10.4 Electromagnetic Radiation

electromagnetic radiation radiation that consists of interacting electric and magnetic fields that travel at the speed of light

In the early decades of the nineteenth century, discoveries by scientists such as Hans Christian Oersted, André-Marie Ampère, and Michael Faraday established the basic relationship between electric and magnetic fields. Other scientists then worked on extending electromagnetic radiation theory to related phenomena. **Electromagnetic radiation** consists of interacting electric and magnetic fields that travel at the speed of light. Some examples are visible light, X-rays, infrared light, ultraviolet light, and gamma rays. One result of this work was the discovery of how electromagnetic waves could travel through space.

Faraday's law describes how a changing magnetic field by itself can produce an electric field. Many physicists wondered if the reverse were possible, whether an electric field by itself could produce a magnetic field. Scottish physicist and mathematician James Clerk Maxwell (**Figure 1**) hypothesized that this was possible. He proposed that a changing electric field produces a magnetic field. Maxwell expressed his theory of electromagnetism in four equations, generally called Maxwell's equations. The key ideas that his equations express are the following:

- Electric charges in space produce an electric field, and currents produce a magnetic field.
- Magnetic field lines form continuous closed loops that have neither a beginning nor an end. Electric field lines always begin and end on charges.
- A changing electric field produces a magnetic field.
- A changing magnetic field produces an electric field.

Figure 1 James Clerk Maxwell formulated the known laws of electromagnetism into a theory that led to the prediction of electromagnetic waves.

The symmetry of the relationship between electric and magnetic fields led Maxwell to an important conclusion. In 1864, he predicted the existence of repeated motions, or oscillations, between electric and magnetic fields. Moreover, he believed that these would take the form of electromagnetic waves travelling through space. Maxwell devised a series of equations that allowed him to calculate the speed of propagation of these oscillating electric and magnetic fields. From these equations, he was able to determine that the waves travelled at the speed of light. Heinrich Hertz confirmed these predictions in 1887 when he discovered radio waves and verified that they obey Maxwell's equations.

The changing fields of an electromagnetic wave can be produced by an accelerating electric charge. In practice, this could be from an oscillating current in a coil or from charged particles that change velocity in some other way. If periodic motion produces the changing fields, the frequency of the electromagnetic wave is the same as the frequency of the current producing it.

Faraday's law explains one important property of these waves. According to Faraday's law, the direction of the electric field, $\vec{\varepsilon}$, is perpendicular to the direction of the magnetic field, $\vec{B}$, that produced it. Similarly, the magnetic field produced by a changing electric field is perpendicular to the electric field that produced it. Therefore, the electric and magnetic fields in an electromagnetic wave are perpendicular to each other (**Figure 2**). In addition, the direction of travel, or propagation, of an electromagnetic wave is perpendicular to both $\vec{\varepsilon}$ and $\vec{B}$, and the two fields oscillate in phase.

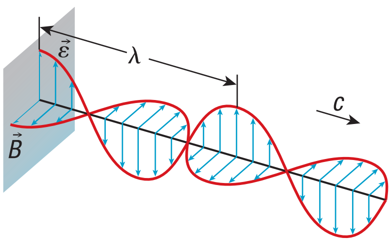

Figure 2 In an electromagnetic wave, the electric and magnetic fields are perpendicular to each other and to the direction of propagation. The fields oscillate in phase with each other.

The three central properties of electromagnetic waves are as follows:

- An electromagnetic wave has both an electric field and a magnetic field.
- The electric and magnetic fields are perpendicular to each other and oscillate in phase.
- The direction of propagation of the wave is perpendicular to both $\vec{\varepsilon}$ and $\vec{B}$.

The Electromagnetic Spectrum

All electromagnetic waves travel through a vacuum at the speed of light. Researchers have measured this speed, designated by the letter c, to be $2.997\ 924\ 58 \times 10^8$ m/s. The measurements are so accurate that, as of 1983, the speed of light is now used to define the length of the metre. In this textbook, though, we use the number 3.0×10^8 m/s.

Researchers classify electromagnetic waves according to their wavelength, λ, and frequency, f. The wavelength and frequency are related to each other through the universal wave equation, $v = f\lambda$. The universal wave equation applies to electromagnetic waves as well as to mechanical waves. However, for electromagnetic waves, we use c to represent speed instead of v. A longer wavelength corresponds to a lower frequency. **Figure 3** shows the frequencies and wavelengths of the parts of the **electromagnetic spectrum**, which is the range of all possible electromagnetic waves. The lowest and highest frequencies have no specific lower or upper limit. The assigned names in different frequency ranges reflect how the waves are typically generated and how they interact with matter.

electromagnetic spectrum the range of frequencies and wavelengths of all electromagnetic waves

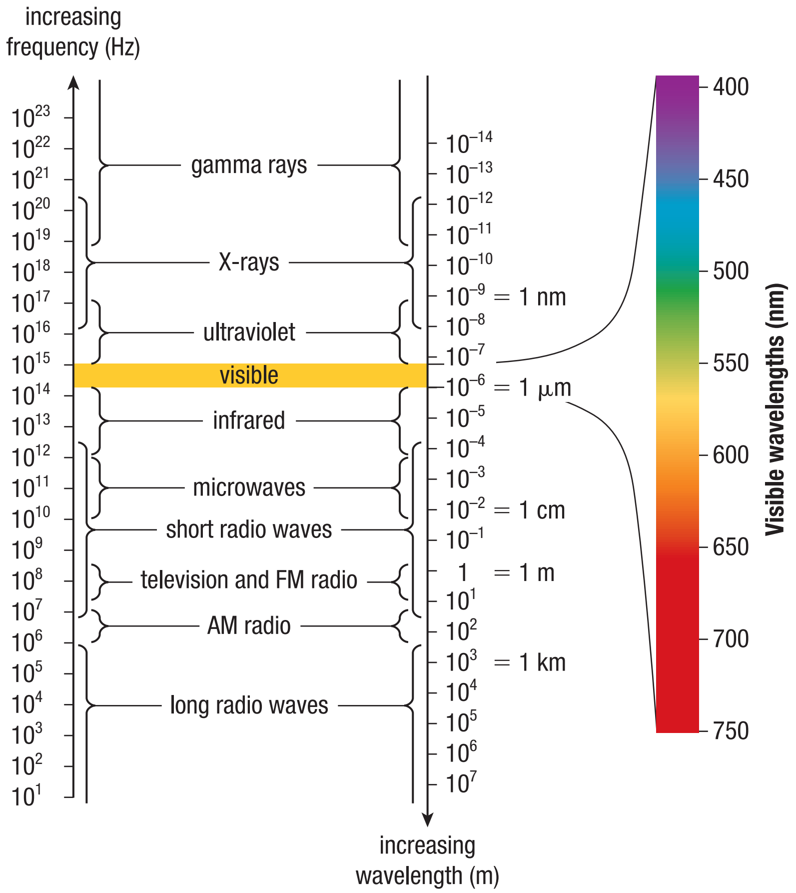

Figure 3 In this diagram of the electromagnetic spectrum, wavelength increases from top to bottom and frequency increases from bottom to top. However this is arbitrary. Some diagrams of the electromagnetic spectrum show the opposite.

Radio waves of all types have frequencies from as low as a few hertz to over 10^{12} Hz. The corresponding wavelengths vary from about 10^8 m to less than a millimetre. Radio waves are usually produced by an alternating-current (AC) circuit attached to an antenna. AC current in an antenna oscillates with time. The moving charges in the antenna accelerate as they oscillate. In general, when an electric charge accelerates, it produces electromagnetic radiation. The frequency of a radio wave generated in this way is equal to the frequency of the current.

Microwaves have frequencies between about 10^9 Hz and 10^{12} Hz. The corresponding wavelengths vary from a few centimetres to a few tenths of a millimetre. Microwave radiation interacts strongly with water molecules. Since most foods contain water, microwaves can be quite useful in the kitchen. Microwave ovens generate radiation with a frequency near 2.5×10^9 Hz. Water molecules readily absorb the energy transmitted by waves of this frequency. As the water molecules absorb this energy, they begin to vibrate. Molecular motion, including vibration, involves the transformation of potential energy within the molecule into thermal energy. That is the way in which microwaves heat food.

Infrared radiation falls in the frequency range from around 10^{12} Hz to about 4×10^{14} Hz (wavelengths from a few tenths of a millimetre to less than a micrometre). Satellite cameras that are sensitive to infrared radiation are useful for monitoring Earth's weather (**Figure 4**). Infrared radiation interacts strongly with molecules and is absorbed by most substances. Vibrating molecules can produce infrared radiation, as can electrons undergoing energy transitions within an atom.

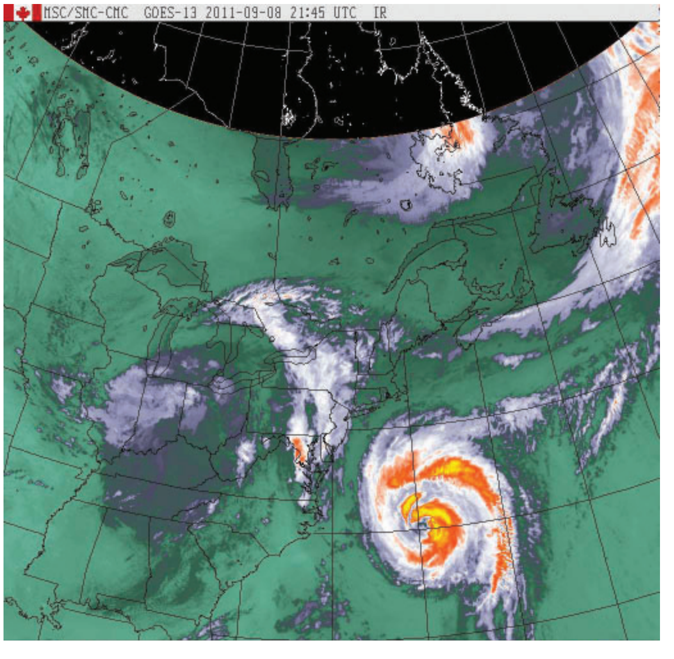

Figure 4 The computer-generated colours correspond to different temperatures. The red, for example, corresponds to higher temperatures.

Figure 5 Laser light, such as in this keychain laser, is monochromatic.

Visible light is the part of the electromagnetic spectrum that we can detect with our eyes. It has a narrow frequency range from about 4×10^{14} Hz to near 8×10^{14} Hz, corresponding to wavelengths from about 750 nm to 400 nm. The colour of visible light varies with its frequency. Light in the lowest frequency range (with the longest wavelengths) appears red. Increasing frequencies correspond in sequence to red, orange, yellow, green, blue, indigo, and violet. White light is a mixture of all these colours of light. Many sources of visible light, such as incandescent light bulbs, produce radiation with a range of frequencies. Some sources, like lasers, produce light of only a single wavelength (**Figure 5**).

Ultraviolet (UV) light has frequencies from about 8×10^{14} Hz to 10^{17} Hz, corresponding to wavelengths from about 3 nm to 400 nm. Ultraviolet radiation stimulates the production of vitamin D in the human body. Nearly all other biological effects of UV radiation are harmful. Excessive exposure to UV light can cause sunburn, skin cancer, and cataracts in the eyes. At shorter wavelengths, the damage to exposed human skin increases. The UV portion of the spectrum is commonly subdivided into several regions, including UV-A, UV-B, and UV-C. UV-C radiation has the highest frequency and the greatest potential for damaging tissue because it has the highest energy. Fortunately, ozone in Earth's atmosphere absorbs UV radiation more strongly at shorter wavelengths, so most UV-C radiation from the Sun does not reach Earth's surface.

X-rays have frequencies of approximately 10^{17} Hz to 10^{20} Hz, with wavelengths of about 0.01 nm to 10 nm. German physicist Wilhelm Röntgen discovered X-rays in 1895 and found that he could use them to form images from inside living tissue. X-rays passing through soft tissue blacken a photographic plate when the plate is processed, while the places where bones absorb the X-rays remain relatively clear. X-rays can show bone fractures, such as in **Figure 6**. All X-ray images used this method until the 1970s, when researchers developed a technique called computed axial tomography (CAT or CT). A CT scan takes many X-ray images at many different angles and then uses sophisticated computer analysis to combine these images into a three-dimensional representation of the object. This allows medical professionals to accurately measure the shape and size of bones, tumours, and so on within the body. Although X-ray imaging is valuable, excessive exposure to X-ray radiation can be harmful. At high exposures, X-rays can damage DNA molecules, which can then cause cancer and other serious diseases.

Gamma rays lie at the high-frequency end of the electromagnetic spectrum, with frequencies above about 10^{20} Hz and wavelengths less than about 10^{-12} m. No precise boundary exists between the X-ray and gamma ray parts of the spectrum. Energy transformations that occur within the nucleus of an atom, such as nuclear fission in nuclear power plants and nuclear fusion in the Sun, produce gamma rays. Gamma rays also reach Earth from sources outside our solar system (**Figure 7**).

UNIT TASK BOOKMARK

You can apply what you have learned about electromagnetic radiation to the Unit Task on page 556.

Figure 6 Doctors use X-rays as an imaging tool to show exactly where bone fractures occur.

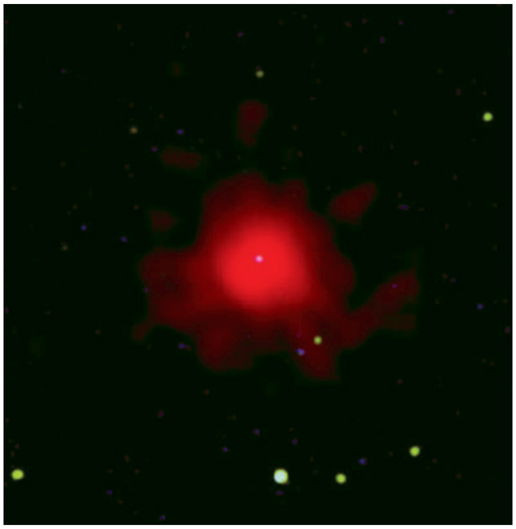

Figure 7 Supernovas are one source of gamma rays that reach Earth.

The following Tutorial shows you how to calculate the frequency, wavelength, and energy of electromagnetic waves.

Tutorial 1 Determining Characteristics of Electromagnetic Waves

Sample Problem 1: Calculating the Frequency of Electromagnetic Waves

Microwaves with a wavelength of 1.5 cm carry television signals using a sequence of relay towers.

(a) Determine the frequency of the microwaves.

(b) How much time does it take for a microwave signal to travel 5.0×10^3 km across Canada from St. John's, Newfoundland, to Victoria, British Columbia?

Solution

(a) **Given:** $\lambda = 1.5 \text{ cm} = 1.5 \times 10^{-2}$ m

Required: f

Analysis: $\lambda f = c$

$$f = \frac{c}{\lambda}$$

Solution: $f = \frac{c}{\lambda}$

$$= \frac{3.0 \times 10^8 \cancel{\text{m}}/\text{s}}{1.5 \times 10^{-2} \cancel{\text{m}}}$$

$$f = 2.0 \times 10^{10} \text{ s}^{-1}$$

Statement: The frequency of the microwaves is 2.0×10^{10} Hz.

(b) **Given:** $d = 5.0 \times 10^3 \text{ km} = 5.0 \times 10^6$ m

Required: Δt

Analysis: $d = c\Delta t$

$$\Delta t = \frac{d}{c}$$

Solution: $\Delta t = \frac{d}{c}$

$$= \frac{5.0 \times 10^6 \cancel{\text{m}}}{3.0 \times 10^8 \cancel{\text{m}}/\text{s}}$$

$$\Delta t = 1.7 \times 10^{-2} \text{ s}$$

Statement: The time required for the microwave signal to travel from St. John's to Victoria is 1.7×10^{-2} s.

Sample Problem 2: Analyzing the Energy of Electromagnetic Waves

An electromagnetic wave in the form of an X-ray transfers its energy to an electron to change its state. The energy of the electromagnetic wave is proportional to its frequency. Suppose the X-ray has a wavelength of 0.025 nm. How does the energy of the electron transition compare with that of 540 nm visible light?

Given: $\lambda_{\text{visible}} = 540$ nm; $\lambda_{\text{X-ray}} = 0.025$ nm

Required: the ratio of energies, $\frac{E_{\text{X-ray}}}{E_{\text{visible}}}$

Analysis: The energy of the electromagnetic wave is proportional to its frequency:

$$\frac{E_{\text{X-ray}}}{E_{\text{visible}}} = \frac{f_{\text{X-ray}}}{f_{\text{visible}}}$$

Substitute the equation for wavelength and frequency into that for the ratio of energies:

$$\frac{E_{\text{X-ray}}}{E_{\text{visible}}} = \frac{\frac{c}{\lambda_{\text{X-ray}}}}{\frac{c}{\lambda_{\text{visible}}}}$$

$$\frac{E_{\text{X-ray}}}{E_{\text{visible}}} = \frac{\lambda_{\text{visible}}}{\lambda_{\text{X-ray}}}$$

Solution: $\frac{E_{\text{X-ray}}}{E_{\text{visible}}} = \frac{540 \text{ nm}}{0.025 \text{ nm}}$

$$\frac{E_{\text{X-ray}}}{E_{\text{visible}}} = 2.2 \times 10^4$$

Statement: The ratio of X-ray energy to visible light energy is 2.2×10^4 to 1 for the electron transition.

Practice

1. An FM station broadcasts at 107.1 MHz. Calculate the wavelength of its signal. T/I [ans: 2.8 m]
2. A particular X-ray machine produces X-rays with a frequency of 3.00×10^{17} Hz. Calculate the wavelength of the X-rays. T/I A [ans: 1.0×10^{-7} cm]
3. A helium–neon laser emits light with a wavelength of 638 nm. Calculate the period of the wave. T/I [ans: 2.1×10^{-15} s]
4. Determine how many wavelengths of radiation from a 60.0 Hz electrical transmission line would be needed to travel across North America (approximately 5.0×10^3 km). T/I A [ans: 1]

10.4 Review

Summary

- Maxwell's theory of electromagnetism predicts that oscillating electric and magnetic fields propagate through space at the speed of light.
- Hertz confirmed experimentally the existence of electromagnetic waves.
- Electromagnetic waves are produced by accelerating electric charges.
- Electromagnetic waves consist of magnetic and electric fields that are perpendicular to each other and to the direction of propagation, and oscillate in phase.
- The electromagnetic spectrum is the range of all possible electromagnetic radiation of various wavelengths and frequencies.
- The main categories of waves in the electromagnetic spectrum are radio waves, microwaves, visible light, ultraviolet light, infrared light, X-rays, and gamma rays.

Questions

1. The light used in a CD player has a frequency of about 5.0×10^{14} Hz. Determine its wavelength. T/I
2. The human eye is most sensitive to light with a wavelength of about 550 nm. Calculate this light's frequency. T/I
3. The dial on an FM radio contains numbers ranging from about 88 to about 108. These numbers correspond to the frequencies of the radio stations as measured in megahertz. Determine the corresponding range of wavelengths. T/I
4. X-rays are electromagnetic waves with very short wavelengths. Suppose an X-ray has a wavelength of 0.10 nm. Calculate its frequency. T/I
5. A microwave oven generates electromagnetic waves that have a wavelength of 12.24 cm. T/I A
   (a) Calculate the frequency of this radiation.
   (b) Explain why most microwave ovens contain rotating carousels.
6. Some cordless telephones use radio waves with a frequency near 2.4 GHz to transmit to their base station. Calculate the wavelength of these waves. T/I
7. The AM radio station 680 News in Toronto uses a frequency of 680 kHz. Determine the corresponding wavelength. T/I
8. Microwaves with a frequency of 7.5 GHz are incident on a slit 6.0 cm wide. Determine the angle from the central maximum to the first diffraction minimum. K/U T/I A
9. Use the Internet or print sources to identify why it is necessary to travel into deep space to detect all parts of the electromagnetic spectrum. Explain your answer. C A
10. When television correspondents are interviewed live in a distant part of the world, there is a delay before hearing their responses. Explain why. K/U A
11. Nearby mountains and airplanes can reflect radio waves. The reflections can interfere with the signal arriving directly from a station. K/U C A
    (a) What kind of interference results when an antenna receives 75 MHz television signals directly from a distant station and also receives waves reflected from an airplane 134 m directly above. (Assume that the phase changes by $\frac{\lambda}{2}$ on reflection.) Explain your answer.
    (b) Identify the type of interference that would result if the plane were 42 m closer to the antenna. Explain your answer.
12. Research how radio transmitters work (**Figure 8**). Write a short journal piece, with an abstract, that describes how a vibrating electric dipole produces electromagnetic radiation. Include an explanation of why antennas are different lengths. T/I C A

Figure 8

WEB LINK