



# RADIATIONS IN THE ENVIRONMENT

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## **VISIBLE AND INVISIBLE RADIATIONS IN THE ENVIRONMENT**

Radiation is the flow of energy packets that propagate radially (through empty space, or in a more complicated way within material media), from a source to a sink. We may think of those energy packets as being a stream of energetic tiny particles (material or immaterial), or a stream of travelling wave fronts, or beams of energetic rays; all are different aspects of the same thing.

The environment is the external surroundings of a system (from Fr. *en-virronner*, to circle), but as radiation may permeate our closer environment, we must consider our far environment too (e.g. cosmic radiations, solar radiation). Our environment comprises the air in the atmosphere, soil under our living quarters, water, and radiations (as in fire; energy in general); water is all around: living beings are aqueous solutions of

biomolecules within permeable membranes, and water is in the hydrosphere, the air and the soil. The Sun's radiation is the ultimate energy source for the Earth's biosphere, and the ultimate driving force for atmospheric and oceanic circulations.

Radiation emanates from matter (radiation sources), propagate through all kind of media (material or vacuum), and can get absorbed by matter and disappear. The human body is exposed to radiations coming from external sources (e.g. solar radiation, radiation from the soil), and to radiations coming from inside our bodies (from radioactive nuclei that we ingest with food, drinks, and breathing). All natural and artificial systems are within a radiation environment, and the radiation-matter interaction may be innocuous, damaging, or a blessing (e.g. X-ray may be helpful in medicine, but may damage and kill too).

We try here to consider all kind of radiations, i.e. all kind of energy propagating radially in isotropic unbound media (material or vacuum). It might be argued that dealing at once with such heterogeneous kinds of radiations (ionising, visual, thermal, radio-electric, particle, acoustic...) is an odd approach creating confusion without any advantage, but sometimes unification efforts help to find new insight and cross-paths.

Radiation is the source of life on Earth through the photosynthesis process in plants, and perhaps the origin of life and the main cause of mutation in life evolution (for good or bad). Most living beings, including ourselves, follow a circadian rhythm in our lives, dictated by solar radiation, which gives us illumination and warmth, and makes crops grow.

It might be interesting to control environmental radiation not just to let it pass or to stop it, but to convert some radiations to some other energy forms, or to store radiation energy in suitable forms; e.g. it would be good to channel outdoors daylight to inner rooms, to store daylight for night illumination (with more efficiency than in phosphorescent emergency way-out signalling), to design more comfortable space heating/cooling systems, to synthesize new materials, and so on.

Some radiations in the environment allow us 'to see the past' by dating ancient events, as with the common carbon-14 method that measures how long ago photosynthesis stopped in an organic material, or the thermo-luminescence method that measures how long ago a pottery was fired. Our living history in geological epochs is marked by a change in thermal radiation; e.g. the Holocene period (10 000 BCE to present; Gr. ὄλος-καινός, totally recent), starts at the end of the last glacial period.

Radiations allow us to see through, not only in the visual range through transparent materials (e.g. air, water, glass, some plastics), but through opaque materials using X-rays or  $\gamma$ -rays, which is advantageously used in medicine, and industry, e.g. casts and welding inspection, metal detectors, security (all luggage at airports go through X-ray computerised [tomography](#)), etc. And radiations allow not only seeing but smelling, as in explosive detectors based on neutron beams, which can detect the signature of gamma radiation decay from different atomic compositions (most explosives have similar ratios of C, H, O, and N atoms).

In short, radiation is ubiquitous and a genuine part of our environment, and its understanding can be of a great advantage to humankind, as well as a great risk if not mastered (it can be ill-used, like any other kind of energy). The need to better understand radiation effects gets even more stringent when going away of our usual environment, as in space exploration.

Radiation interactions of a person and its environment are rich and varied, but there are other kinds of interactions, and a short review follows (to put radiation interactions under a wider perspective).

## INTERACTIONS BETWEEN A PERSON AND ITS ENVIRONMENT

Living organisms are physical systems subjected to environmental stimuli that cause sensations which, by comparison with previous expectations, give way to a response, acting to satisfy needs and procure additional benefit.

The mutual interaction between the environment and the human body can be classified, according to the physical magnitude involved (following the International System of Quantities, [ISQ](#)) as:

- Matter-flow interactions, labelled Chemo (Lat. medieval *chemia*, from Arab. *al-kīmīā*, from Gr. *χημεία*, cast together). They correspond to intake or release of chemical species through the whole body envelops, including ingestion of solid, liquid and gas, but with emphasis on absorption/release associated to human smell and taste senses.
- Mechanical interactions, labelled Tango (Lat. *tango*, touch), short-distance electromagnetic human-skin interaction ( $10^{-10}$  m) related to matter impenetrability. Some authors refer to all contact interactions (i.e. other than EM radiations and acoustics) as [haptic](#) (Gr. *ηαπτοσ*, contact).
- Energy interactions:
  - Acoustic, labelled Audio (Lat. *audio*, to hear), associated to our hearing sense. Notice that acoustic waves exert a pressure on our eardrum, but it is not only the force what matters here but the information conveyed, associated to frequency and force.
  - Electromagnetic (EM), split as:
    - Video (Lat. *video*, to see), if detectable by the human-eye. It corresponds to the wavelength band  $0.4 \cdot 10^{-6} \text{ m} < \lambda < 0.7 \cdot 10^{-6} \text{ m}$ , composed of the three primary colour bands ([RGB](#)): blue (0.4..0.5  $\mu\text{m}$ ), green (0.5..0.6  $\mu\text{m}$ ), and red (0.6..0.7  $\mu\text{m}$ ). In the four-dimensional world we live in (3D-space plus time), our sense of vision is the largest and safer in information content: it is a far-reaching detector (non-contact), with the highest bandwidth (the highest electromagnetic frequency before radiation becoming ionising and damaging to living matter).
    - Calor (Lat. *calor*, heat), electromagnetic interaction causing thermal effects. However, all kinds of heat transfer are here included; i.e. not only by distant coupling (thermal radiation), but also by direct contact (thermal conduction and convection).
    - Radio (Lat. *radius*, ray), radiation interaction in general. It includes all EM-radiations except visual radiation (dealt separately because of its importance, as said), and thermal radiation (grouped with other thermal effects, as said), as well as elementary particle radiations.

We intend here to present the interaction of environmental radiations with the human body (and with matter in general), in a broad approach, i.e. including all kinds of radiations, and aiming at all kind of applications: energetics, communications, health (risks, medical diagnosis and treatment), guidance and navigation, measurements, biometrics, contaminations (acoustic, visual, radiological...).

## TYPES OF RADIATION

Radiometry is the most general term referring to the detection and quantifying of any kind of radiation (electromagnetic or particulate). The main characteristics of a radiation are: direction of propagation, speed of propagation ( $c$ ), energy content (power), and energy distribution among its vibration modes (the spectrum); other characteristics of interest may be its radiation pressure, collimation, coherence, polarization, etc.

Radiation can be studied either as parcels (of matter or energy), or as wave-trains ([wave-particle duality](#) principle), in both cases with an intrinsic oscillatory motion which is longitudinal for non-spin particles like [phonons](#), and transversal for particles with [spin](#), both for fermions (half-integer spin: electrons, protons, and neutrons), and for bosons (integer spin: photons; a photon is the smallest relativistic quantum energy-packet in the [Standard Model](#)).

The interaction between radiation and matter explains all radiation characteristics: emission, transmission, absorption, scattering (spatial 'dispersion', including diffraction), dispersion (spectral 'dispersion')... We here focus the analysis to energy packets propagating at very high speed, like electron beams and radio waves, although there are many commonalities between that and radiation of low-speed energy packets like [acoustic waves](#), [gravity waves](#), [capillary waves](#)... (e.g. absorption, reflection, interference, dispersion...).

Electromagnetic radiation propagates in straight line under vacuum at the speed of light,  $c_0=300\cdot 10^6$  m/s (first measured by Röemer in 1670 based on Io's eclipses, later measured by Fizeau in 1850 with a mirror 9 km away), and along a path of minimum action in material media (in straight line too within isotropic media). Neither the direction nor the speed of propagation can be modified by other EM fields, but light can be deflected when travelling through a material medium, and it can be channelled to travel through tubes of almost any shape using fibre optics.

Acoustic radiation cannot propagate under vacuum; it needs elastic media, and propagates at the sound speed  $c$  such that  $c^2=\partial p/\partial \rho|_s$  (e.g.  $c=340$  m/s in ambient air,  $c=1500$  m/s in water,  $c=5100$  m/s in steel). Acoustic radiation is most important for hearing (language, alerts, music...), for underwater communication (e.g. sonar), and can be used for several types of diagnosis (e.g. echography), but may be a nuisance (noise) and even pose health problems (e.g. shock waves). As quantum particles acting as force carriers, both phonons and photons obey Bose-Einstein statistics for the distribution of energy in the frequency spectrum.

## IONISING AND NON-IONISING RADIATION

[Ionizing radiation](#) is characterised by producing free radicals and ions on living matter (and on other organic material, and under certain circumstances on inorganic materials too). Even at low radiation intensities, very high frequency radiations are ionising because it is a quantum interaction at atomic level.

Most environmental radiations (e.g. radio waves, light) are non-ionising because their interaction with matter spreads over a macroscopic region, but, without a qualifier, radiation usually refers to ionising radiation because they can be the most harmful to life (e.g. burns, cataracts, cancer), although they can also be a health remedy (radiodiagnosis and radiotherapy). People must be protected from unnecessary radiations (both ionising and non-ionising), and protected from excessive dose even from beneficial radiations like those used for medical diagnosis or radio-communication (even excessive solar radiation cause damage).

Difference between radiative and radioactive:

- The word ‘radiative’ means 'related to radiation in general', usually electromagnetic radiation, which, according to its interaction with matter may be:
  - Non-ionizing: radio waves, microwaves, thermal radiation, visual radiation, and some [ultraviolet](#) radiation (UV-A).
  - Ionizing: ultraviolet rays (UV-B and UV-C), X-rays, and  $\gamma$  rays.
- The word ‘radioactive’ is restricted to radiation from spontaneous nuclear decay, i.e.  $\alpha$ ,  $\beta$ , and  $\gamma$  rays (i.e. helium nuclei, electrons, and very-high-frequency electromagnetic radiation coming emitted by atomic nuclei), either from natural radioisotopes (like radium and uranium), or from artificially created radionuclides. Radioactive decay occurs spontaneously and randomly (there is no way to predict when a given atom will disintegrate), but its half-life,  $t_{1/2}$  (the time for half of an amount of them to disintegrate) is well defined. The number of radioactive particles remaining at time  $t$  is  $N(t)=N_0\exp(-t/t_{ml})$ , with  $N_0$  being the quantity at  $t=0$ , and  $t_{ml}$  the mean-life (or life expectancy), related to half-life in this exponential decay by  $t_{ml}=t_{1/2}/\ln 2=t_{1/2}/0.69=1.44\cdot t_{1/2}$ ; i.e. after a half-life, 50 % of the initial population has disappeared, whereas after a mean-life, only 37 % ( $1/e$ ) remain.

It is important to realise that all kind of radiations tend to decay by exhaustion of the source, although the decay time may be too long in comparison with a person's life (fortunately in the case of solar radiation, which may last another  $5\cdot 10^9$  years, but unfortunately in the case of unwanted radiation sources (e.g.  $t_{1/2}=700\cdot 10^6$  years for U-235, contained in spent fuel of nuclear power plants, which amounts to 95 % of the total radioactive mass artificially produced worldwide; the 0.7 % U-235 in natural uranium ores is not a problem, but spent fuel has  $>1$  % U-235, with other poisoning radionuclides).

## PARTICLE AND WAVE RADIATION

According to its rest mass (a relativistic variable that is the same in all frames of reference), and leaving aside material waves like in acoustics, two types of radiation can be distinguished:

- Particle radiations (beams of very small particles moving at very high speeds, all of them harmful to living matter, if in high enough dose):
  - Electrically charged particles: electrons (including  $\beta$  rays), protons, helium-4 nuclei ( $\alpha$  rays), metal ions beams (as in ion thrusters, sputtering, carbon-ion therapy...). Rarefied electrically-charged particles compose a plasma (Gr.  $\pi\lambda\acute{\alpha}\sigma\mu\alpha$ , formation), the state of matter most abundant in the Universe (electrically conductive and very sensitive to electromagnetic

fields). Some particle beams (e.g. linearly accelerated electrons) are used in medical radiotherapy.

- Electrically uncharged particles: neutrons, and atoms, which are unaffected by electromagnetic fields. It is difficult to produce high-speed beams of atoms because they cannot be accelerated electromagnetically.
- Electromagnetic radiation (EMR): immaterial energy packets (can be treated as waves or as photon particles) generated by moving electric charges, and propagating in vacuum at  $c=3\cdot 10^8$  m/s independently of source and detector motions according to relativity theory (within a medium of refractive index  $n$ , the speed reduces to  $c/n$ ). EMR is produced from other types of energy when created (emitted), and it is converted to other types of energy when it is destroyed (absorbed), and it is the most important for vision and illumination, radio-communications and remote sensing, thermal control, biology (photosynthesis), medicine (radio-diagnosis and radiotherapy), chemical analysis...

EM radiation may be accompanied by particle radiation, as when a hot cathode emits thermal radiation and electrons.

Radiation in general was poorly understood until the 20<sup>th</sup> century, although many optical applications had been developed before. Physical theories of visible light started with Pascal in 1637 (who proposed that light was a wave phenomenon like sound), followed by Huygens in 1678, who extended wave theory); however, explanations took a parallel-side path with Newton in 1704, who developed a corpuscular theory of light and set up light experiments for the first time using lenses and prisms; at the end of the 19<sup>th</sup> c. explanations seemed to definitely move towards a wave theory culminating with [Maxwell equations](#) of the electromagnetic field (EMF) in 1873; however, Planck's assumption of [energy quantization](#) in 1900, and Einstein's [mass-energy equivalence](#) of 1905, provided the final arguments for De Broglie's hypothesis of 1924 of [wave-particle duality](#): to any wave of wavelength  $\lambda$  can be associated a particle of momentum  $p$  (and vice versa), such that  $\lambda p=h$ , the Planck's constant.

## WAVE PROPAGATION

A wave is a disturbance that propagates through space and time, carrying with it energy and momentum. Waves usually propagate as vibrations (periodic fluctuations around an equilibrium state), but they can also travel as isolated disturbances (solitons). The basic requirement for waves is self-propagation far away, not just oscillation induced by an oscillating source. Self-propagation requires a more-than-linear coupling between the excitation and the response, like for a spring ( $E_p=1/2kx^2$ , where  $k$  is the spring-recovery constant in the force-displacement relation,  $F=-kx$ ); that is why thermal systems do not show vibrations ( $\Delta E=mc\Delta T$ ), although they may show (dumped) oscillations if so excited.

Standing waves may be said to propagate along both opposite directions. In wave propagation, there are always periodic exchanges of energy between two kinds of disturbances (kinetic and potential, in material waves; electric and magnetic, in EM waves). Besides this especial inertia (accumulative capacity for overshooting), stable systems always must have positive stiffness (restoring force), and all active systems must show some dumping (at least if isolated) due to energy dissipation.

According to the constitution of the propagation media, one may distinguish between:

- Mechanical waves, which can only propagate in material media, generating deformations and elastic restoring forces.
- Electromagnetic waves (and [gravitational waves](#)), which can also travel through vacuum.

According to homogeneity of the propagating media, one may distinguish between:

- Bulk waves (on homogeneous media):
  - Acoustics (usually longitudinal, linear and periodic). Period:  $T=10^{-5}..10^{-2}$  s.
  - Shock waves, expansion waves, water hammer, hydraulic jump (non-linear acoustics).
  - Inertial waves, which occur in rotating fluids and are restored by the Coriolis effect.
  - Electromagnetic waves (transversal, linear or non-linear).
  - Gravitational waves (non linear).
- Interfacial waves:
  - Capillary waves.  $T=10^{-3}..10^{-1}$  s. Waves travelling along the interface between two fluids, whose dynamics are dominated by the effects of surface tension.
  - Gravity waves.  $T>10^{-1}$  s. Waves travelling along the interface between two fluids of different density in a gravity field, including wind waves and tides.

According to the direction of vibrations relative to propagation:

- Longitudinal waves, like sound in fluids.
- Transversal waves, like light. All electromagnetic waves are transversal, but mechanical waves can be either transversal or longitudinal, or both (as in water surface waves; a surface point describes an unduloid curve).

According to linearity

- Linear waves (propagation speed invariable with distance; wavelength invariable with distance; conservative interaction (superposition principle, spectral analysis)).
- Non-linear waves (sea waves, shallow-water waves, solitons).

Waves travel and transfer energy from one point to another, often with little or not-permanent displacement of the particles of the medium (i.e. little or no associated mass transport); instead there are oscillations around almost fixed positions. Periodic waves are characterized by crests (highs) and troughs (lows).

When waves of different wavelengths have different propagation velocities, the propagation is said to be dispersive (a multi-frequency packet spreads with time). In dispersive systems, two wave velocities appear: the group velocity of the wave,  $c_g$  (that is, the speed at which a wave packet travels), and the phase velocity,  $c$ . For instance, for deep water waves:  $c = \sqrt{g/k} = c_g/2$ , where  $g$  is the acceleration due to gravity, and  $k$  the wavenumber ( $k=2\pi/\lambda$ ). The shortest wind-generated waves on a water surface are combined gravity-capillary waves, and the phase velocity is  $c = \sqrt{g/k + \sigma k/\rho}$ , where  $\sigma$  is the surface tension. Electromagnetic waves in vacuum are non-dispersive, with a unique wave speed  $c=3 \cdot 10^8$  m/s.

All waves have common behaviour under a number of standard situations:

- Rectilinear propagation: waves move in straight lines through homogeneous isotropic media (but bend along transversally-non-homogeneous media).
- Reflection: wave direction changes after hitting a reflective surface. All solid and liquid surfaces reflect somehow; most reflective surfaces (at most wavelengths) are metals. A water surface is a common reflector under some conditions. Most surfaces reflect in all directions, in a more or less diffuse manner, but predominantly in the mirror-like direction (i.e. with the incident and the reflected directions forming equal angles with the normal, each to one side of it).
- Refraction: wave direction changes when entering (under tilted incidence) a medium of different refractive index. The larger the refractive index, the smaller the angle formed by the propagation direction with the normal.
- Diffraction: a wave spreads spherically when passing through a small hole or hitting a small object (of size comparable to wavelength). This is based on [Huygens Principle](#) that every point in a propagating wave-front can be considered a source of radiation. In this way, EM-waves can 'go around corners' (but with significantly less energy than that of the incoming wave).
- [Interference](#): two waves that come into contact with each other superpose, modifying the amplitude of the resulting wave (it is usually assumed that the two original waves have the same frequency and a constant phase difference, e.g. [lasers](#), otherwise the interference is difficult to observe). In information technology, the word interference is used in a wider sense, as a disturbance from other EM sources.
- Dispersion: wave splitting up by frequency. The function  $\omega(k)$ , which gives the (angular) frequency  $\omega$  as a function of  $k$ , is known as the dispersion relation. If  $\omega$  is directly-proportional to  $k$ , then the group velocity is exactly equal to the phase velocity. Otherwise, the envelope of the wave will become distorted as it propagates. This 'group velocity dispersion' is an important effect in the propagation of signals through optical fibres, and in the design of high-power short-pulse lasers.
- [Doppler effect](#) (named after Christian Doppler-1842): it is the change in frequency and wavelength of a wave as perceived by an observer moving relative to the source of the waves. For waves that propagate in a material medium, such as sound waves, the velocity of the observer and of the source are reckoned relative to the medium in which the waves are transmitted, and the total Doppler effect may therefore result from either motion of the source or motion of the observer. Each of these effects is analysed separately. For waves which do not require a material medium, such as light or gravity in special relativity, only the relative difference in velocity between the observer and the source needs to be considered.
- [Polarisation](#) (only in transverse waves): it is the direction of transversal vibrations; in EMR it is the electrical field vector that is chosen (the magnetic field is perpendicular to that and to the propagation direction). Polarization effects are important when aligning antennas, and in reflections.

The simplest wave model is  $y=A\sin(\omega t-kx+\phi)$ , where  $y$  is elongation (in the transversal  $y$ -direction for transversal waves, or in the  $x$ -direction for longitudinal waves),  $A$  the amplitude (amplitude envelop if  $A(x,t)$ ),  $\omega=2\pi/T=2\pi f$  the angular frequency (with  $T$  the period and  $f$ , or  $\nu$ , the frequency),  $k=2\pi/\lambda$  the wavenumber (and  $\lambda$  the wavelength),  $\phi$  the phase,  $c=\omega/k=\lambda/T=\lambda f$  the phase velocity (phase propagation), and  $c_g=\partial\omega/\partial k$  the group velocity (energy propagation). The idea of a group velocity distinct from a wave's

phase velocity was first proposed by W.R. Hamilton in 1839, and the first full treatment was by Rayleigh in his "Theory of Sound" in 1877. For harmonic waves, the propagation equation is  $\partial^2 y / \partial t^2 = c^2 \partial^2 y / \partial x^2$ , with the general solution  $y(x,t) = f(x-ct) + g(x+ct)$ .

Mind that we have only considered wave propagation of radiation (EM or particles), and not convective propagation of radiation sources (e.g. wind transport of radionuclides).

## NATURAL AND ARTIFICIAL RADIATION

We live in a world made of radiation and matter (initially, after the [Big Bang](#), just radiation, until nucleosynthesis took place some  $10^2$  s after the Big Bang; we still have from that time the residual cosmic background radiation at 2.7 K). In fact, one can say that life has evolved in the ashes left by a supernova explosion that gave birth to our Solar System 5000 million year ago.

According to the origin of radiation sources, one may distinguish between natural radiations in the environment (at Earth's surface or any other place), and artificial radiation (being released at present or from past human activities).

### Natural radiations

We are exposed to many natural radiations, coming from:

- Above: ionizing particle radiation (cosmic rays and solar wind), and EMR (basically solar radiation). The latter, with an average of  $240 \text{ W/m}^2$  at the ground surface, is mainly non-ionizing: about 50 % thermal infrared, some 40 % visible, and about 10 % ultraviolet (a fraction of which is ionizing).
- Below: radioactive decay from [radon](#), thorium and uranium in the crust, with an average of  $0.065 \text{ W/m}^2$  at the surface. Earth's interior background radiation, basically consists of radioactive radon (Rn-222) out-gassing into the atmosphere, which contributes to more than half the average natural radiation dose (ionising radiation from rocks containing Th-232 ( ${}^{232}_{90}\text{Th}$ ), K-40 ( ${}^{40}_{19}\text{K}$ ), U-235 ( ${}^{235}_{92}\text{U}$ ), Ra-226 ( ${}^{226}_{88}\text{Ra}$ ), U-238 ( ${}^{238}_{92}\text{U}$ ) with  $t_{1/2}=4500 \text{ Myr}$ , Rb-87 ( ${}^{87}_{37}\text{Rb}$ )... contribute some 1 %, similar to cosmic radiation, and a little less than radiation from natural decay of radionuclides within our body).
- Around us: the air around us contains some radioactive radon gas. Besides this ionizing radiation (stronger over granite soil), we are exposed to natural thermal radiation from all objects around us (land, atmosphere, sky)
- Inside our body: the human body contains some C-14 and K-40 radionuclides.

Cosmic radiation may interact with Earth's atmosphere and generate secondary radiations, most readily near the magnetic poles (where the Earth's magnetic field is weakest), and at high altitudes (where the Earth's atmosphere is thinnest. Cosmic radiation is composed of:

- Particles: mainly protons (around 90 % of particles), helium nuclei (around 10 %), other atom nuclei ( $< 1$  %), electrons, and neutrinos. Cosmic rays only constitute a fraction of the annual ionising radiation exposure of humans on the Earth's surface (some 10..20 %), but a major hazard for astronauts.

- Waves: gravitational, and EM waves in all spectral bands. Cosmic microwave background radiation, [CMB](#), is received quasi-isotropically from all parts of the universe, with an equivalent blackbody temperature of 2.7 K, which is a relic of the universe expansion after the Big Bang.

Our main natural radiation source is the Sun. Life on Earth is governed by solar radiation. We not only depend on solar radiation for a warm environment and natural illumination (governing daylight activities and sleep); even our mood depends on lighting changes, with a stimulant ([cortisol](#)) being produced in our hypothalamus during morning hours (by bluish cold light), and a relaxant ([melatonin](#)) during evening hours (by reddish warm light). It has been found important to use dynamic lighting to maintain this circadian rhythm for people in confined spaces (e.g. submarine crews and astronauts).

Natural ionizing radiation was discovered in 1896 by H. Becquerel while working on phosphorescent materials (he found that uranium salts caused fogging of an unexposed photographic plate). In 1899, E. Rutherford discovered alpha, beta, and gamma particles while applying EMF to uranium radio-sources; late in 1899 Marie Curie discovered radium in pitchblende (2 million times more radioactive than uranium), naming this behaviour radioactivity. Early researchers also discovered that many other chemical elements, besides uranium, have radioactive isotopes.

### **Artificial radiations**

Besides artificial light and other non-ionizing radiations, the first artificial ionizing radiation developed was the electron beam (cathode rays), in 1869, but this radiation is readily blocked by solids (it was discovered by using vacuum tubes).

A more penetrating radiation was discovered in 1895 by W. Röntgen when experimenting with high-voltage electrodes in a vacuum tube (the effect of these X-rays, as he called them, on photographic plates had been observed earlier).

More powerful radiations were obtained by concentration natural radioactive sources, presented above ( $\alpha$ ,  $\beta$ , and  $\gamma$ , in radioactive decay). Neutron radiation was discovered in 1931, a powerful penetrating radiation (massive and without electric charge) that eventually allowed the splitting of atomic nuclei (fission), producing free neutrons, gamma photons, and heavy [radionuclides](#) ([nuclear waste](#)) that we still ignore how to return to the natural environment safely.

## **ELECTROMAGNETIC RADIATION. PHYSICAL CHARACTERISTICS**

### **ELECTROMAGNETIC RADIATION VERSUS ELECTROMAGNETIC FIELDS**

There are four fundamental forces: gravitation (mass attraction), electromagnetic (attraction, repulsion, or deviation between electrically-charged particles), weak nuclear force, and strong nuclear force. The last two are confined to nuclear distances ( $10^{-15}$  m, or below). The force of gravity is only important when large masses are present. Finally, the electromagnetic force is responsible for almost all the phenomena encountered in daily life, from the touch (the impenetrability of matter), to molecular structure, and all kind of electromagnetic radiations.

A fixed electric charge generates an electric field (EF),  $\vec{E}$ , such that any other electric charge  $q$  within reach is subjected to a force  $\vec{F} = q\vec{E}$ . Electric fields are created by spatial separation of electric charges (e.g. applying a voltage between two separate conductor-plates), and the units of  $\vec{E}$  are [V/m]=[N/C]).

A steadily-moving electric charge (i.e. an electric current) generates, besides the electric field  $\vec{E}$ , a magnetic field (MF),  $\vec{B}$ , such that any other electric charge  $q$  within reach is subjected to a force (Lorentz force)  $\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$ ; magnetic fields are measured in tesla [T], and can be generated by an electric current  $I$  circulating along a length  $d\vec{l}$  of conductor, such that  $d\vec{B} = \mu(I d\vec{l} \times \vec{r}) / (4\pi r^3)$ , known as Biot-Savart law, where  $\mu$  is [magnetic permeability](#) of the medium (under vacuum  $\mu = \mu_0 = 4\pi \cdot 10^{-7} = 1.26 \cdot 10^{-6}$  V·s/(A·m)). [Earth's magnetic field](#), which has a magnitude from 25 to 65  $\mu$ T at the surface and is tilted at an angle of 11° with respect to Earth's rotational axis, is created by the motion of molten iron alloys in the Earth's outer core. Magnetic fields can also be generated by the intrinsic magnetism of elementary particles, such as the electron spin. The magnetic moment,  $\vec{m}$ , is a quantity that determines the force that the magnet can exert on electric currents and the torque that a magnetic field will exert on it. A loop of electric current, a bar magnet, an electron, a molecule, and a planet all have magnetic moments. For an electric charge  $q$  moving along a circular path of radius  $r$ , the magnetic moment is  $\vec{m} = \frac{1}{2} q\vec{r} \times \vec{v}$ , and for a planar closed loop carrying an electric current  $I$ , the magnetic moment is  $\vec{m} = \frac{1}{2} I \int \vec{r} \times d\vec{r} = IA\vec{n}$ , where  $A$  is the loop area and  $\vec{n}$  the normal in the direction of advance of a corkscrew rotating in the sense of the current,  $\vec{l}$ . An external magnetic field  $\vec{B}$  creates a torque  $\vec{M}$  on a magnetic moment  $\vec{m}$  such that  $\vec{M} = \vec{m} \times \vec{B}$ , which may serve to measure magnetic moments and is the basis of magnetometers and galvanometers; e.g. in the latter, the rotatory deflection of a coil of cross-section  $A$  along which circulates a current  $I$  in the presence of a magnetic field  $B$ , is due to the torque  $\vec{M} = IA\vec{n} \times \vec{B}$ . A MF creates a force  $\vec{F} = I(\vec{l} \times \vec{B})$  on a straight conductor of length  $\vec{l}$ , what is known as Laplace law; between two straight parallel conductors separated a distance  $r$ , the force per unit length is  $F/L = \mu I_1 I_2 / (2\pi r)$ , known as Ampere law.

The EF and MF due to steadily-moving electric charges are uncoupled, but non-uniformly moving electric charges (i.e. if they have linear or angular acceleration) the EF and MF become coupled, i.e. a changing electric field creates a magnetic fields, and a changing magnetic field induces an electric field, all related by Maxwell's equations, which in differential form under vacuum are:  $\nabla \cdot \vec{E} = \rho / \epsilon_0$ ,  $\nabla \cdot \vec{B} = 0$ ,  $\nabla \times \vec{E} = -d\vec{B}/dt$ , and  $\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \epsilon_0 d\vec{E}/dt$ , where  $\rho$  is the charge density,  $\epsilon_0 = 8.85 \cdot 10^{-12}$  F/m is the [permittivity](#) of free space,  $\mu_0 = 4\pi \cdot 10^{-7} = 1.26 \cdot 10^{-6}$  V·s/(A·m)) ( $\mu_0 \epsilon_0 = 1/c_0^2$ , with  $c_0$  the speed of light), and  $\vec{J}$  is the current density vector. The term electromagnetic field (EMF) is often restricted to this coupled EF and MF (although a steady-moving charge generates a decoupled EF-MF that could also be named EMF). In absence of charges, Maxwell's equations under vacuum read:  $\nabla \cdot \vec{E} = 0$ ,  $\nabla \cdot \vec{B} = 0$ ,  $\nabla \times \vec{E} = -d\vec{B}/dt$ , and  $\nabla \times \vec{B} = (1/c_0^2) d\vec{E}/dt$ , showing that the electric and magnetic fields are perpendicular ( $\vec{E} \cdot \vec{B} = 0$ ) and their coupling follows the wave equation  $d^2 \vec{E}/dt^2 = c_0^2 \nabla^2 \vec{E}$  (or  $d^2 \vec{B}/dt^2 = c_0^2 \nabla^2 \vec{B}$ ), propagating at the speed of light.

Electromagnetic radiation (EMR) is thus an oscillating EM-field far from the oscillating electrical charges that created it, usually electrons oscillating in an atom or in a macroscopic conductor called [antenna](#), a device designed to converts alternate electric currents into radio waves, and vice versa. The simplest means to create an alternating electrical dipole is the half-wave dipole antenna (formed by two quarter-wave

conductor wires); when fed with alternate current of frequency  $f$  (wavelength  $\lambda=c/f$ ), a standing half-wave is established in the antenna if its length is  $L=\lambda/2=c/(2f)$ ; otherwise, the radiating efficiency is much smaller. Early wireless telegraphy in 1900 used antennas of some  $L=150$  m fed from LC-resonant circuits at 800 kHz (around the  $f=c/(2L)=1$  MHz corresponding to the half-wave dipole antenna. Shorter EMR like infrared and visible radiations are generated by electrons oscillating within molecules and atoms. X-rays are created by highly accelerated electrons in a vacuum tube colliding on a metal anode (usually wolfram). Some quantum processes like radionuclide gamma-decay also generate electromagnetic radiation ( $\gamma$ -rays); however, most nuclear processes emit material radiations. In the EMR, i.e. in the far field of an oscillating EMF, at a distance  $d \gg \lambda$  from the source, both the EF and the MF are oscillating in phase, perpendicular to each other and to the direction of energy propagation (a straight line in vacuum).

All fields (EM, MF, and EMF) hold some volumetric energy even under vacuum, although in small amount; e.g. for static fields in vacuum the energy density  $u$  [J/m<sup>3</sup>] associated to the superposition of an electric field and a magnetic field is  $u=1/2\epsilon_0 E^2+1/2B^2/\mu_0$ . Rapidly-changing EMF (as those created by an alternating current in a piece of wire) emit energy; e.g. for the simplest case a an electrical dipole of amplitude  $p$  [C·m] oscillating with frequency  $f$ , the power radiated under vacuum is  $\dot{W} = 4\pi^3 p^2 f^4 / (3c_0^3 \epsilon_0)$ , showing the great dependence on frequency. In general, the directional energy flux density (power per unit normal area) for a EMF is the [Poynting vector](#), defined by  $\vec{S} = (1/\mu_0) \vec{E} \times \vec{B}$ ; for EM-radiation, i.e. in the propagation of a planar monochromatic wave, the Poynting vector always points in the direction of propagation while oscillating in magnitude, and its time-averaged value is the radiation irradiance, studied below.

We want to analyse radiation-matter interactions, and to this goal, among the different physical characteristics of radiation: speed  $c$ , power  $\Phi$ , frequency of oscillation  $\nu$ ..., the latter, or the wavelength  $\lambda=c/\nu$ , is the one that best characterises radiation-matter interactions, because it shows the characteristic size,  $\lambda$ , and the characteristic energy,  $E=h\nu=hc/\lambda$ . The electromagnetic spectrum is the range of all possible wavelengths of electromagnetic radiation (really from Planck's length,  $L_P=(hG/(2\pi c^3))^{1/2}=1.6 \cdot 10^{-35}$  m, to the size of the Universe).

Matter is formed by very tiny elementary particles (say of  $10^{-18}$  m in size), some of them tightly bonded in nuclei (some  $10^{-15}$  m in size) surrounded by an electronic cloud that constitutes the atoms (which are some  $10^{-10}$  m in size), which are most often bonded to other atoms forming molecules of very different sizes which, alone or weakly bonded to others, make up our environment and ourselves. A piece of matter can be subjected to:

- Non-contact electromagnetic fields of different strength (in [V/m] for EF, and in [T] for MF) and different frequencies (from static fields with constant EM or MF, to very high-frequency EMF).
- Contact electromagnetic fields. Besides the non-contact configurations just described, electrodes of different kinds and sizes can be in contact with matter, generating not only EM-fields inside, but electrical charge flows (ionic, in solutions and in ionic-conductive materials, or electronic, in metals). Living matter is basically an aqueous ionic solution with suspended macromolecules forming small packets (cells) within semipermeable membranes. Notice that net electrical conduction within an electrolyte usually implies electrochemical reaction at some electrodes where

the electrical circuit can be closed by a flow of electrons through electronic conductors (although the electrical circuit might be closed by ion diffusion through semi-permeable membranes).

## SPECTRUM

The word spectrum (Lat. *spectre*, apparition) was first used to describe the rainbow of colours in visible light when separated by Newton in 1666 using a prismatic lens (he realised that individual colours cannot be further separated, and that the colours can be merged with an oppositely arranged prism to reconstruct the original white light, but he misinterpreted different colours as particles of different speeds). Spectral characteristics can be defined in terms of frequency ( $\nu$ , does not depend on the propagating media), wavelength (decreases with refractive index  $n$  of the medium,  $\lambda=\lambda_0/n$ ), wavenumber ( $\bar{\nu} \equiv 1/\lambda$ , but sometime  $k=2\pi/\lambda$ ), or energy ( $E=h\nu$ , usually in [eV](#) units). The wave-particle duality is a general principle, but the wave behaviour is more apparent in low-frequency radiations, and the particle behaviour is more apparent in high-frequency radiations.

The spectral distribution for electromagnetic radiation in thermodynamic equilibrium (named blackbody radiation) is described by Planck's law of 1901, which gives the unitary power as a function of wavelength, named spectral irradiance,  $M_\lambda$ , usually given in units of [(W/m<sup>2</sup>)/ $\mu\text{m}$ ]:

$$M_{bb,\lambda} = \frac{A}{\lambda^5 \left[ \exp\left(\frac{B}{\lambda T}\right) - 1 \right]} = \frac{2\pi hc^2}{\lambda^5 \left[ \exp\left(\frac{hc}{k_B \lambda T}\right) - 1 \right]} \quad (1)$$

where  $h$ ,  $c$ ,  $\lambda$ ,  $k_B$ , and  $T$ , are Planck's constant ( $h=6.6 \cdot 10^{-34}$  J·s), the light speed in vacuum ( $c=3 \cdot 10^8$  m/s), wavelength (related to frequency by  $c=\lambda\nu$ ), Boltzmann's constant ( $k_B=1.38 \cdot 10^{-23}$  J/K), and temperature of matter in equilibrium with blackbody radiation. For a given temperature, maximum irradiance in (1) occurs at  $\lambda_{|M_{\max}}=C/T$ , with  $C=0.003$  m·K, showing that for our common hottest objects, e.g. a lamp filament at 3000 K, we are limited to  $\lambda_{|M_{\max}} > 0.003/3000 = 1 \mu\text{m}$  in the generation of blackbody radiation (we can generate shorter- $\lambda$  radiation, as X-ray, but not in equilibrium with matter). We need very hot plasmas, like those existing in stars, to produce more energetic (shorter- $\lambda$ ) blackbody radiation (e.g. the Sun radiates as a blackbody at 6000 K).

Usually, a small range in the spectrum is of interest, what is termed the bandwidth, measured as a wavelength range (or frequency range; e.g. visible radiation has a bandwidth of  $\Delta\lambda=0.7-0.4=0.3 \mu\text{m}$  and  $\Delta\nu=0.75-0.43=0.32 \cdot 10^{15}$  Hz). Notice that the term 'bandwidth' is also used for data rate, which are related in signal processing by Nyquist–Shannon sampling theorem (e.g. when we say that we have a 100 Mbps Internet connection, we mean that we can get 100 megabits per second of information, which demands a bandwidth of at least  $100/2=50$  MHz around the carrier frequency, of order  $0.3 \cdot 10^{15}$  Hz for fibre optics, or  $2.4 \cdot 10^9$  Hz for a radio [WiFi](#)-connection). As a general rule, the shortest the wavelength, the more information it can convey, but the shortest it propagates (and the less able to go around objects).

Hence, different regions in the EM spectrum correlate to different intensities in the energetic interaction between radiation and matter. From most energetic to less energetic ( $E=h\nu=hc/\lambda$ ):

- Nuclear changes,  $\lambda \ll 10^{-10}$  m ( $\gamma$ -ray). Only the most energetic (shorter- $\lambda$ ) EM-radiation can interact with atomic nuclei and give way to nuclear reactions. Most natural and artificial nuclear reactions are not due to EM-radiation but to highly accelerated particle radiation, or to initially unstable nuclei. Neutron beams are most used in nuclear research because they are not deviated by the electron shell of atoms. In the international thermonuclear experimental reactor ([ITER](#)), in order to procure the nuclear reaction  ${}^2_1\text{H} + {}^3_1\text{H} \rightarrow {}^4_2\text{He} + {}^1_0\text{n}$ , the hydrogen plasma must be heated to some  $10^8$  K, by a combination of ohmic resistance, microwaves, and cyclotron resonance (and maintained confined within a magnetic field).
- Chemical changes,  $10^{-10}$  m  $< \lambda < 10^{-7}$  m (X-ray and UV-ray). Changes in chemical behaviour are due to changes in the electronic clouds surrounding the nuclei (which do not change), either by removing electrons from the atomic or molecular shell (i.e. ionisation), or by rearrangement of atoms in molecules (dissociation and association). All EM-radiations with  $\lambda < 10^{-7}$  m are ionising radiations, and are usually harmful to living matter because key biomolecules like ADN get damaged.
- Physical changes,  $\lambda \gg 10^{-7}$  m (visual, infrared, and radio waves). Changes here do not significantly alter the atomic structure; at most, electrons in an atom cloud may temporally change cloud shell (e.g. energetic radiation can pump electrons up in the shell and may yield stimulated emission); less energetic radiation can only modify molecular or atomic vibration states, or rotation states if less energetic, or just produce translation state changes, usually dissipated in a random way (thermal). Very low-energy EM-radiation ( $\lambda \gg 10^{-4}$  m, radio waves), hardly produce significant effects on matter, and require fine-tuned macroscopic electrical circuits to detect them, and to emit them. Radiation-matter interaction in this whole range  $\lambda \gg 10^{-7}$  m have similar propagation characteristics: can be reflected on a material interfase (ionising radiation cannot be mirror-like reflected because atomic size is of the same order or larger than its wavelength), refract, scatter, polarise, etc. Low energy EM-radiation may also have some influence at nuclear level, as in nuclear magnetic resonance ([NMR](#)), where atoms with an odd mass number (i.e. having non-zero nuclear spin:  ${}^1\text{H}$ ,  ${}^{13}\text{C}$ ...), under a strong magnetic field  $B$ , absorb EM-radiation of some frequency (e.g. UHF at some 900 MHz) and re-emit electromagnetic radiation of another frequency proportional to  $B$  depending on the magnetic properties of the isotope of the atoms (it is used in [magnetic resonance](#) tomography in medicine, providing better resolution on soft tissue than X-ray tomography, without using ionising radiation).

## APPLICATIONS

According to application, EM radiation can be classified by decreasing wavelength range (increasing frequency range) as:

- Low frequency radio waves,  $\lambda > 10$  m ( $f < 30$  MHz), including very-low-frequencies (VLF,  $\lambda > 10$  km,  $f < 30$  kHz), low-frequency (LF or long-waves), mid-frequency (MF or middle-waves), and high-frequency (HF, up to 30 MHz, also known as short-waves,  $\lambda < 10$  km). The HF, MF, and LF bands were much used for radio broadcasting in the first half of the 20th century, but now they are scarcely used. In the VLF band ( $f < 30$  kHz), the bandwidth is so small that only low-data-rate signals can be transmitted (no audio, no video), but they can penetrate more than 10 m in seawater (up to 40 m sometimes) and have little attenuation in the atmosphere (but interferences are large), bending along mountains and being reflected at the ionosphere. They are used for military communication with

submarines. Antennas are very inefficient because of size limitations and the vertical polarization of the EMF; transmitters using wires a few km long have been built. The VLF-band was the one used for transcontinental wireless telegraphy from 1900 to 1920 (radio waves were predicted by Maxwell in 1864, discovered by Hertz in 1887, and first used by Marconi in 1897 for telecommunications). VLF EM-fields like these and frequencies below (e.g. those generated by alternate currents at 50 Hz from the mains) can be treated as quasi-static electrical and magnetic fields, and they are usually just a source of electromagnetic interference ([EMI](#)).

- High frequency radio waves,  $0.3 \text{ m} < \lambda < 10 \text{ m}$  ( $30 \text{ MHz} < f < 1 \text{ GHz}$ ), encompassing the very-high-frequency band (VHF, with  $1 \text{ m} < \lambda < 10 \text{ m}$  and  $30 \text{ MHz} < f < 300 \text{ MHz}$ ) and the ultra-high-frequency band (UHF, with  $0.3 \text{ m} < \lambda < 1 \text{ m}$  and  $300 \text{ MHz} < f < 1 \text{ GHz}$ ). Used for broadcasting, for two-way personal and machine radio-communication (from short-range [RFID](#) tags, to deep-space probes), in nuclear magnetic resonance, etc. A radio transmitter gets the electrical signal from the source (e.g. a microphone) and combines it with a carrier, i.e. a radio frequency alternating current, which is then sent to an antenna (an arrangement of metallic conductors, adjacent or detached), and finally radiated as EM waves. A radio receiver has an antenna (exposed to all kind of radiations) and a tuner, i.e. a resonant electric circuit (in its simplest form, a circuit with a capacitance  $C$  and an inductance  $L$ ) that selects just one frequency to be amplified ( $f = 1 / (2\pi\sqrt{LC})$ ); the inductor or the capacitor of the resonator is adjustable, allowing the user to change the tuning frequency). In its century of existence, there has been a tendency for applications to change to higher and higher frequencies, to have larger bandwidths, leaving the old LF+MF+HF bands superseded. Digital TV works at 700..900 MHz (the same band used in NMR), and the future very-wide-area mobile internet connection seems to aim at this range too.
- Microwaves,  $10^{-3} \text{ m} < \lambda < 0.3 \text{ m}$  ( $1 \text{ GHz} < f < 300 \text{ GHz}$ ), used for point-to-point telecommunication (includes [GPS](#) at 1.2..1.6 GHz, mobile cellular phones at 1.7..2.1 GHz, wireless connections like [Bluetooth](#) and WiFi at 2,45 GHz), radiolocation, heating of polar-molecule materials (microwave ovens, at 2.45 GHz), remote sensing, medical therapy (millimetre-wave therapy), full-body scanning... In this region lays the Industrial, Scientific, and Medical band ([ISM](#)), which is really a set of small bands not regulated for public telecommunication services but let free for other uses, including remote-control gadgets like RFID tags, garage door openers, etc. A millimetre-wave [full-body scanner](#) (as used in airport security checking) is based on reflection at dense materials of EM-radiation in the 30 GHz range, which is almost translucent to clothing and other light materials; this MW-scanners are competing with the former backscatter X-ray technology based on ionising EM-radiation.
- Infrared (IR) radiation,  $0.7 \cdot 10^{-6} \text{ m} < \lambda < 10^{-3} \text{ m}$  ( $300 \text{ GHz} < f < 430 \text{ THz}$ ), important for heating (infrared heaters and ovens), and for remote sensing (chemical analysis and thermography, including night vision). Thermal radiation is usually synonymous with infrared radiation, although visual radiation and MW may have important thermal effects too. Many lasers actually work in the IR, i.e. they are irasers (e.g. neodymium at  $\lambda = 1.06 \mu\text{m}$ , and CO<sub>2</sub> lasers at  $\lambda = 10.6 \mu\text{m}$ ).
- Visible radiation,  $0.4 \cdot 10^{-6} \text{ m} < \lambda < 0.7 \cdot 10^{-6} \text{ m}$ , usually restricted to human vision. Visual radiation is important to animal vision and other image-forming and illumination-processes (optical instruments), photosynthesis and other solar energy collection processes, and many recent laser uses (communication, cutting, medicine...). Visual sources may be very hot objects, hot plasmas, and

cold plasmas and other electro-luminescent phenomena. Applications of solar radiation (basically half and half visible and IR) merits a separate account due to its importance. We learnt from school-time that we get light and heat from the Sun. But we can use solar energy to produce motion, electricity, cooling, convey information, synthesize fuels, grow crops... [Photometry](#) refers to the measurement of absolute radiometric quantities filtered by an agreed upon standard human vision spectral sensitivity curve. Presently, the SI nomenclature makes use of different names for [photometric units and their equivalent radiometric units](#); e.g. instead of saying that maximum solar irradiance in the visible band (0.4..0.7  $\mu\text{m}$ ) is  $400 \text{ W/m}^2$  from a total-spectrum value of  $1000 \text{ W/m}^2$  on ground (which reduces to  $150 \text{ W/m}^2$  visible radiation after being passed through the [standard vision filter](#)), one says that solar illuminance is  $100 \cdot 10^3 \text{ lx}$ , although knowing that by definition  $1 \text{ lx} = 1 \text{ lm/m}^2 = 1/683 \text{ W/m}^2$  of monochromatic radiation of  $\lambda = 555 \text{ nm}$ , one can easily check that  $100 \cdot 10^3 \text{ lx}$  corresponds to the said  $150 \text{ W/m}^2$  visible.

- Ultraviolet (UV) radiation,  $10 \cdot 10^{-9} \text{ m} < \lambda < 400 \cdot 10^{-9} \text{ m}$ , can be subdivided is:
  - UVA ( $300 < \lambda < 400 \text{ nm}$ ), is not-ionizing, and may be beneficial (suntan), but overexposure cause sunburn and photokeratitis. The Sun emits UVA, UVB, and UVC, but oxygen in the atmosphere absorbs most of UVB and UVC (at the Earth surface, 9 % is UVA). The mercury vapour within fluorescent lamps, without a phosphorescent coating to convert UV to visible light, would emit just two peaks: some 9 % at  $\lambda = 253.7 \text{ nm}$ , and some 1 % at  $\lambda = 185 \text{ nm}$ ; the latter being used in naked lamps for disinfection, and being blocked by coatings in normal lamps. There are many animals with some vision capabilities in the UVA: fishes, reptiles, birds, and mammals (bats, rats, cats, dogs...).
  - UVB (around  $\lambda = 300 \text{ nm}$ ), is not-ionizing, and may be beneficial in small amounts (vitamin-D production), but overexposure cause sunburn, photokeratitis, and give rise to skin cancer (malignant melanoma) by indirect DNA damage (even UVA overexposure is considered carcinogen).
  - UVC ( $100 < \lambda < 300 \text{ nm}$ ), is ionizing, but may be beneficial in small amounts (germicidal).
  - Extreme-UV ( $10 < \lambda < 100 \text{ nm}$ ), is ionizing; valence electrons are pulled out if  $\lambda < 30 \text{ nm}$ , and inner shell electrons if shorter wavelengths.
- X-rays,  $0.1 \cdot 10^{-9} \text{ m} < \lambda < 10 \cdot 10^{-9} \text{ m}$ , are emitted by inner-shell electrons (outside the nucleus); they are used in radiography for medical diagnosis, and in crystallography.
- Gamma rays ( $\gamma$ -rays),  $\lambda < 10^{-10} \text{ m}$ , are emitted from the atom nuclei, either after impact of cosmic rays, by radioactive nuclear decay (after emission of either alpha or beta particles), or by lightning in thunderstorms. They are the most penetrating. Because of the broad overlap in energy bands, the modern trend is not to distinguish X-rays and  $\gamma$ -rays by their wavelength but by their origin: X-ray from inner-shell electron interaction,  $\gamma$ -rays from radionuclides. Gamma radiation in the 3..10 MeV range is the most dangerous ionizing source (higher energy rays pass throughout); that is for radiations external to the human body (internal radiation from inhaled and ingested  $\alpha$  and  $\beta$  particles may be worse). The satellite Gamma-ray Observatory detected  $\gamma$ -ray sources in distant galaxies (mainly from [pulsars](#) in our galactic plane), and in nearby solid bodies the largest in angle being our Moon (the Sun is not emitting  $\gamma$ -ray because they are trapped inside), due to cosmic ray bombardment ( $>20 \text{ MeV}$ ) of heavy nuclei. Some  $\gamma$ -ray sources like Co-60 or Cs-137 isotopes are used in industry for opaque imaging sensing.

[Spectrometry](#) (or spectro-radiometry) refers to the measurement of radiometric quantities in narrow bands of wavelength (or in wavenumber bands, or in frequency bands). A common laboratory spectroscope (as used in chemical analysis or remote sensing) can detect wavelengths from 2 nm to 2500 nm. Spectral analysis started with Newton's dispersion of Sun's light with a prism, and developed in the 19<sup>th</sup> century with Ångström, Fraunhofer, Bunsen, Kirchhoff... The first measurements of wavelengths in the visible band were carried out by T. Young in 1803 from the spacing of interference fringes in his famous double-slit experiment (see Diffraction, below).

## POWER EMITTED AND POWER RECEIVED

A propagating radiation has several characteristics, amongst which, a measure of its power is most important. Radiation power,  $\Phi$ , with SI unit of watts [W], is the total energy emitted by a source per unit time, and can be deduced from an overall energy balance (e.g. by electrical heating of a suspended solid in a thermal vacuum chamber, [TVC](#)).

Several different magnitudes are in use to characterise radiation power level or 'intensity', each of them showing certain advantages (see Fig. 1):

- Power,  $\Phi$  [W], also radiant energy flux (although the word flux in heat transfer always refers to flow per unit area).
- Irradiance,  $E \equiv d\Phi_{in}/dA$  [ $W/m^2$ ], incident radiant energy flux on a surface from all directions.
- Exitance,  $M_{in}$  [ $W/m^2$ ], emerging radiant energy flux from a surface in all directions, due to own emission (emittance) plus reflections from other sources (plus transmission from behind, if any).
- Intensity  $I \equiv d\Phi/d\Omega$  [ $W/sr$ ], either incident or emerging radiant energy flux in a given solid-angle direction  $\Omega$ .
- Radiance,  $L \equiv d\Phi/(dA_{\perp}d\Omega)$  [ $W/(m^2 \cdot sr)$ ], either incident or emerging radiant energy flux in a given solid-angle direction, per unit normal surface  $dA_{\perp}$  (normal to the direction considered).

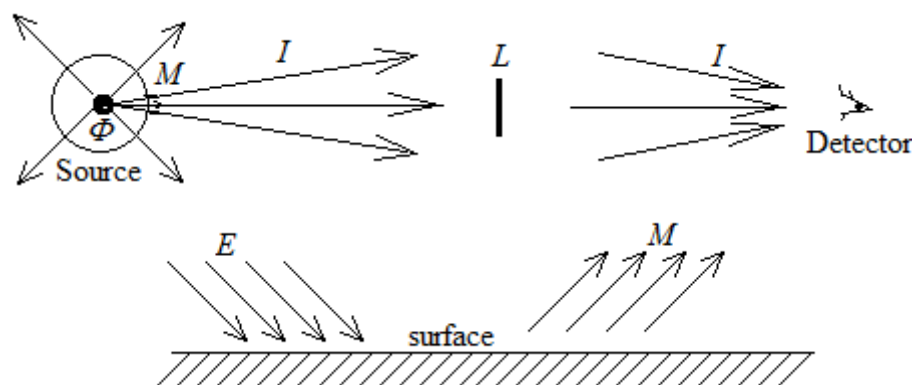


Fig. 1. Different radiation magnitudes (radiometric and corresponding photometric units are given): power  $\Phi$  [W] or [lm], intensity  $I$  [ $W/sr$ ] or [ $lm/sr \equiv cd$ ], radiance  $L$  [ $W/(m^2 \cdot sr)$ ] or luminance [ $lm/(m^2 \cdot sr) = cd/m^2$ ], exitance (or emittance)  $M$  [ $W/m^2$ ] or [ $lm/m^2 \equiv lx$ ], and irradiance  $E$  [ $W/m^2$ ] or illuminance [ $lm/m^2 \equiv lx$ ]. The source may be point-like or of finite extension.

Related to radiation power is radiation dose (power multiplied by time-exposure). Dosimetry refers to total absorbed radiation by a receptor in a given period (see Radiation effects on humans and materials).

## IRRADIANCE

The basic measure of radiation amount is irradiance,  $E$  [ $\text{W}/\text{m}^2$ ], which is the power per unit area impinging on a given surface (normal to the propagation direction if not otherwise stated). Irradiance accounts for any incoming radiation, either directly from a source, or through reflections.

For one-directional radiation, irradiance on a surface depends on its inclination in the way  $E=E_0\cos\beta$ , where  $E_0$  is normal irradiance and  $\beta$  the normal-to-incidence angle. Notice that, in general, only a fraction of the irradiance on a surface is absorbed, the rest being reflected and, for semi-transparent materials, transmitted. Irradiance is measured with a broadband hemispheric radiometer (as with a [pyranometer](#)).

For an isotropic source of power  $\Phi$  [W] (point-like or finite) in non-absorbing media, the normal irradiance  $E$  at a distance  $d$  from the source, verifies  $\Phi=4\pi d^2E$ , known as the inverse square law. For instance, if we know that at the Sun-Earth distance ( $R_{S-E}=1 \text{ AU}=150\cdot 10^9 \text{ m}$ ) solar irradiance is  $E_0=1360 \text{ W}/\text{m}^2$ , solar irradiance at Mars (with  $R_{S-M}=1.5 \text{ AU}$ , although it has some ellipticity) would be  $E=E_0(R_{S-E}/R_{S-M})^2=1360\cdot(1/1.5)^2=604 \text{ W}/\text{m}^2$ . Notice, however, that irradiance from an infinite planar source does not depend on the distance, and that for an infinite line source, irradiance falls with distance (not distance squared).

In meteorology, direct solar radiation is measured with a narrow beam radiometer (i.e. with a small aperture) called [pyroheliometer](#), while the hemispheric solar radiation (direct beam, plus reflection and scatter from other bodies) is measured with a radiometer called hemispheric pyranometer. From the  $1360 \text{ W}/\text{m}^2$  top-of-the-atmosphere time-average irradiance normal to the Sun direction, at sea level on a clear day at noon only around  $900 \text{ W}/\text{m}^2$  reach the surface as a direct beam, with an additional  $90 \text{ W}/\text{m}^2$  diffuse radiation coming from the rest of the hemisphere (i.e. a total of almost  $1000 \text{ W}/\text{m}^2$  at the subsolar point, the other  $370$  being lost in the way down by scattering and, in lesser amounts by absorption, in air molecules). With clouds, or when sunrays fall inclined, much less solar energy reaches the surface.

Irradiance  $E$  is related to the root-mean-square (rms) amplitude of the electric-field  $E_{\text{rms}}$  (it is unfortunate that the International System of Quantities, [ISO](#), recommends the same symbol for irradiance and for electric field); in vacuum by  $E=\frac{1}{2}c\epsilon_0E_{\text{rms}}^2$ , where the electric [permittivity](#) of vacuum is  $\epsilon_0=1/(c^2\mu_0)=8.85\cdot 10^{-12} \text{ F}/\text{m}$  ( $c$  is the speed of light and  $\mu_0=4\pi\cdot 10^{-7} \text{ H}/\text{m}$  the magnetic [permeability](#) of vacuum); e.g. to an extra-terrestrial solar irradiance of  $E=1360 \text{ W}/\text{m}^2$  corresponds an electric field of  $E_{\text{rms}}=1020 \text{ V}/\text{m}$  (the corresponding magnetic flux density, under vacuum, is  $B_{\text{rms}}=E_{\text{rms}}/c=3.4\cdot 10^{-6} \text{ T}$ , which may be compared with the  $10^6 \text{ V}/\text{m}$  of electrical discharge in vacuum, or the  $10^{-4} \text{ T}$  of the geomagnetic field). Notice that, although for static fields in vacuum the energy density  $u$  [ $\text{J}/\text{m}^3$ ] associated to the superposition of an electric field and a magnetic field is  $u=\frac{1}{2}\epsilon_0E^2+\frac{1}{2}B^2/\mu_0$ , and that for EM-radiation in vacuum  $B=E/c$  and thus  $\frac{1}{2}\epsilon_0E^2=\frac{1}{2}B^2/\mu_0$ , the  $\frac{1}{2}$  in  $E=\frac{1}{2}c\epsilon_0E_{\text{rms}}^2$  comes from the averaging of the oscillations:  $\langle\cos(kx-\omega t)\rangle=\frac{1}{2}$ . Furthermore, notice how small the energy density of EMF is; even for the maximum electric field in vacuum before discharge, some  $10^6 \text{ V}/\text{m}$ ,  $u=\frac{1}{2}\epsilon_0E_{\text{rms}}^2=\frac{1}{2}(8.85\cdot 10^{-12})\cdot(10^6)^2=4.5 \text{ J}/\text{m}^3$ , equivalent to a radiation pressure of just  $p=4.5 \text{ Pa}$  (for solar radiation  $p=E_0/c=1360/(3\cdot 10^8)=4.5\cdot 10^{-6} \text{ Pa}$ ).

## EXITANCE AND EMITTANCE

For a given area-distributed source (of its own or reflecting other sources, see Fig. 1), the total power per unit surface issuing from that surface is termed exitance,  $M$  [ $\text{W}/\text{m}^2$ ] (formerly called radiosity with symbol  $J$ ). For ideal black bodies,  $M=M_{\text{bb}}=\sigma T^4$  (all being of its own emission, without any reflexions), but in a more general case (termed grey body if its emissivity  $\varepsilon$  and reflectance  $\rho$  are not wavelength-dependent), exitance accounts for three different effects: the own emission by being hot,  $\varepsilon\sigma T^4=\varepsilon M_{\text{bb}}$ , the part reflected from irradiance falling on it,  $\rho E$ , and the part coming by transmission from the back, although the latter is absent in opaque objects and will not be considered here. The emissivity of a surface,  $\varepsilon$ , is the ratio of power really emitted to power that a blackbody at the same temperature would emit. The reflectance of a surface,  $\rho$ , is the fraction of incident radiant power reflected back (in all directions). The exitance of a grey surface is thence:

$$M=\varepsilon M_{\text{bb}}+\rho E \quad (2)$$

For a given distributed source, the emittance,  $M$  [ $\text{W}/\text{m}^2$ ] (mind that the same symbol is presently used in the SI system for emittance and exitance), is the power emitted per unit surface area by being hot,  $M=\varepsilon\sigma T^4=\varepsilon M_{\text{bb}}$ , known as Stefan's law (with  $\varepsilon=1$  in the ideal case of a blackbody); i.e. emittance is that part of exitance not including reflections from incoming radiation. Notice that for a convex surface source,  $\Phi = \int M dA$ ; e.g. for a uniform spherical source of radius  $R_0$ ,  $M=\Phi/(4\pi R_0^2)$ . Close enough to an emitting surface (to avoid reflections), irradiance equals emittance, but, as said above, irradiance decrease with distance in non-planar configurations (with the inverse square law in spherical propagation). For irradiance to be greater than emittance, a converging radiation is needed (i.e. concentration from concave radiators).

## INTENSITY AND RADIANCE

For a given point source (see Fig. 1, above), the power radiated in a given direction (per unit of solid angle) is named intensity  $I \equiv d\Phi/d\Omega$  [ $\text{W}/\text{sr}$ ], being important when the source is non-isotropic, since for non-absorbing media, intensity is a conservative quantity with the distance travelled (really, the invariant is radiance divided by the index of refraction squared). For a point source it is simply  $I=\Phi/(4\pi)$ .

For a given distributed source, the power radiated in a given direction (the intensity) per unit radiating area projected in that direction, is termed radiance  $L$  [ $\text{W}/(\text{m}^2 \cdot \text{sr})$ ] (see Fig. 1). Radiance is a useful magnitude because it indicates how much of the power issuing from an emitting or reflecting surface will be received by an optical system looking at the surface from some angle of view (the solid angle subtended by the optical system's entrance pupil, like in our eye). But the major advantage of radiance is that, in many real cases, it is nearly independent of direction considered, and the idealised model of 'a perfect diffuser', i.e. a surface whose radiance is the same in all directions, is most important in radiometry. A blackbody is also a perfect diffuser. Notice, however, that the power radiated in a given direction (the intensity) per unit radiating area (not projected) in that direction is  $L \cos\beta$ , but per unit of projected area is  $L$ ,  $\beta$  being the zenith angle of the direction considered (you may think on the directional dependence of a flux of photons emanating from a hole in a cavity). Any surface that radiates (by own emission or by reflection from other sources) with a directional intensity following this cosine law is named 'perfect diffuser' or Lambertian surface, in honour of J.H. Lambert's 1760 "Photometria". A radiation detector pointing to a Lambertian

planar surface detects the same irradiance at any position because the projected area at a given distance is constant (only depends on the aperture of the detector); it sees uniform radiance because, although the emitted power from a given area element is reduced by the cosine of the emission angle, the size of the observed area is increased by a corresponding amount. The relation between emittance (exitance in general) and radiance for perfect diffusers is:

$$\Phi = \int_A M dA = \int_A \int_{\Omega} L dA_{proj} d\Omega \rightarrow M = \int_0^{\pi/2} L \cos(\beta) d\Omega = \int_0^{\pi/2} L \cos(\beta) 2\pi \sin(\beta) d\beta = \pi L \quad (3)$$

Notice that the energy balance in non-absorbing media implies that the radiance seen from a detector must be equal to the radiance emitted by the source.

## OTHER EFFECTS ON THE PROPAGATION OF TRANSVERSAL WAVES

Besides the energy content of EM radiation (and its spectral distribution), which can be described with the beam model (or ray tracing model) used above, other physical characteristics of EM-radiation require a more detailed study of the phase and vibration direction of electromagnetic fields, e.g. to analyse polarization and interference effects. Although we focus here on EM radiation, the same applies to any other form of transversal waves (e.g. waves in a string), and some of them even to longitudinal waves (e.g. interference, but not polarization).

Consider the simplest case of a planar harmonic EM wave travelling to the right of an observer (Fig. 2; we take Cartesian coordinates, with the  $z$  direction to the right). As said above, the EMF is defined by its electrical field vector  $\vec{E}(z,t)$ , perpendicular to the propagation direction  $z$ , and with transversal components  $E_x$  and  $E_y$  such that

$$\left. \begin{aligned} E_x(z,t) &= A_x \cos(kz - \omega t + \phi_x) \\ E_y(z,t) &= A_y \cos(kz - \omega t + \phi_y) \end{aligned} \right\} \quad (4)$$

where  $A_x$  and  $A_y$  are the maximum amplitude of each component,  $\phi_x$  and  $\phi_y$  are the phase of each component (relative to a given origin),  $k=2\pi/\lambda$  is the wavenumber ( $\lambda$  the wavelength), and  $\omega=2\pi f$  the angular frequency ( $f$  the frequency). The propagation speed is  $\omega/k=f\lambda=c$ . If the planar wave were not propagating along the  $z$  direction but along a generic direction indicated by a wave-vector  $\vec{k}$  in a rectangular coordinate system  $\vec{r}$ , the  $k_z$ -term should be substituted by scalar product  $\vec{k} \cdot \vec{r}$ .

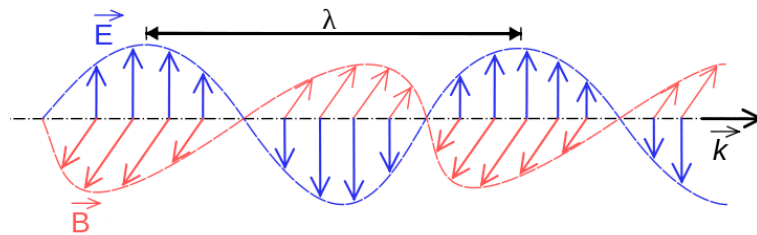


Fig. 2. Sketch of a linearly polarized planar EM wave propagating from left to right.

Recall that the energy 'intensity' of the EMF, measured by the irradiance  $E = \frac{1}{2} \epsilon_0 E_{rms}^2$ , is the only property measured by a radiation detector (our eye, a chemical film, a photodiode, a CCD, etc. Notice that  $E_{rms} = \sqrt{A_x^2 + A_y^2} / 2$  (the  $\frac{1}{2}$  coming from the rms-averaging).

Collimated radiation is a parallel beam (in practice, when rays diverge or converge slowly as they propagate). A collimator (Fig. 3) may be created from a point source placed at the focus of a lens or a mirror. The width of a collimated beam can be changed (e.g. to get a wider beam from a laser), by using two lenses with different powers and a common focal point.

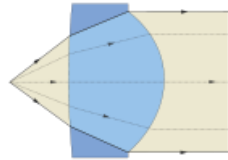


Fig. 3. A collimating lens.

Most of the radiation properties that follow are analysed by considering an incident beam collimated, which is the best way to have planar waves.

## POLARIZATION

Polarization is a property of transversal waves indicating the direction of oscillation; in EM radiation, it describes the orientation of the electric field vector  $\vec{E}(z, t)$ . Considering the two components of the electric field in a planar wave like in (4), the polarization is said linear if  $\phi_y = \phi_x$  (in general if  $\phi_y = \phi_x + n\pi$ ), and in this case the projection of  $\vec{E}(z, t)$  on a  $z$ -plane is a straight line (i.e., looking along the propagating direction, the vector tip oscillates in that line); otherwise, the vector-tip projection describes an ellipse (a circle in the case  $A_y = A_x$ ), going round either right-handed or left-handed (what is a chirality property). All these projections are Lissajous figures bounded in the rectangle  $|x| < A_x$  and  $|y| < A_y$ , but are restricted to an elliptic figure (with its two extremes of a circle and a line) because both components have the same frequency. Polarization is conserved when propagating in vacuum, but it may be altered when interacting with matter.

Individual photons are completely polarized, and their polarization state can be elliptical, circular, or linear, but real EM-sources contain a large number of atoms or molecules that emitting radiation; if the orientation of the electric fields produced by these emitters is un-correlated, the resulting radiation is said un-polarized (it has random polarization angles), but there may be partial correlation between the emitters and radiation is said to be partially polarised. Polarisation may occur:

- By selective emission (the source emits only linearly polarized light, like dipole antennas).
- By reflection. Light reflected by shiny transparent materials gets partly or fully polarized, except when the light is normal (perpendicular) to the surface (it was through this effect that polarization was first discovered in 1808 by Malus). At the Brewster angle (1815),  $\theta_B = \arctan(n_2/n_1)$ , e.g. for air-to-glass  $\theta_B = \arctan(1.5/1) = 56^\circ$ , reflected light is linearly polarized, and light with a particular polarization is perfectly transmitted through a transparent dielectric surface, with no reflection.
- By refraction.
- By dispersion.
- By selective absorption.

[Birefringence](#) is the optical property of an anisotropic material having a refractive index that depends on the polarization and propagation direction of EM radiation. Isotropic solids, although not show birefringence if unstressed, show it under mechanical stress, what is used in the photo-elasticity technique. Birefringence is used in liquid crystal displays ([LCD](#)), colour filters, 3D-imaging, etc. In some 3D-system movies, images intended for each eye are either projected from two different projectors with orthogonally oriented polarizing filters, or from a single projector with time multiplexed polarization (a fast alternating polarization device for successive frames). Polarized 3D glasses with similarly oriented polarized filters ensure that each eye receives only the correct image. Circular polarization is used to make the channel separation insensitive to the viewing orientation. The 3D-effect only works on a silver screen since it maintains polarization, whereas the scattering in a normal projection screen would destroy polarization.

Many animals are apparently capable of perceiving some of the components of the polarization of light, e.g. linear horizontally-polarized light. This is generally used for navigational purposes, since the linear polarization of sky light is always perpendicular to the direction of the sun. This ability is very common among insects.

[Polarimetry](#) is the measurement (using a polarimeter) and interpretation of the polarization of transverse waves. A [polarizer](#) is a device that affects polarization.

## REFLECTION

For any kind of radiation, reflection is the change in direction of propagation at an interface when it returns into the incident medium. Reflection may be mirror-like if the interface roughness is much smaller than the wavelength (e.g. a polished solid surface, or a quiet liquid surface), perfectly diffuse (according to Lambert's cosine law), or any real intermediate case. Perfectly retro-reflecting surfaces are like a perfect set of trihedral mirrors which reflect light rays precisely back along the incoming direction. All kind of EM radiations may reflect on interfaces, even X-ray. In a reflection, the intensity, polarization, and phase, may change.

[Fresnel equations](#) describe the behaviour of light when moving between media of differing refractive indices. Reflectance  $\rho$  (and transmittance without absorption,  $\tau=1-\rho$ ) depend on the incident angle and polarization, but for normal incidence it is just  $\rho=((n_2-n_1)/(n_2+n_1))^2$ ; e.g. when normal light passes from air to window glass,  $\rho=((1.5-1)/1.5+1)^2=0.04$ , i.e. a 4 % is reflected; a glass plate then transmits a maximum of 92 % (4 % reflected at each face).

In a specular reflection, the reflected wave has a phase-shift jump of  $180^\circ$  on external reflections (i.e. if the refractive index grows in the incident direction, as from air to any solid or liquid medium), but has no jump on 'internal reflections' if the refractive index decreases in the incident direction (e.g. for a glass pane with air on both sides, the reflected wave has a phase jump of  $180^\circ$  on the first surface and of  $0^\circ$  on the second surface, but if a heavy [flint glass](#) ( $n=1.65$ ) is placed just behind the normal glass ( $n=1.5..1.6$ ), then the second surface reflection has  $180^\circ$  of phase shift.

## REFRACTION

Refraction is the change in direction of propagation of a radiation entering into a medium of different refractive index  $n$  (it is essentially a surface phenomenon, governed by the law of conservation of energy and momentum). The refractive index,  $n=c_0/c$ , is the ratio of speed of light in vacuum to that on another medium, and it varies with the material, with its density (i.e. with temperature and pressure), and with radiation wavelength. It is best measured by ray deflection at a planar interface, using [Snell's law](#):  $n_1\sin\beta_1=n_2\sin\beta_2$ . Other refractive effects are:

- Limit angle (total reflection):  $n_1\sin\beta_{1,\text{lim}}=n_2$ . For water,  $n=1.33$ ,  $\beta_{1,\text{lim}}=48.6^\circ$ . Used in fibre optics.
- Parallel shift after traversing a plate:  $S=L\sin(\beta_1-\beta_2)/\cos\beta_1$ .
- Prism deflection:  $\delta=\beta_1+\beta_2-\alpha$ .
- Prism dispersion (chromatic):  $\delta(\lambda)=\beta_1+\beta_2(\lambda)-\alpha$ , due to  $n(\lambda)$ . As in the rainbow. Prism chromatic dispersion yields a non-linear relation,  $\theta(\lambda)$ ; linear chromatic dispersion are obtained with diffraction gratings (as used in monochromators).

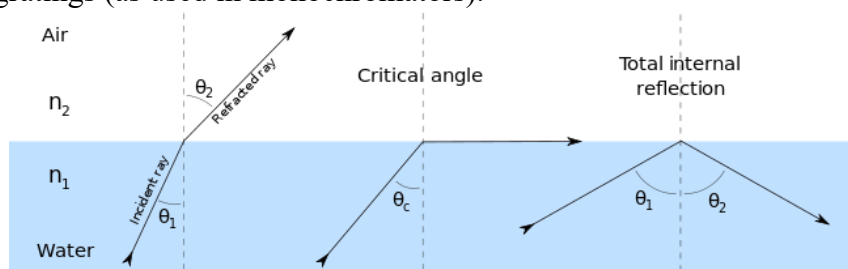


Fig. 4. Refraction of light at the interface between two media.

## COHERENCE

[Coherence](#) is the in-phase correlation of waves that allows a stationary interference. [Laser](#) light (stimulated emission) has great coherence, whereas thermal emission (as from the Sun) is incoherent because their particles emit at random times (lasting some  $10^{-8}$  s) and with a wide band of frequencies (from  $10^{14}$  Hz to  $10^{15}$  Hz).

Before lasers were invented in the 1960s, light coherence was achieved by passing sunlight through a small hole, which becomes a new source (the smallest hole the more coherent source; coherence length is inversely proportional to hole size,  $L_c\sim 1/d$ ), and through spectral filters (monochromators). The coherence length is proportional to the square of the average wavelength divided by the spectral band width,  $L_c\sim\lambda^2/\Delta\lambda$ ; e.g. for white light, with  $\lambda=0.6\ \mu\text{m}$  and  $\Delta\lambda=0.4..0.7\ \mu\text{m}$ ,  $L_c\sim\lambda^2/\Delta\lambda=(0.6\cdot 10^{-6})^2/(0.7\cdot 10^{-6}-0.4\cdot 10^{-6})=1.2\cdot 10^{-6}$  m; for a gas-discharge lamp with a band-pass filter selecting the 589..590 nm interval,  $L_c\sim(0.6\cdot 10^{-6})^2/(0.590\cdot 10^{-6}-0.589\cdot 10^{-6})=0.4\cdot 10^{-3}$  m; for a He-Ne laser with a 0.001 nm bandwidth at 633 nm,  $L_c\sim(0.633\cdot 10^{-6})^2/(10^{-12})=0.4$  m (in practice, a typical He-Ne laser may have a coherence length in excess of 5 m). A monochromatic wave cannot exist in strict sense. The degree of coherence is measured by the visibility of [interference fringes](#).

## SCATTERING AND DIFFRACTION

Scattering, diffraction, and interference, are related terms about directional dispersion of radiation propagating through discontinuities (i.e. in its interaction with material particles or holes in materials), their difference being on the number of elements considered, details to be analysed, and historical tradition

(scattering is usually associated to particles, diffraction is usually associated to holes, and interference is usually associated to the patterns formed).

Nephelometry (from Gr. νεφέλη, cloud) uses a light beam and a detector at right angle, to measure particle size and concentration in the size range  $10^{-8} < d/[m] < 10^{-6}$ .

### Scattering

When EM-radiation interacts with matter, it induces dipolar fluctuations in the atoms, which act as new radiation sources producing the scattering, which, according to the energy transfer, can be:

- Elastic (involving negligible energy transfer):
  - [Rayleigh scattering](#), when size is  $d < \lambda$  (up to  $d = 1.1\lambda$ ). The scattering has a two lobe-shape, axisymmetric and symmetrical to the particle plane, with intensity proportional to  $d^6/\lambda^4$ ; the wavelength dependence means that transparent materials (gases, liquids, or solids) are seen bluish (as the atmosphere in daytime).
  - [Mie scattering](#), when  $d > \lambda$ . The scattering has two unequal lobes, with the upstream smaller than the downstream one, with intensity proportional to  $d^2$  and nearly independent of  $\lambda$ . Mie scattering in colloidal mixtures and suspensions is often named [Tyndall effect](#) (the whitish we can see on a light beam traversing a dark and dusty air space).
  - [Thomson scattering](#). It is due to the interaction of photons with free electrons (the low-energy limit of [Compton scattering](#)). The cosmic microwave background is linearly polarized as a result of Thomson scattering. Electron temperatures and densities in very-hot plasmas can be measured with high accuracy by detecting the effect of Thomson scattering of a high-intensity laser beam.
- Inelastic (involving some energy transfer):
  - [Brillouin scattering](#). It is due to the interaction of photons with acoustic phonons in solids. It is used to measure sound velocities in a material.
  - [Raman scattering](#). It is due to the interaction of photons with [optical phonons](#) in solids. It is used to measure chemical composition and molecular structure.
  - Inelastic X-ray scattering. It is due to the interaction of photons with bounded electrons. This is used to analyse crystal structure, chemical composition, and physical properties of materials and thin films.
  - Compton scattering. It is due to the interaction of photons with free electrons. Compton scattering of X-ray beams can be used in a similar way as normal X-rays when only one side of the sample is available for examination, or when less-invasive examination is required (as in the [full-body scanners](#) in airports where the X-ray backscatter pattern from organic matter is used for imaging; not to be confused with other full-body scanners based on microwaves, or with the X-ray tomography used for luggage inspection).

### Diffraction

Diffraction is the apparent bending of radiation going around obstacles. It was first observed and named (from Lat. diffringere, 'to break into pieces') by Grimaldi around 1650. Diffraction can be explained by the [Huygens-Fresnel principle](#), stating that an advancing wavefront is equivalent to a set of coherent point-

sources. The simplest descriptions of diffraction are those in which the situation can be reduced to a two-dimensional problem. For water waves, this is already the case; water waves propagate only on the surface of the water. For EM radiation we can often neglect one direction if the diffracting object extends in that direction over a distance far greater than the wavelength. A generic [Fresnel-Kirchhoff diffraction equation](#) can be obtained from the wave equation to describe diffraction at any point, but we restrict here the description to the far field ([Fraunhofer diffraction](#) approximation).

When a planar wave passes through a slit of width  $\delta \gg \lambda$ , the rectangular beam develops far downstream (at a distance  $L \gg \delta$ ) into an intensity distribution:  $I(\theta) = I_0 \text{sinc}^2[(\pi\delta/\lambda)\sin\theta]$ , where  $\text{sinc}x \equiv \sin x/x$ , and  $\theta \equiv z/L$  is the angular separation relative to the initial beam direction (see Fig. 5a); i.e. a brilliant band of width  $w = 2\lambda L/\delta$  appears centred at the slit projection, and a set of attenuated light bands at both sides. This effect sets a limit on the angular resolution of optical instruments,  $z/L = \lambda/\delta$ ; e.g. for the human eye in the visible ( $\lambda = 0.5 \cdot 10^{-6}$  m), with  $\delta = 1$  mm aperture lens, the limit of resolution (seeing two points as separated) is  $z/L = 0.5 \cdot 10^{-6}/10^{-3} = 0.5 \cdot 10^{-3}$  rad, i.e. 0.5 mm at 1 m, or 200 m at 400 km, the altitude of the [ISS](#), which is seen as a point because its size is only 100 m). It is also interesting the case of more than one slit separated a distance  $d$  ( $d > \delta$ ); Fig. 5b shows the intensity distribution for a two-slit case.

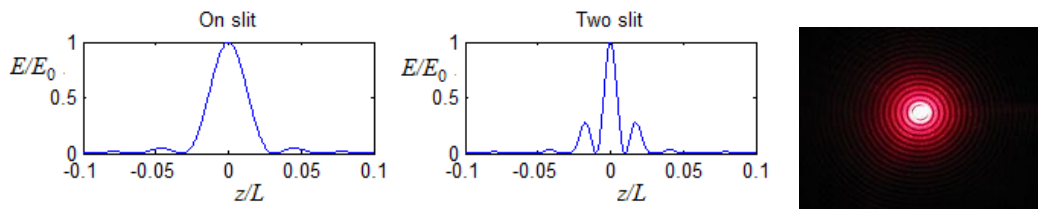


Fig. 5. Diffraction patterns. Relative irradiance versus angular separation ( $z/L$ ). Slit width in this case is  $\delta = 10\lambda$ , and slit separation is  $d = 5\delta$ . a) One slit, b) Two slits, c) One hole ([Wiki](#)).

A diffraction grating is a multi-slit device; as the angular deviation depends on wavelength, the grating acts as a spectral dispersive element (with better resolution than a prism), being commonly used as monochromators in spectrometers.

## INTERFERENCE

[Interference](#) is the superposition of two waves to form a resultant wave of greater or lower amplitude depending on their relative phase, and is related to scattering and diffraction, as above-mentioned. Interference effects can be observed with all types of waves: EM-radiation, acoustic, surface water waves... Each of the two waves must be coherent (i.e. their phase must have a well-defined phase origin), otherwise, the interference pattern would change as the phase origin changes, and interferences could not be detected. It is very easy to create coherent water waves by applying periodic stimuli. Two loudspeakers driven by the same amplifier (in mono, not stereo, with frequencies in the range 0.1..10 kHz) also produce coherent sound waves. But for very-high-frequency waves like light,  $f = c/\lambda = 3 \cdot 10^8 / (0.5 \cdot 10^{-6}) \approx 10^{15}$  Hz, coherence between separate sources is too difficult, and the common way to have coherent waves is to get them from the same source (by beam splitting, either in size or in intensity). Besides, for the interference pattern to be stationary, the two waves must be monochromatic (natural light sources are both non-coherent and polychromatic, and thus interferences in nature only occur when some special circumstances select some wavelengths, split the beam, and make them combine).

The simplest wave model is a planar wavefront propagating along the  $x$ -axis,  $y(x,t)=A\sin(\omega t-kx+\phi)$ , where  $y$  is elongation (for EM-radiations in a perpendicular direction to  $x$ -axis, but for longitudinal waves along the  $x$ -axis),  $A$  the amplitude,  $\omega=2\pi f$  the angular frequency,  $k=2\pi/\lambda$  the wavenumber, and  $\phi$  the phase shift (relative to  $t=x=0$ ). The simplest interference is the superposition of two such planar wavefront with only a phase difference,  $y_1+y_2=A_1\sin(\omega t-kx+\phi_1)+A_2\sin(\omega t-kx+\phi_2)$ ; if the trigonometric relation  $\sin(a+b)=\sin a \cdot \cos b + \cos a \cdot \sin b$  is taken into account, it is easily demonstrated that the result is another planar wavefront propagating along the  $x$ -axis,  $y_3=y_1+y_2=A_3\sin(\omega t-kx+\phi_3)$ , with  $A_3^2=A_1^2+A_2^2+2A_1A_2\cos(\phi_2-\phi_1)$ , and  $\tan\phi_3=(A_1\sin\phi_1+A_2\sin\phi_2)/(A_1\cos\phi_1+A_2\cos\phi_2)$ . Hence, we see that the irradiance  $E$  [ $\text{W}/\text{m}^2$ ] on a screen is not the sum of irradiances but  $E_3 = E_1 + E_2 + 2\sqrt{E_1E_2} \cos(\phi_2 - \phi_1)$ .

A classical interference configuration is the Young's [double-slit](#) experiment, already mentioned above. When two similar wavefronts, generated when a planar wave meets two equal slits of width  $\delta$  separated a distance  $d$  ( $d > \delta$ ), combine on a screen a distant  $L \gg d$  downstream, an interference pattern forms, with bright and dark bands in regular and predictable patterns; the lit fringes are at angular position  $z_{\text{lit}}/L = n\lambda/d$  (with  $n$  integer), and the shaded slits at  $z_{\text{unlit}}/L = (n+1/2)\lambda/d$ . This simple setup is an easy method of experimentally determining the wavelength of a beam of monochromatic light:  $\lambda = d\Delta z/L$ .

Laser doppler velocimetry ([LDV](#)) is also based on the interference of two wavefronts from the same coherent source, in this case intersecting at an angle  $\theta$ . The interference fringe pattern produced is a uniformly-spaced bright and dark bands (Fig. 6), with a separation  $d = \lambda/\sin\theta$ . When some small particles, either naturally occurring or purposely added to a fluid, cross these bands and its reflected light is focused on a photodetector, its frequency  $f$  correlates with the component of the flow speed as  $v = fd = f\lambda/\sin\theta$ .

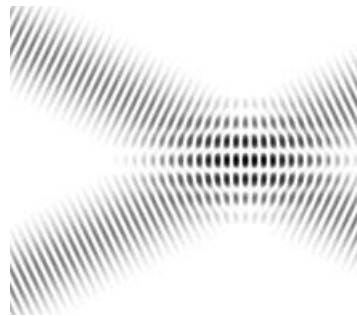


Fig. 6. Interference fringes in overlapping plane waves coming from the left ([Wiki](#)).

Another classical application of interference is the combination of reflections on both sides of thin transparent dielectric layers (much used to measure the smoothness of lenses or mirrors). Several cases are of interest:

- Interference of the first and second reflection in a uniform film of thickness  $\delta$  and refractive index  $n$ , as used for [antireflection coatings](#) on windows and lenses. Assuming normal incidence, the coating material and thickness are selected to procure a phase shift of  $\lambda/2$  between the two reflected waves at the wavelength of interest ( $\lambda$  always refer to propagation in air; within another medium, wavelengths shorten proportionally to refractive index, i.e.  $\lambda = \lambda_0/n$ ); e.g. a  $\delta = 0.1 \mu\text{m}$  thin layer of [MgF<sub>2</sub>](#) ( $n = 1.38$ ) deposited (under vacuum) on glass ( $n > 1.5$ ), produces destructive interference (not complete because the intensity of the second reflection is some 9 % of the first one) on a normal

light beam of  $\lambda=4n\delta=4\cdot 1.38\cdot 10^{-7}=0.55\cdot 10^{-6}$  m (centre of visible band), since the extra  $2\delta$  optical-path length should coincide with  $\lambda/2$  (corrected with the refractive index of the coating); mind that in this case both reflected waves have a  $180^\circ$  phase jump (see Reflection, above). As another example, if a thin film of kerosene ( $n=1.44$ ) on water ( $n=1.33$ ) appears yellow instead of white, the reason may be that its thickness precludes reflection of the blue component ( $\lambda=470$  nm), what happens when  $2\delta=m\lambda/n$ , i.e. for  $\delta=m\lambda/(2n)=m\cdot 470\cdot 10^{-9}/(2\cdot 1.44)=0, 163$  nm, 326 nm... (Notice that, in any case, the border of the film appears black because near  $\delta=0$  all wavelengths have destructive interference).

- Interferences in a variable-thickness layer. Constructive and destructive interference occurs at different thicknesses, and bright or dark fringes correspond to constant-thickness strips (for a given angle of incidence). For instance, if a wedge-like gap of air exists between two glass slides, a normal monochromatic light would produce a pattern of equally spaced light and dark fringes parallel to the vertex (they are known [Fizeau fringes](#)). If the incident light is sunlight the film will have fringes of different colours, as can be seen sometimes on asphalt pavements, particularly when rain dissolves some oily components, and in the beautiful soap bubbles. Fizeau fringes can be used to measure the smoothness of a surface by creating an air gap between it and some very flat reflective surface and shining a monochromatic light on it; e.g. if a thin convex lens sits on top of a very flat solid, a fringe pattern can be seen, dark at the point of contact, and with concentric rings alternating bright and dark outwards, what is known as [Newton's rings](#)); this technique may also be used to measure the radius of curvature of the lens surface (notice that if the flat surface is transparent a complementary fringe pattern is formed by the light transmitted through it).

### [Interferometry](#)

Interferometry makes use of superimposition of a reference and a sampling wave (split from one coherent source) to extract information from the intensity patterns about the optical path and its cause (different length or thickness, changes in refractive index, and so on).

### [Holography](#)

Holography is a technique which enables storage and reconstruction of three-dimensional images; it requires light with long spatial and temporal coherence. The holographic recording itself is not an image but an apparently random structure of interferences (a hologram); it is with the help of a coherent source identical to the reference beam used to record the hologram, that the original waveform is reconstructed, and it can be captured by an image-forming optics (an eye or a camera).

### [TRANSPARENCY](#)

When radiation propagating in vacuum reaches some material, several phenomena occur, first at the incident interface (reflections), and after inside the material (refraction, scattering, and absorption). A material is said transparent if it allows the propagation of radiation without scattering (the direction of propagation follows Snell's law of refraction). If the medium has inhomogeneities of size comparable to the wavelength, then radiation scattering occurs (i.e. non-uniform deviations from a straight trajectory), and the medium is said to be translucent (if not all the intensity is absorbed). Translucent materials scatter so

much the incident radiation (in the waveband considered) that no imaging is possible. Opaque materials absorb or reflect all the radiations in the waveband considered, transmitting nothing across.

Most pure liquids and gases (e.g. water, alcohols), and true solutions (e.g. seawater, distilled oils), are highly transparent in the visible band of the spectrum because they are formed by short-chain molecules of size  $d \ll \lambda$  ( $d \sim 10^{-10}$  m against  $\lambda \sim 10^{-6}$  m) with no larger structure. Liquid and gas suspensions (e.g. milk, juice, clouds), on the contrary, are mostly opaque because they have particles with size similar or larger than the wavelength of light. Absorptance (the fraction of radiation absorbed) dependent on radiation wavelength (when this dependence is negligible in the visual band we say the material is clear-transparent).

There are some transparent solid materials like [glasses](#) (e.g. window glass), plastics (e.g. [methacrylate](#)), and perfect-crystalline minerals (e.g. [sapphire](#)), but most solids are opaque because:

- Common crystalline materials have structural defects (grain boundaries, cracks, voids...).
- Metals are opaque and shiny because the EM radiation strongly interacts with the free-electrons in metals and reflect most of the incoming radiation.
- Most amorphous materials (ceramic, polymers, composites) are opaque because incident photons get quickly absorbed by inelastic scattering in the material. However, transparent ceramics and polymers have large electron band-gaps in their atomic structure that allow the photon to pass through with little interaction.

Living matter is opaque because of the cellular structure. Paper and weaves are also opaque because of their fibre structure; however, they may become translucent when soaked, due to the uniformity caused by water filling the pores.

The apparent [colour](#) of a material depends on the selective absorption or scattering of radiations (the colour we see is the less absorbed).

## MOMENTUM

EM-radiation carries both momentum and angular momentum, what can be imparted in a conservative process to matter with which it interacts. In particular linear momentum yields a [radiation pressure](#),  $p$ , related to irradiance,  $E$ , by  $p=E/c$ . For solar radiation at 1 ua,  $E=1360$  W/m<sup>2</sup> and  $p=E/c=1360/(3 \cdot 10^8)=4.5 \cdot 10^{-6}$  Pa; this pressure-effect has been suggested as a possible future means of space propulsion ([space sailing](#)).

## REFERENCES

- [http://en.wikipedia.org/wiki/Electromagnetic\\_radiation](http://en.wikipedia.org/wiki/Electromagnetic_radiation)
- [http://en.wikipedia.org/wiki/Radio-frequency\\_identification](http://en.wikipedia.org/wiki/Radio-frequency_identification)
- <http://www.lbl.gov/abc/wallchart/outline.html>
- [http://www.who.int/ionizing\\_radiation/env/en/](http://www.who.int/ionizing_radiation/env/en/)
- <http://www.esr.cri.nz/competencies/nrl/faq/Pages/RadiationintheEnvironment.aspx>
- Howell, J.R., Thermal radiation heat transfer, CRC, 2011.

- Fundamentals of Atmospheric Radiation, Craig F. Bohren, Eugene E. Clothiaux, John Wiley & Sons, 2006.

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