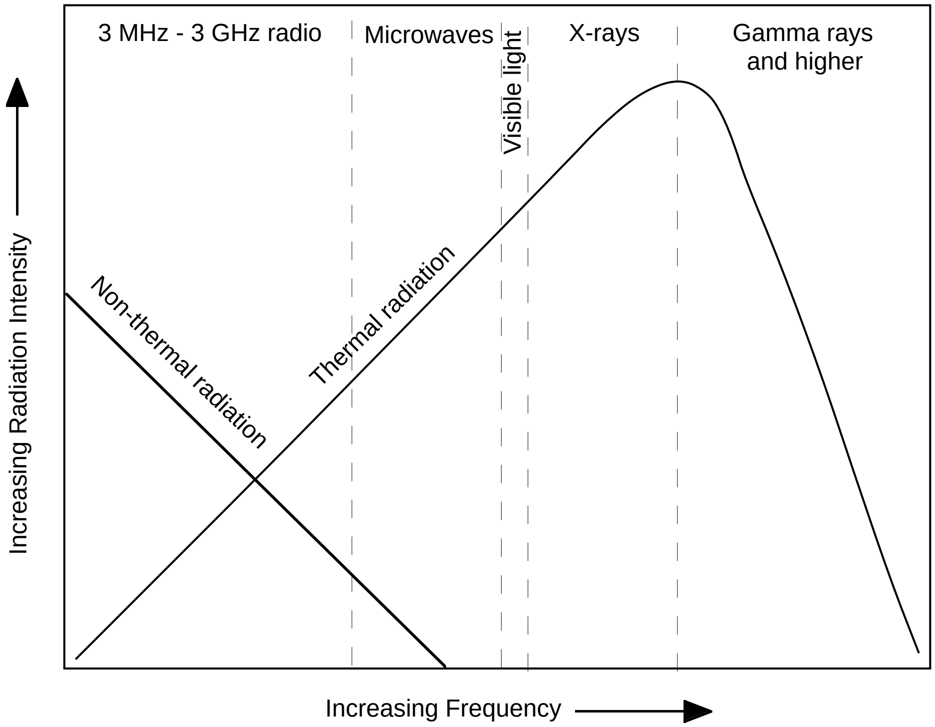
Emission of Synchrotron Radiation



Quasars (described in Chapter 6) are one source of synchrotron radiation not only at radio wavelengths, but also at visible and x-ray wavelengths.

An important difference in radiation from thermal versus non-thermal mechanisms is that while the intensity (energy) of thermal radiation *increases* with frequency, the intensity of non-thermal radiation usually *decreases* with frequency.

Relative Variation of Thermal and Non-thermal Radiation Emissions



Masers

Astronomical *masers* are another source of non-thermal radiation. “Maser” is short for micro-wave-amplified stimulated emission of radiation. Masers are very compact sites within molecular clouds where emission from certain molecular lines can be enormously amplified. The interstellar medium contains only a smattering of molecular species such as water (H_2O), hydroxl radicals (OH), silicon monoxide (SiO), and methanol (CH_3OH). Normally, because of the scarcity of these molecules, their line emissions would be very difficult to detect with anything but very crude resolution. However, because of the phenomenon of “masing,” these clouds can be detected in other galaxies!

In simplified terms, masing occurs when clouds of these molecules encounter an intense radiation field, such as that from a nearby source such as a luminous star, or when they collide with the far more abundant H_2 molecules. What is called a “population inversion” occurs, in which there are more molecules in an excited state (that is, their electrons have “jumped” to a higher energy level), than in a stable, ground state. This phenomenon is called *pumping*. As the radiation causing the pumping travels through the cloud, the original ray is amplified exponentially, emerging at the same frequency and phase as the original ray, but greatly amplified. Some masers emit as powerfully as stars! This phenomenon is related to that of spectral line emissions, explained in Chapter 4.

Incidentally, this same principle is used in a device called a maser amplifier, which is installed as part of some radio telescopes (not in the GAVRT, however) to amplify the signal received by the antenna.

Recap

1. ______________________ ____________________ is a non-thermal mechanism producing electromagnetic radiation by accelerating charged particles in a magnetic field to nearly the speed of light.
2. The intensity of non-thermal radiation often __________________ with frequency.
3. In the interstellar medium, areas within clouds of molecules that greatly amplify the radiation passing through them are called astrophysical ___________.

1. synchrotron radiation   2. decreases   3. masers

For Further Study

- *Synchrotron radiation:* Wynn-Williams, 104, 108.
- *Masers:* Kaufmann, 378-379; Wynn-Williams, 95-97.

Chapter 4

Effects of Media

Objectives: When you have completed this chapter, you will be able to describe several important variables in the media through which the radiation passes and how they affect the particles/waves arriving at the telescope. You will be able to describe atmospheric "windows" and give an example. You will be able to describe the effects of absorbing and dispersing media on wave propagation. You will be able to describe Kirchhoff's laws of spectral analysis, and give examples of sources of spectral lines. You will be able to define reflection, refraction, scintillation, and Faraday rotation.

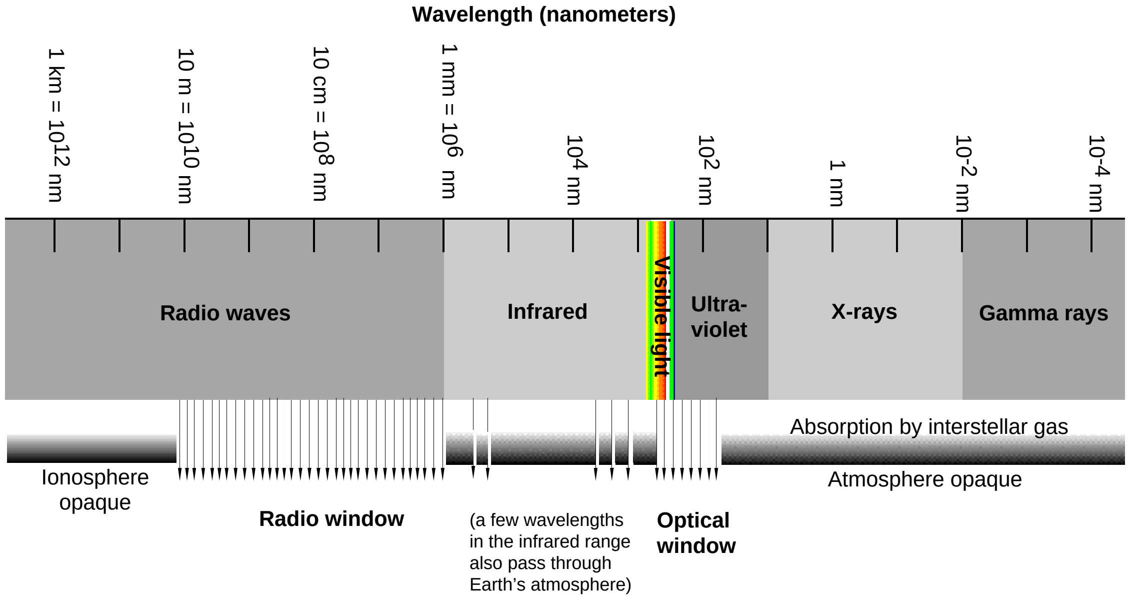
Electromagnetic radiation from space comes in all the wavelengths of the spectrum, from gamma rays to radio waves. However, the radiation that actually reaches us is greatly affected by the media through which it has passed. The atoms and molecules of the medium may absorb some wavelengths, scatter (reflect) other wavelengths, and let some pass through only slightly bent (refracted).

Atmospheric "Windows"

Earth's atmosphere presents an opaque barrier to much of the electromagnetic spectrum. The atmosphere absorbs most of the wavelengths shorter than ultraviolet, most of the wavelengths between infrared and microwaves, and most of the longest radio waves. That leaves only visible light, some ultraviolet and infrared, and short wave radio to penetrate the atmosphere and bring information about the universe to our Earth-bound eyes and instruments.

The main frequency ranges allowed to pass through the atmosphere are referred to as the radio window and the optical window. The radio window is the range of frequencies from about 5 MHz to over 300 GHz (wavelengths of almost 100 m down to about 1 mm). The low-frequency end of the window is limited by signal absorption in the ionosphere, while the upper limit is determined by signal attenuation caused by water vapor and carbon dioxide in the atmosphere.

Atmospheric Windows to Electromagnetic Radiation



The optical window, and thus optical astronomy, can be severely limited by atmospheric conditions such as clouds and air pollution, as well as by interference from artificial light and the literally blinding interference from the sun's light. Radio astronomy is not hampered by most of these conditions. For one thing, it can proceed even in broad daylight. However, at the higher frequencies in the atmospheric radio window, clouds and rain can cause signal attenuation. For this reason, radio telescopes used for studying sub-millimeter wavelengths are built on the highest mountains, where the atmosphere has had the least chance for attenuation. (Conversely, most radio telescopes are built in low places to alleviate problems with human-generated interference, as will be explained in Chapter 6.)

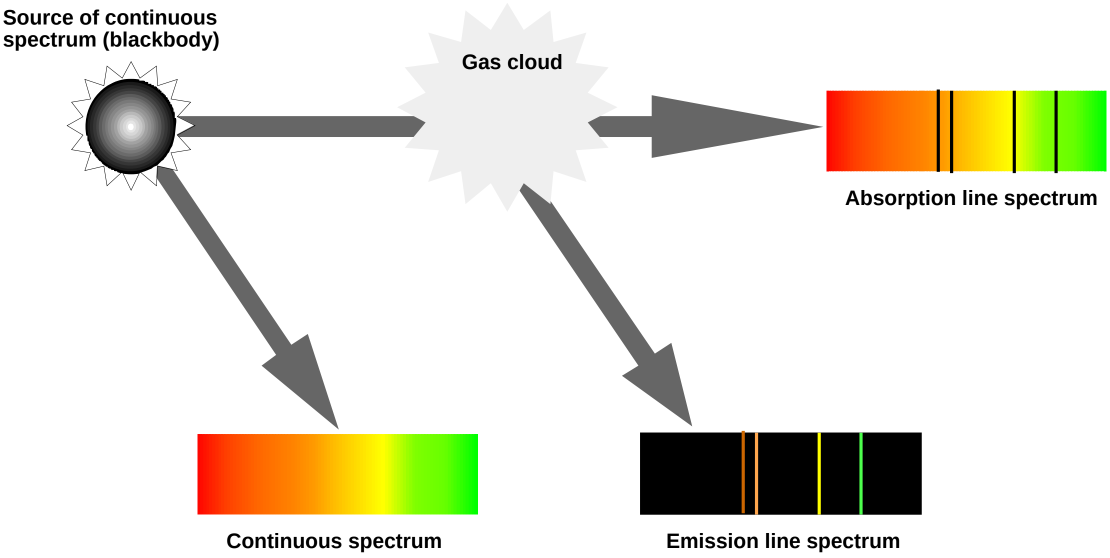
Absorption and Emission Lines

As described in Chapter 3, a blackbody object emits radiation of all wavelengths. However, when the radiation passes through a gas, some of the electrons in the atoms and molecules of the gas absorb some of the energy passing through. The particular wavelengths of energy absorbed are unique to the type of atom or molecule. The radiation emerging from the gas cloud will thus be missing those specific wavelengths, producing a spectrum with dark absorption lines.

The atoms or molecules in the gas then re-emit energy at those same wavelengths. If we can observe this re-emitted energy with little or no back lighting (for example, when we look at clouds of gas in the space between the stars), we will see bright emission lines against a dark background. The emission lines are at the exact frequencies of the absorption lines for a given gas. These phenomena are known as Kirchhoff's laws of spectral analysis:

1. When a continuous spectrum is viewed through some cool gas, dark spectral lines (called absorption lines) appear in the continuous spectrum.
2. If the gas is viewed at an angle away from the source of the continuous spectrum, a pattern of bright spectral lines (called emission lines) is seen against an otherwise dark background.

Kirchhoff's Laws of Spectral Analysis



The same phenomena are at work in the non-visible portions of the spectrum, including the radio range. As the radiation passes through a gas, certain wavelengths are absorbed. Those same wavelengths appear in emission when the gas is observed at an angle with respect to the radiation source.

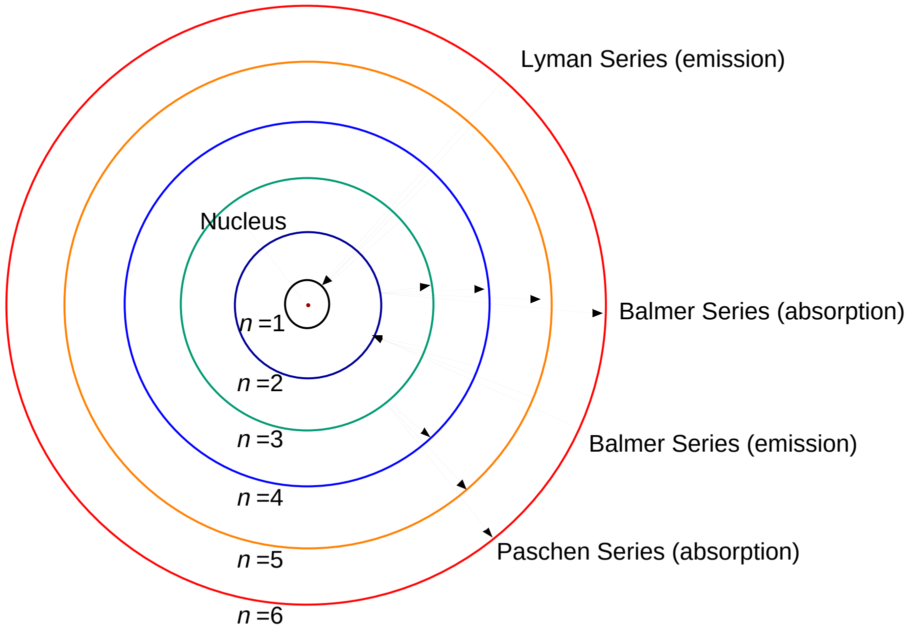
Why do atoms absorb only electromagnetic energy of a particular wavelength? And why do they emit only energy of these same wavelengths? What follows here is a summarized explanation, but for a more comprehensive one, see Kaufmann's *Universe*, pages 90-96.

The answers lie in quantum mechanics. The electrons in an atom may be in a number of allowed energy states. In the atom's ground state, the electrons are in their lowest energy states. In order to jump to one of a limited number of allowed higher energy levels, the atom must gain a very specific amount of energy. Conversely, when the electron "falls" to a lower energy state, it releases a very specific amount of energy. These discrete packets of energy are called photons.

Thus, each spectral line corresponds to one particular transition between energy states of the atoms of a particular element. An absorption line occurs when an electron jumps from a lower energy state to a higher energy state, extracting the required photon from an outside source of energy such as the continuous spectrum of a hot, glowing object. An emission line is formed when the electron falls back to a lower energy state, releasing a photon.

The diagram on the next page demonstrates absorption and emission of photons by an atom using the Neils Bohr model of a hydrogen atom, where the varying energy levels of the electron are represented as varying orbits around the nucleus. (We know that this model is not literally true, but it is useful for describing electron behavior.) The varying series of absorption and emission lines represent different ranges of wavelengths on the continuous spectrum. The Lyman series, for example, includes absorption and emission lines in the ultraviolet part of the spectrum.

Hydrogen Atom
(with allowed electron energy levels n = 1, 2, 3, etc.)



Emission and absorption lines are also seen when oppositely charged ions recombine to an electrically neutral state. The thus formed neutral atom is highly excited, with electrons transitioning between states, emitting and absorbing photons. The resulting emission and absorption lines are called recombination lines. Some recombination lines occur at relatively low frequencies, well within the radio range, specifically those of carbon ions.

Molecules, as well as atoms, in their gas phase also absorb characteristic narrow frequency bands of radiation passed through them. In the microwave and long wavelength infrared portions of the spectrum, these lines are due to quantized rotational motion of the molecule. The precise frequencies of these absorption lines can be used to determine molecular species. This method is valuable for detecting molecules in our atmosphere, in the atmospheres of other planets, and in the interstellar medium. Organic molecules (that is, those containing carbon) have been detected in space in great abundance using molecular spectroscopy. Molecular spectroscopy has become an extremely important area of investigation in radio astronomy.

As will be discussed in Chapter 5, emission and absorption lines in all spectra of extraterrestrial origin may be shifted either toward higher (blue) or lower (red) frequencies, due to a variety of mechanisms.

Recap

1. Earth’s atmospheric radio window allows frequencies of about _______ to _________ to pass through.
2. When a continuous spectrum is viewed through a cool gas, dark _____________ _________________ appear in the spectrum.
3. Each spectral line corresponds to one particular ______________ between energy states of particular atoms or molecules.
4. The method of identifying molecules in atmospheres by observing their absorption lines is called _______________ _______________.
5. _______________ lines occur when oppositely charged ions recombine to a neutral, yet highly excited state.

---

1. 5 MHz, 300 GHz 2. absorption lines 3. transition 4. molecular spectroscopy 5. Recombination

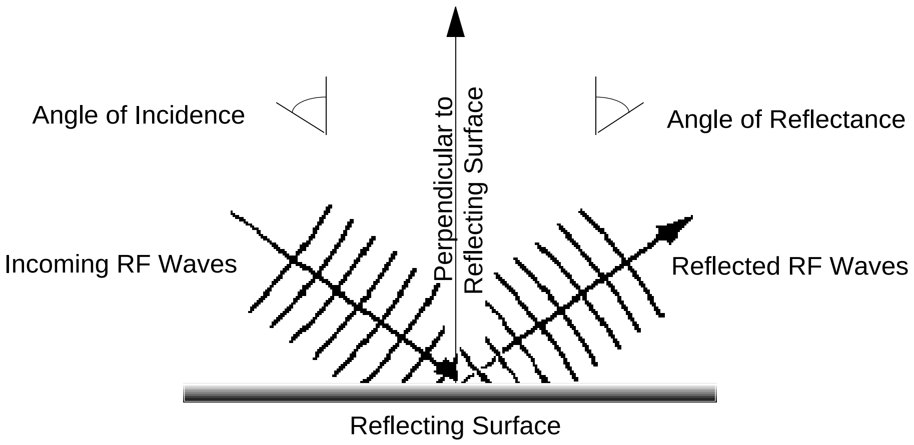
For Further Study

- *Atmospheric windows:* Kaufmann, 116-117; Wynn-Williams, 13-15; Morrison et al., 141, 169-172.
- *Spectral lines:* Kaufmann, 90-96; Wynn-Williams, 18-27.

Reflection

RF radiation generally travels through space in a straight line. RF waves can be reflected by certain substances, much in the same way that light is reflected by a mirror. The angle at which a radio wave is reflected from a smooth metal surface, for example, will equal the angle at which it approached the surface. In other words, the angle of reflection of RF waves equals their angle of incidence.

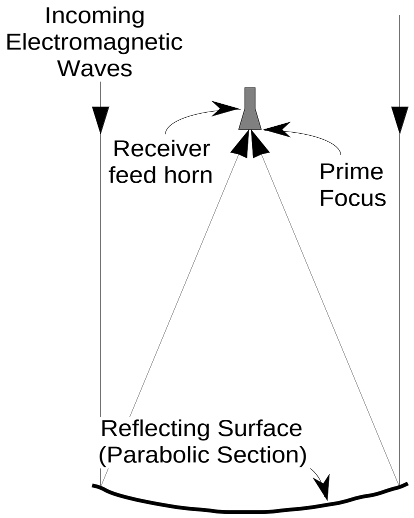
RF Reflected



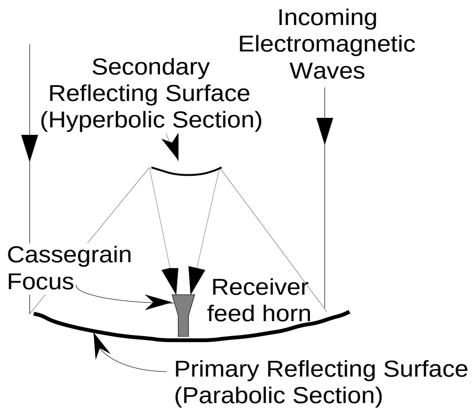
This principle of RF reflection is used in antenna design to focus transmitted waves into a narrow beam and to collect and concentrate received RF signals for a receiver. If a reflector is designed with the reflecting surface shaped like a paraboloid, electromagnetic waves approaching parallel to the axis of the antenna will be reflected and will focus above the surface of the reflector at the feed horn. This arrangement is called prime focus and provides the large aperture (that is, antenna surface area) necessary to receive very weak signals.

However, a major problem with prime focus arrangements for large aperture antennas is that the equipment required at the prime focus is heavy and the supporting structure tends to sag under the weight of the equipment, thus affecting calibration. A solution is the Cassegrain focus arrangement. Cassegrain antennas add a secondary reflecting surface to “fold” the electromagnetic waves back to a prime focus near the primary reflector. The DSN’s antennas (including the GAVRT) are of this design because it accommodates large apertures and is structurally strong, allowing bulky equipment to be located nearer the structure’s center of gravity.

Prime Focus Antenna



Cassegrain Focus Antenna



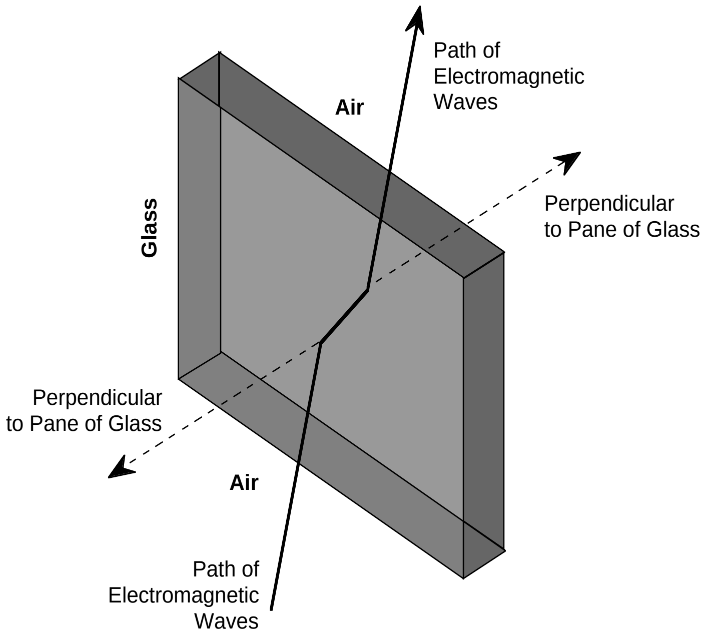
The reflective properties of electromagnetic waves have also been used to investigate the planets using a technique called planetary radar. With this technique, electromagnetic waves are transmitted to the planet, where they reflect off the surface of the planet and are received at one or more Earth receiving stations. Using very sophisticated signal processing techniques, the receiving stations dissect and analyze the signal in terms of time, amplitude, phase, and frequency. JPL's application of this radar technique, called Goldstone Solar System Radar (GSSR), has been used to develop detailed images and measurements of several main belt and near-Earth asteroids.

Refraction

Refraction is the deflection or bending of electromagnetic waves when they pass from one kind of transparent medium into another. The index of refraction is the ratio of the speed of electromagnetic energy in a vacuum to the speed of electromagnetic energy in the observed medium. The law of refraction states that electromagnetic waves passing from one medium into another (of a differing index of refraction) will be bent in their direction of travel.

Usually, substances of higher densities have higher indices of refraction. The index of refraction of a vacuum, by definition, is 1.0. The index of refraction of air is 1.00029, water is 1.3, glass about 1.5, and diamonds 2.4. Since air and glass have different indices of refraction, the path of electromagnetic waves moving from air to glass at an angle will be bent toward the perpendicular as they travel into the glass. Likewise, the path will be bent to the same extent away from the perpendicular when they exit the other side of glass.

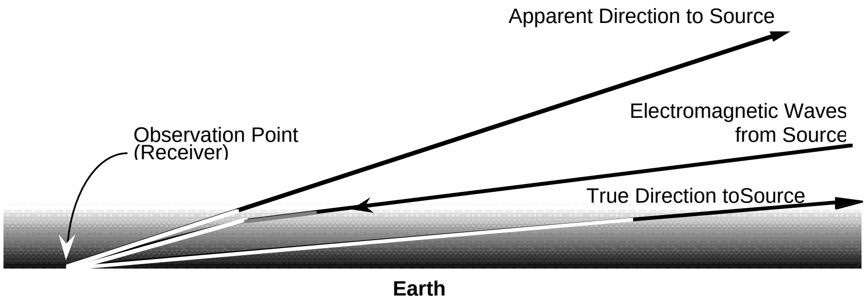
Air-Glass-Air Refraction



In a similar manner, electromagnetic waves entering Earth's atmosphere from space are slightly bent by refraction. Atmospheric refraction is greatest for radiation from sources near the horizon (below about 15˚ elevation) and causes the apparent altitude of the source to be higher than the true height. As Earth rotates and the object gains altitude, the refraction effect decreases, becoming zero at zenith (directly overhead). Refraction's effect on sunlight adds about 5 minutes to the daylight at equatorial latitudes, since the sun appears higher in the sky than it actually is.

Refraction in the Earth's Atmosphere

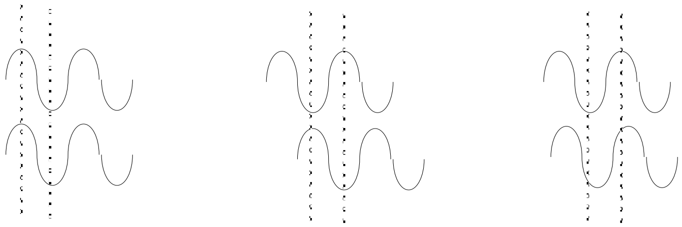
Note: Angles have been greatly exaggerated to emphasize the effect



Phase

As applied to waves of electromagnetic radiation, phase is the relative measure of the alignment of two wave forms of similar frequency. They are said to be in phase if the peaks and troughs of the two waves match up with each other in time. They are said to be out of phase to the extent that they do not match up. Phase is expressed in degrees from 0 to 360.

Phase



Waves in Phase 180° Out of Phase 20° Out of Phase

Scintillation

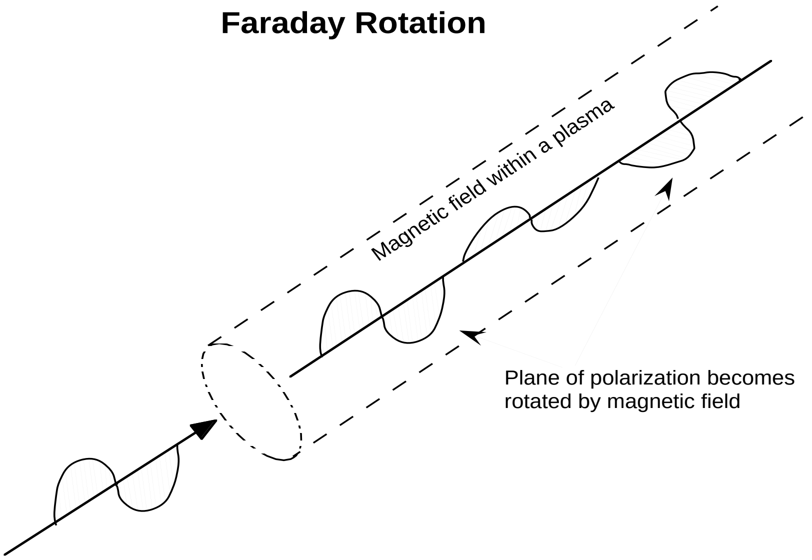
As electromagnetic waves travel through Earth's atmosphere, they pass through areas of varying pressure, temperature, and water content. This dynamic medium has rapidly varying indices of refraction, causing the waves to take different paths through the atmosphere. The consequence is that at the point of observation, the waves will be out of phase and appear to be varying in intensity. The effect in the visual range is that stars appear to twinkle and distant scenes on the horizon appear to shimmer (for example, when we see distant "water" mirages in the hot desert). In the radio range, the same phenomenon is called scintillation. The interplanetary and interstellar media can have a similar effect on the electromagnetic waves passing through them.

A star will scintillate or twinkle most violently when it is low over the horizon, as its radiation passes through a thick layer of atmosphere. A planet, which appears as a small disk, rather than a point, will usually scintillate much less than a star, because light waves from one side of the disk are "averaged" with light waves coming from other parts of the disk to smooth out the overall image.

Technology has been developed for both radio and optical telescopes to significantly cancel out the phase changes observed for a given source, thus correcting the resulting distortion. This technology is not implemented on the GAVRT.

Faraday Rotation

Faraday rotation (or Faraday effect) is a rotating of the plane of polarization of the linearly polarized electromagnetic waves as they pass through a magnetic field in a plasma. A linearly polarized wave may be thought of as the sum of two circularly polarized waves of opposite hand. That is, one wave is polarized to the right and one wave is polarized to the left. (Both waves are at the same frequency.) When the linearly polarized wave passes through a magnetic field, the right polarized wave component travels very slightly faster than the left polarized wave component. Over a distance, this phenomenon has the effect of rotating the plane of the linearly polarized wave. A measure of the amount of rotation can give a value of the density of a plasma.



Recap

1. The angle of reflectance of electromagnetic radiation from a surface is equal to the angle of __________________.

2. For a radio telescope, Earth's atmosphere causes refraction of the radiation from a source such that the source appears (higher/lower) ____________ than it really is.

3. The ratio of the speed of electromagnetic energy in a vacuum to its speed in a given medium is the medium's ____________ ____ ________________.

4. Scintillation is caused by electromagnetic waves being out of _________ after passing through a dynamic medium.

5. Faraday rotation occurs when an electromagnetic wave's _______________ is changed as it passes through magnetic lines of force parallel to the wave and moving in the same direction.

1. incidence 2. higher 3. index of refraction 4. phase 5. polarization

For Further Study

- *Reflection, refraction, and telescope design:* Kaufmann, 102-116; Morrison et al., 140-147, 150-158, 161-178.
- *Radio metrics:* http://deepspace.jpl.nasa.gov/920/public/923tech/95_20/radio.htm; Morrison et al., 95-96, 167-168, 187-188.
- *Faraday rotation:* Wynn-Williams, 108-110.

Chapter 5

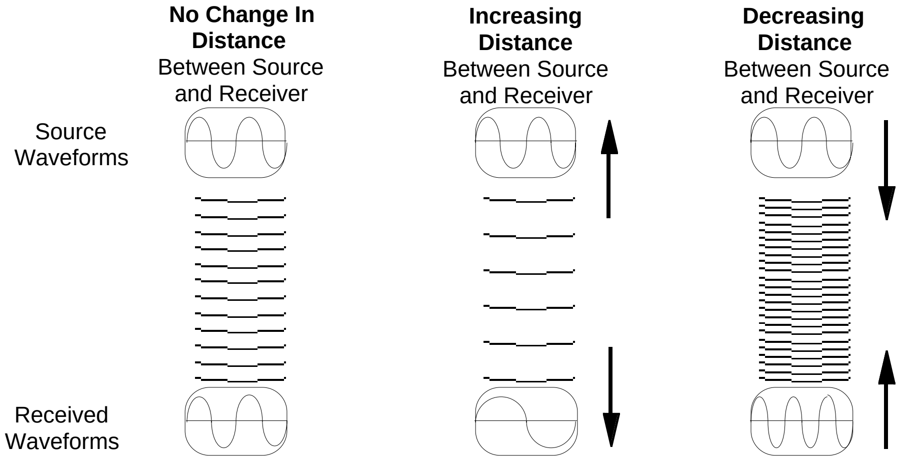
Effects of Motion and Gravity

Objectives: When you have completed this chapter, you will be able to describe the Doppler effect on the frequency of the received particles/waves; describe the significance of spectral red shifting and blue shifting; describe the effects of gravity on electromagnetic radiation; describe superluminal expansion; and define occultation.

Doppler Effect

Regardless of the frequency of electromagnetic waves, they are subject to the Doppler effect. The Doppler effect causes the observed frequency of radiation from a source to differ from the actual radiated frequency if there is motion that is increasing or decreasing the distance between the source and the observer. The same effect is readily observable as variation in the pitch of sound between a moving source and a stationary observer, or vice versa.

Doppler Effects



When the distance between the source and receiver of electromagnetic waves remains constant, the frequency of the source and received wave forms is the same. When the distance between the source and receiver of electromagnetic waves is increasing, the frequency of the received wave forms is lower than the frequency of the source wave form. When the distance is decreasing, the frequency of the received wave form will be higher than the source wave form.

The Doppler effect is very important to both optical and radio astronomy. The observed spectra of objects moving through space toward Earth are shifted toward the blue (shorter wavelengths), while objects moving through space away from Earth are shifted toward the red. The Doppler effect works at all wavelengths of the electromagnetic spectrum. Thus, the phenomenon of apparent shortening of wavelengths in any part of the spectrum from a source that is moving toward the observer is called blue shifting, while the apparent lengthening of wavelengths in any part of the spectrum from a source that is moving away from the observer is called red shifting.

Relatively few extraterrestrial objects have been observed to be blue shifted, and these, it turns out, are very close by, cosmically speaking. Examples are planets in our own solar system with which we are closing ranks due to our relative positions in our orbits about the sun, some other objects in our galaxy, some molecular clouds, as well as some galaxies in what is termed the local group of galaxies.

Almost all other distant objects are red shifted. The red shifting of spectra from very distant objects is due to the simple fact that the universe is expanding. Space itself is expanding between us and distant objects, thus they are moving away from us. This effect is called cosmic red shifting, but it is still due to the Doppler effect.

Distances to extragalactic objects can be estimated based in part on the degree of red shifting of their spectra. As the universe expands, all objects recede from one another at a rate proportional to their distances. The Hubble Constant relates the expansion velocity to the distance and is most important for estimating distances based on the amount of red shifting of radiation from a source. Our current estimate for the Hubble Contant is 60-80 km/s per million parsecs (1 parsec = 3.26 light years).

The spectra from quasars, for example, are quite red-shifted. Along with other characteristics, such as their remarkable energy, this red shifting suggests that quasars are the oldest and most distant objects we have observed. The most distant quasars appear to be receding at over 90% the speed of light!

Gravitational Red Shifting

Red shifting, of course, indicates an elongating of the wavelength. An elongated wavelength indicates that the radiation has lost some of its energy from the instant it left its source.

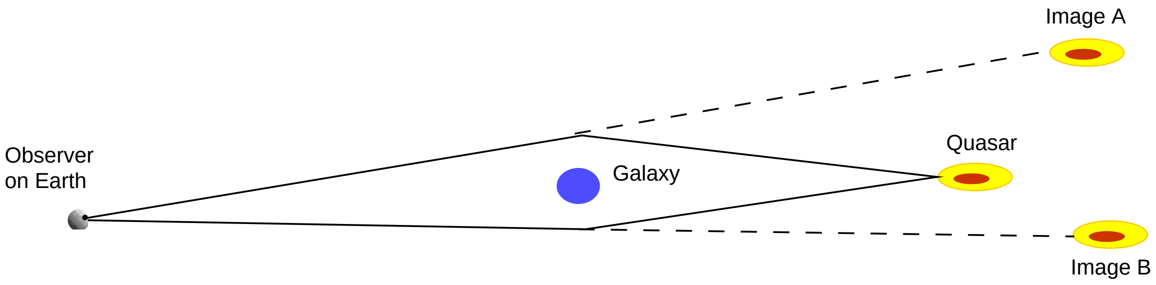
As predicted by Einstein, radiation also experiences a slight amount of red shifting due to gravitational influences. Gravitational red shifting is due to the change in the strength of gravity and occurs mostly near massive bodies. For example, as radiation leaves a star, the gravitational attraction near the star produces a very slight lengthening of the wavelengths, as the radiation loses energy in its effort to escape the pull of gravity from the large mass. This red shifting diminishes in effect as the radiation travels outside the sphere of influence of the source's gravity.

Gravitational Lensing

Einstein's theory of general relativity predicts that space is actually warped around massive objects.

In 1979, astronomers noticed two remarkably similar quasars very close together. They had the same magnitude, spectra, and red shift. They wondered if the two images could actually represent the same object. It turned out that a galaxy lay directly in the path between the two quasars and Earth, much closer to Earth than the quasars. The geometry and estimated mass of the galaxy were such that it produced a gravitational lens effect—that is, a warping of the light as it passes through the space around the galaxy.

Gravitational Lensing



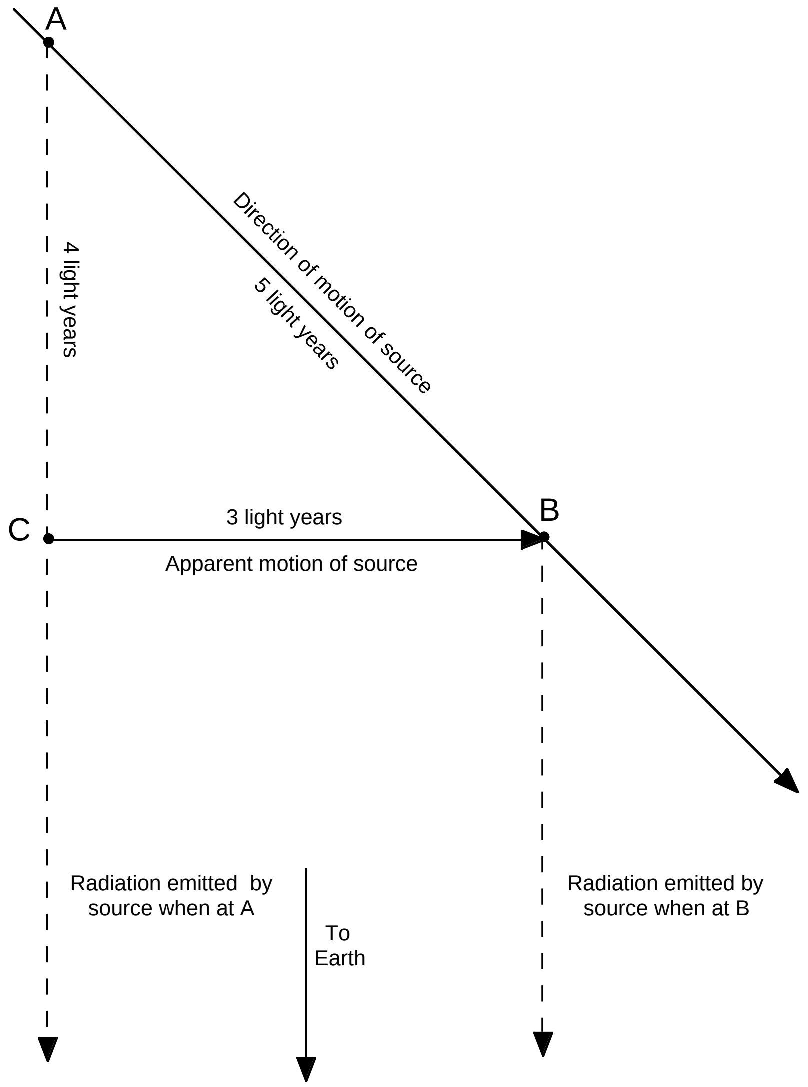
Many other instances of gravitational lensing have now been detected. Gravitational lensing can produce more than two images, or even arcs. Images produced by point-like gravitational lenses can appear much brighter than the original source would appear in the absence of the gravitational lens.

Superluminal Velocities

Some discrete (defined in the next chapter) sources within quasars have been observed to change positions over a brief period. Their motion generally appears to the observer to be radially outward from the center of the quasar image. The apparent velocities of these objects have been measured, and if the red shifts actually do represent the distance and recession velocities of the quasar, then these discrete objects are moving at speeds greater than the speed of light! We call these apparent speeds superluminal velocities or superluminal expansion.

Well, we know this is impossible, right? So astronomers had to come up with a more reasonable explanation. The most widely accepted explanation is that the radiation emitted from the object at the first position (A in the diagram below) has travelled farther and thus taken longer to reach Earth than the radiation emitted from the second position (B), 5 LY from A.

Superluminal Velocity



Suppose A is 4 light years (LY) farther from Earth than B (that is, AC is 4 LY). Moving just a bit under the speed of light, the object takes just over 5 LY to travel from A to B. However, the radiation it emitted at A reaches C in 4 years. As that radiation continues toward Earth, it is one year ahead of the radiation emitted toward us by the object when it arrived at B. When it finally (after several billion years) reaches Earth, the radiation from A is still one year ahead of the radiation from B. It appears to us that the object has moved tangentially out from the center of the quasar, from C to B and (from the Pythagorean theorem) has gone 3 LY in just over one year! That the object appears to travel at nearly three times light speed is only because of the projection effect, with its radiation travelling from A to C in 4 years, while the object itself went from A to B in 5 years.

Occultations

When one celestial body passes between Earth and another celestial body, we say that the object that is wholly or partially hidden from our view is occulted. Examples of occultations are the moon passing in front of a star or a planet, or a planet passing in front of a star, or one planet passing in front of another planet, such as in 1590 when Venus occulted Mars.

An occultation can provide an unparalleled opportunity to study any existing atmosphere on the occulting planet. As the radiation from the farther object passes through the atmosphere at the limb of the nearer object, that radiation will be influenced according to the properties of that atmosphere. The degree of refraction of the radiation gives information about the atmosphere's density and thickness. Spectroscopic studies give information about the atmosphere's composition.

Recap

1. Doppler effect causes the wavelength of energy emitted from an object moving away from the observer to appear ______________ than when it left the source.
2. The spectra of objects moving toward us are _________ shifted.
3. Besides Doppler effect, another cause of spectral red shifting is the pull of _______________ on radiation traveling away from a massive source.
4. The spectra from quasars are quite red shifted, indicating that these objects are moving _________________ from us.
5. The warping of space around massive objects accounts for the effect of ________________ lensing.
6. It is generally accepted that apparently superluminal velocities that have been observed are due to a ___________________ effect.

1. longer 2. blue 3. gravity 4. away 5. gravitational 6. projection

For Further Study

- *Doppler effect:* Kaufmann, 96-97, 460-461; Wynn-Williams, 24-25, 186; Morrison et al., 120-121.
- *Hubble Constant:* Kaufmann, 482-485; Morrison et al., 563, 607-609.
- *Gravitational lensing:* Kaufmann, 445-447; Morrison et al., 581-583.
- *Superluminal motion:* Kaufmann, 515-516.
- *Occultations:* Kaufmann, 243.

Chapter 6

Sources of Radio Frequency Emissions

Objectives: Upon completion of this chapter, you will be able to define and give examples of a “point source,” a “localized source,” and an “extended source” of radio frequency emissions; distinguish between “foreground” and “background” radiation; describe the theoretical source of “cosmic background radiation”; describe a radio star, a flare star, and a pulsar; explain why pulsars are sometimes referred to as standard clocks; describe the relationship between pulsar spin down and age; describe “normal” galaxies and “radio” galaxies; describe the general characteristics of the emissions from Jupiter, Io, and the Io plasma torus; describe the impact of interference on radio astronomy observations; and describe a major source of natural interference and of human made interference.

Classifying the Source

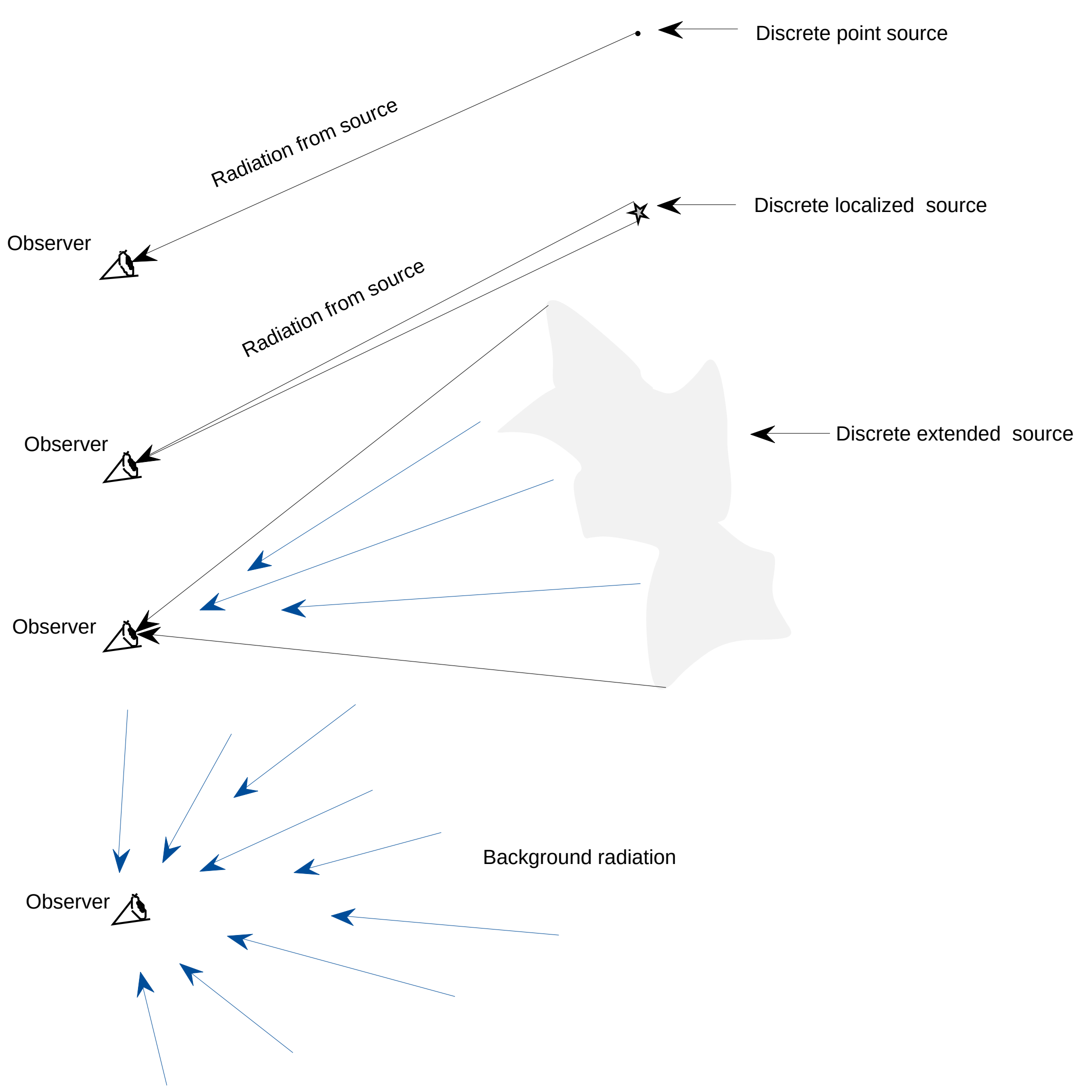
Radiation whose direction can be identified is said to originate from a *discrete source*. A discrete source often can be associated with a visible (whether by the naked eye or by optical telescope) object. For example, a single star or small group of stars viewed from Earth is a discrete source. Our sun is a discrete source. A quasar is a discrete source. However, the definition of “discrete,” in addition to the other terms used to describe the extent of a source, often depends upon the beam size of the radio telescope antenna being used in the observation.

Discrete sources may be further classified as point sources, localized sources, and extended sources.

A *point source* is an idealization. It is defined as a source that subtends an infinitesimally small angle. All objects in reality subtend at least a very tiny angle, but often it is mathematically convenient for astronomers to regard sources of very small extent as point sources. Objects that appear smaller than the telescope’s beam size are often called “unresolved” objects and can effectively be treated as point sources. A *localized source* is a discrete source of very small extent. A single star may be considered a localized source.

Emitters of radiation that covers a relatively large part of the sky are called *extended sources*. An example of an extended source of radiation is our Milky Way galaxy, or its galactic center (called Sagittarius A) from which radiation emissions are most intense.

Classifying the Extent of the Source



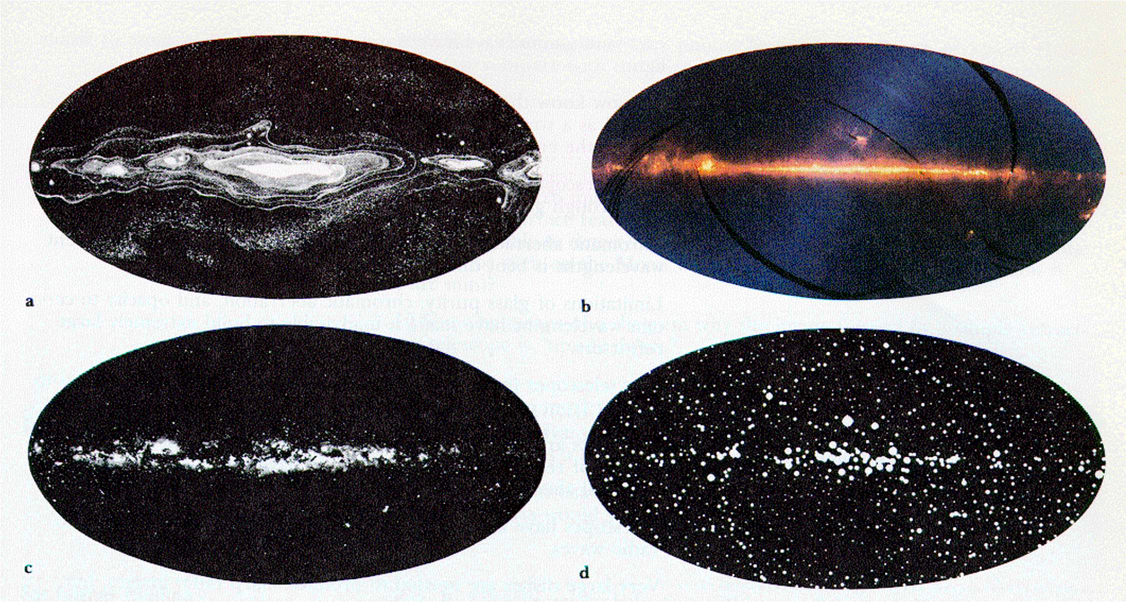
An optical analogy to the extended source would be the view of a large city at night from an airplane at about 10 km altitude. All the city lights would tend to blend together into an apparently single, extended source of light. On the other hand, a single searchlight viewed from the same altitude would stand out as a single object, analogous to a localized or point source.

The terms localized and extended are relative and depend on the precision with which the telescope observing them can determine the source.

Background radiation is radio frequency radiation that originates from farther away than the object being studied, whereas *foreground radiation* originates from closer than the object being studied. If an astronomer is studying a specific nearby star, the radiation from the Milky Way may be considered not merely an extended source, but background radiation. Or, if it is a distant galaxy being observed, the Milky Way may be considered a pesky source of foreground radiation. Background and foreground radiation may consist of the combined emissions from many discrete sources or may be a more or less continuous distribution of radiation from our galaxy.

Cosmic background radiation, on the other hand, is predicted to remain as the dying glow from the big bang. It was first observed by Arno Penzias and Robert Wilson in 1965. (They won a Nobel Prize for this discovery in 1978). As discussed in Chapter 3, much of background and foreground radiation tends to be of non-thermal origin. The cosmic background radiation, however, is thermal.

In the group of pictures below (from Griffith Observatory and JPL), the entire sky is shown at (a) radio, (b) infrared, (c) visible, and (d) X-ray wavelengths. Each illustration shows the Milky Way stretching horizontally across the picture. It is clear that radio wavelengths give us a very different picture of our sky.



Star Sources

Many thousands of visible stellar objects have been discovered to also be strong emitters of radio frequency radiation. All such stars may be called radio stars.

It is helpful in discussing star types and activities to review stellar evolution. For a discussion of star birth, maturation, old age, and death, please read Chapters 20-22 in *Universe*, by William J. Kaufmann III, or Chapters 28-30 in *Abell's Exploration of the Universe*, by David Morrison, Sidney Wolff, and Andrew Fraknoi.

Variable Stars

Stars do not shine uniformly brightly all the time. Stars that show significant changes in brightness over periods we short-lived humans can perceive are of great importance to astronomy because of what we can surmise from those changes. And fortunately for radio astronomy, it has been discovered that stars whose output of visible radiation varies over short periods, either regularly or irregularly, have corresponding variations in their output of radio frequency emissions.

Some *variable stars* , such as *Cepheids* (SEE-fee-ids), are absolutely regular in their cyclic changes, varying from a few days to a few weeks. It has been found that stars with longer regular periods are always more luminous (emitting more energy) than those with shorter regular periods. Variable stars with very short periods (1.25 to 30 hours) are called *RR Lyrae variables*. None of these shorter period variables is bright enough to see with the naked eye. Because the intrinsic luminosities of Cepheids and RR Lyraes with similar periods are comparable, variable stars such as these can be used to work out interstellar and even intergalactic distances.

Other variable stars have much longer periods, are less regular in their cycles, and vary by a much greater magnitude. These are called *semi-regular variables*. The red giant Betelgeuse in the Orion constellation is an example. No period-luminosity relationship has been found for semi-regular variables.

Irregular variables have no set periods at all. They usually are young stars and their luminosities may vary over a very large range.

Flare stars are faint red dwarf stars (older and feebler than white dwarfs) that exhibit sudden increases in brightness over a period of a few minutes due to intense flare activity, fading back to their usual brightness within an hour or so. Typical flare stars are UV Ceti and AD Leonis.

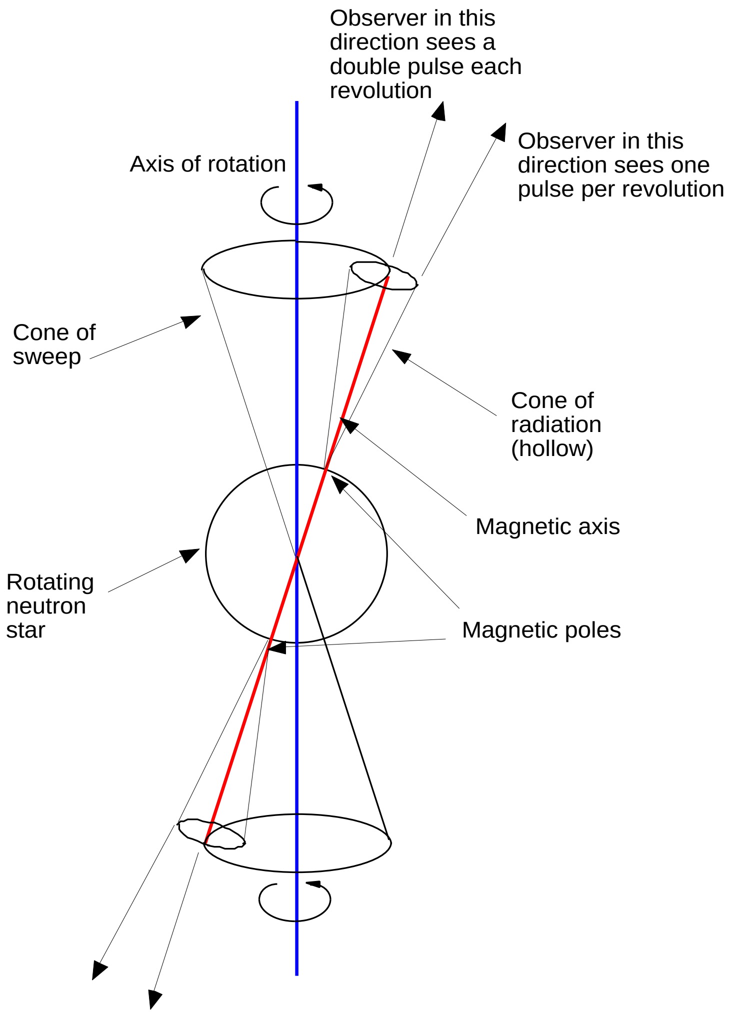
Binary (double) *stars* may produce apparently regularly varying radiation if the two stars eclipse one another in their orbits. Also, radio emissions from binaries are more common than for single stars. The interaction of stellar winds and magnetospheres, bow shocks, and tidal effects may contribute to the conditions producing radio frequency emissions.

Pulsars

Sometimes when a star goes supernova, all that is left after this most violent of processes is a cloud of expanding gas and the tiny remnant of extremely dense material only a few tens of kilometers in diameter. The supernova implosion is so intense that the protons and electrons in the atoms of the star are jammed together, thus canceling out their electrical charges and forming neutrons. This neutron star may be 1014 times as dense as water! It will have extremely powerful magnetic fields and may rotate very rapidly. Because the magnetic axis may not correspond to the spin axis, a beam of radiation emitted from the magnetic poles may seem to an observer to pulse like a rotating searchlight. Thus we call these rotating neutron stars *pulsars*. Although some pulsars are seen at visible and x-ray frequencies, many more are seen at radio frequencies.

Since 1967, when the first pulsar was detected by Jocelyn Bell, hundreds of pulsars have been discovered. The Crab pulsar spins at 30 times per second. The pulsar 1937+21 in Cygnus pulses 642 times per second. We receive this emission on Earth as if it were a signal produced by a cosmic clock. Over the brief period we have been observing them, however, they all them seem to be gradually slowing down. Their energy is dissipating with age. After correction for this effect, some millisecond pulsars are at least as accurate at timekeeping as the best atomic clocks. The rate at which pulsars slow down has been helpful in confirming aspects of Einstein's theory of general relativity. Also, the timing of pulsars can be useful in determining properties of the interstellar medium.

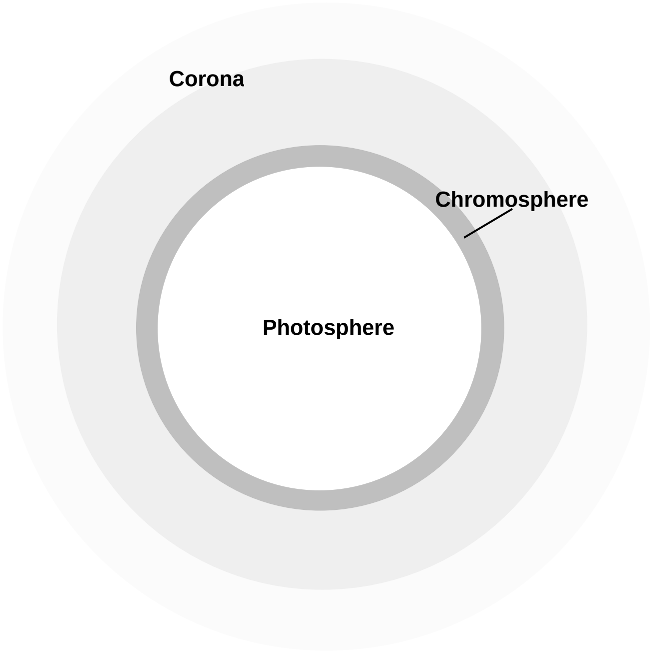
Pulsar


Observer in this direction sees a double pulse each revolution
Observer in this direction sees one pulse per revolution
Axis of rotation
Cone of sweep
Cone of radiation (hollow)
Magnetic axis
Rotating neutron star
Magnetic poles

Our Sun

The strongest extraterrestrial radio source we experience here on Earth is our own star. The Sun is a very ordinary star—not particularly massive or small, not particularly hot or cold, not particularly young or old. Perhaps we are fortunate it is so typical because from it we can learn much about stars in general.

Our Sun

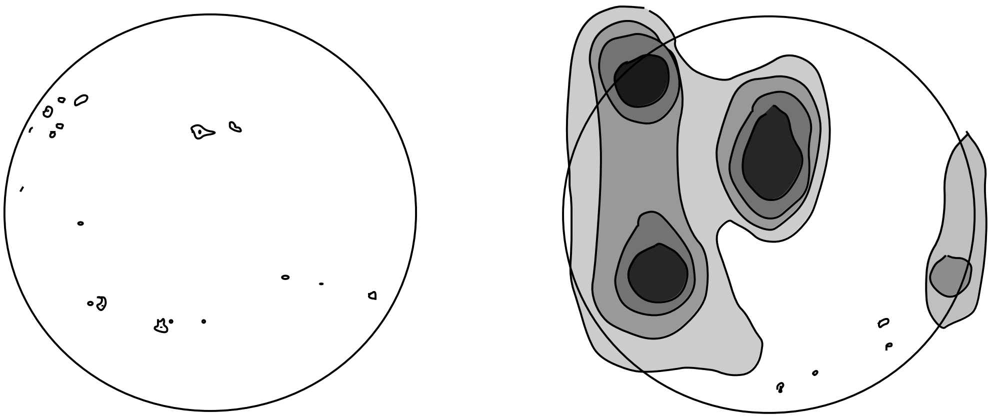


The photosphere is the part of the sun's atmosphere that emits most of the visible light, while the corona, the sun's outer atmosphere, is much less dense and emits only a very small amount of visible light. The chromosphere, cool and dim compared to the photosphere, forms the boundary between the photosphere and the corona.

The sun seems to have about an 11-year cycle of activity. When the sun is in a quiet phase, radio emissions from the photosphere (the part that also emits radiation in the visible wavelength) are in the wavelength range of 1 cm, while radio emissions from the corona approach a wavelength of one meter. The size of the radio solar disk appears only slightly larger than the optical solar disk as long as the telescope is tuned to only the 1-cm to 10-cm wavelength range. But at the longer wavelengths, the radio solar disk is much larger, including, as it does, the corona, which extends millions of kilometers above the photosphere.

Sunspots are darker appearing areas on the photosphere, and, as mentioned above, they seem to fluctuate in frequency over about an 11-year cycle. They appear darker because they are a "cool" 4,000°C relative to the surrounding 6,000°C surface. They are the centers of magnetic fields, apparently related to the sun's magnetic field. It is possible that the sun's magnetic lines of force periodically get "tangled" and destabilized since the sun's rate of rotation varies from the equator to the poles. Solar flares breaking out of the sun's upper atmosphere are usually associated with sunspot groups.

Comparison of Optical and Radio Solar Flares



Optical View

Radio Pattern

Solar flares emit short bursts of radio energy, with wavelengths observable from the ground from about 1 to 60 m (300-5 MHz). Sometimes during intense flares, a stream of high-energy cosmic ray particles is emitted, travelling at over 500-1000 km per sec. When these charged particles reach Earth's magnetic field, we get magnetic storms and the aurora. The pattern of radio emissions from solar flares appears to originate from a larger area of the solar surface than does the pattern of visible-range radiation, but it is still apparent that they are the result of the same activity.

The radiation associated with solar flares is circularly polarized, rather than randomly polarized as is usual from extraterrestrial sources. This polarization may be caused by electrons gyrating in the localized, intense magnetic field of the flare.

The sun is studied by radio astronomers both directly, by observing the actual radio emissions from the sun, and indirectly, by observing the effect of the sun's radiation on Earth's ionosphere.

Recap

1. The Milky Way galaxy is an example of a(n) ______________ source of radio emissions.
2. A single star is a _________________ discrete source.
3. Stars that show significant changes in brightness over short periods are called ________________ stars.
4. Cepheids with longer periods are always ____________ luminous than those with shorter periods.
5. It is believed that pulsars are rapidly spinning _____________ stars.
6. The strongest source of radio emissions that we experience on Earth is the __________.
7. Solar flares, associated with groups of sun spots, emit short bursts of ___________ ______________.

1. extended 2. localized 3. variable 4. more 5. neutron 6. sun 7. radio energy (or radio emissions)

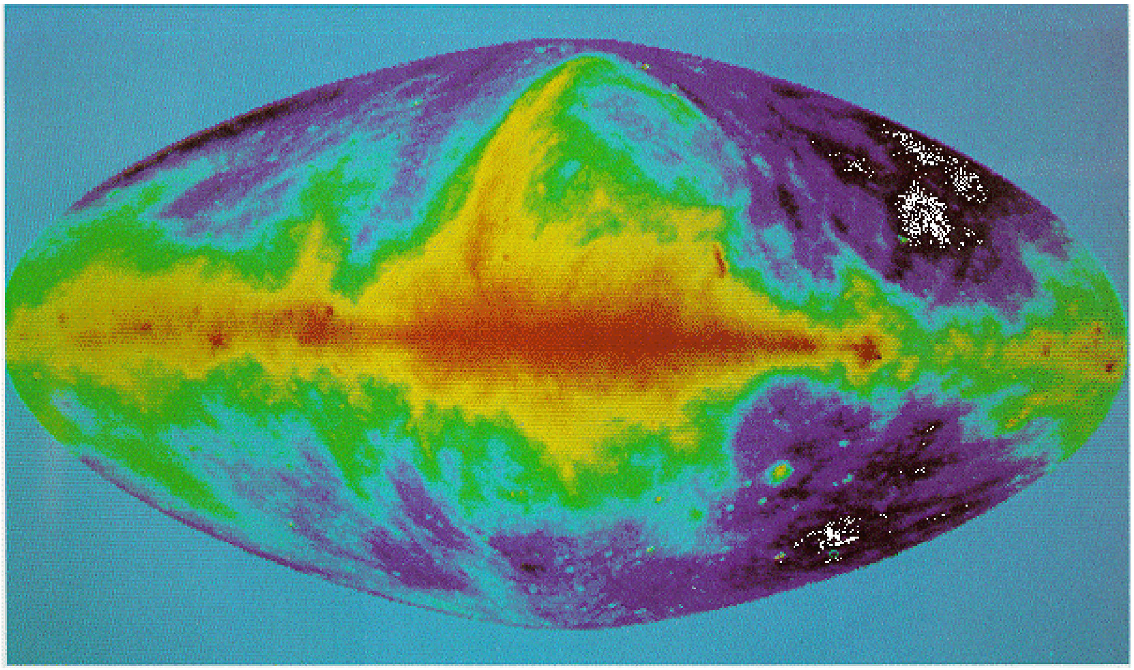
For Further Study

- *Cosmic background radiation:* Kaufmann, 532-535; Morrison et al., 616-619.
- *Star evolution:* Kaufmann, 364-420; Morrison et al., 467-520.
- *Our sun:* Kaufmann, 310-335; Morrison et al., 434-466.
- *Variable stars:* Kaufmann, 396-398, 477; Morrison et al., 488-492, 661.
- *Pulsars:* Kaufmann, 310-335; Morrison et al., 516-518, 529; Wynn-Williams, 119.

Galactic and Extragalactic Sources

We can think of extra-terrestrial radio emissions as originating either within our galaxy or outside our galaxy. Inside our galaxy, remnants of supernova explosions are strong sources of radio emissions.

Outside our galaxy, we find great variation in the radio emissions from different galaxies. So we have arbitrarily divided these other galaxies into “*normal*” and “*active*” galaxies.



Radio View of the Milky Way

Normal galaxies are not very strong sources. For example, the Great Andromeda Spiral, the largest galaxy in our so-called local group of galaxies, emits 10^{32} watts of power. In contrast, Cygnus A, over half a billion light years from Earth, is one of the most conspicuous radio sources in the sky, with a power output of 10^{38} watts. (See figures at end of Chapter 8 for a rough idea of the locations of these galaxies.)

Active galaxies include radio galaxies, quasars, blasars, and Seyfert Galaxies.

Radio galaxies emit a very large quantity of radio waves.

Quasars, coined from the phrase “quasi-stellar radio source,” may be pouring out energy a million times more powerfully than a normal galaxy. Quasars are the most distant objects we have detected, some approaching 15 billion light years distant—their radiation requiring nearly the age of the universe to reach us. And some seem to be receding from us at a rate 90% the speed of light.

Blasars are galaxies with extremely bright centers, whose luminosity seems to vary markedly over a very short period.

Seyfert galaxies are also intense sources of radiation whose spectra include emission lines.

In all these, the predominant radiation-producing mechanism is synchrotron radiation. An active galaxy may radiate 1,000,000 times more powerfully in the radio frequencies than a normal galaxy. Much of the radiation often seems to come from the nucleus of the galaxy. Astronomers are now investigating the plausibility of a “unified theory of active galaxies,” which would account for the varying behavior observed by all these types of active galaxies. It may be that these galaxies have a black hole or a supermassive black hole at their centers, and their appearance to us depends on the angle at which we are observing them.

Please read Chapter 27 of *Universe*, by Kaufmann, for more information, including many color photos, about these fascinating and mysterious objects.

Planetary Sources and Their Satellites

Unlike stars, the radio energy observed from planets and their satellites (except the Jupiter system and, to a small extent, Saturn) is mostly thermal blackbody radiation. The wavelengths of radiation observed from these bodies gives us fairly precise indications of their temperatures, both at their surfaces and at varying depths beneath their surfaces.

The Jupiter System

By far the most interesting planet for radio astronomy studies is Jupiter. As beautiful and fascinating as it is visually, it is even more fascinating and complex to observe in the radio frequency range. Most of the radiation from the Jupiter system is much stronger at longer wavelengths than would be expected for thermal radiation. In addition, much of it is circularly or elliptically polarized—not at all typical of thermal radiation. Thus, it must be concluded that non-thermal processes similar to those taking place in galaxies are at work. That is, ions and electrons accelerated by the planet's spinning magnetic field are generating synchrotron radiation.

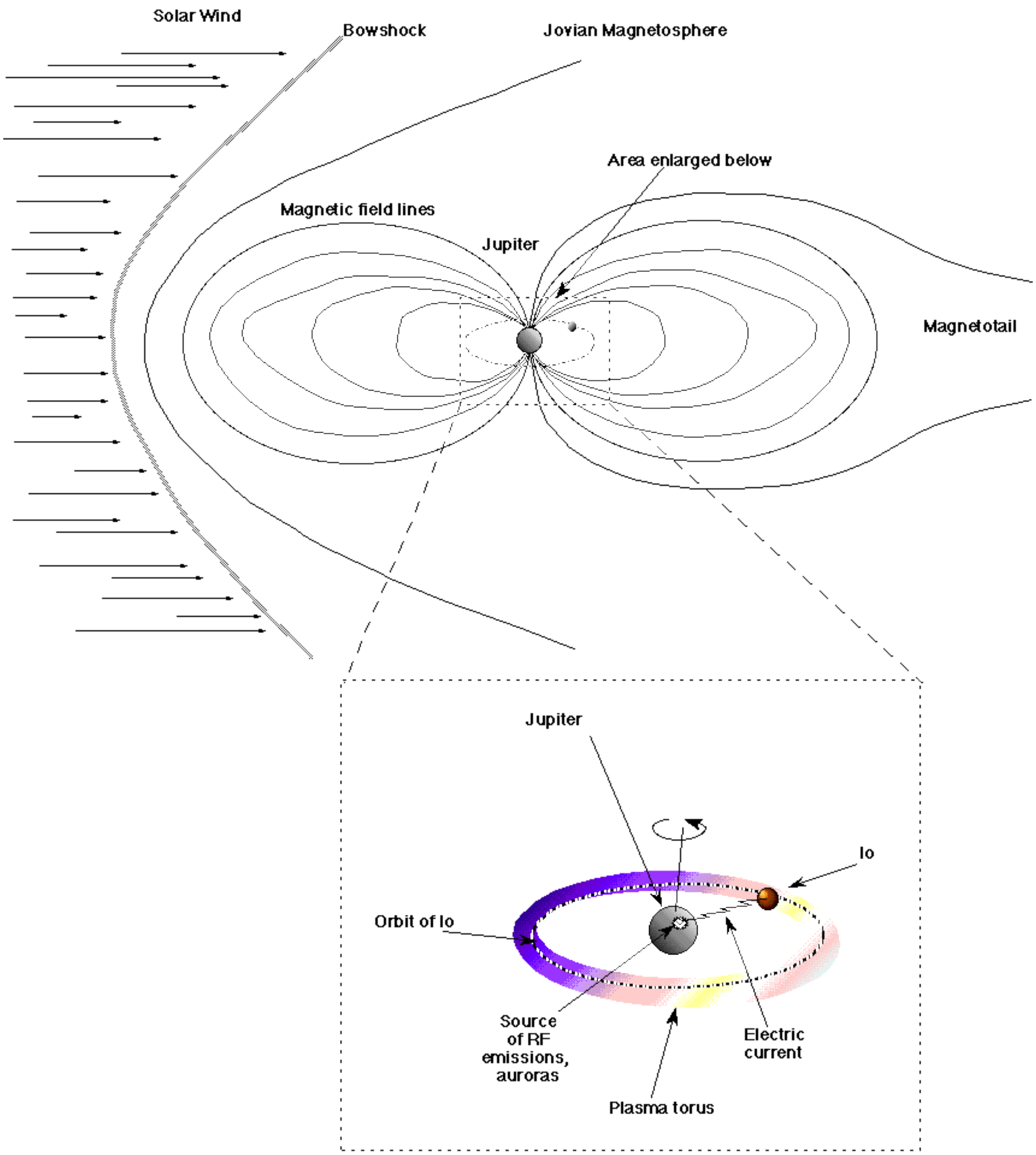
Jupiter is 318 times as massive as Earth. Its magnetic axis is tilted 15° from its rotational axis and offset from the planet's center by 18,000 km. Its polarity is opposite that of Earth (that is, a compass needle would point south).

Jupiter's surface magnetic field is 20 to 30 times as strong as that of Earth. The *magnetosphere* of a planet is the region around it in which the planet's magnetic field dominates the interplanetary field carried by the solar wind. If we could see Jupiter's magnetosphere from Earth, it would appear as large as our moon!

The farther a planet is from the sun, the weaker will be the pressure from the solar wind on the planet's magnetosphere. Thus, Jupiter's magnetic field, already quite intense, has considerably less pressure holding it close to the planet than does Earth's magnetic field. Jupiter's magnetosphere expands and contracts with variations in the solar wind. Its upstream (closest to the sun) boundary (called the *bowshock*) varies from 50 to 100 Jupiter radii and envelopes Jupiter's four large Galilean satellites. (Sixteen Jupiter satellites have been discovered; the Galilean satellites are by far the largest).

The magnetosphere of a planet traps plasma, as magnetic lines of force catch protons and electrons carried on the solar wind and atoms that escape upward from the planet's atmosphere. In the case of Jupiter, since the magnetosphere is so large, it also traps atoms from the surfaces of the satellites orbiting within it. Io, the innermost Galilean satellite, is an especially rich source of oxygen and sulfur ions from its many violently active volcanoes. Io is estimated to contribute 10 tons of material to the magnetosphere per second!

Magnetosphere of Jupiter



As a matter of fact, a predominant feature of Jupiter's magnetosphere is the plasma torus that surrounds the planet, corresponding closely with the orbit of Io, which is at about five Jupiter radii. It is an intensely radiating plasma within a slightly less active outer plasma. To add to the adventure, as Io orbits through the magnetic field lines, an electric current of up to 5 million Amps is generated between Io and the planet! Where this current reaches the atmosphere of Jupiter, it generates strong radio frequency emissions that can be associated with the orbital position of Io. The current also generates auroras in the upper atmosphere of Jupiter.

The Goldstone-Apple Valley radio telescope will be used to measure time variable radio frequency emissions from Jupiter's magnetic field. These observations can provide new information about the magnetosphere, the plasma torus, and the rotation of Jupiter's core and how it differs from the rotation of the visible atmosphere.

Sources of Interference

Radio frequency "noise" complicates the task of the radio astronomer, at times making it difficult to distinguish emissions from an object under study from extraneous emissions produced by other nearby sources. Interference comes from both natural and artificial sources, the latter ones becoming a bigger problem every day. By international agreement (the World Administrative Radio Conference), certain frequencies have been allocated strictly for radio astronomy (Kraus, p. A 24). However, there is disagreement about how far beyond the restricted limits is acceptable "spillover" (for example, radio broadcasters may think 10mm over their wavelength limit is acceptable, while radio astronomers may think .001 mm is too much). In some countries, the restrictions are not enforced, so may as well not exist.

Natural sources of interference include:

- Radio emissions from the Sun
- Lightning
- Emissions from charged particles (ions) in the upper atmosphere

Among the growing list of human-made sources of interference are:

- Power-generating and transforming facilities
- Airborne radar
- Ground-based radio and television transmitters (which are getting more powerful all the time)
- Earth-orbiting satellite transmitters and transponders, including Global Positioning Satellites (GPS)
- Cellular phones

Human-generated interference that originates on the ground (such as radio and television transmissions) travels along the ground and over the horizon. It used to be that such interference tended to be weak at ground level, increasing in strength with height above ground. For this reason, most radio telescopes have been situated in valleys or other low places, unlike optical telescopes which are often built on mountain tops. (The exceptions are radio telescopes built for studying sub-millimeter wavelengths, as mentioned in Chapter 4). However, more and more, interference at ground level is becoming a problem even for low-lying radio telescopes.

Recap

1. Galaxies that emit up to 106 times more radio frequency energy than is normally observed from galaxies are called _______________ _____________.
2. ________________ are the most distant objects astronomers have detected.
3. Quasars, blasars, and radio galaxies are examples of __________________ radio sources.
4. The planet in our solar system that emits the most intense radio waves is ______________.
5. An interesting feature of Io is the ____________ ___________, which surrounds Jupiter and corresponds closely with Io's orbit.
6. Lightning is an example of a source of natural RF __________________ for radio astronomy studies.

1. radio galaxies 2. Quasars 3. extra-galactic 4. Jupiter 5. plasma torus 6. interference

For Further Study

- *Our galaxy:* Kaufmann, 454-473; Morrison et al., 539-558.
- *Galaxies and galactic evolution:* Kaufmann, 474-503; Morrison et al., 559-586.
- *Active galaxies:* Kaufmann, 504-525; Morrison et al., 576-577.
- *Jupiter and its magnetosphere:* Kaufmann, 228-240; Morrison et al., 284-288.

Chapter 7

Mapping the Sky

Objectives: When you have completed this chapter, you will be able to describe the terrestrial coordinate system; define and describe the relationship among the terms commonly used in the “horizon” coordinate system, the “equatorial” coordinate system, the “ecliptic” coordinate system, and the “galactic” coordinate system; and describe the difference between an azimuth-elevation antenna and hour angle-declination antenna.

In order to explore the universe, coordinates must be developed to consistently identify the locations of the observer and of the objects being observed in the sky.

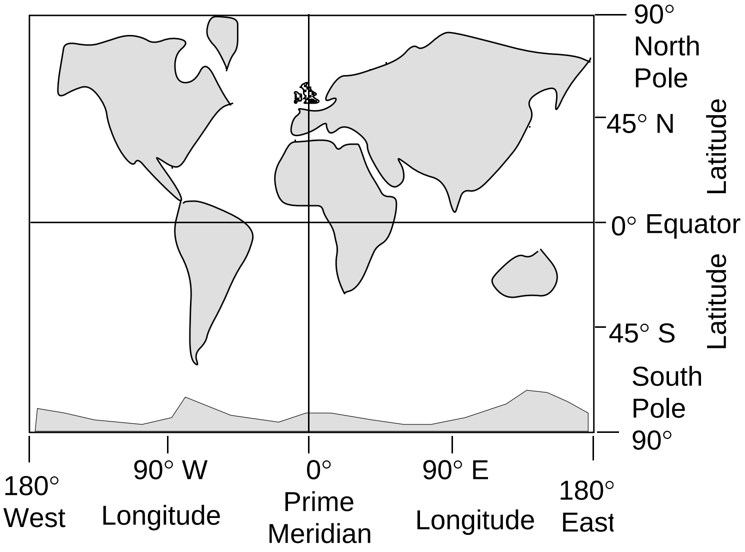
Because space is observed from Earth, Earth’s coordinate system must be established before space can be mapped. Earth rotates on its axis daily and revolves around the sun annually. These two facts have greatly complicated the history of observing space. However, once known, accurate maps of Earth could be made using stars as reference points, since most of the stars’ angular movements in relationship to each other are not readily noticeable during a human lifetime. Although the stars do move with respect to each other, this movement is observable for only a few close stars, using instruments and techniques of great precision and sensitivity.

Earth’s Coordinate System

A great circle is an imaginary circle on the surface of a sphere whose center is at the center of the sphere. The *equator* is a great circle. Great circles that pass through both the *north and south poles* are called *meridians*, or lines of *longitude*. For any point on the surface of Earth a meridian can be defined. The *prime meridian*, the starting point measuring the east-west locations of other meridians, marks the site of the old Royal Observatory in Greenwich, England. Longitude is expressed in degrees, minutes, and seconds of arc from 0 to 180 degrees eastward or westward from the prime meridian. For example, the GAVRT is located at 116.805 degrees, or 116 degrees, 48 minutes, 18 seconds of arc westward of the prime meridian: 116deg. 48' 18" W.

The starting point for measuring north-south locations on Earth is the equator (the equator is the imaginary circle around the Earth which is everywhere equidistant from the poles). Circles in parallel planes to that of the equator define north-south measurements called parallels, or lines of *latitude*. Latitude is also expressed in degrees, minutes, and seconds of the arc subtended from the center of the Earth. The GAVRT is located at 35.300 degrees, or 35 degrees, 18 minutes of arc north of the equator: 35deg. 18' 00" N.

Terrestrial Coordinates



Revolution of Earth

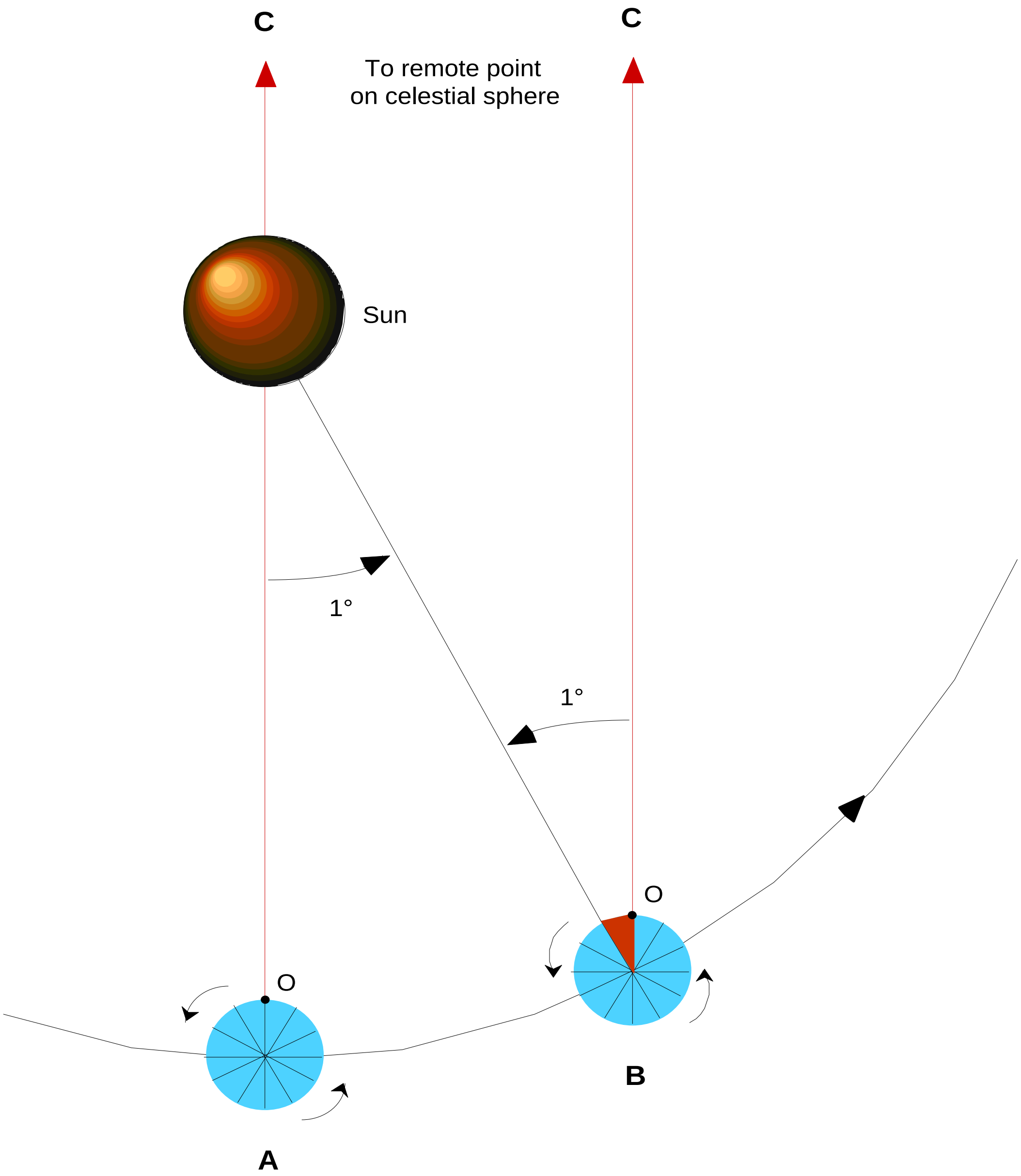
Earth revolves around the sun in 365 days, 6 hours, 9 minutes with reference to the stars. Its mean orbital speed is about 100,000 km per hour. The 6 hours, 9 minutes adds up to about an extra day every fourth year, which is designated a leap year, with the extra day added as February 29th.

Solar vs. Sidereal Day

The Earth rotates on its axis relative to the sun every 24.0 hours mean solar time, with an inclination of 23.5 degrees from the plane of its orbit around the sun. Mean solar time represents an average of the variations caused by Earth's non-circular orbit. Earth’s rotation period relative to the other stars (sidereal time) is 3 minutes 56.55 seconds shorter than the mean solar day.

The following figure explains this apparent discrepancy. Suppose the day starts when Earth’s orbital position is at A and the Sun on the meridian (that is, directly above the local southern horizon) of an observer at point O on Earth’s surface. When Earth has completed one rotation with respect to the distant stars (C), the Sun will not yet have advanced to the meridian for the observer at point O due to the movement of Earth along its orbit about the sun from A to B. To complete a solar day, Earth must rotate an additional 1/365 of a full turn, which takes nearly 4 minutes. Thus the solar day is about 4 minutes longer than the sidereal day. Therefore, a clock geared to sidereal time, in the space of one year, falls behind a regular clock by an amount equal to about one solar day (24 hours).

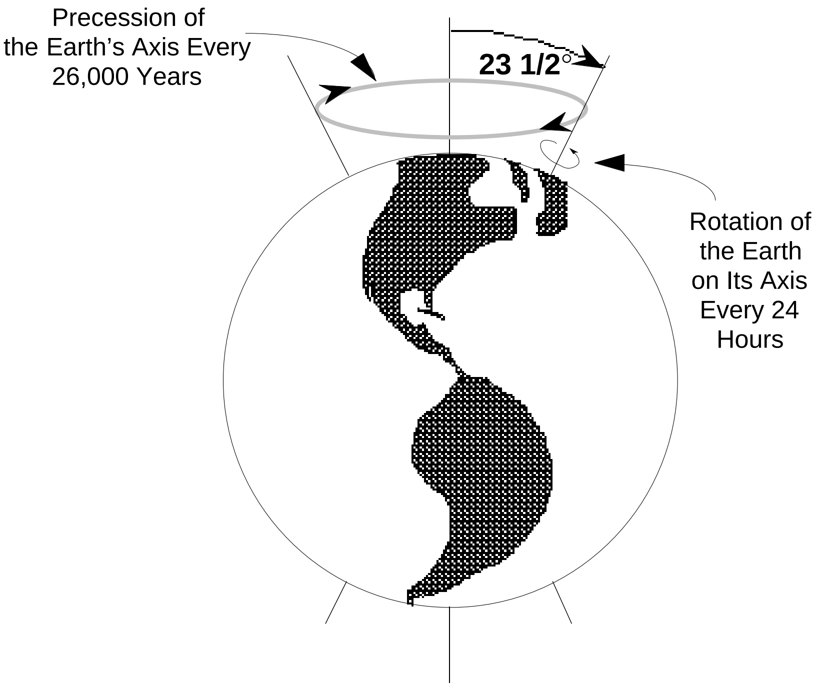
Solar Day vs. Sidereal Day



Precession of the Earth Axis

Like a spinning top with a slow wobble, Earth’s axis slowly wobbles, or *precesses*, relative to its orbital plane. The moon's gravity, primarily, and to a lesser degree the sun's gravity, acting on Earth's oblateness tries to move Earth's axis perpendicular to the plane of Earth's orbit. However, due to gyroscopic action, Earth's poles do not “right themselves” to a position perpendicular to the orbital plane. Instead, they precess at 90 degrees to the force applied. This precession causes the axis of Earth to describe a circle having a 23.5 degree radius relative to a fixed point in space over about 26,000 years.

Precession of the Earth



Astronomical Coordinate Systems

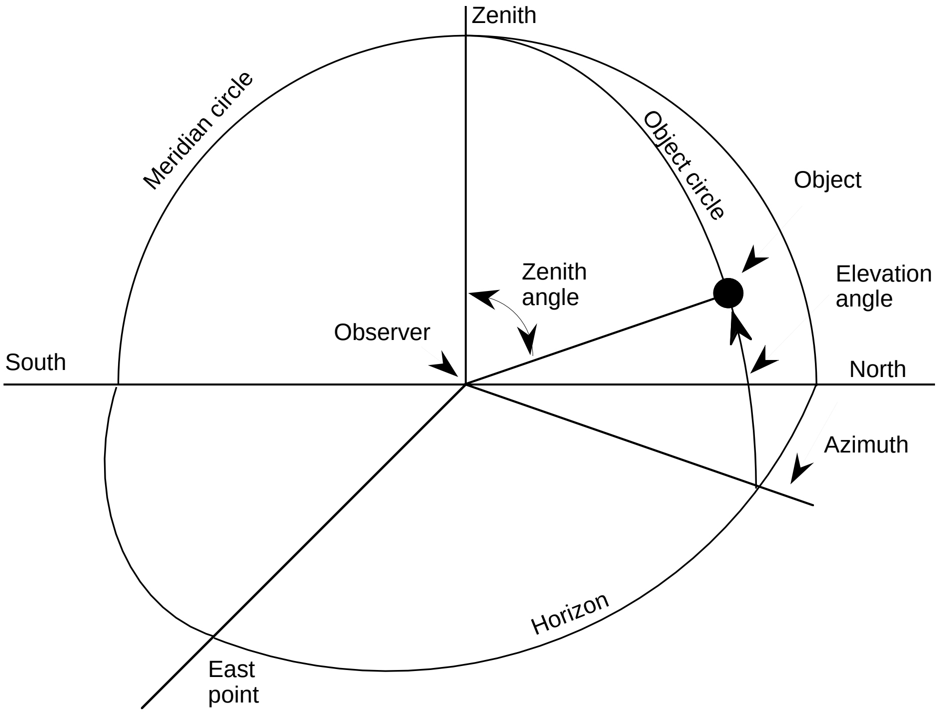
Mapping locations on Earth is easy because, except for an occasional earthquake and the slow glide of the tectonic plates, things stay put on Earth’s surface. But in the sky, things are moving, and of course we are constantly moving with respect to the sky. Therefore, coordinate systems for locating objects in the sky have to take all this movement into account. Several systems have been devised to describe positions of celestial objects relative to Earth. The choice of which one to use depends on what you are observing and how.

Horizon Coordinate System

The horizon is defined as the dividing line between the Earth and the sky, as seen by an observer on the ground. In the *horizon coordinate system* the *astronomical horizon* is the hypothetical interface between Earth and sky, as would be seen by the observer if the surrounding terrain were perfectly flat (as out on a calm ocean).

Referring to the drawing below, *zenith* is the point straight overhead, perpendicular to the horizon plane, and *nadir* is the point directly under the observer. A vertical circle through an object in the sky and the zenith is the *object circle*. The coordinates of the object are given by the *azimuth*, which is the horizontal angle from north clockwise to the object circle, and the altitude or *elevation* angle, which is measured upward from the horizon to the object. The great circle through the north and south points on the horizon and the zenith is called the *meridian*.

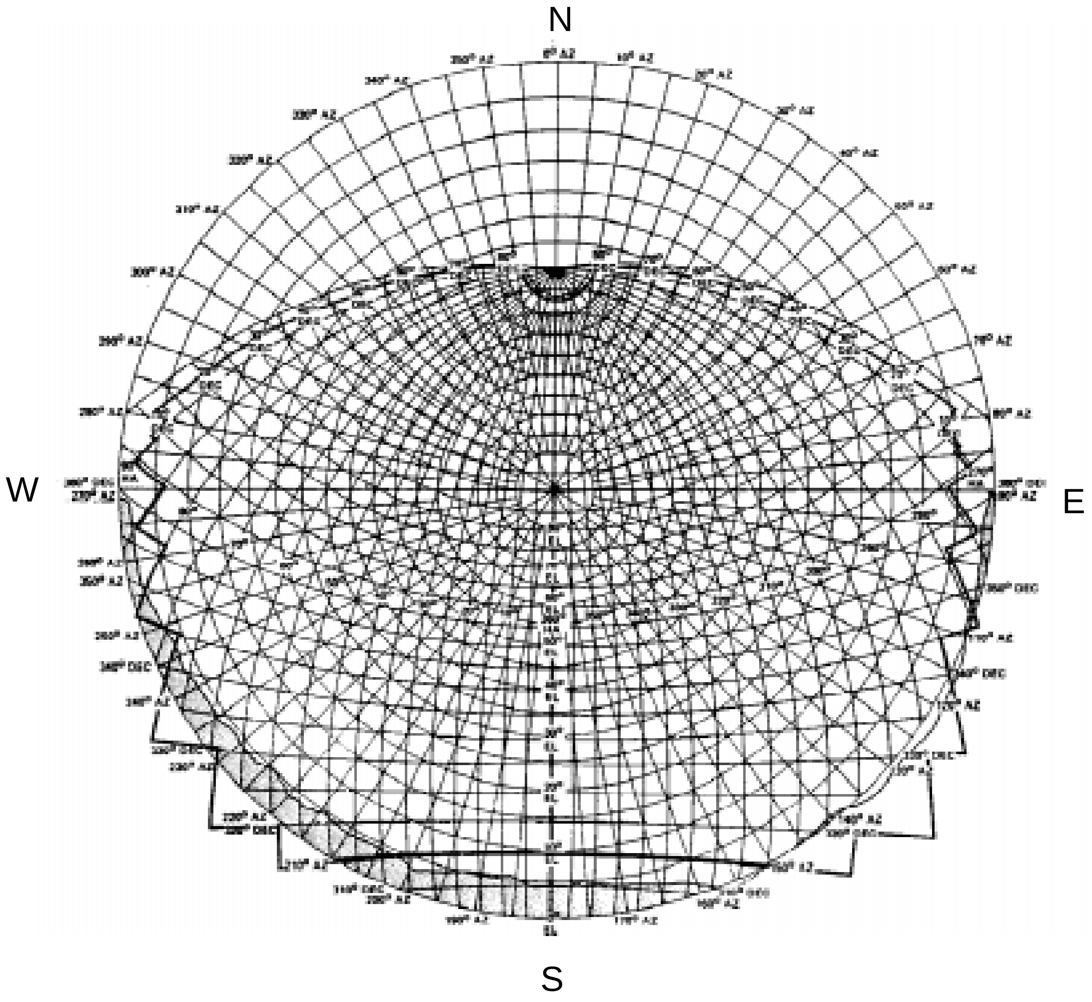
Horizon Coordinate System



A *horizon mask* is a diagram that maps in silhouette the horizon in 360˚ of azimuth as actually seen by the observer, including hills, valleys, mountains, buildings, trees, and anything else that would hide from view any part of the sky that would be visible if the terrain were perfectly flat. A horizon mask for the GAVRT is shown on the next page.

In the horizon system, the coordinates of an object in the sky change throughout the day with Earth's rotation. While the azimuth and elevation angles are convenient for positioning a radio telescope antenna that rotates around horizontal and vertical axes (AZ-EL mounted), they are not so convenient for specifying the position of a celestial object. Better for this purpose are systems using fixed coordinates, such as the equatorial coordinate system.

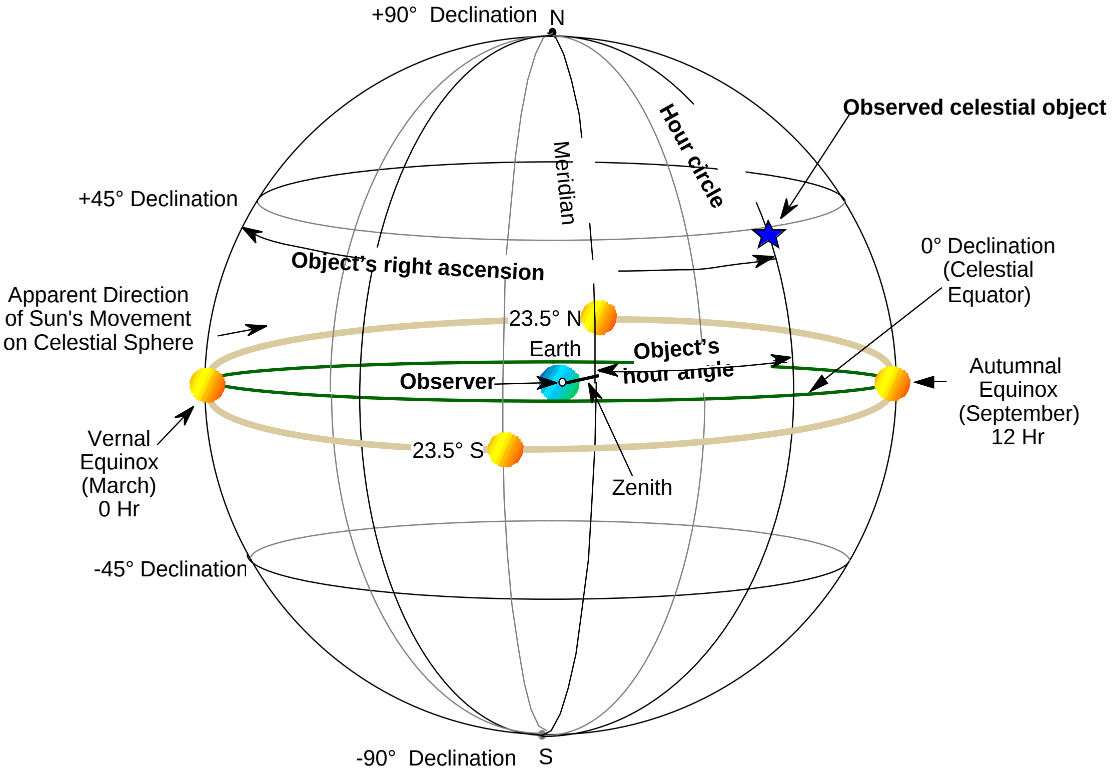
Horizon Mask for the Goldstone-Apple Valley Radio Telescope



Equatorial Coordinate System

In the *equatorial coordinate system*, Earth's equator is the plane of reference. Earth's axis of rotation points to the north and south *celestial poles*. The *celestial sphere* is as large as the known universe, and Earth is at the center of this sphere. The celestial poles do not move as Earth rotates. For an observer standing at Earth's equator, the celestial poles are on opposite horizons at exactly the north and south points, and the *celestial equator* passes overhead going exactly from the east to west horizon.

Equatorial Coordinate System



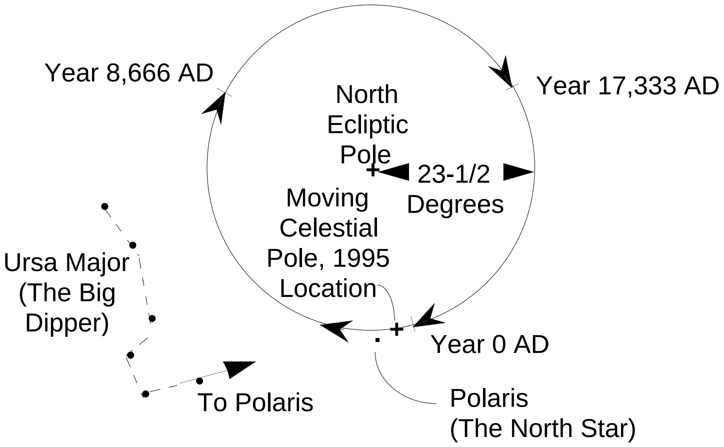
To describe an object's location in the sky, we imagine a great circle through the celestial poles and the object and call this the object's *hour circle*. Where the sun in its path crosses the celestial equator each year around March 21 is called the *vernal equinox*, and it is this line that is the reference for the east-west coordinate of the object. Because Earth's axis is inclined 23.5˚ to the plane of its orbit around the sun, objects in the solar system (such as the planets and, from our perspective, the sun) move across the celestial sphere not along the equator, but rather in their own orbits, most of which are in nearly the same plane as Earth's orbit. This imaginary path of the sun's apparent motion, called the ecliptic, is a curving line that runs around the sphere ranging between 23.5˚ north and 23.5˚ south. The constellations of the zodiac all lie on the ecliptic. The object's elevation above the celestial equator is called *declination*.

The coordinates of the object, then, are given by its *declination* and its *right ascension* or hour angle between the object's hour circle and the vernal equinox. Declination is expressed in degrees (0° to +90° if north of the equator, 0° to -90° if south of the equator). Right ascension is expressed either in degrees (0° to 360° measured eastward from the vernal equinox) or, more commonly, in hours, minutes, and seconds of time (0 to 24 hours).

Declination and right ascension are absolute coordinates regardless of the observer's location on Earth or the time of observation. The only exception is due to the slight 26,000-year cyclic change in the equatorial coordinates because of the precession of Earth's axis. Precession causes the stars to appear to shift west to east at the rate of .01 degree (360 degrees/26,000 years) with respect to the vernal equinox each year. For example, in the time of ancient Rome, the vernal equinox was located in the constellation of Aries. It is now moving into the constellation of Aquarius.

Precessional Path of the North Celestial Pole

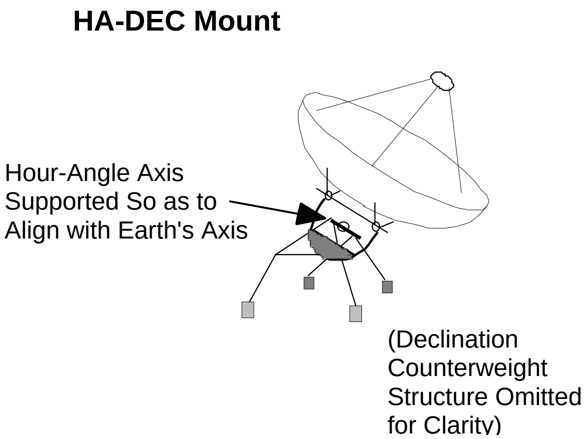
(Earth's Axis Projected on the Northern Sky)

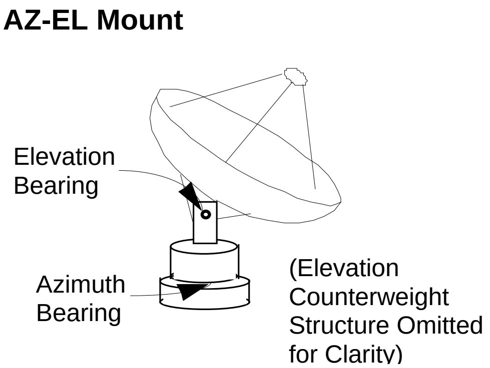


For this reason, sky almanacs identify the date and time of the instant used as the date of reference, or *epoch*, and provide equations for updating data based on the almanac to the current date. Epochs are named in 50-year increments. The 1950 epoch, for example, gives the coordinates precisely as they were on January 1, 1950.

Coordinates may also be given relative to the observer's location and time of observation. The great circle that passes through the celestial poles and the zenith is called the *meridian circle*. The angle between the object's hour circle and the meridian circle is the object's *hour angle*. The hour angle increases with time, being negative before the object's hour circle crosses the meridian and positive afterwards. Hour angle is measured either in degrees or hours, minutes, and seconds of sidereal time.

Radio telescopes are designed with mountings that are engineered to take best advantage of either the hour angle-declination (HA-DEC) coordinate system or the azimuth-elevation (AZ-EL) system (also called the altitude-elevation system, or ALT-EL). In an HA-DEC system, the HA axis is parallel to Earth's axis of rotation. In this way, since Earth is turning toward the east, the telescope is mounted to turn toward the west (backwards) on an axis exactly parallel to Earth's, thus cancelling out the east-west motion and simplifying the task of tracking objects in the sky. Thus, the mounting built for a telescope near the equator would appear different from one built for use in high latitudes. AZ-EL systems would appear the same no matter where on Earth they are being used.





HA-DEC antenna mounting systems require an asymmetrical structural design unsuited to the support of very heavy structures. Their advantage is that motion is required mostly in only one axis to track an object as Earth rotates, although this advantage has largely been obviated by the use of digital computers that can drive both axes of AZ-EL systems properly while they track. The GAVRT uses an HA-DEC mount.

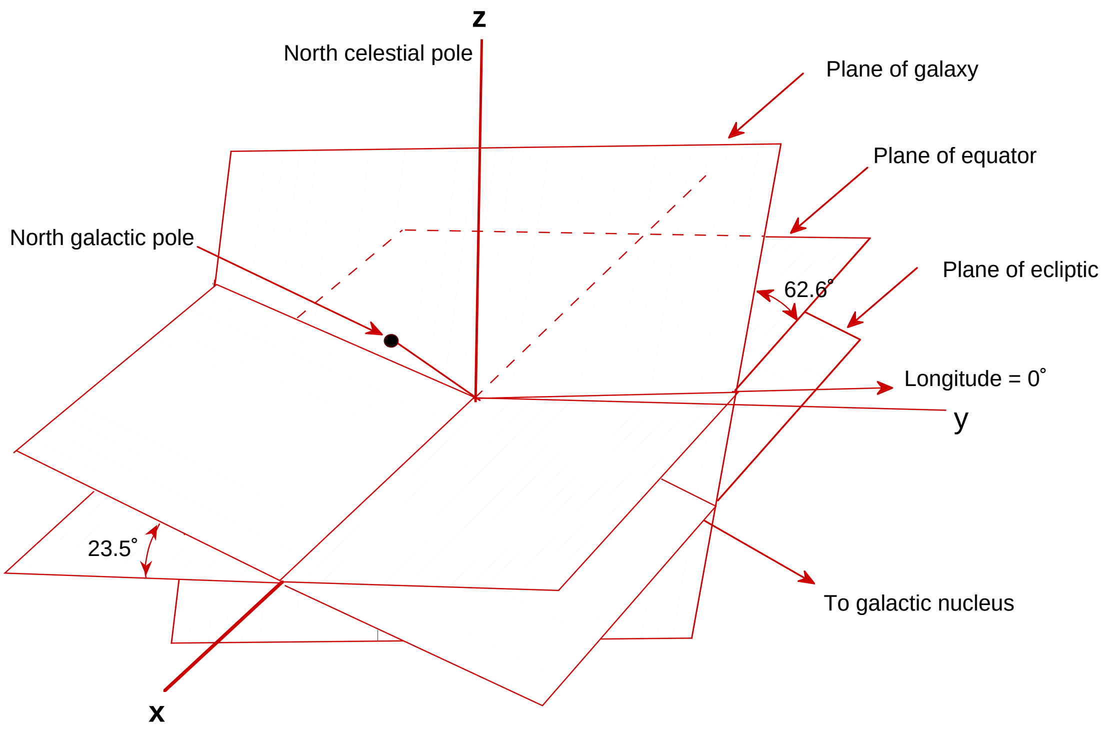
Ecliptic Coordinate System

In the ecliptic coordinate system, the reference is the plane of the ecliptic—that is, the plane formed by Earth's orbit around the sun. The orbits of the other planets in the solar system, with the except of Pluto, lie within 7° of this plane. (Pluto's orbit is inclined 17° to the ecliptic.) The coordinates of an object are given as celestial longitude, measured eastward along the ecliptic from the vernal equinox, and celestial latitude, measured north (+) or south (-) from the ecliptic. This system is handy for studying the solar system.

Galactic Coordinate System

In the galactic coordinate system, the reference is a plane through the sun parallel to the mean plane of the galaxy. By specifying the orientation of the north galactic pole in terms of its equatorial coordinates, equatorial coordinates can be converted into galactic coordinates, and vice versa, using transformation equations on a pocket calculator.

Galactic Coordinate System



Latitude in this system is given in degrees, + toward the north galactic pole, - toward the south galactic pole. Longitude is measured along the galactic equator to the east from the galactic center, with 0° at the intersection of the galactic equator with the celestial equator.

Recap

1. A sidereal day is approximately four minutes _____________ than a solar day.
2. The period of the precession of Earth's axis is about ___________ years.
3. ___________ is the point directly over the observer's head.
4. In the horizon system, an object's coordinates are given in _____________ for the vertical coordinate and ______________ for the horizontal coordinate.
5. In the equatorial coordinate system, objects in the sky are imagined to be positioned on the inside surface of a huge celestial _____________.
6. A great circle through the celestial poles and an observed object is called the object's _________ _____________.
7. The ______________ ________________ is the point on the celestial sphere where the sun crosses the intersection of the celestial equator and the plane of Earth's orbit around the sun (the ecliptic).
8. In the equatorial system, an object's coordinates are given in ____________ for the north-south coordinate, and ____________ _______________ for the east west coordinate.
9. In an hour angle-declination (HA-DEC) radio telescope antenna, the HA axis is parallel to ___________ ____________ _________.
10. Because Earth rotates on its axis once in 24 hours, a HA-DEC telescope can track a star by rotating in the ______________ direction every 24 hours.

1. shorter 2. 26,000 3. Zenith 4. elevation, azimuth 5. sphere 6. hour circle 7. vernal equinox 8. declination, right ascension 9. Earth's rotation axis 10. opposite

For Further Study

- *Precession of Earth's axis:* Kaufmann, 26-29; Morrison et al., 70-72.
- *Sidereal time:* Kaufmann, 31; Morrison et al., 83-84.
- *Astronomical coordinate and timekeeping systems:* Morrison et al., 75-86, 651

Chapter 8

Our Place in the Universe

Objectives: When you complete this chapter, you will be able to describe the relative position of Earth in the solar system and our solar system in the galaxy; describe the approximate size of the known universe; and summarize the major issues astronomers have considered in the search for extraterrestrial intelligence.

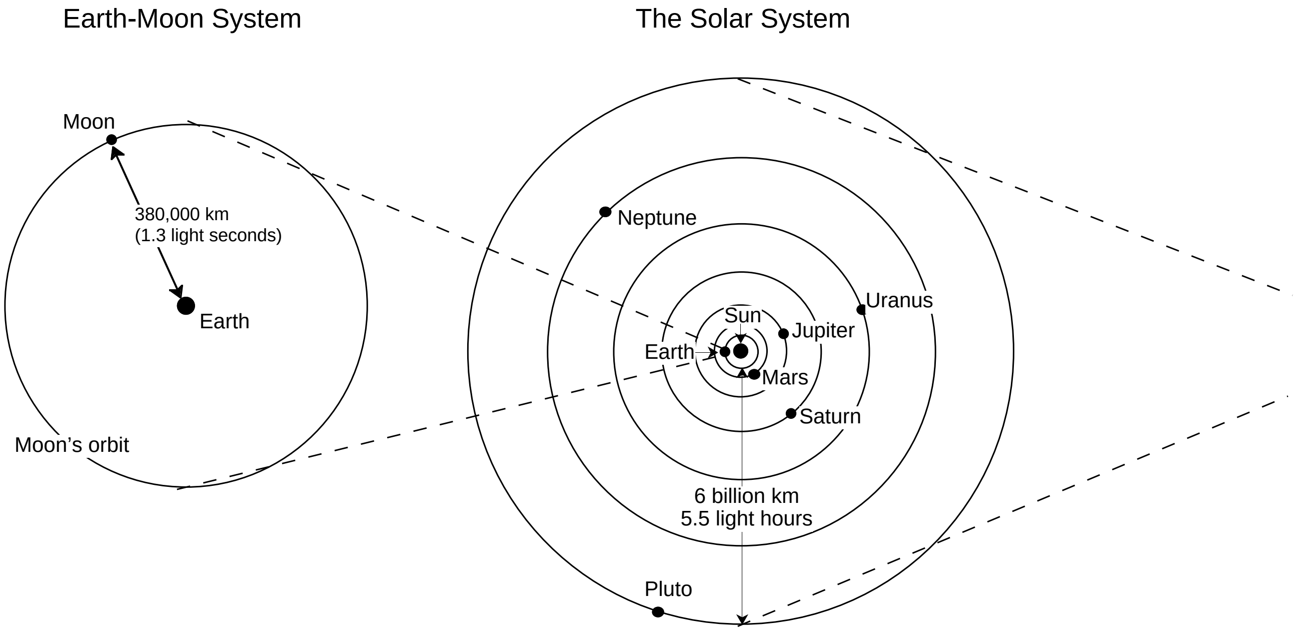
The Universe in Six Steps

The vastness of the universe is unimaginable for us humans. Perhaps the best we can do is to try to conceive a model of the universe that begins to show us our relative size and position, at least in our local neighborhood.

Gareth Wynn-Williams in *The Fullness of Space* uses the following analogy to help demonstrate some of these distances:

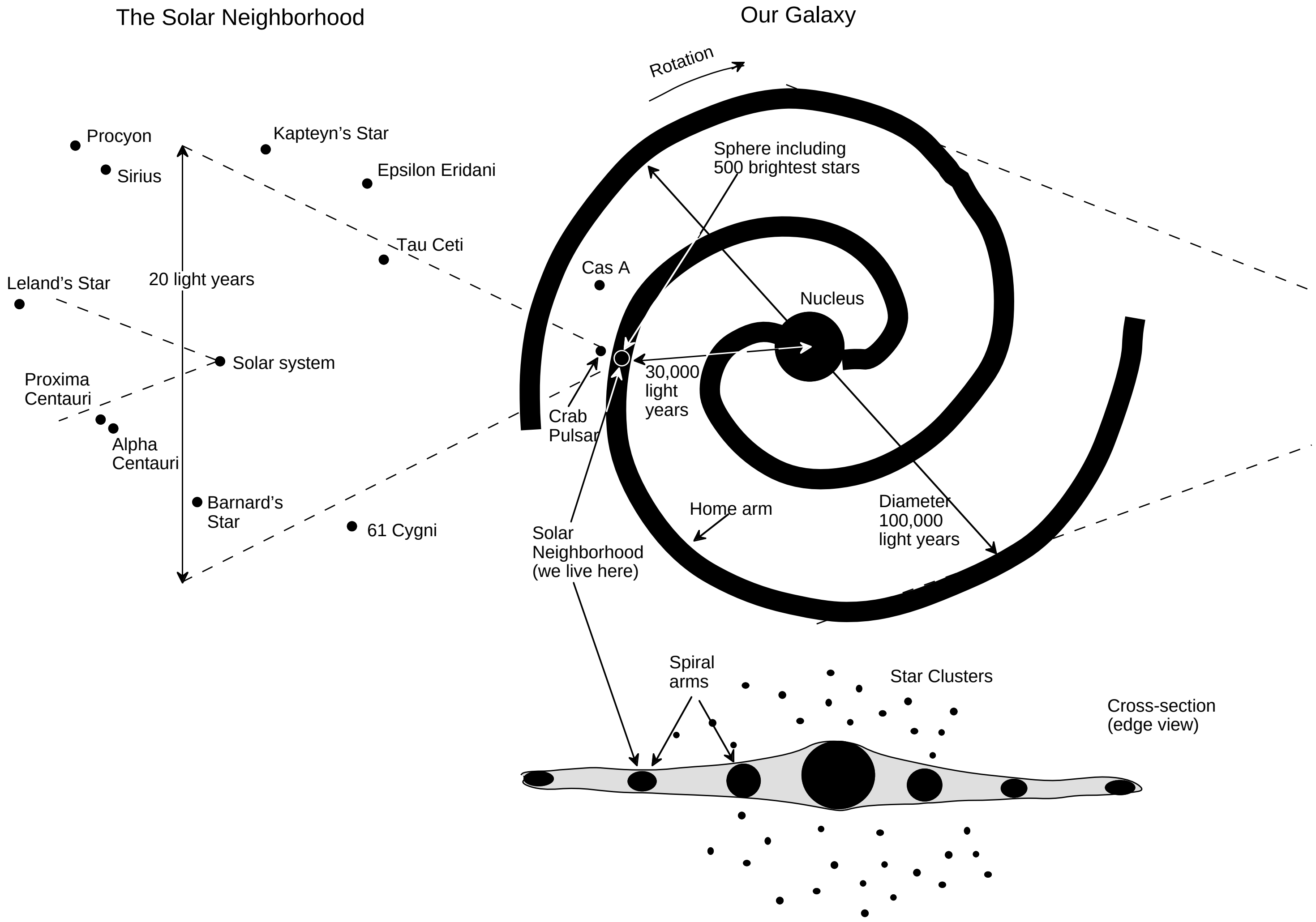
> Some idea of the vastness of the Universe may be gained by considering a model in which everything has been scaled down by a factor of a billion. In this model the Earth would have the dimensions of a grape. The Moon would resemble a grapeseed 40 cm away while the Sun would be a 1.4-meter diameter sphere at a distance of 150 meters. Neptune would be more than 4 km away. On this one-billionth scale, the nearest star would be at a distance of 40,000 km – more than the actual diameter of the Earth. One would have to travel five thousand times farther yet to reach the center of the Milky Way Galaxy, another 80 times farther to reach the next nearest spiral galaxy, and another several thousand times farther still to reach the limits of the known Universe.

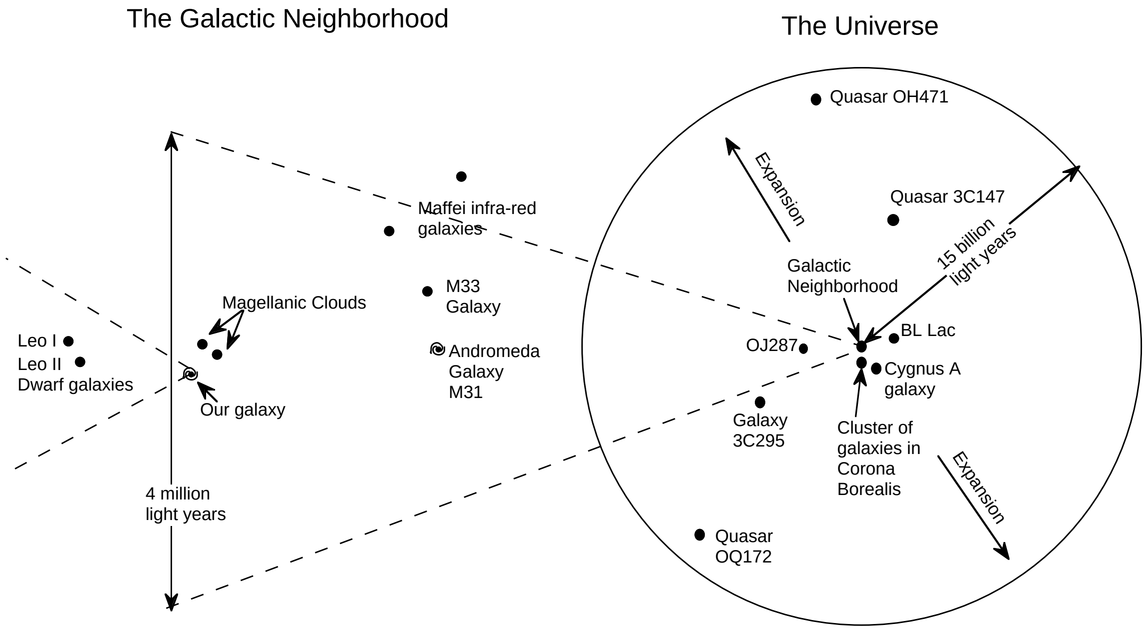
To further make our point, the following drawings (from Kraus, 1986) represent the universe in six steps: (1) the Earth Moon system, (2) the solar system, (3) the solar neighborhood, (4) our galaxy, (5) the galactic neighborhood, and (6) the universe.



Orbits not to scale. This table gives mean distance from sun of each planet in astronomical units (AU). (1 AU = mean Earth-sun distance.)

Mercury	0.39
Venus	0.72
Earth	1.00
Mars	1.52
Jupiter	5.20
Saturn	9.54
Uranus	19.19
Neptune	30.06
Pluto	39.53


The Solar Neighborhood
Our Galaxy
Rotation
Procyon
Sirius
Kapteyn's Star
Epsilon Eridani
Tau Ceti
Leland's Star
20 light years
Solar system
Proxima Centauri
Alpha Centauri
Barnard's Star
61 Cygni
Sphere including 500 brightest stars
Cas A
Nucleus
30,000 light years
Crab Pulsar
Home arm
Diameter 100,000 light years
Solar Neighborhood (we live here)
Spiral arms
Star Clusters
Cross-section (edge view)


The Galactic Neighborhood
The Universe
Quasar OH471
Expansion
Quasar 3C147
15 billion light years
Maffei infra-red galaxies
Galactic Neighborhood
M33 Galaxy
Magellanic Clouds
BL Lac
Leo I
OJ287
Andromeda Galaxy M31
Leo II
Dwarf galaxies
Cygnus A galaxy
Our galaxy
Galaxy 3C295
Cluster of galaxies in Corona Borealis
Expansion
4 million light years
Quasar OQ172

The Search for Extraterrestrial Intelligence

Perhaps the most urgent question the human species ever asks itself is “are we alone?” Scientists, philosophers, and “ordinary” people address the question in unique ways, some optimistic, some pessimistic, some very certain the answer is “No,” despite a dearth of physical evidence or likelihood. Unable to travel interstellar distances, humans have only one tool currently capable of answering this question, and that is the radio telescope. So let’s have a closer look at these endeavors.

Even the most objective attempts to calculate the likely number of planets in our galaxy that could produce an intelligent life form with whom we might communicate come up with estimates of anywhere from 1 (us) to 10 million planets. These planets include those that

(a) could support life as we know it,

(b) have evolved a species with enough intelligence to have a technology,

(c) are in a period of the planet’s history when this intelligent species has the capability of transmitting electromagnetic signals into space,

(d) is in a period of the planet’s history before that intelligent species goes extinct or otherwise loses its technology, and

(e) the planet is at the right distance from us for their signals to be reaching us about now.

Since the early 1980s, several projects have been undertaken to search for some sort of signal from outer space that could be a message from another civilization. Complicating this type of search is the possibility that another species might choose any frequency along the entire electromagnetic spectrum to carry its signal. However, frequencies within the radio band would be the most reasonable choices for communication because a minimum of energy is required to transmit signals in this range. Furthermore, frequencies within the 1-10 GHz ranges, known as the “microwave window,” are considered likely candidates since they would stand out from the galactic background radiation. In addition to searching over a considerable range of frequencies, there is the problem of where to look. Even within the Milky Way galaxy, the number of target stars with possible planets is in the billions.

In 1960, radio astronomer Frank Drake conducted the first radio frequency search, Project Ozma, for signals from other planetary systems. He aimed his 85-foot radio telescope toward two close by sun-like stars, and tuned it to the frequency of radiation emitted by neutral hydrogen, assuming that another intelligent species might select this frequency because of its astronomical importance. He didn’t find anything, but his attempt spurred others to take up the search for extraterrestrial intelligence (SETI).

The Soviet Union dominated SETI in the 1960s, turning their antennas in almost every direction, hoping that at least a few advanced civilizations might be radiating very strong signals. Then, in the early 1970s, NASA’s Ames Research Center in Mountain View, California, did a comprehensive study called Project Cyclops. This project produced an analysis of the scientific and technological issues involved in SETI that has been the basis of much of the SETI work since.

During the 1970s, many American radio astronomers conducted searches using existing antennas and receivers. A few efforts from that era continue to this day. By the late-’70s, SETI programs had been established at NASA’s Ames Research Center and at the Jet Propulsion Laboratory

(JPL). These two labs developed a dual strategy for a large scale study. Ames would examine 1,000 sun-like stars in a targeted search capable of detecting weak or sporadic signals. JPL, on the other hand, would systematically survey the sky in all directions. In 1992, NASA had formally adopted and funded this strategy, and observations began. This project was called the High Resolution Microwave Survey (HRMS). However, within a year, Congress terminated the funding.

Since then, SETI programs have continued with private funding. The SETI Institute, founded in 1984, helps coordinate research and find funding for numerous SETI researchers and projects. The most comprehensive SETI project ever undertaken is Project Phoenix. Project Phoenix will "listen" for radio signals from 1000 nearby, Sun-like stars, using the largest antennas in the world. In addition, The Planetary Society, based in Pasadena, California, also has an active SETI program.

NASA has recently initiated its new Origins Program, which takes a different approach in addressing the question of life elsewhere in the Universe. The Origins Program seeks to learn how stars and planets are formed. In the process, very advanced technology telescopes will use the techniques of astrometry and direct imaging to look for evidence of planets around other stars. The assumption is that a planet is the first requirement for life to emerge and evolve. If we discover that planets are very common, then we will at least be encouraged in our other techniques for detecting extraterrestrial intelligence.

Recap

1. On a one-billionth scale, wherein Earth is the size of a grape, the nearest _____________ would be at a distance greater than the diameter of the actual Earth.
2. Our solar system is located in one of the spiral ______ of what we call the Milky Way Galaxy, about _____________ light years from the galaxy's center.
3. One of the difficulties of searching for intelligently modulated signals of extraterrestrial origin is guessing what _______________ another intelligent species might use for its signal.

1. star 2. arms, 30,000 3. frequency (or wavelength)

For Further Study

- *The vastness of the Universe:* Powers of Ten. Video, Pyramid Films.
- *Cosmology (origin and fate of the Universe):* Kaufmann, 526-552; Morrison et al., 602-624.
- *SETI:* Kaufmann, 572-578; Morrison et al., 475-478; SETI Institute Home Page, http://www.seti-inst.edu.

Appendix A

Glossary

Absolute magnitude	Apparent magnitude a star would have at a distance of 10 parsecs (32.6 LY).
Absorption lines	Dark lines superimposed on a continuous electromagnetic spectrum due to absorption of certain frequencies by the medium through which the radiation has passed.
AM	Amplitude modulation. Imposing a signal on transmitted energy by varying the intensity of the wave.
Ångstrom	Unit of length equal to 10^{-10} m. Sometimes used to measure wavelengths of visible light. Now largely superseded by the nanometer (10^{-9} m).
Aphelion	The point in a body's orbit (Earth's, for example) around the sun where the orbiting body is farthest from the sun.
Apogee	The point in a body's orbit (the moon's, for example) around Earth where the orbiting body is farthest from Earth.
Apparent magnitude	Measure of the observed brightness received from a source.
Astrometry	Technique of precisely measuring any wobble in a star's position that might be caused by planets orbiting the star and thus exerting a slight gravitational tug on it.
Astronomical horizon	The hypothetical interface between Earth and sky, as would be seen by the observer if the surrounding terrain were perfectly flat.
Astronomical unit	Mean Earth-to-sun distance, approximately 150,000,000 km.
Atmospheric window	Property of Earth's atmosphere that allows only certain wavelengths of electromagnetic energy to pass through, absorbing all other wavelengths.
AU	Abbreviation for astronomical unit.
Azimuth	In the horizon coordinate system, the horizontal angle from some arbitrary reference direction (north, usually) clockwise to the object circle.
Background radiation	Electromagnetic radiation originating from no specific location.
Beam width	The angle within which an antenna receives radio waves.

Binary stars	Two stars that are so close as to orbit around a common center of gravity.
Black dwarf	One possible final stage in the evolution of a star, in which all the energy is exhausted and it no longer emits radiation.
Black hole	A region of space surrounding a very massive collapsed star. Gravity is so intense in a black hole that the escape velocity is equal to or greater than the speed of light, thus no radiation can escape.
Blackbody	A hypothetical object that is a perfect radiator, absorbing and re-emitting all radiation that impinges upon it.
Blazar	Short for BL Lacertae object: a class of galaxies whose light is polarized and has a non-thermal spectrum, and whose brightness fluctuates dramatically.
Blue shift	Apparent shortening of the wavelength, due to Doppler effect, of radiation received from a source in motion toward the observer.
Bowshock	The upstream (closest to the sun) boundary of a planet’s magnetosphere, interfacing with the solar wind.
Brightness spectrum	Variation of radiation brightness with frequency.
Brightness	Also referred to as surface brightness. Power of radiation received per unit area per unit solid angle per unit frequency interval. Note that this is not the common usage of “brightness.” What is commonly referred to as brightness is a characteristic of the source of the radiation (rather than the radiation received) and is what astronomers call *luminosity*.
Celestial equator	A great circle on the celestial sphere, concentric with Earth’s equator.
Celestial latitude	In the ecliptic coordinate system, the angle of an object in the sky north or south (±90°) of the ecliptic plane.
Celestial longitude	In the ecliptic coordinate system, the angle of an object in the sky eastward along the ecliptic from the vernal equinox (0-360°).
Celestial poles	Points about which the celestial sphere appears to rotate; intersections of the celestial sphere with Earth’s axis.
Celestial sphere	Apparent sphere of the sky, whose diameter is the distance from Earth to the farthest observable object.
Cepheid	A type of regular variable star that has a short period of a few days to a few weeks. It has been found that in these stars, the longer the period, the more luminous the star.
Chromosphere	The part of the sun’s atmosphere lying above the photosphere and below the outer corona.
Corona	The outer atmosphere of the sun. Visible to the naked eye only during a total solar eclipse.

Cyclotron radiation	Electromagnetic radiation emitted when charged particles are moved within a magnetic field at non-relativistic speeds (that is, not close to the speed of light).
Declination	Angular distance north or south of the equator of some object in the sky, measuring along an hour circle passing through that object.
Discrete source	A sources of radiation whose direction can be identified. Discrete sources may be further classified as point sources, localized sources, and extended sources.
Doppler effect	Apparent change in wavelength of the radiation from a source due to its motion relative to the observer.
Ecliptic coordinate system	Coordinate system using the plane of the ecliptic as the reference.
Electromagnetic spectrum	The full range of wavelengths or frequencies of electromagnetic radiation.
Electromagnetic radiation	Radiation consisting of waves propagated through the building up and breaking down of electric and magnetic fields; include radio, infrared, light, ultraviolet, x-rays, and gamma rays.
Elevation	In the horizon coordinate system, the angle upward from the horizon to an object in the sky.
Emission lines	Discrete, bright lines in the spectrum.
Epoch	A date chosen for reference purposes in quoting astronomical coordinates, to account for the slight changes in the apparent positions of objects in the sky due to Earth’s precession.
Equator	A great circle on Earth 90° from its poles.
Equatorial coordinate system	A coordinate system using Earth’s equator as the plane of reference.
Extended source	Discrete emitter of radiation that covers a relatively large part of the sky, for example, the Milky Way galaxy. The terms localized and extended are relative and depend on the angular resolution of the telescope observing them.
Faraday rotation	Rotation of an electromagnetic wave’s polarization as it passes through a magnetic field parallel to the propagation of the wave in a medium.
Field	The effect of forces, such as gravity and magnetism, that act on distant objects.
Flare star	Faint red dwarf stars that may brighten up by several magnitudes over a few minutes, and fade back to their usual brightness within an hour.
FM	Frequency modulation. Imposing a signal on transmitted energy by varying the frequency of the wave.

Galactic coordinate system	A coordinate system using the plane of the Milky Way galaxy as the reference.
Gravitational lens	An effect produced by the bending of radiation as it passes within the gravitational field of another object. May appear to an observer on Earth as one or more duplicate images of the same source.
Horizon coordinate system	A coordinate system using a plane through the observing point parallel to the horizon as the reference.
Horizon mask	A diagram that maps in silhouette the horizon in 360˚ as actually seen by the observer.
Hour angle	The elapsed time since an object in the sky crossed the meridian point of the observer.
Hour circle (object's)	A great circle on the celestial sphere that passes through both poles and the object being observed in the sky.
Index of refraction	Ratio of the speed of electromagnetic radiation in a vacuum to the speed of electromagnetic radiation in a given medium.
Intensity	Power of electromagnetic radiation received per unit area.
Interferometry	In radio astronomy, use of more than one radio telescope to enhance the resolution of the radio image from a source.
Inverse-square law	The amount of electromagnetic energy reaching a given point in a given unit of time decreases in proportion to the square of the distance from the source of the energy.
ISM	Interstellar medium.
Kelvin	A unit of absolute temperature. In the Kelvin temperature scale, 0 is absolute zero, the temperature where molecular motion ceases and the material has no kinetic energy. Water freezes at 273 K.
Light year	Distance light (electromagnetic energy) travels in a vacuum during one year, or 9.46 x 10^{12} km.
Localized source	A discrete radiation source of very small extent. A single star is normally considered a localized source.
LY	Abbreviation for light year.
Magnetosphere	Region around a planet in which its magnetic field dominates the interplanetary field carried by the solar wind.
Maser (astronomical)	For Microwave-amplified Stimulated Emission of Radiation. An ultracompact site in molecular clouds (usually of water vapor, hydroxl radicals, silicon monoxide, or methanol) in the interstellar medium or very near long-period variable stars, in which certain molecular emissions lines are enormously amplified.

Meridian	A great circle on the celestial sphere that passes through both poles and the zenith.
Nadir	The point on the celestial sphere immediately below the observer. Directly opposite the overhead point, or zenith.
Nanometer	One thousand-millionth of a meter, 10^{-9} m. Commonly used to measure wavelengths in the visible light and UV ranges.
Nebula	Cloud of interstellar gas or dust.
Neutron star	A star of extremely high density but low luminosity, composed almost entirely of neutrons.
Non-thermal emissions	Electromagnetic radiation produced by synchrotron radiation, maser line emissions from atoms and molecules, or other mechanisms not related to temperature.
Nutation (Earth’s)	A slight, slow nodding of Earth’s axis (about 9 arcsecs to either side of its mean position in about 18 years 220 days). This motion is apart from precession of the axis and is caused by the gravitational pull of the moon on Earth’s equatorial bulge as the moon moves slightly above and slightly below the ecliptic in its orbit.
Object circle	In the horizon coordinate system, the vertical circle through a celestial object and the zenith.
Oblateness	The flattening of a sphere. Earth is oblate such that its diameter from pole to pole is 43 km less than its equatorial diameter.
Occultation	Passing of one celestial body in front of another as observed from Earth.
Optical astronomy	Study of the extraterrestrial universe using primarily visible light observations.
Optical window	The characteristic of Earth’s atmosphere that allows visible light to pass through.
Parsec	The distance of an object at which 1 AU would subtend one arcsec; 1 parsec = 3.26 light years.
Perigee	The point in a body’s orbit (the moon’s, for example) around Earth when the orbiting body is closest to Earth.
Perihelion	The point in a body’s orbit (Earth’s, for example) around the sun when the orbiting body is closest to the sun.
Phase	Angular distance between peaks or troughs of two wave forms of similar frequency.
Photon astronomy	Study of the extraterrestrial universe using observations of the entire electromagnetic spectrum.
Photosphere	The region of the sun (or any star) from which continuous spectrum radiation escapes into space; the visible disk of the sun.

Plasma	A hot, ionized gas.
Point source	An idealized discrete source of radiation that subtends an infinitesimally small angle.
Polarization	The direction of the electric vector of an electromagnetic wave. Polarization may be linear, circular, random, elliptical, or any combination.
Precession (Earth's)	A slow, conical motion of Earth's axis of rotation, similar to the wobble of a spinning top.
Prime vertical	In the horizon coordinate system, the great circle through the east and west points and the zenith.
Pulsar	A neutron star radio source that emits in rapid, regular pulses.
Quasar	A very distant, very luminous source of visible and radio energy. May be the oldest and most distant objects in the universe.
Radio astronomy	Study of the extraterrestrial universe using observations of radio frequency radiation, rather than visible light.
Radio galaxy	Galaxy that is a strong emitter of radio energy, perhaps emitting 10^5 - 10^6 times more radio energy than a "normal" galaxy.
Radio star	A star that is a strong emitter of radio frequency radiation.
Radio window	The property of Earth's atmosphere that allows certain wavelengths of electromagnetic radiation in the radio range to pass through.
Recombination lines	Emission and absorption lines seen when oppositely charged ions recombine to an electrically neutral state, producing a highly excited neutral atom, with electrons transitioning between states, emitting and absorbing photons.
Red shift	Apparent lengthening of the wavelength of radiation received from a source. May be caused by Doppler effect, the expansion of space, or gravitational effects of very massive objects.
Right ascension	In the equatorial coordinate system, the angle (usually in hours, minutes, seconds) measured eastward along the celestial equator from the vernal equinox to the hour circle passing through an object in the sky.
R_j	Abbreviation for one Jupiter radius (about 5 million km). Used to describe distances in the Jupiter system.
RR Lyrae variable	Regular variable stars whose periods are very short (between about 1.25 and 30 hours).
S-band	Range of radio frequencies of about 2-4 GHz, or wavelengths of 15 - 7.5 cm.
Scintillation	Effect produced by phase shifting of electromagnetic waves from a discrete source as they pass through Earth's atmosphere. In the visible light range, perceived as twinkling of stars.

SETI	Search for extraterrestrial intelligence. Using radio telescopes, astronomers “listen” for artificially modulated radio frequency signals from parts of the universe most “likely” to spawn life as we know it.
Sidereal day	The time required for Earth to revolve 360° with respect to a celestial object outside the solar system. About 23 hours 56 minutes duration in terms of solar time.
Solar day	The time required for Earth to revolve 360° with respect to the sun.
Solar flare	Brilliant outbreak in the sun’s outer atmosphere, usually associated with active groups of sunspots.
Spectral power	Power of electromagnetic radiation per unit of frequency bandwidth.
Stellar wind	The outflow of gas from a star, sometimes at speeds as high as hundreds of kilometers per second.
Sunspot	A temporary cool region in the solar photosphere that appears dark by contrast against the surrounding hotter photosphere.
Superluminal velocity	Apparent motion of an object at greater than light speed; apparency is caused by a projection effect due to the motion’s vector component toward Earth.
Supernova	A star that experiences a cataclysmic explosion, sending much of its material into space.
Surface brightness	See *brightness*.
Synchrotron radiation	Radiation emitted by charged particles being accelerated in magnetic fields and moving at near the speed of light.
Thermal emissions	Radiation emitted due to an object’s temperature (for example, blackbody radiation) or by an ionized gas.
Vernal equinox	The point on the celestial sphere where the sun crosses the celestial equator from south to north. The date of this crossing (about March 21) is also called the vernal equinox.
X-band	Range of radio frequencies of about 8-12 GHz, or wavelengths of 3.75 - 2.4 cm.
Zenith	The point on the celestial sphere directly overhead the observer.

Appendix B

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Water Masers in the Direction of the Galactic Center,

http://www.cv.nrao.edu/~eschulma/h2o.html.

What is the VLA?

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2	16	Wave cross-section	Halliday & Resnick, 981
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Name ____ Date ______________________

Basics of Radio Astronomy

Final Quiz

1. The radio frequency static Karl Jansky observed in 1931 with his rudimentary radio frequency antenna peaked 4 minutes ________________ each day, confirming for him that the source could not be the sun.

2. Radio frequency radiation induces a weak __________________ in a radio telescope antenna.

3. Electromagnetic radiation travels through space at approximately ______________ km per second.

4. The frequency of electromagnetic waves is given in units called ______________.

5. Wavelength of electromagnetic energy is given in _____________ or some decimal fraction thereof.

6. As electromagnetic radiation spreads out from a source, the area it covers is proportional to the ________________ of the distance the radiation has traveled.

7. The property that primarily determines the effects of electromagnetic energy, and therefore how we categorize it, is its ___________________.

8. Electromagnetic radiation in the frequency range just higher than x-rays is called __________________ _______.

9. The radio range includes the ________________ (longest/shortest) wavelengths in the electromagnetic spectrum.

10. The range of electromagnetic radiation with wavelengths slightly shorter than visible light is called _______________________.

11. The range of electromagnetic radiation with wavelengths slightly longer than visible light is called ____________________.

12. The GAVRT is currently capable of receiving radio waves in the _______ and _______ bands.

13. Electromagnetic waves include both a(n) __________________ and a(n) ________________ vector at right angles to each other and to the direction of wave propagation.

14. The direction of the electric vector describes an electromagnetic wave's ______________________.

15. The most important property of objects in determining the frequency of the radiation they emit is ___________________.

16. In the case of thermal radiation, the higher the temperature of an emitting object, the ______________ energy is contained in its radiation.

17. An object that absorbs and re-emits all the energy that hits it is called a(n) _____________________.

18. Wien's Law states that the peak amount of energy is emitted at ____________ wavelengths for higher temperatures.

19. ___________ ______________ is defined as the energy received per unit area per unit of frequency bandwidth.

20. A plot of a brightness spectrum shows the brightness of radiation from a source plotted against the discrete _______________ comprising that radiation.

21. Emissions due to temperature of an object, ionization of a gas, and line emissions from atoms are all examples of _______________ radiation.

22. Neutral hydrogen emits radiation at a characteristic wavelength of ________ cm .

23. A region of interstellar space containing neutral hydrogen gas is called a(n) _____ region, while a region containing ionized hydrogen is called a(n) _______ region.

24. Synchrotron radiation is produced when charged particles spiral about within __________________ field lines.

25. Unlike thermal radiation, the intensity of non-thermal radiation often ________________ with frequency.

26. A dense molecular cloud that greatly amplifies and focuses radiation passing through it is called a _______________.

27. The wavelengths of radiation that we can observe from the ground are limited by Earth’s _________________.

28. Radiation that has passed through a cloud of gas produces a spectrum with a characteristic set of dark __________________ __________.

29. Complex organic molecules have been detected in space using the discipline of ________________ ___________________.

30. The angle at which an electromagnetic wave is ______________ from a surface equals the angle at which it impinged on that surface.

31. The ratio of the speed of electromagnetic energy in a vacuum to its speed in a given medium is that medium’s _____________ ____ ____________________.

32. Extraterrestrial objects seen near the horizon are actually (lower or higher) ______________ than they appear.

33. ____________________ is caused by electromagnetic waves from a source becoming out of phase as they pass through a dynamic medium such as Earth’s atmosphere.

34. __________________ ______________ is the effect produced when electromagnetic waves become circularly polarized in opposite directions as they pass through magnetic lines of force moving in the same direction as the waves.

35. Gravitational lensing is caused by the _________________ of space around large masses.

36. Doppler effect causes the frequency of waves from a receding object to appear (lower or higher) ______________.

37. ____________________ ____________ is the apparent faster-than-light motion of a discrete source within a quasar.

38. Occultations provide astronomers good opportunities to study any existing __________________ of the occulting object.

39. A source of radiation whose direction can be identified is said to be a ________________ source.

40. The origin of cosmic background radiation is believed to be _______ _______ ________.

41. Cepheid variable stars with longer regular periods are more ________________ than those with shorter regular periods.

42. The activity of the sun varies over about a(n) _____-year cycle.

43. Sunspots are (cooler or hotter) ____________ than the surrounding surface of the sun.

44. The aurora that sometime appears in Earth's upper atmosphere are associated with solar ____________.

45. A _______________ is a rapidly spinning neutron star.

46. The predominant mechanism producing radiation from a radio galaxy is _______________ ______________________.

47. The most distant objects so far discovered are ______________.

48. The radio energy from most planets in the solar system is (thermal or non-thermal) __________________ radiation.

49. On Jupiter, a compass needle would point ___________.

50. The ___________________ is the region around a planet where the planet's magnetic field dominates the interplanetary field carried by the solar wind.

51. Surrounding Jupiter at approximately the orbit of Io is a strongly radiating ______________ _____________.

52. Radio telescopes are best placed in (high or low) _____________ locations.

53. The great circle around Earth that is at every point the same distance from the north and south poles is called ____________________.

54. Great circles that pass through Earth's north and south poles are called ________________.

55. In Earth's coordinate system, the north-south component of a location is called ________________ .

56. In Earth's coordinate system, longitude is measured from the _____________ _________________ .

57. A solar day is about 4 minutes (longer or shorter) ______________ than a sidereal day.

58. The Earth's axis precesses around a complete circle having a 23.5 degree radius relative to a fixed point in space over a period of about _________ ___________.

59. A diagram that shows a 360º silhouette of the horizon as viewed from a particular location is called a(n) ________________ ___________.

60. In all astronomical coordinate systems and in general usage, _____________ is directly overhead and ____________ is directly below the observer.

61. In the horizon system of coordinates, the horizontal component of an object's coordinates is given by the _________________.

62. In the horizon system of coordinates, the vertical component of an object's coordinates is given by the _________________.

63. In the equatorial coordinate system, an object's east-west component is given as its __________ _______________.

64. In the equatorial coordinate system, an object's north-south component is given as its _______________.

65. ___________ is a date of reference used in sky almanacs to take into account slight variations in the celestial coordinates of objects due to the precession of Earth's axis.

66. The ____________ is the plane formed by the orbit of Earth around the sun.

67. The reference in the _______________ coordinate system is a plane through the sun parallel to the mean plane of the Milky Way galaxy.

68. In the Milky Way galaxy alone, the number of planetary systems could be on the order of _________________.

69. The diameter of our galaxy is around _____________ light years.

70. Astronomers estimate the age of the Universe to be on the order of 15 ___________________ years.

Name ____ Date ______________________

Basics of Radio Astronomy

Final Quiz

1. The radio frequency static Karl Jansky observed in 1931 with his rudimentary radio frequency antenna peaked 4 minutes _________________ each day, confirming for him that the source could not be the sun. *earlier*

2. Radio frequency radiation induces a weak ___________________ in a radio telescope antenna. *current*

3. Electromagnetic radiation travels through space at approximately _______________ km per second. *300,000 (299,792)*

4. The frequency of electromagnetic waves is given in units called _______________. *Hertz*

5. Wavelength of electromagnetic energy is given in ______________ or some decimal fraction thereof. *meters*

6. As electromagnetic radiation spreads out from a source, the area it covers is proportional to the _________________ of the distance the radiation has traveled. *square*

7. The property that primarily determines the effects of electromagnetic energy, and therefore how we categorize it, is its ____________________. *wavelength (or frequency)*

8. Electromagnetic radiation in the frequency range just higher than x-rays is called ___________________ ________. *gamma rays*

9. The radio range includes the _________________ (longest/shortest) wavelengths in the electromagnetic spectrum. *longest*

10. The range of electromagnetic radiation with wavelengths slightly shorter than visible light is called ________________________. *ultraviolet*

11. The range of electromagnetic radiation with wavelengths slightly longer than visible light is called _____________________. *Infrared*

12. The GAVRT is currently capable of receiving radio waves in the _______ and _______ bands. *S, X*

13. Electromagnetic waves include both a(n) __________________ and a(n) ________________ vector at right angles to each other and to the direction of wave propagation. *electric, magnetic*

14. The direction of the electric vector describes an electromagnetic wave's ______________________. *polarization*

15. The most important property of objects in determining the frequency of the radiation they emit is ___________________. *temperature*

16. In the case of thermal radiation, the higher the temperature of an emitting object, the ______________ energy is contained in its radiation. *more*

17. An object that absorbs and re-emits all the energy that hits it is called a(n) _____________________. *blackbody*

18. Wien's Law states that the peak amount of energy is emitted at ____________ wavelengths for higher temperatures. *shorter*

19. ___________ ______________ is defined as the energy received per unit area per unit of frequency bandwidth. *Flux density*

20. A plot of a brightness spectrum shows the brightness of radiation from a source plotted against the discrete _______________ comprising that radiation. *wavelengths (or frequencies)*

21. Emissions due to temperature of an object, ionization of a gas, and line emissions from atoms are all examples of _______________ radiation. *thermal*

22. Neutral hydrogen emits radiation at a characteristic wavelength of ________ cm . *21.11 (or 21)*

23. A region of interstellar space containing neutral hydrogen gas is called a(n) _____ region, while a region containing ionized hydrogen is called a(n) _______ region. *H I, H II*

24. Synchrotron radiation is produced when charged particles spiral about within __________________ field lines. *magnetic*

25. Unlike thermal radiation, the intensity of non-thermal radiation often ________________ with frequency. *decreases*

26. A dense molecular cloud that greatly amplifies and focuses radiation passing through it is called a ______________. *maser*

27. The wavelengths of radiation that we can observe from the ground are limited by Earth's ________________. *atmosphere*

28. Radiation that has passed through a cloud of gas produces a spectrum with a characteristic set of dark _________________ _________. *absorption lines*

29. Complex organic molecules have been detected in space using the discipline of _______________ __________________. *molecular spectroscopy*

30. The angle at which an electromagnetic wave is _____________ from a surface equals the angle at which it impinged on that surface. *reflected*

31. The ratio of the speed of electromagnetic energy in a vacuum to its speed in a given medium is that medium's ____________ ____ ___________________. *index of refraction*

32. Extraterrestrial objects seen near the horizon are actually (lower or higher) _____________ than they appear. *lower*

33. ___________________ is caused by electromagnetic waves from a source becoming out of phase as they pass through a dynamic medium such as Earth's atmosphere. *Scintillation*

34. _________________ _____________ is the effect produced when electromagnetic waves become circularly polarized in opposite directions as they pass through magnetic lines of force moving in the same direction as the waves. *Faraday rotation*

35. Gravitational lensing is caused by the ________________ of space around large masses. *warping*

36. Doppler effect causes the frequency of waves from a receding object to appear (lower or higher) _____________. *lower*

37. ___________________ ___________ is the apparent faster-than-light motion of a discrete source within a quasar. *Superluminal velocity*

38. Occultations provide astronomers good opportunities to study any existing _________________ of the occulting object. *atmosphere*

39. A source of radiation whose direction can be identified is said to be a ________________ source. *discrete*

40. The origin of cosmic background radiation is believed to be _______ _______ ________. *the big bang*

41. Cepheid variable stars with longer regular periods are more ________________ than those with shorter regular periods. *luminous*

42. The activity of the sun varies over about a(n) _____-year cycle. *11*

43. Sunspots are (cooler or hotter) ____________ than the surrounding surface of the sun. *cooler*

44. The aurora that sometime appears in Earth's upper atmosphere are associated with solar ____________. *flares* (or *wind)*

45. A _______________ is a rapidly spinning neutron star. *pulsar*

46. The predominant mechanism producing radiation from a radio galaxy is _______________ ______________________. *synchrotron radiation*

47. The most distant objects so far discovered are ______________. *quasars*

48. The radio energy from most planets in the solar system is (thermal or non-thermal) __________________ radiation. *thermal*

49. On Jupiter, a compass needle would point ___________. *south*

50. The ___________________ is the region around a planet where the planet's magnetic field dominates the interplanetary field carried by the solar wind. *magnetosphere*

51. Surrounding Jupiter at approximately the orbit of Io is a strongly radiating _______________ ______________. *plasma torus*

52. Radio telescopes are best placed in (high or low) _____________ locations. *low*

53. The great circle around Earth that is at every point the same distance from the north and south poles is called _____________________. *the equator*

54. Great circles that pass through Earth's north and south poles are called _________________. *meridians*

55. In Earth's coordinate system, the north-south component of a location is called _________________ . *latitude*

56. In Earth's coordinate system, longitude is measured from the _____________ __________________ . *prime meridian*

57. A solar day is about 4 minutes (longer or shorter) ______________ than a sidereal day. *longer*

58. The Earth's axis precesses around a complete circle having a 23.5 degree radius relative to a fixed point in space over a period of about _________ ___________. *26,000 years*

59. A diagram that shows a 360º silhouette of the horizon as viewed from a particular location is called a(n) _________________ ___________. *horizon mask*

60. In all astronomical coordinate systems and in general usage, _____________ is directly overhead and ____________ is directly below the observer. *zenith, nadir*

61. In the horizon system of coordinates, the horizontal component of an object's coordinates is given by the __________________. *azimuth*

62. In the horizon system of coordinates, the vertical component of an object's coordinates is given by the __________________. *elevation*

63. In the equatorial coordinate system, an object's east-west component is given as its __________ _______________. *right ascension*

64. In the equatorial coordinate system, an object's north-south component is given as its _______________. *declination*

65. ___________ is a date of reference used in sky almanacs to take into account slight variations in the celestial coordinates of objects due to the precession of Earth's axis. *epoch*

66. The ____________ is the plane formed by the orbit of Earth around the sun. *ecliptic*

67. The reference in the _______________ coordinate system is a plane through the sun parallel to the mean plane of the Milky Way galaxy. *galactic*

68. In the Milky Way galaxy alone, the number of planetary systems could be on the order of _________________. *billions*

69. The diameter of our galaxy is around _____________ light years. *100,000*

70. Astronomers estimate the age of the Universe to be on the order of 15 ___________________ years. *billion*