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.

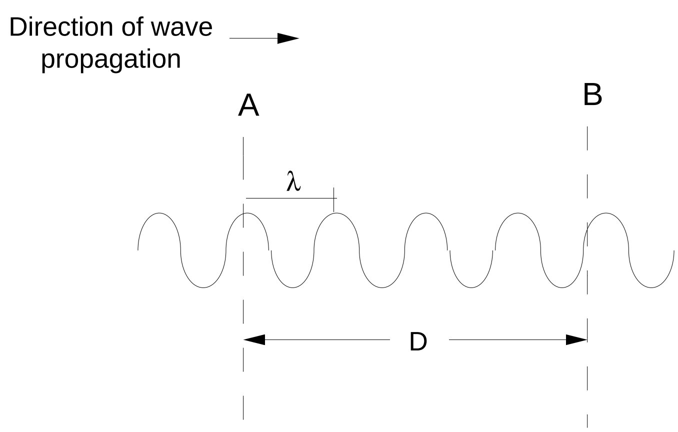
Frequency and Wavelength

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

Speed of light = Wavelength x Frequency

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

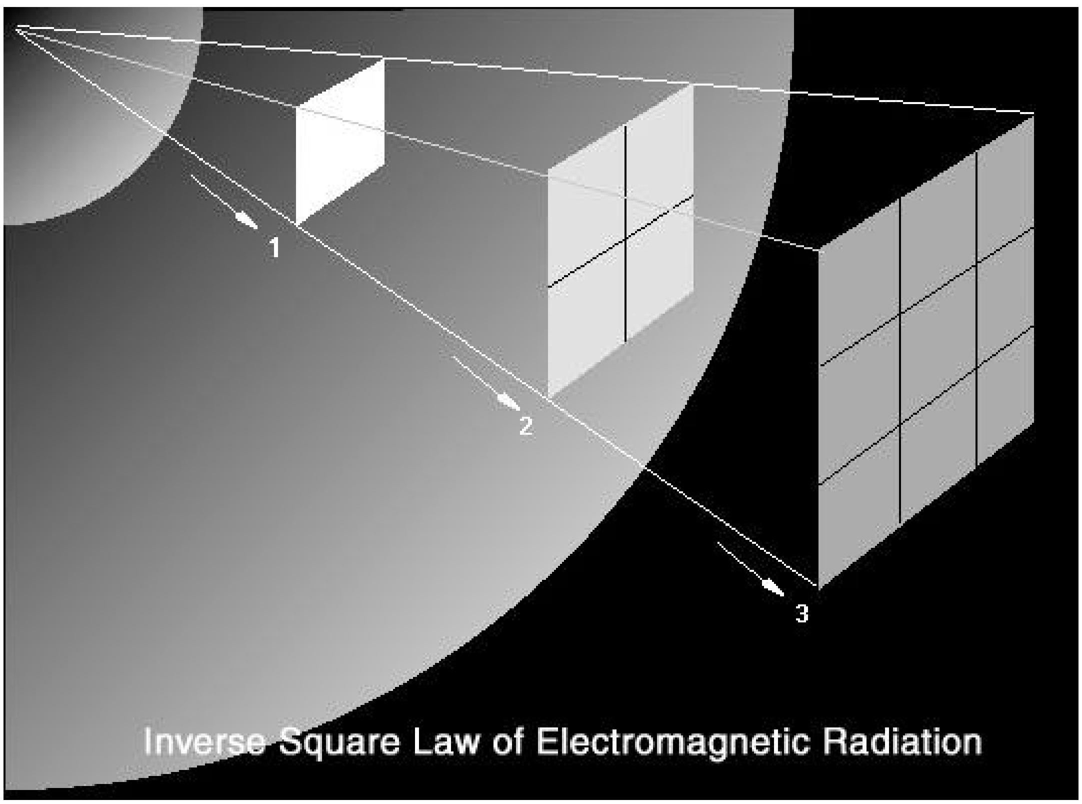
$$\text{Frequency} = \frac{\text{Speed of light}}{\text{Wavelength}}$$

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.



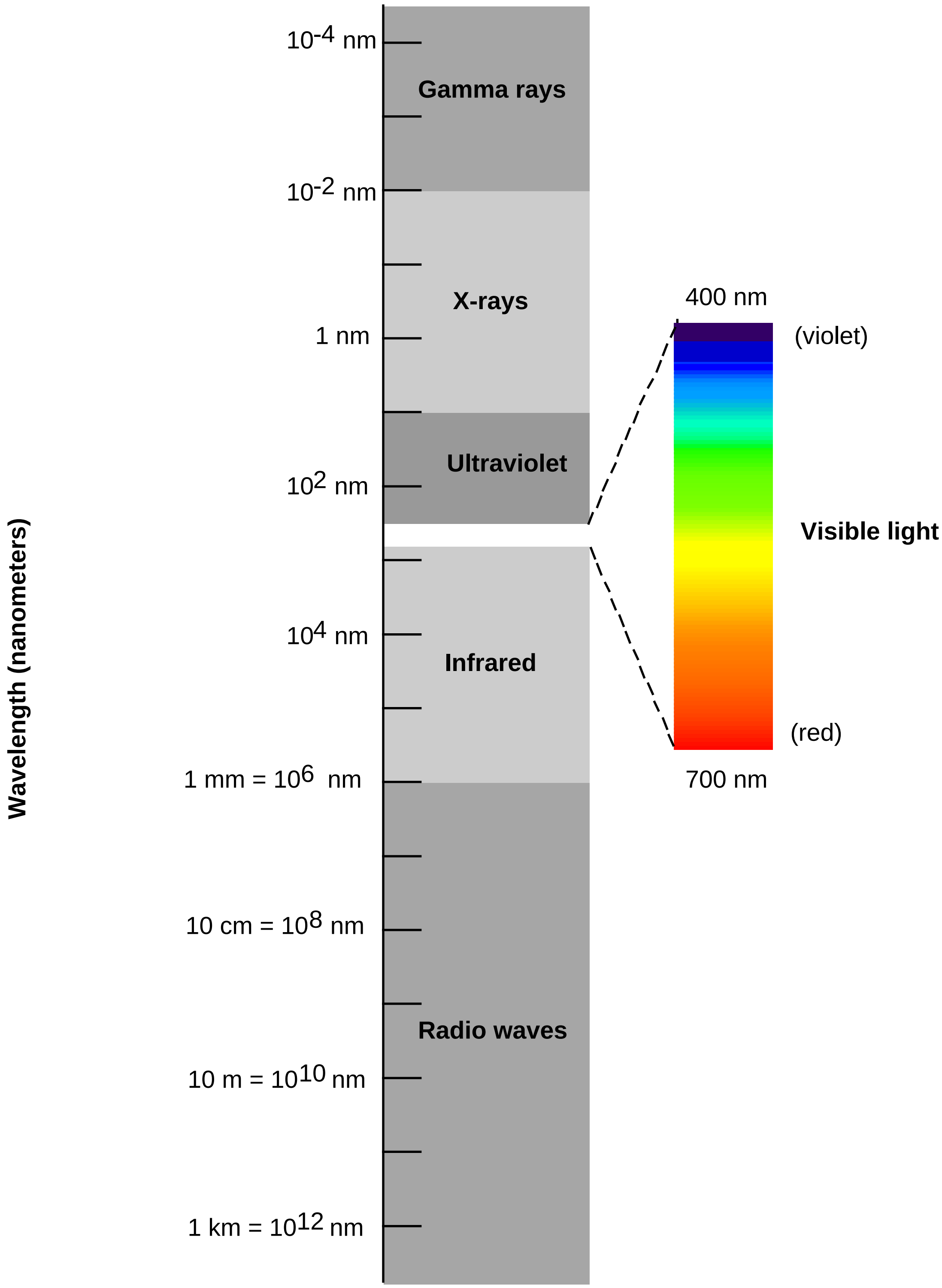
The inverse-square law is significant to the exploration of the universe. It means that the concentration of electromagnetic radiation decreases very rapidly with increasing distance from the emitter. Whether the emitter is a spacecraft with a low-power transmitter, an extremely powerful star, or a radio 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

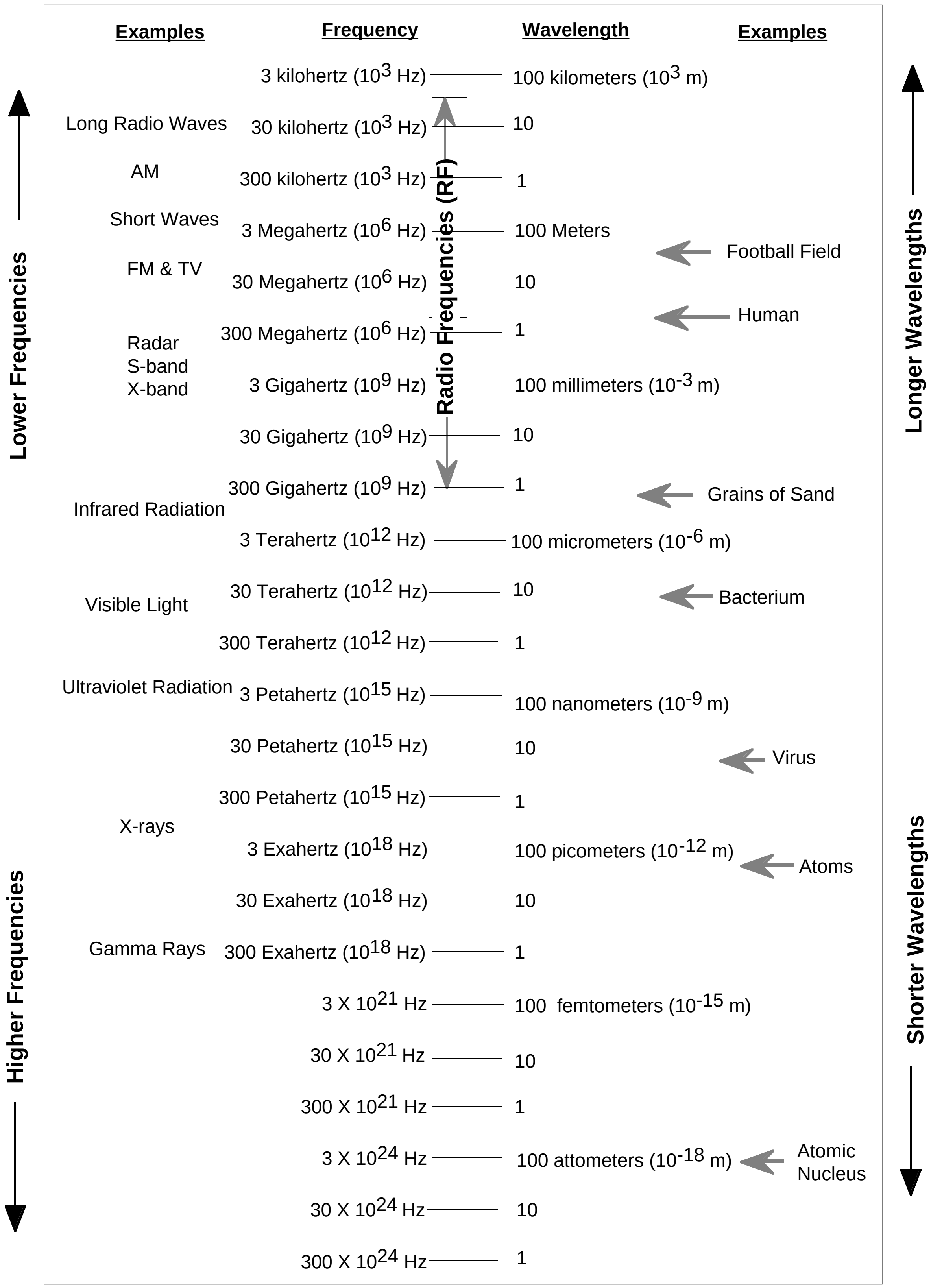
Light is electromagnetic radiation at those frequencies to which human eyes (and those of most other sighted species) happen to be sensitive. But the electromagnetic spectrum has no upper or lower limit of frequencies. It certainly has a much broader range of frequencies than the human eye can detect. 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



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

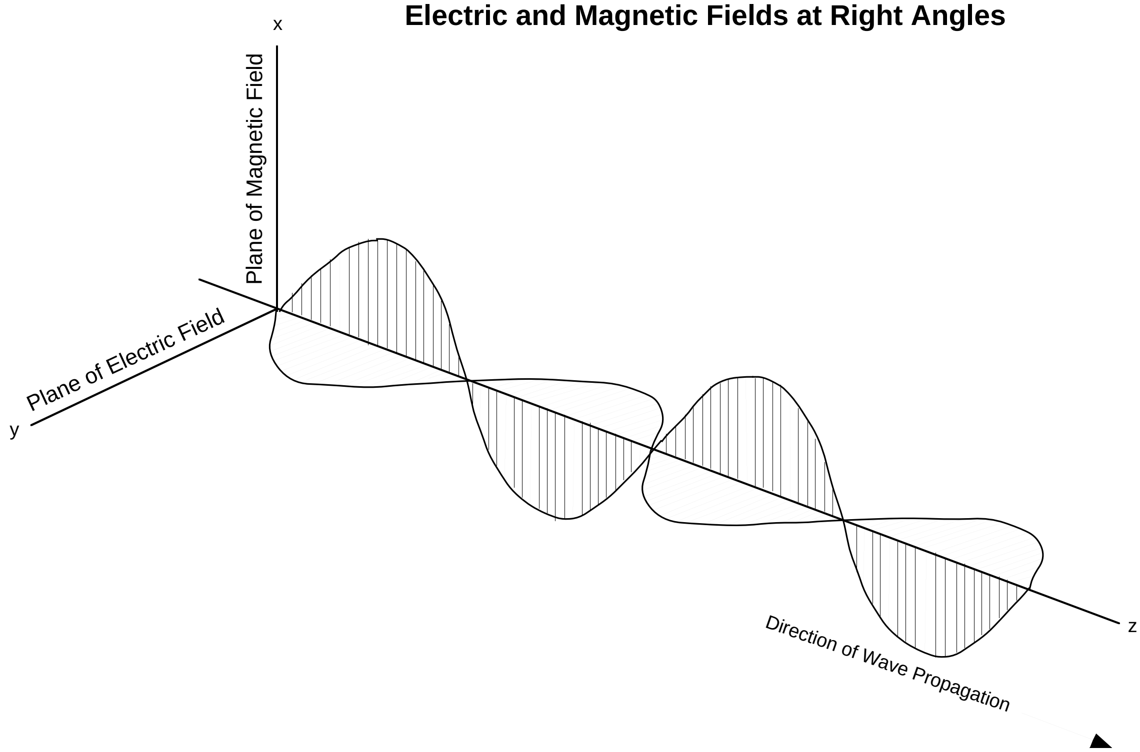
Note: Band definitions vary slightly among different sources. These are ballpark values.

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

Wave Polarization

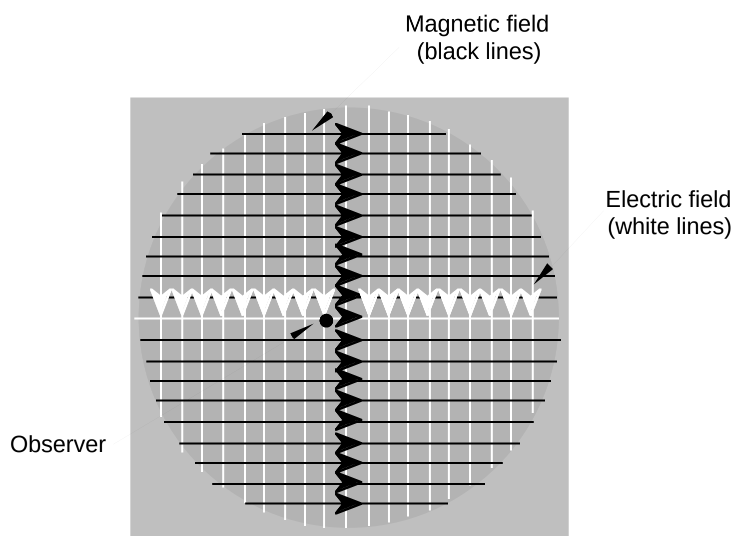
If electromagnetic waves meet no barriers as they travel through an idealized empty space, they travel in straight lines. As mentioned at the beginning of this chapter, stationary electric charges produce electric fields, and moving electric charges produce magnetic fields. Thus, there are two components 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



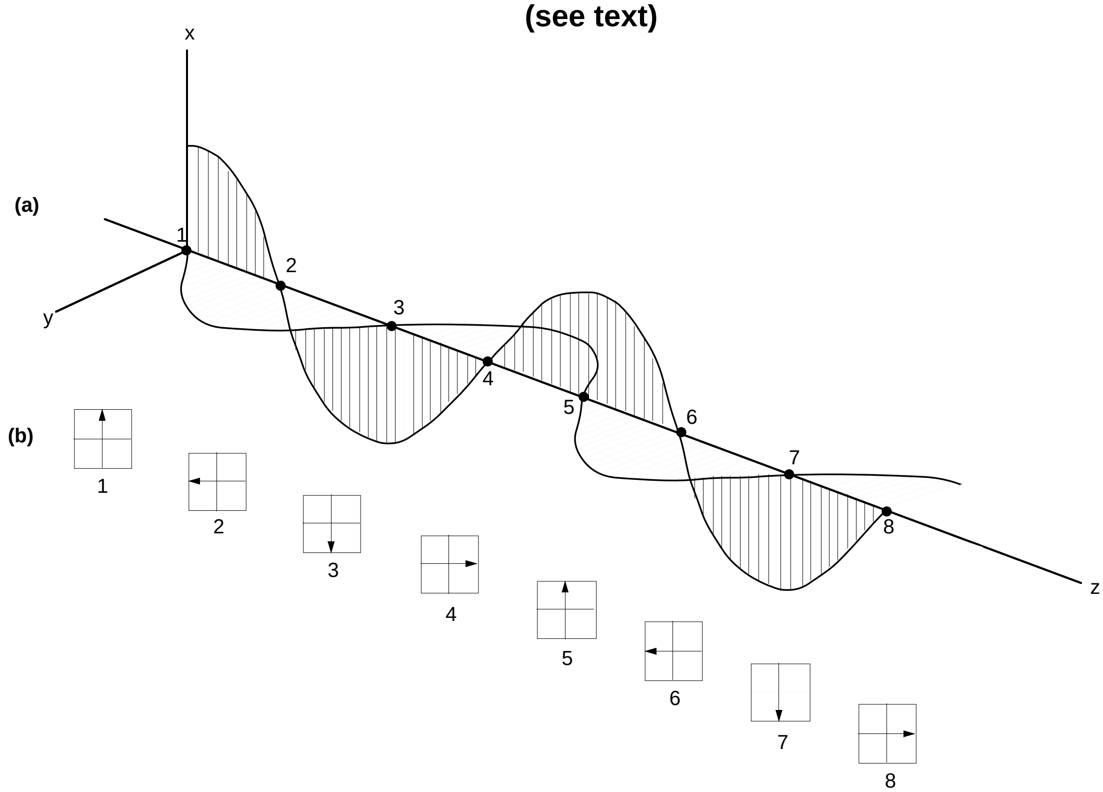
The drawing below shows part of a wavefront as it would appear to an observer at the point indicated in the drawing. The wave is moving directly out of the page. One-half a period later, the observer will see a similar field pattern, except that the directions of both the electric and the magnetic fields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

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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.