SAMPLE

The Electromagnetic Spectrum

Beyond Visible Light

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Conclusion

This free sample contains the Introduction and Chapter 1. The complete book contains the full contents above.

Introduction

Light, radio, heat radiation, X-rays: these do not look like relatives, yet every one of them is the same thing, an electromagnetic wave, differing only in wavelength. The electromagnetic spectrum is the complete family, arranged by frequency, from the leisurely swings of power-line radiation a hundred kilometres crest to crest, through the colours our eyes were built to see, up to gamma rays whose crests repeat every thousandth of a nanometre.

The scale is hard to exaggerate. In frequency the spectrum spans more than twenty orders of magnitude, and the photon energy climbs with every step of it. That single fact explains most of the spectrum's practical personality: the low end (radio waves and microwaves) is gentle stuff that travels far and carries information well, which is why it hosts broadcasting, navigation and every wireless gadget of modern life. The middle (infrared, visible light) is the radiation of warmth and sight. The high end (X-rays and gamma rays) carries such concentrated energy that it tears electrons from atoms, which is what makes those rays both a medical marvel and a hazard to be respected.

Each region of the spectrum was discovered separately, and often by accident. Infrared was found because a thermometer registered warmth beyond the red end of a sunbeam; ultraviolet because silver salts darkened beyond the violet; radio waves because a spark jumped across a room. Only when Maxwell's equations predicted waves of every frequency did these scattered curiosities resolve into a single, continuous whole, one of physics' great unifications.

This book follows that spectrum band by band: how each part was discovered, what makes it behave as it does, how it is measured and regulated, what it is used for, and where our command of it is heading next.

Chapter 1: The Discovery of The Electromagnetic Spectrum

These behaved similarly to visible violet light rays, but were beyond them in the spectrum. They were later renamed ultraviolet radiation. The study of electromagnetism began in 1820 when Hans Christian Ørsted discovered that electric currents produce magnetic fields (Oersted's law). Light 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 Clerk Maxwell developed four partial differential equations (Maxwell's 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 range 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 he hypothesized might be created by oscillating charges. 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 this radiation "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 this radiography.

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 at 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.

The wave-particle debate was rekindled in 1901 when Max Planck discovered that light is absorbed only in discrete "quanta", now called photons, implying that light has a particle nature. This idea was made explicit by Albert Einstein in 1905, but never accepted by Planck and many other contemporaries. The modern position of science is that electromagnetic radiation has both a wave and a particle nature, the wave- particle duality. The contradictions arising from this position are still being debated by scientists and philosophers.

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 2.4×1023 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, 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 indefinitely long.

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: f = c E h where: c is the speed of light in vacuum h is the Planck constant. Whenever electromagnetic waves travel in a medium with matter, their wavelength is decreased.

Wavelengths of electromagnetic radiation, whatever 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 sorted by wavelength, from the longest radio waves and microwaves, through infrared, the visible colours and ultraviolet, to the shortest of all in X-rays and gamma rays. How EM radiation behaves depends

on its wavelength, and when it meets single atoms and molecules, on how much energy each quantum of it carries.

Spectroscopy can detect a much wider region of the EM spectrum than the visible wavelength range of 400 nm to 700 nm in a vacuum. A common laboratory spectroscope can detect wavelengths from 2 nm to 2500 nm. Detailed information about the physical properties of objects, gases, or even stars can be obtained from this type of device.

In 1800, William Herschel discovered infrared radiation. He was studying the temperature of different colours 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", 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).

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 and frequencies as high as 2.9×1027 Hz have been detected from astrophysical sources.

Gamma radiation

X-ray radiation

Ultraviolet radiation

Visible light (light that humans can see)

Infrared radiation

Microwave radiation

Radio waves

There are no precisely defined boundaries between the bands of the electromagnetic spectrum; rather they fade into each other like the bands in a rainbow. Radiation of each frequency and wavelength (or in each band) has a mix of properties of the two regions of the spectrum that bound it.

For example, red light resembles infrared radiation, in that it can excite and add energy to some chemical bonds and indeed must do so to power the chemical mechanisms responsible for photosynthesis and the working of the visual system. In atomic and nuclear physics, the distinction between X-rays and gamma rays is based on sources: the photons generated from nuclear

decay or other nuclear and subnuclear/particle process are termed gamma rays, whereas X-rays are generated by electronic transitions involving energetically deep inner atomic electrons.

Electronic transitions in muonic atoms transitions are also said to produce X-rays. In astrophysics, energies below 100keV are called X-rays and higher energies are gamma rays. The region of the spectrum where electromagnetic radiation is observed may differ from the region it was emitted in due to relative velocity of the source and observer, (the Doppler shift), relative gravitational potential (gravitational redshift), or expansion of the universe (cosmological redshift).

For example, the cosmic microwave background, relic blackbody radiation from the era of recombination, started out at energies around 1eV, but as has undergone enough cosmological red shift to put it into the microwave region of the spectrum for observers on Earth. 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 arising from these qualitative interaction differences. Radio waves are emitted and received by antennas, which consist of conductors such as metal rod resonators. In artificial generation of radio waves, an electronic device called a transmitter generates an alternating electric current which is applied to an antenna.

The oscillating electrons in the antenna generate oscillating electric and magnetic fields that radiate away from the antenna as radio waves. In reception of radio waves, the oscillating electric and magnetic fields of a radio wave couple to the electrons in an antenna, pushing them back and forth, creating oscillating currents which are applied to a radio receiver. Earth's atmosphere is mainly transparent to radio waves, except for layers of charged particles in the ionosphere which can reflect certain frequencies.

Radio waves are extremely widely used to transmit information across distances in radio communication systems such as radio broadcasting, television, two way radios, mobile phones, communication satellites, and wireless networking. In a radio communication system, a radio frequency current is modulated with an information-bearing signal in a transmitter by varying either the amplitude, frequency or phase, and applied to an antenna.

The radio waves carry the information across space to a receiver, where they

are received by an antenna and the information extracted by demodulation in the receiver. Radio waves are also used for navigation in systems like Global Positioning System (GPS) and navigational beacons, and locating distant objects in radiolocation and radar. They are also used for remote control, and for industrial heating.

The use of the radio spectrum is strictly regulated by governments, coordinated by the International Telecommunication Union (ITU) which allocates frequencies to different users for different uses. Microwaves are radio waves of short wavelength, from about 10 centimeters to one millimeter, in the SHF and EHF frequency bands. Microwave energy is produced with klystron and magnetron tubes, and with solid state devices such as Gunn and IMPATT diodes.

Although they are emitted and absorbed by short antennas, they are also absorbed by polar molecules, coupling to vibrational and rotational modes, resulting in bulk heating. Unlike higher frequency waves such as infrared and visible light which are absorbed mainly at surfaces, microwaves can penetrate into materials and deposit their energy below the surface. This effect is used to heat food in microwave ovens, and for industrial heating and medical diathermy.

The copper cables (transmission lines) which are used to carry lower-frequency radio waves to antennas have excessive power losses at microwave frequencies, and metal pipes called waveguides are used to carry them.

Although at the low end of the band the atmosphere is mainly transparent, at the upper end of the band absorption of microwaves by atmospheric gases limits practical propagation distances to a few kilometers. Terahertz radiation, also known as sub-millimeter radiation, THF, T-rays, or T-light, is a region of the spectrum from about 100 GHz to 30 terahertz (THz) between microwaves and far infrared which can be regarded as belonging to either band.

Until recently, the range was rarely studied and few sources existed for microwave energy in the so-called terahertz gap, but applications such as imaging and communications are now appearing. Scientists are also looking to apply terahertz technology in the armed forces, where high- frequency waves might be directed at enemy troops to incapacitate their electronic equipment. Terahertz radiation is strongly absorbed by atmospheric gases, making this frequency range useless for long-distance communication.

The infrared part of the electromagnetic spectrum covers the range from roughly 300 GHz to 400 THz (1 mm - 750 nm).

Far-infrared, from 300 GHz to 30 THz (1 mm - 10 μm). The lower part of this

range may also be called microwaves or terahertz waves. This radiation is typically absorbed by so-called rotational modes in gas-phase molecules, by molecular motions in liquids, and by phonons in solids.

Radiation of this kind is what a warm object gives off purely by being warm, the glow sometimes called heat radiation, from objects at temperatures often encountered on Earth.

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ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.