SAMPLE

The Electromagnetic Spectrum

Beyond Visible Light

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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.

Chapter 2: Key Characteristics of The Electromagnetic Spectrum

Microwaves are the main wavelengths used in radar, and are used for satellite communication, and wireless networking technologies such as Wi-Fi. The water in Earth's atmosphere absorbs so strongly in this range that it renders the atmosphere in effect opaque. However, there are certain wavelength ranges ("windows") within the opaque range that allow partial transmission, and can be used for astronomy.

The wavelength range from approximately 200 µm up to a few mm is often referred to as Submillimetre astronomy, reserving far infrared for wavelengths below 200 µm. Mid-infrared, from 30 THz to 120 THz (10–2.5 µm). Hot objects (black-body radiators) can radiate strongly in this range, and human skin at normal body temperature radiates strongly at the lower end of this region. This radiation is absorbed by molecular vibrations, where the different atoms in a molecule vibrate around their equilibrium positions.

This range is sometimes called the fingerprint region, since the mid-infrared absorption spectrum of a compound is very specific for that compound. Near-infrared, from 120 THz to 400 THz (2,500–750 nm). Physical processes that are relevant for this range are similar to those for visible light. The highest frequencies in this region can be detected directly by some types of photographic film, and by many types of solid

state image sensors for infrared photography and videography. Above infrared in frequency comes visible light.

The sun emits its peak power in the visible region, although integrating the entire emission power spectrum through all wavelengths shows that it emits slightly more infrared than visible light. By definition, visible light is the part of the EM spectrum the human eye is the most sensitive to. Visible light (and near-infrared light) is typically absorbed and emitted by electrons in molecules and atoms that move from one energy level to another.

This action allows the chemical mechanisms that underlie human vision and plant photosynthesis. The light that excites the human visual system is a very small portion of the electromagnetic spectrum. A rainbow shows the optical (visible) part of the electromagnetic spectrum; infrared (if it could be seen) would be located just beyond the red side of the rainbow whilst ultraviolet would appear just beyond the opposite violet end.

Electromagnetic radiation with a wavelength between 380 nm and 760 nm (400–790 terahertz) is detected by the human eye and perceived as visible light. Other wavelengths, especially near infrared (longer than 760 nm) and ultraviolet (shorter than 380 nm) are also sometimes referred to as light, especially when the visibility to humans is not relevant. White light is a combination of lights of different wavelengths in the visible spectrum.

Passing white light through a prism splits it up into the several colours of light observed in the visible spectrum between 400 nm and 780 nm. If radiation having a frequency in the visible region of the EM spectrum reflects off an object, say, a bowl of fruit, and then strikes the eyes, this results in visual perception of the scene.

The brain's visual system processes the multitude of reflected frequencies into different shades and hues, and through this insufficiently understood psychophysical phenomenon, most people perceive a bowl of fruit. At most wavelengths, however, the information carried by electromagnetic radiation is not directly detected by human senses. Natural sources produce EM radiation across the spectrum, and technology can also manipulate a broad range of wavelengths.

Optical fiber transmits light that, although not necessarily in the visible part of the spectrum (it is usually infrared), can carry information. The modulation is similar to that used with radio waves. Next in frequency comes ultraviolet (UV). In frequency (and thus energy), UV rays sit between the violet end of the visible spectrum and the X-ray range.

Two further properties give each band its working personality. The first is polarization: electromagnetic waves oscillate at right angles to their direction of travel, and the orientation of that oscillation can be filtered, rotated and read. Polarizing sunglasses exploit it to strip the glare from horizontal surfaces, liquid-crystal displays depend on it to switch pixels, and astronomers use it to map magnetic fields across the Milky Way.

The second is dispersion: different frequencies travel through materials at slightly different speeds, so a prism or a droplet of water unwinds white light into its component colours, and a rainbow is simply the sky performing the experiment on sunlight. The same effect, writ large, limits how fast pulses can travel down the optical fibres that carry the internet, because a pulse made of many frequencies smears out as it runs; engineers fight it with carefully chosen wavelengths and compensating fibre.

The atmosphere, too, behaves like a selective window. It is broadly transparent in the visible and in good slices of the radio band, swallows most infrared and ultraviolet, and shuts almost completely at X-ray and gamma energies. Every telescope built on the ground works inside this transparency; everything else has to be watched from balloons, high-flying aircraft or orbit.

The cleanest key to each band, though, is the line spectrum. Atoms absorb light, and emit it back, only at the particular frequencies their electrons are built to jump between, so every element broadcasts a comb of narrow lines as personal as a signature. Neon glows its famous red-orange because that is where neon's lines cluster; low-pressure sodium streetlights were chosen for their single efficient yellow line; astronomers can tell the mix of gases in a star's atmosphere from the combs it shows, and chemists the impurities in a flame. A century and a half of spectroscopy rests on this one stubborn fact: matter is fussy about which frequencies it deals in.

Chapter 3: The Science Behind The Electromagnetic Spectrum

The UV wavelength spectrum ranges from 399 nm to 10 nm and is divided into 3 sections: UVA, UVB, and UVC. UV is the lowest energy range energetic enough to ionize atoms, separating electrons from them, thereby causing chemical reactions. UV, X-rays, and gamma rays are collectively called ionizing radiation; exposure to them can damage living tissue. UV can also cause substances to glow with visible light, a phenomenon called fluorescence.

UV fluorescence has many practical applications, and is used in fields such as forensic science, conservation, medical imaging, and killing insects. At the middle range of UV, UV rays cannot ionize but can break chemical bonds, making molecules unusually reactive. Sunburn, for example, is caused by the disruptive effects of middle range UV radiation on skin cells, which is the main cause of skin cancer.

UV rays in the middle and shorter range can irreparably damage the complex DNA molecules in the cells producing thymine dimers making it a very potent mutagen. Sunscreen can protect against this radiation. Short range wavelengths are called UVC. UVB and UVC lights utilize the destructive nature of these wavelengths to sterilize, and have other scientific applications.

The sun emits UV radiation (about 10% of its total power), including extremely short wavelength UV that could potentially destroy most life on land (ocean water would

provide some protection for life there). However, most of the sun's damaging UV wavelengths are absorbed by the atmosphere before they reach the surface. The higher energy (shortest wavelength) ranges of UV (called "vacuum UV") are absorbed by nitrogen and, at longer wavelengths, by simple diatomic oxygen in the air.

Most of the UV in the mid-range of energy is blocked by the ozone layer, which absorbs strongly in the important 200–315 nm range, the lower energy part of which is too long for ordinary dioxygen in air to absorb. This leaves less than 3% of sunlight at sea level in UV, with all of this remainder at the lower energies. The remainder is UV-A, along with some UV-B.

The very lowest energy range of UV between 315 nm and visible light (called UV-A) is not blocked well by the atmosphere, but does not cause sunburn and does less biological damage. However, it is not harmless and does create oxygen radicals, mutations and skin damage. After UV come X-rays, which, like the upper ranges of UV are also ionizing. However, due to their higher energies, X-rays can also interact with matter by means of the Compton effect.

Hard X-rays have shorter wavelengths than soft X-rays and as they can pass through many substances with little absorption, they can be used to 'see through' objects with 'thicknesses' less than that equivalent to a few meters of water. One notable use is diagnostic X-ray imaging in medicine (a process known as radiography). X-rays are useful as probes in high-energy physics. In astronomy, the accretion disks around neutron stars and black holes emit X-rays, enabling studies of these phenomena.

X-rays are also emitted by stellar corona and are strongly emitted by some types of nebulae. However, X-ray telescopes must be placed outside the Earth's atmosphere to see astronomical X-rays, since the great depth of the atmosphere of Earth is opaque to X-rays (with areal density of 1000 g/cm2), equivalent to 10 meters thickness of water. This is an amount sufficient to block almost all astronomical X-rays (and also astronomical gamma rays—see below).

After hard X-rays come gamma rays, discovered by Paul Ulrich Villard in 1900. These are the most energetic photons, having no defined lower limit to their wavelength. In astronomy they are valuable for studying high-energy objects or regions, however as with X-rays this can only be done with telescopes outside the Earth's atmosphere. Gamma rays are used experimentally by physicists for their penetrating ability and are produced by a number of radioisotopes.

They are used for irradiation of foods and seeds for sterilization, and in medicine they are occasionally used in radiation cancer therapy. More commonly, gamma rays are used for diagnostic imaging in nuclear medicine, an example being PET scans. The wavelength of gamma rays can be measured with high accuracy through the effects of Compton scattering. Next in frequency comes ultraviolet (UV).

The high end of the ultraviolet and the soft X-ray region now carry surprising industrial weight. Extreme ultraviolet lithography, which prints chip patterns by reflecting EUV light off staggered mirrors, is the process behind the most advanced computer processors, a use nobody imagined for that band a century ago. Farther along,

water-purification plants run their flow under ultraviolet lamps that scramble the DNA of pathogens without adding chemicals to the water, and astronomers watch the same radiation from young, massive stars to trace where new stars are being born in distant galaxies.

Infrared also powers a whole family of seeing in the dark. A thermal camera reads the radiation a warm body gives off on its own, no illumination needed, which is why firefighters use it to find people through smoke and electricians use it to find a joint about to fail by its heat. Night-vision gear that amplifies starlight works differently, in the near-infrared just past the eye's reach, and the two technologies are often confused though they read almost opposite ends of the same band.

Chapter 4: Observation and Measurement of The Electromagnetic Spectrum

The English zoologist Hugh Cott, in his 1940 book Adaptive Coloration in Animals, wrote that some caterpillars such as the eyed hawk-moth Smerinthus ocellatus, and tree frogs such as the red-snouted treefrog Hyla coerulea, are coloured so as to blend with their backgrounds whether observed in visible light or in infra-red.

Cott noted the importance of camouflage in the infra-red, given the ability of tactical reconnaissance to observe in this part of the spectrum: Because such screens are effective against direct observation and ordinary photography, by no means does it follow that they will be hidden in the infra-red photograph. Comparison of aerial photographs taken simultaneously on panchromatic and infra-red plates will reveal much that before the advent of this new technique would have been adequately camouflaged...

A German-led NATO research project concluded in 2004 that while "the multispectral signatures of most military equipment can be significantly reduced by combinations of various camouflage materials", multi-spectral camouflage for individual soldiers remained lacking. The main problems identified were operational constraints such as mobility, weight, and the soldier's physiology. Multi-spectral camouflage can be applied to individuals, to vehicles, and to buildings.

It can take the form of specialised paints or camouflage nets that provide conventional camouflage, reduce the amount of heat given off by an object, and alter the shape and size of its radar signature. The Saab Barracuda Mobile Camouflage System provides a degree of concealment in the visible, thermal infrared, and radar parts of the electromagnetic spectrum, as does the Miranda Berberys-R multispectral camouflage system from Poland.

Similarly, other companies such as the American-Israeli Fibrotex and Ametrine, and the Greek Intermat Defence proposed their own products ranging from static vehicle camouflage fabric to multispectral spray paints. Saab AB began offering a multi-spectral personal camouflage system known as the Special Operations Tactical Suit (SOTACS) as early as 2005. And as of 2018, multiple countries are phasing out

legacy camouflage systems with multi-spectral systems. In 2024, IIT Kanpur introduced Anālakṣhya, a Meta-material Surface Cloaking System (MSCS).

The Meta-material Microwave Absorber improves stealth capabilities against Synthetic Aperture Radar (SAR) imaging by wave absorption across a wide spectrum. In the last decade other companies developed their own individual multispectral camouflage, such as the Israeli SpectralX (former Polaris Solutions), the German Phantom Leaf, the American Relv Camo, and the Italian ProApto.

The latter developed the first Italian patent in matter of multispectral camouflage and specifically focuses on 3D individual camouflage, producing multispectral Ghillie Suits designed also for amphibious operations and both tropical and arctic environments. As this type of camouflage hinders electromagnetic radiation, radio-communications and GPS are also hindered. This can be overcome by using frequency selective surfaces, allowing specific frequencies to pass through.

In addition, multispectral camouflage effectiveness depends on many factors including environmental conditions, global electromagnetic irradiance, the kind of environment (urban and human artefacts VS natural environments) and individual variations related to physical conditioning and clothing layering (particularly in matter of human thermal concealment). Multispectral image

In physics, radiation is the emission or transmission of energy in the form of waves or particles through space or a material medium.

This includes: electromagnetic radiation consisting of photons, such as radio waves, microwaves, infrared, visible light, ultraviolet, x-rays, and gamma radiation (γ) particle radiation consisting of particles of non-zero rest energy, such as alpha radiation (α), beta radiation (β), proton radiation and neutron radiation acoustic radiation, such as ultrasound, sound, and seismic waves, all dependent on a physical transmission medium gravitational radiation, in the form of gravitational waves, ripples in spacetime Radiation is often categorized as either ionizing or non-ionizing depending on the energy of the radiated particles.

Ionizing radiation carries more than 10 electron volts (eV), which is enough to ionize atoms and molecules and break chemical bonds. This is an important distinction due to the large difference in harmfulness to living organisms. A common source of ionizing radiation is radioactive materials that emit α, β, or γ radiation, consisting of helium nuclei, electrons or positrons, and photons, respectively.

Other sources include X-rays from medical radiography examinations and muons, mesons, positrons, neutrons and other particles that constitute the secondary cosmic rays that are produced after primary cosmic rays interact with Earth's atmosphere. Gamma rays, X-rays, and the higher energy range of ultraviolet light constitute the ionizing part of the electromagnetic spectrum. The word "ionize" refers to the breaking of one or more electrons away from an atom, an action that requires the relatively high energies that these electromagnetic waves supply.

Further down the spectrum, the non-ionizing lower energies of the lower ultraviolet

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.