Electromagnetic spectrum

The **electromagnetic spectrum** is the entire range and scope (spectrum) of frequencies of electromagnetic radiation and their respective wavelengths and photon energies.

The electromagnetic spectrum extends from below the low frequencies used for modern radiocommunication to gamma radiation at the short-wavelength (high-frequency) end, thereby covering wavelengths from thousands of kilometers down to a fraction of the size of an atom. Visible light lies toward the shorter end, with wavelengths from 400 to 700 nanometres. The limit for long wavelengths is the size of the universe itself, while it is thought that the short wavelength limit is in the vicinity of the Planck length.[4] Until the middle of the 20th century it was believed by most physicists that this spectrum was infinite and continuous.

Nearly all types of electromagnetic radiation can be used for spectroscopy, to study and characterize matter.[5] Other technological uses are described under electromagnetic radiation.

History of electromagnetic spectrum discovery

See also: History of electromagnetism, History of radio, History of electrical engineering, and History of optics

For most of history, visible light was the only known part of the electromagnetic spectrum. The ancient Greeks recognized that light traveled in straight lines and studied some of its properties, including reflection and refraction. The study of light continued, and during the 16th and 17th centuries conflicting theories regarded light as either a wave or a particle.[6]

The first discovery of electromagnetic radiation other than visible light came in 1800, when William Herschel discovered infrared radiation.[7] He was studying the temperature of different colors by moving a thermometer through light split by a prism. He noticed that the highest temperature was beyond red. He theorized that this temperature change was due to "calorific rays" that were a type of light ray that could not be seen.

The next year, Johann Ritter, working at the other end of the spectrum, noticed what he called "chemical rays" (invisible light rays that induced certain chemical reactions). These behaved similarly to visible violet light

rays, but were beyond them in the spectrum.[8] They were later renamed ultraviolet radiation.

Electromagnetic radiation was first linked to electromagnetism in 1845, when Michael Faraday noticed that the polarization of light traveling through a transparent material responded to a magnetic field(see Faraday effect). During the 1860s James Maxwell developed four partial differential equations for the electromagnetic field. Two of these equations predicted the possibility and behavior of waves in the field. Analyzing the speed of these theoretical waves, Maxwell realized that they must travel at a speed that was about the known speed of light. This startling coincidence in value led Maxwell to make the inference that light itself is a type of electromagnetic wave.

Maxwell's equations predicted an infinite number of frequencies of electromagnetic waves, all traveling at the speed of light. This was the first indication of the existence of the entire electromagnetic spectrum.

Maxwell's predicted waves included waves at very low frequencies compared to infrared, which in theory might be created by oscillating charges in an ordinary electrical circuit of a certain type. Attempting to prove Maxwell's equations and detect such low frequency electromagnetic radiation, in 1886 the physicist Heinrich Hertz built an apparatus to generate and detect what are now called radio waves. Hertz found the waves and was able to infer (by measuring their wavelength and multiplying it by their frequency) that they traveled at the speed of light. Hertz also demonstrated that the new radiation could be both reflected and refracted by various dielectric media, in the same manner as light. For example, Hertz was able to focus the waves using a lens made of tree resin. In a later experiment, Hertz similarly produced and measured the properties of microwaves. These new types of waves paved the way for inventions such as the wireless telegraph and the radio.

In 1895 Wilhelm Röntgen noticed a new type of radiation emitted during an experiment with an evacuated tube subjected to a high voltage. He called these radiations x-rays and found that they were able to travel through parts of the human body but were reflected or stopped by denser matter such as bones. Before long, many uses were found for them in the field of medicine.

The last portion of the electromagnetic spectrum was filled in with the discovery of gamma rays. In 1900 Paul Villard was studying the radioactive emissions of radium when he identified a new type of radiation that he first thought consisted of particles similar to known alpha and beta particles, but with the power of being far more penetrating than either. However, in 1910, British physicist William Henry

Bragg demonstrated that gamma rays are electromagnetic radiation, not particles, and in 1914, Ernest Rutherford (who had named them gamma rays in 1903 when he realized that they were fundamentally different from charged alpha and beta particles) and Edward Andrade measured their wavelengths, and found that gamma rays were similar to X-rays, but with shorter wavelengths and higher frequencies.

Range of the spectrum

Electromagnetic waves are typically described by any of the following three physical properties: the frequency *f*, wavelength λ, or photon energy *E*. Frequencies observed in astronomy range from 2.4×10^{23} Hz (1 GeV gamma rays) down to the local plasma frequency of the ionized interstellar medium (~1 kHz). Wavelength is inversely proportional to the wave frequency,[5] so gamma rays have very short wavelengths that are fractions of the size of atoms, whereas wavelengths on the opposite end of the spectrum can be as long as the universe. Photon energy is directly proportional to the wave frequency, so gamma ray photons have the highest energy (around a billion electron volts), while radio wave photons have very low energy (around a femtoelectronvolt). These relations are illustrated by the following equations:

where:

- c = 299792458 m/s is the speed of light in a vacuum
- $h = 6.62606896(33)\times10^{-34}$ J·s = $4.13566733(10)\times10^{-15}$ eV·s is Planck's constant.[9]

Whenever electromagnetic waves exist in a medium with matter, their wavelength is decreased. Wavelengths of electromagnetic radiation, no matter what medium they are traveling through, are usually quoted in terms of the *vacuum wavelength*, although this is not always explicitly stated.

Generally, electromagnetic radiation is classified by wavelength into radio wave, microwave, terahertz (or sub-millimeter) radiation, infrared, the visible region that is perceived as light, ultraviolet, X-rays and gamma rays. The behavior of EM radiation depends on its wavelength. When EM radiation interacts with single atoms and molecules, its behavior also depends on the amount of energy per quantum (photon) it carries.

Spectroscopy can detect a much wider region of the EM spectrum than the visible range of 400 nm to 700 nm. A common laboratory spectroscope can detect wavelengths from 2 nm to 2500 nm[*citation needed*]. Detailed information about the physical properties of objects, gases, or even stars can be obtained from this type of device. Spectroscopes are widely used in astrophysics. For example, many hydrogen atoms emit a radio wave photon that has a wavelength of 21.12 cm. Also, frequencies of 30 Hz and below can be produced by and are important in the study of certain stellar nebulae[10] and frequencies as high as 2.9×10^{27} Hz have been detected from astrophysical sources.[11]

Rationale for spectrum regional names

Electromagnetic radiation interacts with matter in different ways across the spectrum. These types of interaction are so different that historically different names have been applied to different parts of the spectrum, as though these were different types of radiation. Thus, although these "different kinds" of electromagnetic radiation form a quantitatively continuous spectrum of frequencies and wavelengths, the spectrum remains divided for practical reasons related to these qualitative interaction differences.

Electromagnetic radiation interaction with matter

Region of the spectrum	Main interactions with matter
Radio	Collective oscillation of charge carriers in bulk material (plasma oscillation). An example would be the oscillatory travels of the electrons in an antenna.
Microwave through far infrared	Plasma oscillation, molecular rotation
Near infrared	Molecular vibration, plasma

	oscillation (in metals only)
Visible	Molecular electron excitation (including pigment molecules found in the human retina), plasma oscillations (in metals only)
Ultraviolet	Excitation of molecular and atomic valence electrons, including ejection of the electrons (photoelectric effect)
X-rays	Excitation and ejection of core atomic electrons, Compton scattering (for low atomic numbers)
Gamma rays	Energetic ejection of core electrons in heavy elements, Compton scattering (for all atomic numbers), excitation of atomic nuclei, including dissociation of nuclei
High-energy gamma rays	Creation of particle-antiparticle pairs. At very high energies a single photon can create a shower of high-energy particles and antiparticles upon interaction with matter.

Types of radiation

- Boundaries
- Regions of the spectrum
- Radio frequency
- Microwaves

- Terahertz radiation
- Infrared radiation
- Visible radiation (light)
- Ultraviolet radiation
- X-rays
- Gamma rays