Electromagnetic Radiation Principles and Concepts as Applied to Space Remote Sensing

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> *"And God said, 'Let there be light,' and there was light."*
> *Genesis, chapter 1, verse 3, The Holy Bible, New International Version*

Contents

Abstract

Here, we consider a topic which is absolutely central to the successful operation of all satellites and spacecraft, namely, the basic principles and fundamental concepts of visible light in particular and of electromagnetic radiation in general. Both the wavelike nature of light (the speed of light being 300,000 km/s through free space) and its particle-like nature (as photons) are considered. We introduce its wave properties which explain the phenomena of reflection, refraction, diffraction, interference, polarization, and the Doppler effect. The photon properties explain blackbody radiation, continuous spectra, emission spectra, absorption

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spectra, and the photoelectric effect. We mention how electromagnetic radiation is used actively for radio communications with Earth-orbiting satellites and passively for remote sensing investigations not only of the atmospheres of the Earth and other planets but also of distant stars and the structure of Universe.

Keywords
Electromagnetic radiation • Electromagnetic waves • Frequency • Gamma-rays • GPS • Infrared • Light • Milky Way • Photons • Radar • Radio waves • Spectra • Sun • Ultraviolet • Universe • Velocity of light • Wavelength • X-rays

Introduction

Our human eyes are tuned to receive radiation from the Sun, in the form of light. Light is one type of electromagnetic radiation which, from many different viewpoints, is crucial for space studies and space applications. Thus an understanding of both electromagnetic waves and the electromagnetic spectrum is essential for all readers of this volume. Electromagnetic radiation is used for both active and passive studies carried out from space – in the former, waves are transmitted and received (e.g., in a radar altimeter) and, in the latter, they are only received, for example, from a star or from the Sun, the star of our solar system. Electromagnetic radiation from the Sun, whose intensity peaks in the visible part of the spectrum, is the source of energy for almost all processes occurring on the Earth, and for all life on Earth, for the fauna and flora which abound. Light takes about 8 min to travel the $\sim$150 million kilometers from the Sun to the Earth; thus, when we observe the Sun we see it as it was 8 min ago.

Nowadays, electromagnetic waves give us much information on the Earth's atmosphere and its weather systems and on the atmospheres of our neighboring planets. Such passive remote sensing studies are carried out using the observations made by diverse instruments on geostationary or polar-orbiting satellites or aboard spacecraft. Such studies also give us valuable information on the Earth's sea and land surfaces, such as its vegetation cover and the development of urban sprawl.

Radio waves are used to command satellite operations from the ground. They are also used in order to transmit scientific data from satellites, as modulated telemetry signals, to ground stations or to transmit very high frequency radio signals or TV broadcasts from space to different parts of the globe. Radio waves are essential for the operation of positioning and navigation services using satellites, such as provided by the GPS (Global Positioning System) signals now commonly received by the ubiquitous "sat nav" equipment in our cars. A thorough appreciation of the behavior and properties of electromagnetic waves is therefore crucial when discussing the performance and reliability of applications satellites.

The Fundamentals

Visible light is a wave motion, for which electric and magnetic fields oscillate extremely rapidly. Two cycles, or two periods, of a sinusoidally varying wave motion are illustrated in Fig. 1. In this diagram, the horizontal distance between two successive crests of the wave is one wavelength of the wave, which is denoted by the Greek letter λ. The vertical distance between the maximum and the minimum shown is twice the amplitude of the wave. The intensity, or power, of the wave is proportional to the product of the wave electric field amplitude and the wave magnetic field amplitude. Light carries energy radially away from a source, with the light rays traveling in straight lines. The wave electric and magnetic fields are perpendicular to each other, and they are both perpendicular to the direction of propagation of the wave. That result is obtained by solving Maxwell's four equations of electromagnetism (Grant and Phillips 1990).

Light travels at an incredibly high speed. In free space (a vacuum), the velocity of light, c, equals 3×10^8 meters per second (m/s), or 300,000 km/s. For yellow light, its wavelength λ has the value of 600 nm, that is, 6×10^{-7} m, or 0.6 μm. The velocity of light, c, is equal to the product of (i.e., is obtained by multiplying) the frequency f of vibration, or oscillation, of the wave (in cycles/s, now termed Hertz, Hz) and the wavelength λ (in m). The equation $f = c/\lambda$ is the fundamental relation connecting these three quantities.

Inserting the numbers for yellow light, $f = 5 \times 10^{14}$ Hz, 500 million million vibrations per second. Now blue light has a wavelength ~400 nm and red light ~700 nm, which differ by nearly a factor of two – in between blue and red are all the colors of the rainbow. Their frequencies are 7.0×10^{14} Hz (blue) and $\sim 4.3 \times 10^{14}$ Hz (red). We can only see radiation in the visible (Vis) part of the spectrum, with wavelengths between 400 and 700 nm. At shorter wavelengths, there is ultraviolet (UV) radiation, with infrared (IR) radiation at longer wavelengths, as shown in the third line down from the top of Fig. 2 that shows the entire electromagnetic spectrum.

The electromagnetic spectrum stretches from the lowest radio frequencies, 8 Hz (to the left of the bottom of Fig. 2), where the wavelength is equal to the circumference of the Earth (~40,000 km), through radio frequencies, ~100 MHz (or 10^8 Hz) where frequency modulated (FM) commercial radio stations operate, through the microwave (radar) part of the spectrum, at 10 GHz (10^{10} Hz, often termed X-band),

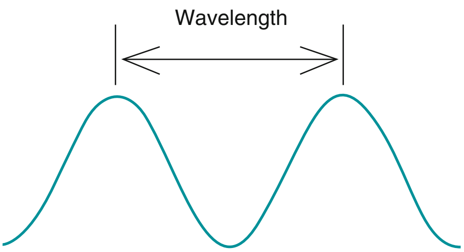


Fig. 1 Diagram showing one wavelength of a wave motion (From www.nrao.edu/index.php/learn/radioastronomy/radiowaves, courtesy of NRAO)

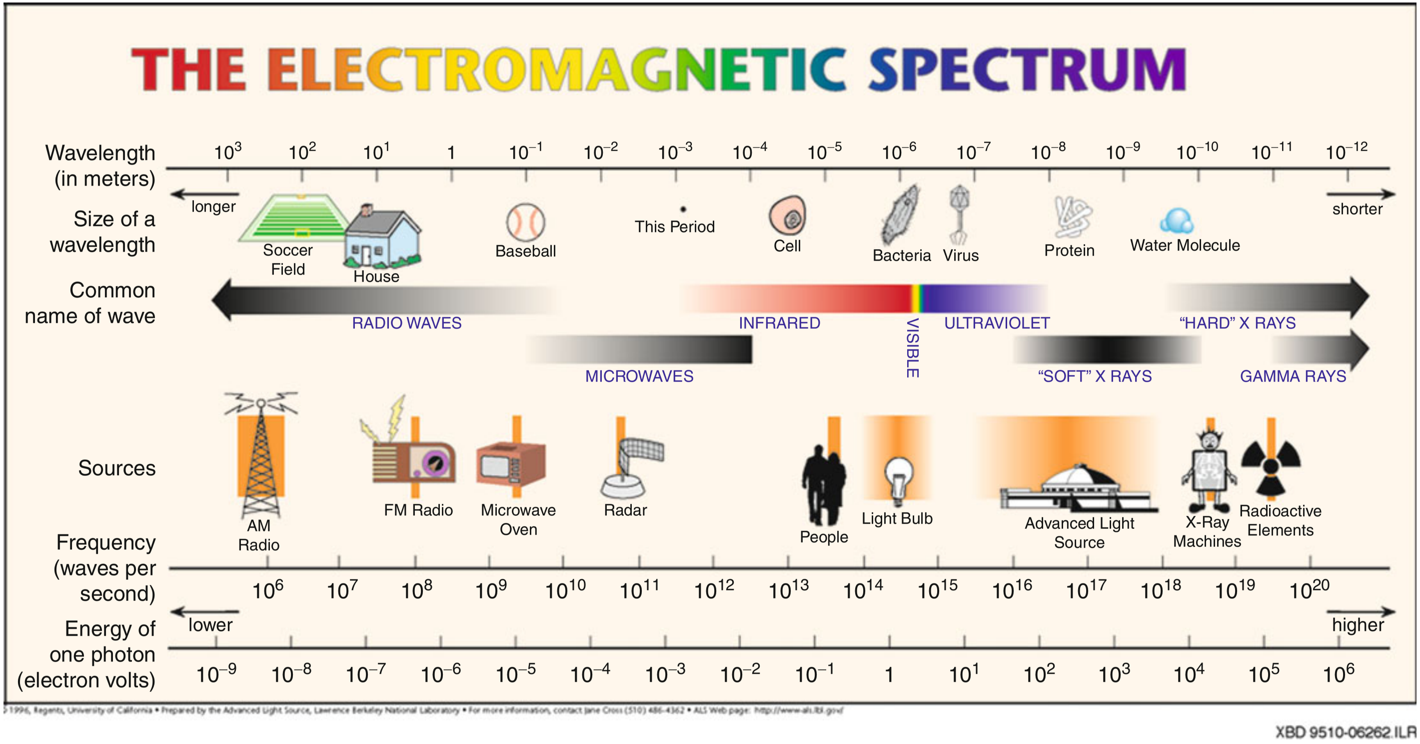


Fig. 2 Diagram showing the full electromagnetic spectrum, in all its glory; the wavelengths (*top*) range from 1 km on the *left* to 10^{-12} m on the *right*, and the corresponding frequencies, given at the *bottom*, go from radio waves of 300 kHz on the *left* to 3×10^{20} Hz gamma-rays on the *right*. The second row from the *top* illustrates different typical objects whose size is that of the corresponding wavelength. Different sources of electromagnetic radiation are shown above the frequency scale, which is itself above the scale specifying the energy (in electron Volts, eV) of one photon of that radiation (From www.lbl.gov/MicroWorlds/ALSTool/EMSpec?EMSpec2.html, courtesy of The Advanced Light Source, Lawrence Berkeley National Laboratory)

having wavelengths $\sim$3 cm, and up to the infrared. Beyond the visible, the electromagnetic spectrum stretches up in frequency another million times, through X-rays and gamma-rays, radiation whose wavelengths are as small as a millionth of the wavelength of visible light.

It might be helpful to some readers to provide a musical – acoustic – analog of the visible part of the electromagnetic spectrum. The note of middle C on the piano has a frequency of 256 Hz, and the C an octave above has a frequency twice that, namely, 512 Hz. The full range of a piano is from the lowest bass, three and a bit octaves below middle C, at $\sim$25 Hz to the top treble (three octaves above 512 Hz) at $\sim$4 kHz, that is, it covers a range of 160 times (1.6×10^2 times) in frequency. So the full electromagnetic spectrum from 10 to 10^{21} Hz, that is, over 20 orders of magnitude in frequency, is equivalent to having five more bass "pianos" and three more treble "pianos," as well as the actual piano! The electromagnetic spectrum indeed spans an incredibly wide frequency range.

At higher frequencies it is valuable to think of light as a particle as well as a wave. A beam of light is then represented as a stream of particles, each of which is called a photon. A photon is both massless and without an electric charge; it travels at the velocity of light. The energy of an individual photon, a quantum of energy, which is shown on the bottom line of Fig. 2, is a well-defined quantity. It is given by the product of a fundamental constant known as Planck's constant (6.6×10^{-34} Joules. seconds, and abbreviated as Js) and the frequency of the electromagnetic wave of interest (in Hz). Therefore the energy of one photon is directly proportional to its frequency; for yellow light the energy of one photon is $\sim 3 \times 10^{-19}$ J, which may also be expressed as $\sim$2 electron Volts (eV). A photon of blue light has an energy that is almost twice that of a photon of red light. X-rays have very much greater photon energies, $\sim$1–100 keV (thousands of eV), with gamma-ray photon energies exceeding 1 MeV, that is, >1 MeV (millions of eV).

Reflection, Refraction, Diffraction, Interference, and Polarization: Important Properties of Electromagnetic Waves

When a beam of light strikes a mirror, it is reflected. The angle that the beam makes to the perpendicular to the mirror surface (which is sometimes called the normal to the surface), called the angle of incidence (i), is equal to the angle which the reflected beam makes to the perpendicular, known as the angle of reflection (r_l). This relation shows a critical property of the phenomenon of reflection. For a rough surface, the reflected waves have different directions so that we often consider the waves to be scattered by the surface.

When electromagnetic waves travel through any material medium, they may be partially absorbed. For waves traveling through a transparent medium, such as glass, rather than through a vacuum, the velocity of light becomes less than c. In fact, we can write an equation for the velocity of propagation through a medium, v, as $v = c/\mu$, where μ is called the refractive index of the medium; its value is always greater than 1. For glass, μ is $\sim$1.5, and its value is larger for blue light than for red light.

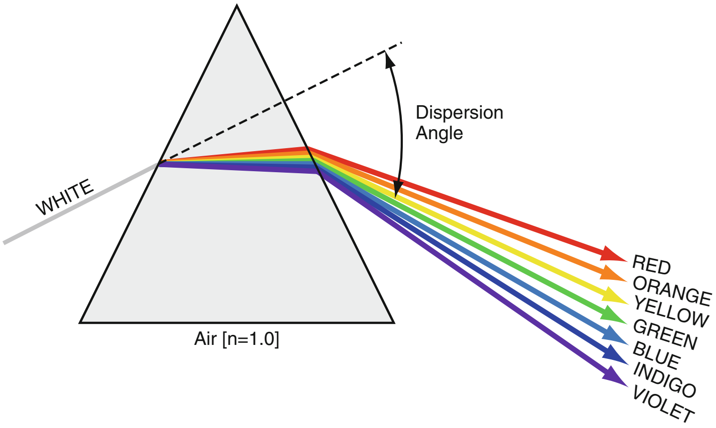


Fig. 3 Diagram illustrating how a glass prism separates a beam of white light into rays having all the colors of the rainbow. This is explained by the phenomenon of refraction (From www.thescienceclassroom.wikispaces.com, or www.heasarc.nasa.gov, courtesy of NASA)

In the year 1665, Isaac Newton carried out experiments on passing a beam of sunlight, white light, through a glass prism. As Fig. 3 indicates, the light beam does not travel along the dashed line, but it is bent, that is to say it is refracted, so that it emerges from the prism at an angle to the dashed line; this is called the dispersion angle. The ray is bent toward the normal to the prism surface, making an angle to the normal of r_r. Going from air, whose refractive index is unity, to glass of refractive index μ, the relation sin i = μ.sin r applies. The blue light is dispersed more than the red light. The beam of white light is split into all the colors of the rainbow by the glass as Fig. 3 shows. Thus the phenomenon of refraction allows us to investigate the spectrum radiated by a light source of interest, such as a star.

Figure 4 shows the spectrum of light emitted by the Sun, from blue at 400 nm at the bottom to red at 700 nm at the top. Each of the 50 horizontal lines shows the spectrum for a width of only ~6 nm. The Sun emits a broad – continuum – spectrum. On this continuum spectrum, dark – absorption – bands appear at generally very well-defined wavelengths. How these are formed will be mentioned later in this chapter.

Knowing about refraction makes it possible for us to design a lens which brings a beam of parallel light to a focus, for example, in the eyepiece of a telescope. With combinations of lenses, prisms, and mirrors, we can design telescopes of several different types (e.g., Newtonian, Cassegrain, or Coudé) to view distant astronomical objects. These range in complexity and performance from the first telescope of Galileo Galilei made in 1609 to view the Sun, when he discovered sunspots that are dark regions on the solar surface, to the Hubble Space Telescope or the Chandra X-ray telescope. Radio telescopes use metal parabolic reflectors to bring the radio beam from a satellite or a distant radio galaxy to a focus, where a sensitive receiver is placed.

The ionospheric plasma is the naturally occurring mixture of positive ions and electrons formed by the action of sunlight in the atmosphere at heights above ~80 km. The refractive index of this plasma is determined in part by the

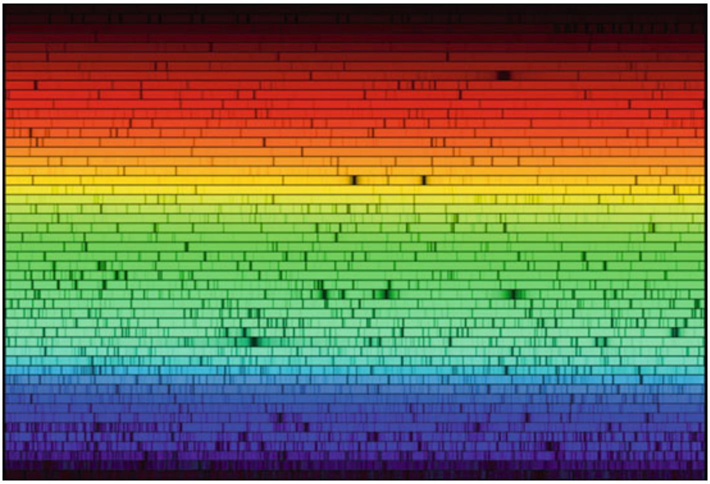


Fig. 4 The Sun's spectrum recorded by an instrument termed a spectrometer (From www.noao.edu, courtesy of NOAO/AURA/NSF)

concentration of electrons. In order to travel through (i.e., not be reflected by) the ionosphere, the command and/or telemetry radio signals must have frequencies exceeding the largest value of the electron plasma frequency along the propagation path from the ground to the satellite, or vice versa. That means that their frequency must exceed ~30 MHz. If the radio frequency is much larger than that, say, ~1 GHz, the refractive index is only slightly larger than unity. In fact, there are two values of the refractive index due to the presence of the Earth's magnetic field, which allows two types of wave to propagate. These are termed ordinary and extraordinary waves.

The performance of every telescope is limited by the phenomenon of diffraction. When light goes through a circular aperture or a slit, it does not travel straight through but is diffracted by some small angle. This phenomenon of diffraction limits the resolving power of a telescope; it determines the angular separation between two nearby objects in the sky that can be distinguished from one another. The 2.4 m diameter of the Hubble Space Telescope determines that its resolving power is equivalent to resolving two pinpricks of yellow light only 1 mm apart at a distance of 2 km, an incredible achievement.

The phenomenon of diffraction and of interference between light waves enables a diffraction grating to be created. This acts like a prism, bending light. Diffraction gratings are often used as spectrometers.

Another important property of an electromagnetic wave is its polarization. For a wave whose electric field always lies in the same direction, the wave is said to be linearly polarized. Alternatively a wave whose plane of polarization rotates as the wave propagates is called a circularly (or elliptically) polarized wave. The rotation can be either clockwise or counterclockwise; this property is what causes ordinary and extraordinary waves to exist. During propagation, the plane of polarization rotates – this is called the Faraday rotation of the plane of polarization. It enables the total electron content along the radio path between a satellite and a ground station to be calculated.

The Doppler Effect

When an observer is moving at a velocity v relative to a source of light, or if the source is moving relative to the observer, then the observer will notice a change in the wavelength of the light. Motion along the line of sight, away from the observer, causes an increase of the wavelength – this is termed a red shift. However, if the motion is toward the observer, a decrease of the wavelength is caused, termed a blue shift. This phenomenon is known as the Doppler effect. The reader may be more familiar with the acoustic analog. The siren of a police car approaching the observer increases in pitch, or frequency, whereas when it is moving away the frequency decreases below the transmitted frequency.

A useful equation is that the magnitude of $\delta\lambda/\lambda = \delta f/f = v/c$, for values of v which are very much less than (<<) c. Measuring the Doppler frequency shift of well-known spectral lines (discussed in the next section) leads directly to an estimate of the source velocity. The application of this result has demonstrated that the Universe is expanding, and that the velocity of more distant objects is larger than that for nearer objects. A space applications example of the Doppler effect is the changing frequency of a radio signal transmitted by a polar-orbiting satellite traveling at 7 km/s; it is increased by up to ~7/300,000, or ~0.002 %, as it approaches the ground station and is decreased by that amount as the satellite moves away.

Multiwavelength Studies and Black Body Radiation

Dust, clouds, and various molecular gases, including water vapor, the most important "greenhouse gas," and carbon dioxide, in the Earth's atmosphere absorb much of the Sun's infrared radiation. Molecular oxygen and ozone in the stratosphere absorb almost all the dangerous – to the DNA molecules in our bodies – ultraviolet radiation from the Sun. Therefore, the only way to carry out experimental gamma-ray, X-ray, ultraviolet, or infrared astronomical studies is to put an instrument aboard a rocket, satellite, or spacecraft. Space technology is essential for such fundamental scientific studies.

Where in the spectrum there is little absorption of radiation is termed a spectral window. The visible (Vis) part of the spectrum is one such region; that is clearly shown between 400 and 700 nm in the upper part of Fig. 5. There is a broad radio window at wavelengths between 0.1 and 10 m, which allows ground-based radio telescopes to operate, as illustrated in the lower part of Fig. 5. Longer wavelength radio waves cannot penetrate the ionosphere; they are reflected by the ionosphere.

Figure 6 plots the atmospheric opacity quantitatively as a function of frequency. An absorption of 1 dB (decibel), shown here as 1.E + 00, is rather negligible. However, 20 dB (two times 1.E + 01) shows absorption of the power of the radio

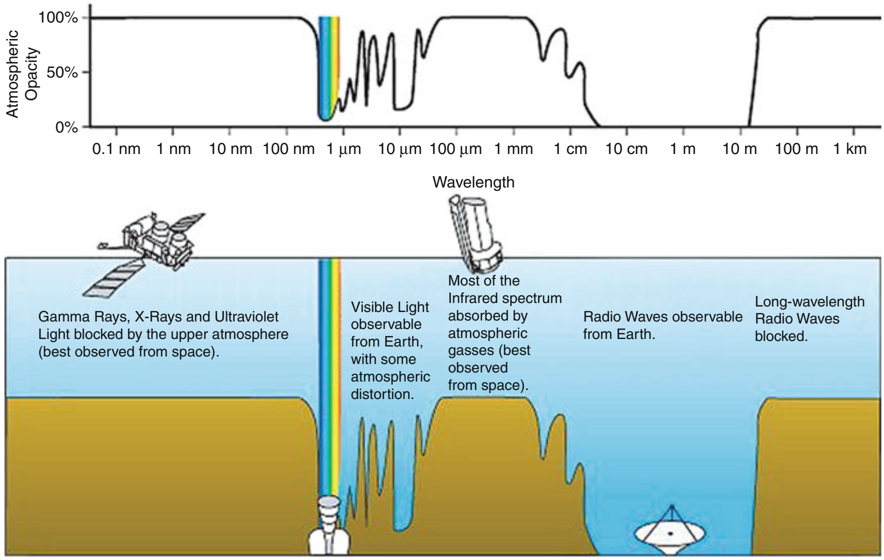


Fig. 5 The *upper* panel shows the percentage absorption (or opacity) due to the atmosphere, which is 100 % for gamma-rays, X-rays, and for ultraviolet, infrared radiation and very long wavelength radio waves. The *lower* panel demonstrates why space technology is required for fundamental scientific studies in these spectral ranges (From http://www.newworldencyclopedia.org/entry/Electromagnetic_spectrum)

signal by one order of magnitude (i.e., ten times); this would be noticeable. Absorption of 100 dB (i.e., by five orders of magnitude, a hundred thousand times, 1.E + 02) would be devastating for any communications system. Thus, this plot informs a communications engineer about those frequencies (such as around 60 GHz and near 118 GHz) which should definitely not be chosen for an effective communications system.

There are three basic types of spectra – the continuous spectrum, the emission (or bright-line) spectrum, and the absorption (or dark-line) spectrum. The continuous spectrum, an uninterrupted sequence of wavelengths, is a broadband spectrum; it is emitted by a hot gas at high pressure (e.g., the photosphere at the Sun's surface). The emission spectrum emitted by an atomic gas (e.g., hydrogen) at low pressure, that is, under rarefied conditions, is a set of discrete bright narrow lines. A particular spectral line is radiated when an electron in a certain excited state falls back to a lower level state or to its ground level state. (An electron is said to have been excited when a photon collided with it, in an atom or molecule, and raised it to a higher energy level.) Spectral lines occur at well-defined wavelengths; they are a characteristic of the particular chemical species radiating them. For molecular gases, the emissions are broader bands rather than narrow lines.

The absorption spectrum is observed when light from a bright source producing a continuous spectrum passes through a cooler gas which absorbs its characteristic line radiation. Radiation at these well-defined wavelengths is removed from the spectrum.

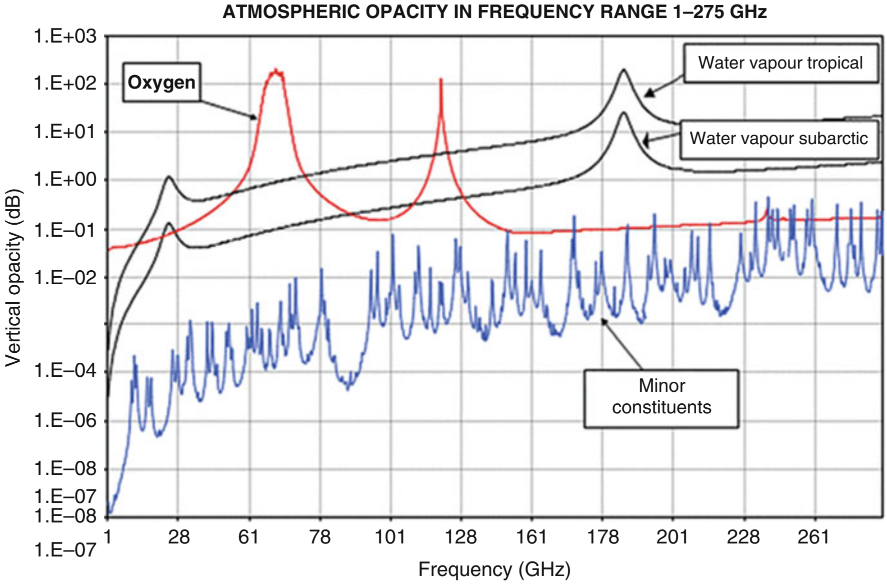


Fig. 6 The atmospheric opacity in the radio part of the spectrum from 1 to 275 GHz; here molecular oxygen and water vapor are the agents most responsible for the absorption (From ITU Report, RO7-SG07-C-0104!!MSW-E, page 11)

Figure 4 presented an example of an absorption spectrum for the Sun. Radiation is absorbed by the cooler gases in the chromosphere just above the solar surface (the photosphere). The thousand or so absorption lines evident in Fig. 4 are called Fraunhofer absorption lines. The most dominant pair of absorption lines is near the center of Fig. 4, in the yellow part of the spectrum, at wavelengths of 589.0 and 589.6 nm. These are due to absorption by atoms of sodium in the solar atmosphere.

The intensity – or brightness – spectrum of a continuum spectrum known as black body radiation, Planck's radiation law, is plotted as a function of wavelength in Fig. 7. A black body is an object that absorbs all the radiation which is incident upon it; it reradiates that energy as radiation which depends solely on the temperature of the object. Stefan-Boltzmann's law states that the total brightness of a black body (the area under the curve) is proportional to the fourth power of the absolute temperatures of that body. The wavelength of the spectral peak also depends on the temperature, expressed in degrees on the absolute (Kelvin) scale. On this scale, the freezing point of water is 273 K and its boiling point is 373 K. The origin of the Kelvin temperature scale is at −273 °C; a negative absolute temperature is impossible.

The range of wavelengths displayed on a logarithmic scale in Fig. 7 is enormous, 14 orders of magnitude. The range of intensities, also shown on a logarithmic scale (but not given quantitatively), is even larger, at least 30 orders of magnitude. The curve shown at 300 K is representative of the black body radiation emitted by the Earth and its atmosphere into space. Most of this radiation lies in the infrared part of the spectrum at wavelengths of ~1–10 μ. The curve at 6,000 K is close to the Sun's

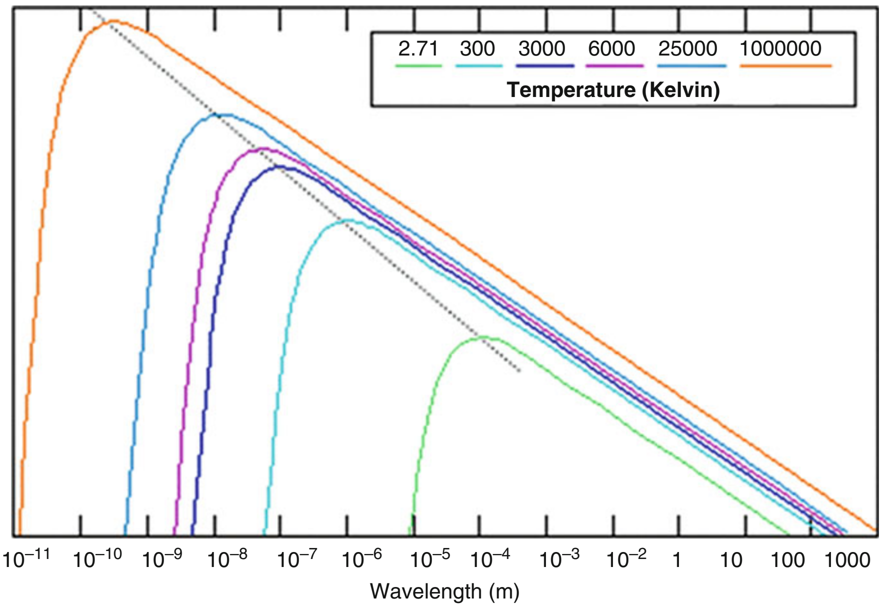


Fig. 7 The intensity (or brightness, on a vertical logarithmic scale of over 30 orders of magnitude) of the continuum spectrum (shown on the horizontal axis using a logarithmic scale from 10^{-11} to 1,000 m, a staggering wavelength range of 14 orders of magnitude) radiated by a black body at different temperatures. These range from microwaves approaching the far infrared, at 2.71° absolute (Kelvin, K), which is the temperature of the cosmic microwave background radiation remaining from the "big bang" origin of the Universe, to X-rays with wavelengths <1 nm at a temperature of a million degrees, which is the temperature of the Sun's outermost atmosphere, the corona (From http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=35774&fbodylongid=1696, or from the encyclopedia of science, www.daviddarling.info)

continuous spectrum; here most radiation is emitted at wavelengths <1 μ. The curve at a million K peaks in the X-ray part of the spectrum. The Sun's outer atmosphere, termed the corona, together with compact and very energetic stars, such as neutron stars, or material falling into a black hole, all emit X-rays. X-ray telescopes in space such as the Chandra Observatory investigate these areas. Figure 8 presents the spectral regions studied by the Chandra Observatory and by other space missions.

The curve below the Earth's spectrum in Fig. 7 is for black body radiation at 2.71 K. This radiation in the microwave part of the spectrum comes from the remnant of the "big bang" origin of the Universe 13.7 billion years ago. The dashed line in Fig. 7 shows Wien's displacement law; this law states that the wavelength of the most intense emission, the peak, is inversely proportional to the absolute temperature. The three fundamental laws of black body radiation introduced here can be proved only on the basis that the concept of radiation as streams of photons is valid.

Figure 9 presents a remarkable composite view of the color-coded intensities of electromagnetic radiation coming from all directions of our galaxy, the Milky Way, in different wavelength regions. The most energetic gamma-rays are shown at the

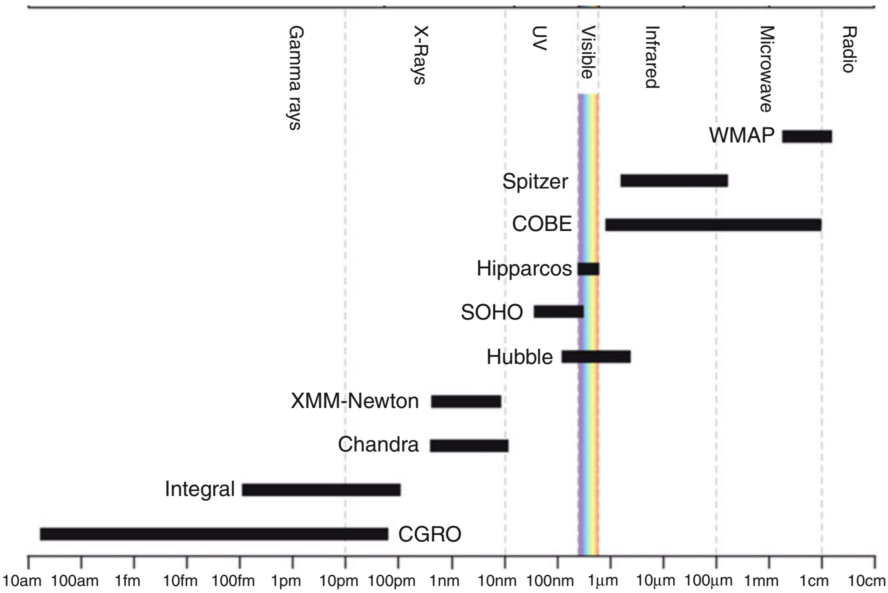


Fig. 8 Diagram indicating the wavelength ranges over 16 orders of magnitude (from 10 attometers, 10 am, or 10^{-18} m, to 0.1 m, or 10 cm) investigated by different space-borne instruments and missions. CGRO refers to the NASA Compton gamma-ray observatory, XMM to the ESA X-ray Multi-Mirror Newton observatory, and SOHO to ESA's solar and heliospheric observatory; COBE (Cosmic Background Explorer) and WMAP (Wilkinson Microwave Anisotropy Probe) both study the cosmic microwave radiation from the "big bang" origin of the Universe (From L.L. Christensen, R. Hurt, R. Fosbury, Hidden Universe, Wiley-VCH)

bottom, with radiation at X-ray wavelengths (e.g., from neutron stars) the next up, then visible radiation, and then infrared radiation from stars that are cooler than our Sun (in three different wavelength regions). Further up in Fig. 9 are displayed intensity maps of radio emissions at various frequencies, including that for atomic hydrogen at 1.42 GHz (at the wavelength of 0.21 m) which is emitted in the cold interstellar medium; it is strongest in star-forming regions. The lowest energies (lowest frequencies and longest wavelengths) are evident at the top. At all wavelengths, there is more radiation coming from the plane (disk) of the galaxy, where most of the $\sim 10^{11}$ stars are to be found. The radiation is especially strong toward the center of the galaxy, at the midpoint of these horizontal images.

Another Effect due to Photons, the Photoelectric Effect

Heinrich Hertz observed in 1887 that a charged metal surface exposed to ultraviolet light lost its electric charge. He had found that the illuminated metal emitted electrons; this effect is called the photoelectric effect. In 1921, Albert Einstein was awarded the Nobel Prize for physics for his 1905 theory that explained the

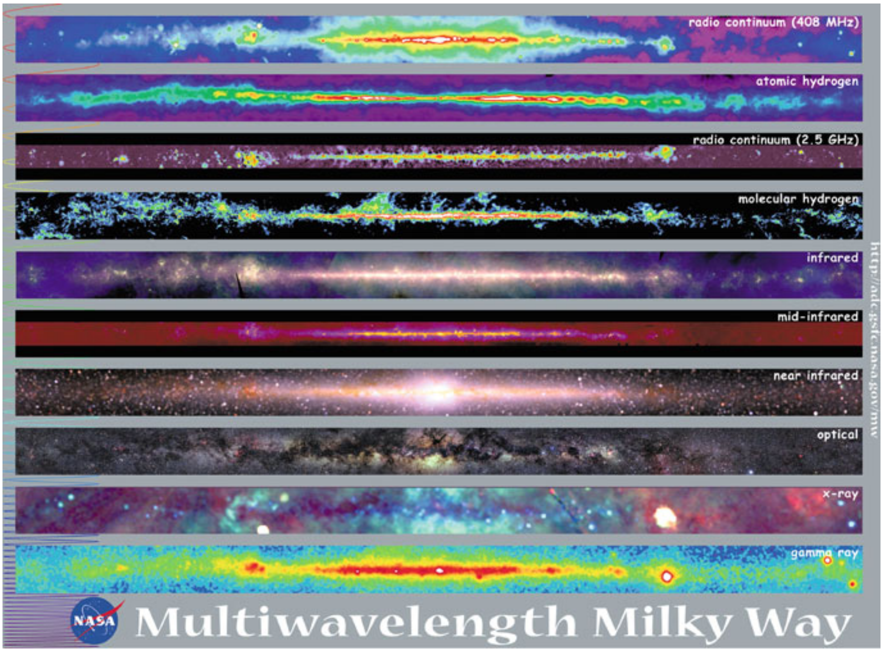
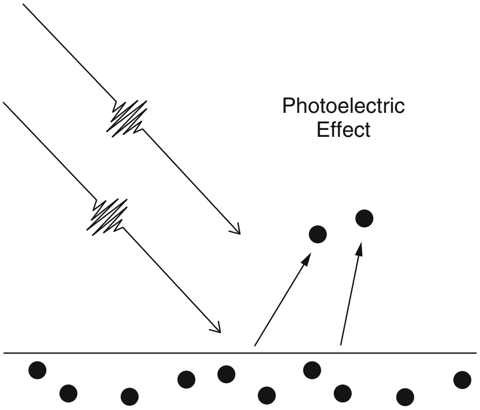


Fig. 9 A view of the entire Milky Way, our galaxy, shown in ten different wavelength regions; the most energetic processes are shown at the *bottom* and the least energetic at the *top*. Some observations are made from the ground and some from space. The central plane of the galaxy is clearly evident in all images, with the galactic center being especially evident in the *top* and *bottom* images (From http://son.nasa.gov/tass/content/emspec.htm, courtesy of NASA)

photoelectric effect. His theory requires that light is considered as a beam of photons, each of which has an energy equal to hf (in J), f being the frequency of the light and h Planck's constant. Electrons which are bound within metal atoms require at least this minimum energy, = hf, a few electron Volts (eV), to be ejected as photoelectrons from the surface of the metal (Fig. 10) and to cause a photoelectric current to flow. A lesser photon energy causes no photoelectric effect whatsoever. A greater intensity of light whose energy exceeds the threshold energy causes a greater photoelectric current. Different metals (different elements) have different threshold energies.

The photoelectric effect causes a satellite or spacecraft having a metal surface which is exposed to the UV radiation and X-rays contained in sunlight to gain a positive electric charge, through the loss of negatively charged electrons. There is a corresponding negative charge in the surrounding plasma in regions of shadow. If this charge becomes large, an electric discharge – a mini lightning discharge – can occur between the two electric charges of opposite sign; that can damage sensitive electronic equipment aboard the satellite. Other sources of danger to equipment operating in space aboard satellites and spacecraft are considered in the chapter "▶ Space Weather and Hazards to Application Satellites."

Fig. 10 Diagram showing two photons (wave packets) of ultraviolet light striking a metal surface and ejecting electrons (*dark dots*) from it, illustrating the photoelectric effect (From www.canadaconnects.ca/quantumphysics/1078/)



Conclusion

In this chapter, we have considered the principles and fundamental concepts of light and electromagnetic radiation as they pertain to the performance and reliability of applications satellites. The topic is a central and essential one. Visible light is the best known example of electromagnetic radiation. Its narrow spectrum from blue to red (with wavelengths varying by less than a factor of two) contrasts markedly with the enormously broad electromagnetic spectrum stretching from radio waves to gamma-rays (where the range of frequencies covered is by 20 orders of magnitude).

We have summarized both the wave and the particle (photon) properties of light and, more broadly, of electromagnetic radiation. We have discussed six different phenomena occurring when light interacts with matter, as well as the concept and basic properties of black body radiation. We have explained the Doppler effect. Almost all our knowledge of the Universe, and much of our understanding of the Earth's and other planetary atmospheres, derives from the passive reception of electromagnetic radiation emitted by atoms and molecules in stars, other celestial objects, and the atmospheres of planets. Both one way and two way radio communications between the ground and rockets, satellites, or space probes, and also the operation of GPS systems and radar altimeters, depend upon the active generation, transmission, and reception of electromagnetic waves.

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