12.5 THE ELECTROMAGNETIC SPECTRUM

Hertz's induction coil produced electromagnetic radiation with a wavelength of about 1 m. This is about one million times the wavelength of visible light. Later experiments showed that a very wide and continuous range of electromagnetic wavelengths (and frequencies) is possible. The entire possible range is called the *electromagnetic spectrum.* The electromagnetic spectrum should not be confused with the *visible spectrum,* which includes only the frequencies of visible light. In principle, the electromagnetic spectrum ranges from close to 0 Hz to infinite Hz, but in practice the range of frequencies from about 1 Hz to 10^{26} Hz, corresponding to wavelengths in the range from 10^{8} m to $10{\sim}^{18}$ m, has been studied. Many of these frequency regions have been put to practical use.

All waves in the electromagnetic spectrum, although produced and detected in various ways, behave as predicted by Maxwell's theory. All electromagnetic waves travel through empty space at the same speed—the speed of light, 3 **X** 10^{8} m/s. They all carry energy; when they are absorbed, the absorber is heated, as, for example, is food in a microwave oven. Electromagnetic radiation, whatever its frequency, can be emitted only if energy is supplied to the source of radiation, which is, ultimately, a charge that is undergoing acceleration. This charge acceleration can be produced in many ways. For example, heating a material will increase the vibrational energy of charged particles. Also, one can vary the motion of charges on an electric conductor—an *antenna*—or cause a charged particle to change its direction. In these and other processes, work is done by the force that is applied to accelerate the electric charge. Some of the energy supplied to the antenna in doing this work is "radiated" away; that is, it propagates away from the source as an electromagnetic wave.

The work of Maxwell and Hertz opened up a new scientific view of nature. It also prepared for a rapid blooming of new technologies. We review below some of the indirect, technological consequences of a scientific advance.

Television, FM, and Radar (λ about 1 m; λ about 10^{8} Hz). Waves at high frequencies of about 10^{8} Hz are not reflected by the layers of electric charge in the upper atmosphere known as the *ionosphere.* Rather, the signals travel in nearly straight lines and pass into space. Thus, they can be used in communication between the Earth and orbiting satellites. But on Earth, TV signals cannot be received directly between points more than about 80 km apart, even if there are no mountains in the way. Instead, communications satellites are used to relay the signals, either directly to the receiver in a home equipped with a satellite dish, or to a cable-company receiver, which then relays the signal to its customers over a large region using cables. Television, in which both sound and picture (in three primary colors) are transmitted, uses both frequency and amplitude modulations. The frequency of the wave is changed in a way that is analogous to the sound, while the picture is transmitted via amplitude modulations. This is called an *analogue wave.* However, in a recent development, the analogue TV signals are gradually being replaced by *digital* signals for digital TV. Here the analogue sound and picture waves are approximated by series of 1's and 0's (or, on and off voltages) that are converted into electromagnetic pulses and compressed at the sender, then transmitted to the receiver where they are decompressed and reconverted into continuous sound and light waves.

Signals at wavelengths of only about 1 m are not diffracted much around objects that have dimensions of several meters, such as cars, ships, or aircraft. Thus, the reflected portions of signals of wavelengths from 1 m down to 1 mm can be used to detect such objects. The interference between the direct waves and reflection of these waves by passing airplanes can distort a television picture considerably. The signal also may be radiated in the form of pulses. If so, the time t between the emission of a pulse and the reception of its echo measures the distance l of the reflecting object ($l = 2\ c/t$). This technique is called "*r*adio *d*etection *a*nd *r*anging," or *radar*. By means of the reflection of a beam that is pulsed, both the direction and distance of an object, such as an aircraft, can be measured. This helps enormously in regulating traffic at busy airports. But initially it had an even more important role in alerting fighters in the United Kingdom during World War II of the approach of German aircraft, e.g., during the "Blitz" meant to destroy London.

Microwave radiation ($\lambda = 10^{-1}$ m to 10^{-4} *m*; $f = 10^{9}$ Hz to 10^{12} Hz). Electromagnetic waves in this region also do not bounce off the ionosphere, but instead pass easily right through it. These waves can thus be used for communicating with devices far beyond the Earth's atmosphere, such as those sent to explore space. Microwave radiation also interacts strongly with the charged particles in ordinary matter, and thus has uses other than communication. When irradiated by microwaves, the matter absorbs the energy in the microwaves. This behavior is used in microwave ovens, in which the kinetic energy of the oscillating charges in food appears as heat, warming the food very quickly. Water, for example, readily absorbs radiation with a wavelength on the order of 10 cm. Thus, any moist substance placed in a region of intense microwave radiation of this wavelength (meat, soup, or a cake batter, for example) will become hot very quickly. Because the heat is generated within the substance itself, rather than conducted inward from the outside, foods can be cooked rapidly in a microwave oven. It is, however, important to keep the radiation confined to the oven because when such microwaves are emitted their radiation can damage living tissue.

Infrared radiation and the greenhouse effect (λ about 10^{-4} m to 10^{-6} m; /about 10^{12} Hz to 10^{14} Hz). Radiation in this region of the electromagnetic spectrum, just below the red end of the visible spectrum, is often called "thermal radiation," because it transmits heat. Because of the oscillation of charges within molecules due to heat energy, all warm objects, such as a glowing fireplace or warm-blooded creatures, emit infrared electromagnetic radiation. This is also how heat is transmitted from the Sun to the Earth, and it is one way in which living creatures can be detected at night by nocturnal predators or by humans using special "night vision" apparatus. Thus, warm objects and animals can be detected or photographed "in the dark" using infrared-sensitive equipment or film.

Visible light ($\lambda = 7 \text{ X } 10^{-7}$ m to $4 \text{ X } 10^{-7}$ m; $f = 4 \text{ X } 10^{14}$ Hz to $8 \text{ X } 10^{14}$ Hz). This small band of frequencies is known as visible light because the visual receptors in the human eye are sensitive only to these frequencies. If light within this band of frequencies is sent through a glass prism or through the raindrops in a cloud, it can be broken down into its constituent frequencies, which are observed by the human eye as the colors of the rainbow. These colors range from red at the low-frequency end ($4 \text{ X } 10^{14}$ Hz) to violet at the high-frequency end ($8 \text{ X } 10^{14}$ Hz). The main colors, in order, are: red, orange, yellow, green, blue, indigo, and violet (which may be remembered by the acronym ROY G BIV).

Ultraviolet waves and ozone depletion (λ about 10^{-7} m to 10^{-8} m; λ about 10^{15} Hz to 10^{16} Hz). Electromagnetic waves above the visible range— ultraviolet, X rays, and gamma rays—can damage living tissue, and some can cause cancer and genetic mutations. Although X rays and gamma rays occur naturally in our environment, they are much less abundant than ultraviolet rays, which are contained in the Sun's rays. Fortunately, a layer in the Earth's atmosphere provides some protection against the Sun's damaging ultraviolet rays. This layer contains a molecule called "ozone," a rare form of oxygen. Normally two oxygen atoms chemically join to form a stable molecule, O_2. However, under certain circumstances, such as those caused by lightning, three oxygen atoms join together loosely to form the molecule, O_3, which is called ozone. At ground level, when ozone combines with exhaust from automobiles or other engines on a hot day, it produces smog that has serious health hazards. However, high in the atmosphere it forms a protection against ultraviolet rays. This molecule vibrates at the frequency of ultraviolet rays and can thus absorb or reflect these rays from the Sun back into space. Unfortunately, man-made chemicals, widely used in industry, known as CFCs (chlorofluorocarbons), have been destroying the ozone layer since the 1930s, creating an "ozone hole" and allowing more of the damaging ultraviolet rays to reach the Earth's surface. This has caused a noticeable increase in skin cancers and eye cataracts in people, and the endangerment of some sea creatures and crops.

X rays ($\lambda = 10^{-8}$ m to 10^{-17} *m*; $f = 10^{16}$ Hz to 10^{25} Hz). Atoms emit X radiation when electrons undergo transitions between the inner shells of the atoms. X rays are also produced by the sudden deflection or stopping of electrons when they strike a metal target. The maximum frequency of the radiation generated is determined by the energy with which the electrons strike the target. In turn, this energy is determined by the voltage through which the electrons are accelerated. So the maximum frequency increases with the accelerating voltage. The higher the frequency of the X rays, the greater is their power to penetrate matter. But the distance of penetration also depends on the nature of the material being penetrated. X rays are readily absorbed by bone, which contains calcium, while they pass much more easily through less dense organic matter such as flesh, which contains mainly the light atoms: hydrogen, carbon, and oxygen.

These properties of X rays, combined with their ability to affect a photographic plate, have led to some of the spectacular medical uses of X-ray photography. Because X rays can damage living cells and even cause genetic mutations, they have to be used with great caution and only by trained technicians. Since some kinds of diseased cells are injured more easily by X rays than are healthy cells, a carefully controlled X ray beam is sometimes used to destroy cancerous growths or other harmful cells. X rays are now widely used by chemists, physicists, mineralogists, and biologists in studying the structure of crystals and complex molecules.

Gamma rays ($\lambda = 10^{-17}$ m and smaller; $f = 10^{25}$ Hz and higher). The gamma-ray region of the electromagnetic spectrum overlaps the X ray region. Gamma radiation is emitted mainly by the unstable nuclei of natural or artificial radioactive materials. They are also a component of so-called cosmic radiation, radiation streaming to the Earth from outer space. Gamma rays are the most energetic radiation known, and, in cosmic radiation, they are produced by the most energy-intensive events in the Universe—the explosions of supernovae and other cataclysmic events. Many of the cosmic events that produce the observed gamma rays are not well understood. A series of gamma-ray sensitive satellites is presently studying these events.

'Physics'
B.K. Cassidy