Light

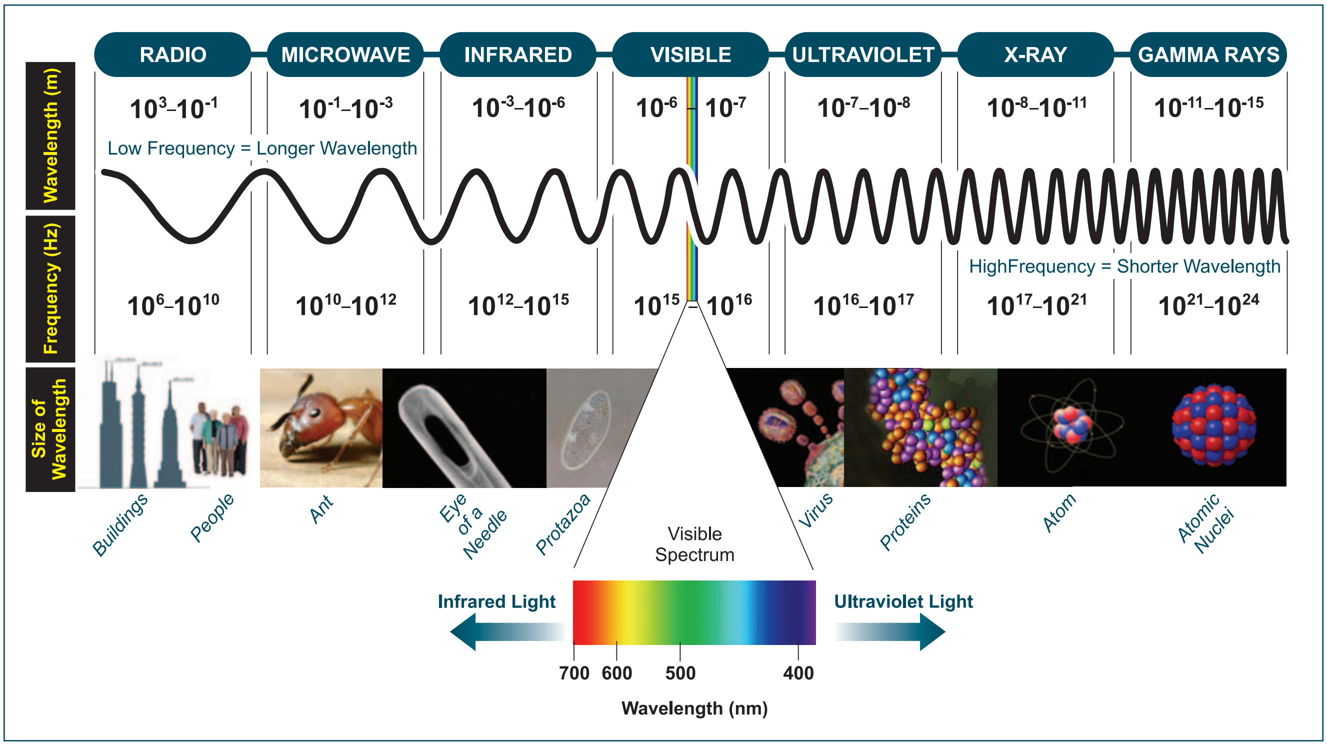

Figure 38 - Electromagnetic Spectrum

Light is part of the electromagnetic spectrum, which ranges from radio waves to gamma rays. Electromagnetic radiation waves, as their names suggest are fluctuations of electric and magnetic fields, which can transport energy from one location to another. Visible light is not inherently different from the other parts of the electromagnetic spectrum with the exception that the human eye has evolved to detect visible waves. Electromagnetic radiation can also be described in terms of a stream of photons which are massless particles each travelling with wavelike properties at the speed of light. A photon is the smallest quantity (quantum) of energy which can be transported and it was the realization that light travelled in discrete quanta that was the origins of Quantum Theory.

It was not by accident that humans evolved to 'see' light. The detection of light is a very powerful tool for probing the universe around us. As light interacts with matter it can be become altered and by studying light that has originated or interacted with matter, many of the properties of that matter can be determined. It is through the study of light that for example we can understand the composition of the stars light years away or watch the processes that occur in the living cell as they happen.

Matter is composed of atoms, ions or molecules and it is light's interaction with matter which gives rise to the various phenomena which can help us understand the nature of matter.

The atoms, ions or molecules have defined energy levels usually associated with energy levels that electrons in the matter can hold. Light can be generated by the matter or a photon of light can interact with the energy levels in a number of ways.

We can represent the energy levels in a diagram known as a Jablonski diagram. An example of one is shown in Figure 39 below.

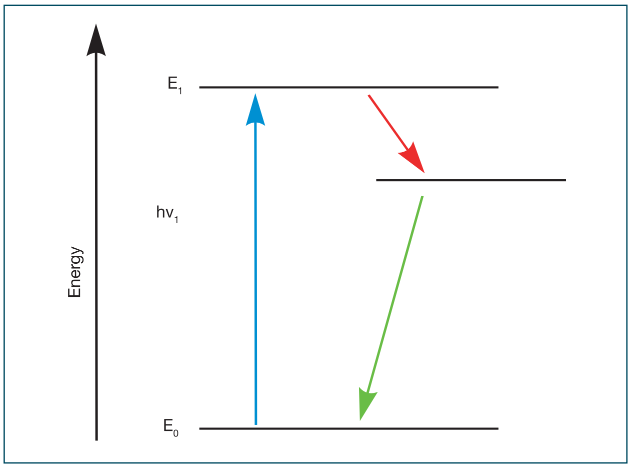

Figure 39 - Jablonski Diagram showing radiative decay

An atom or molecule in the lowest energy state possible known as the ground state can absorb a photon which will allow the atom or molecule to be raised to a higher energy level state or become excited. Hence the matter can absorb light of characteristic wavelengths such as the blue light in Figure 39.

The atom or molecule won't stay in an excited state so it relaxes back to the ground state by in a number of ways. In the simplest way the atom or molecule may re-emit a photon of light of the same energy and effectively the incident photon is scattered. A second way is highlighted in Figure 39 , the atom or molecule emits two photons both of lower energy that the absorbed photon. The photons emitted will be a characteristic energy appropriate for a particular atom or compound and so by studying the light emission the matter under investigation can be determined. A third way is by non radiative decay highlighted in Figure 40 the excited atom or molecule initially loses energy not by emitting a photon but instead relaxes to the lower energy state by internal processes which typically heat up the matter. The intermediate energy level then relaxes to the ground state by the emission of a photon of orange light. .

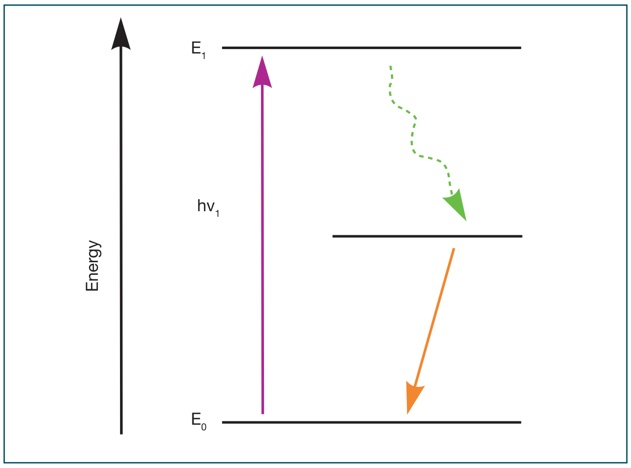

Figure 40 - Jablonski Diagram showing non-radiative decay

Light Emission

Light can be produced by matter which is in an excited state and as it will be shown excitation can come from a variety of sources. The atoms and molecules that make up matter typically emit light at characteristic energies. The light emission can be spontaneous or stimulated. In spontaneous emission matter at a sufficiently high energy level can relax by emitting photons of a characteristic energy, this is the process which occurs in flames, or discharge lamps. Stimulated emission occurs when matter in an excited state is perturbed by a photon of light and gives rise to a further photon of light, typically at the same energy and phase as the perturbing photon. This phenomenon is the process which gives rise to laser emission where you have many photons at the same wavelength and in phase with each other.

A body at a given temperature also emits a characteristic spectrum of light called black body radiation. Consider an electric filament as current is applied to it. As the electric current supplies energy to the filament and it heats up, it starts to glow red, and as it gets hotter it then turns orange and then white. The process underlying this is well understood for a theoretical body known as a 'black body'. Our filament will approximate a black body and as the filament gains energy from the electrical power it tries to equalize its energy with its surroundings by radiating its excess energy. It does this by emitting light starting first in the infrared and as the filament gets hotter or has more energy the radiation moves more into the visible spectrum. The spectral radiance emittance M in W-m-2 nm-1 sr-1 of a black body of Temperature T in Kelvin is given by Planck's Law below

$$M = \frac{2\pi c^2 h}{\lambda^5}\left(\exp\left(\frac{hc}{\lambda kT}\right) -1\right)$$

Where c is the speed of light, h= Planck's constant and K = Boltzmann constant.

The spectral irradiance for artificial sources in general deviate from a perfect black body radiation but the approximation is useful in many applications and by measuring the spectral output of a heated body it's temperature can be remotely measured. For example Sunlight is due to the black body radiation characteristic of a body at approximately 5,800K.

See Figure 41 below

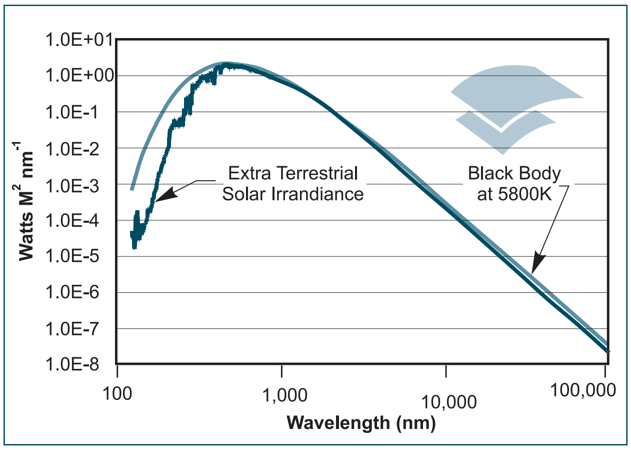

Figure 41 - Theoretical black body at 5,800K versus solar radiation

Introduction

The source of the excitation to produce light emission can come from a variety of sources. The table shown provides some of the sources and examples where they can be used.

Excitation Sources

Name	Excitation source	Examples of use
Chemiluminescence	Chemical reactions	Emergency lighting
Cathodeluminescence	Electron beam	Electron beam
Sonoluminescence	Sound energy	Possible chemical reactions
Triboluminescence	Friction energy	Gives rise to light emission seen when opening gum labels in the dark
Bioluminescence	Biological processes	Light emission seen from Fireflies or some jellyfish
Thermoluminescence	Heat energy	Used for Archaeological dating
Electroluminescence	Electric Voltage	Source of light seen in Led's
Photoluminescence	Photons of Light	Fluorescence markers

Light can also be produced by the acceleration of a free charged particle, such as an electron. The light emission is known as Bremsstrahlung or 'braking radiation'. The emission is characteristically seen in X-ray emission tubes which work by accelerating electrons with a high voltage and then by decelerating them very fast by directing them onto a metal target. A special variety of particle accelerators known as Synchrotrons can be used to generate a wide range of light frequencies of very high power for use in the study of matter. A related effect is Cherenkov radiation which occurs when charged particles move through a medium faster than the speed of light in the medium. This produces the characteristic blue light seen in water ponds containing nuclear fuel.

Light Absorption

In absorption, the frequency of the incoming light wave is at or near the energy levels of the electrons in the matter. The electrons will absorb the energy of the light wave and change their energy state. There are several options as what can happen next, either the electron returns to the ground state emitting the photon of light or the energy is retained by the matter and the light is absorbed. If the photon is immediately re-emitted the photon is effectively reflected or scattered. If the photon energy is absorbed the energy from the photon typically manifests itself as heating the matter up.

The absorption of light makes an object dark or opaque to the wavelengths or colours of the incoming wave. Wood is opaque to visible light. Some materials are opaque to some wavelengths of light, but transparent to others. Glass and water are opaque to ultraviolet light, but transparent to visible light. By which wavelengths of light are absorbed by a material the material composition and properties can be understood.

Another manner that the absorption of light is apparent is by their color. If a material or matter absorbs light of certain wavelengths or colors of the spectrum, an observer will not see these colors in the reflected light. On the other hand if certain wavelengths of colors are reflected from the material, an observer will see them and see the material in those colours. For example, the leaves of green plants contain a pigment called chlorophyll, which absorbs the blue and red colours of the spectrum and reflects the green. Leaves therefore appear green.

Light Scattering

Materials can also be investigated examining the light scattered from a material. There are many forms of scattering but the principal ones are as follows;

Rayleigh

Rayleigh is elastic scattering from small particles such as atoms or molecules, resulting in scattered radiation that occurs in all directions uniformly. Rayleigh scattering is wavelength dependent with shorter wavelengths being more scattered. It is Raleigh scattering from molecules in the atmosphere which gives rise to the blue sky we see on a fine day. The blue light from the sun striking the upper atmosphere is scattered approximately 10 times more than red light so overhead the blue light is scattered into the eye of an observer while the red light goes largely unscattered and back out into space.

Debye or Mie

Debye or Mie is an elastic scattering mechanism which occurs from relatively large particles or molecules with dimensions comparable with the wavelength of the incident radiation or larger and the resulting scattered radiation is non-uniform. The effect is not very wavelength dependent. This process gives rise to the white scattered light seen in clouds or fog.

Brillouin

Brillouin Scattering is an inelastic scattering mechanism which typically occurs in light scattering from solid materials. The incident radiation wavelength is modified by the energy levels of sound waves or Phonons in the solid material which is typically very small shifts.

Raman

Raman is an inelastic scattering mechanism where the frequency of the scattered radiation is changed by the gain or loss of energy which corresponds to energy levels in an atom or molecule. The process is used for many forms of diagnostic analysis. Raman scattering is very weak and is typically much smaller than the Rayleigh scattered light so great care must be taken extract the Raman signal from the Rayleigh signal, particularly for small frequency shifts. For detail see the Raman application notes in the Chemistry section.

Thompson & Compton

Thompson scattering is an elastic scattering mechanism where light is scattered by charged particles. A comparable form of scattering called Compton scattering is an inelastic form of Thompson scattering which occurs when the energy of the incident radiation starts to become comparable to the rest energy of the charged particle. Compton scattering is the main attenuation mechanism of x-rays that provides the contrast in medical x-ray photographs.

Radiometry & Photometry

Radiometry is the science of measuring light in any portion of the electromagnetic spectrum. In practice, the term is usually limited to the measurement of infrared, visible, and ultraviolet light using optical instruments. Irradiance is the intensity of light and is measured in watts per square metre.

Photometry is the science of measuring visible light in units that are weighted according to the sensitivity of the human eye. It is a quantitative science based on a statistical model of the human visual response to light - that is, our perception of light - under carefully controlled conditions. The photometric equivalent of Radiance is called Illuminance and is measured in Lumens per square metre (Lux).

The human visual system responds to the light in the electromagnetic spectrum with wavelengths ranging from 380 to 770 nanometers (nm). We see light of different wavelengths as a continuum of colors ranging through the visible spectrum: 650 nm is red, 540 nm is green, 450 nm is blue, and so on.

The sensitivity of the human eye to light varies with wavelength. A light source with an irradiance of one Watt/m^2 of green light, for example, appears much brighter than the same source with an irradiance of one Watt/m^2 of red or blue light. In photometry, we do not measure Watts of radiant energy. Rather, we attempt to measure the subjective impression produced by stimulating the human eye-brain visual system with radiant energy.

This task is complicated immensely by the eye's nonlinear response to light. It varies not only with wavelength but also with the amount of radiant flux, whether the light is constant or flickering, the spatial complexity of the scene being perceived, the adaptation of the iris and retina, the psychological and physiological state of the observer, and a host of other variables.

Nevertheless, the subjective impression of seeing can be quantified for "normal" viewing conditions. In 1924, the Commission Internationale d'Eclairage (International Commission on Illumination, or CIE) asked over one hundred observers to visually match the "brightness" of monochromatic light sources with different wavelengths under controlled conditions. Taking an average of the measurements results in the so called Photopic response of the perceived 'average' human observer is shown in Figure 42 below.

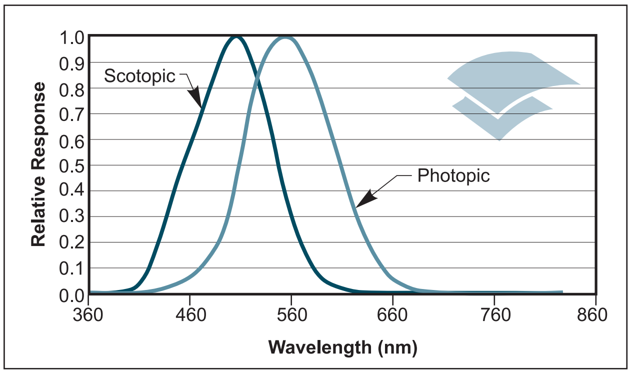

Figure 42 - Photopic and Scotopic Response

The curve on the left shows the response to low levels of light. The shift in sensitivity occurs because two types of photoreceptors, cones and rods, are responsible for the eye's response to light. The curve on the right shows the eye's response under normal lighting conditions and this is called the Photopic response. The cones respond to light under these conditions and they are also responsible for human color perception.

ANDOR™
TECHNOLOGY

The curve on the left shows the eyes response to low levels of light and is called the Scotopic response. At low level of light, the rods are most active and the human eye is more sensitive to any amount of light that is present, but is less sensitive to the range of color. Rods are highly sensitive to light but are comprised of a single photo pigment, which accounts for the loss in ability to discriminate color.

Conversion from Radiometric to Photometric Units

The conversion between photometric units which take into account human physiology and straight radiometric units is given by the following:

(photometric unit) = (radiometric unit) x (683) x V(λ),

where V(λ) is the 'Photopic Response,' shown earlier and basically tells us how efficiently the eye picks up certain wavelengths of light. The Photopic response is a function of the wavelength of light and so to convert from radiometric units to photometric units first requires knowledge of the light source If the source is specified as having a certain color temperature we can assume that its spectral radiance emittance is the same as a perfect black body radiator and use Planck's law defined earlier.

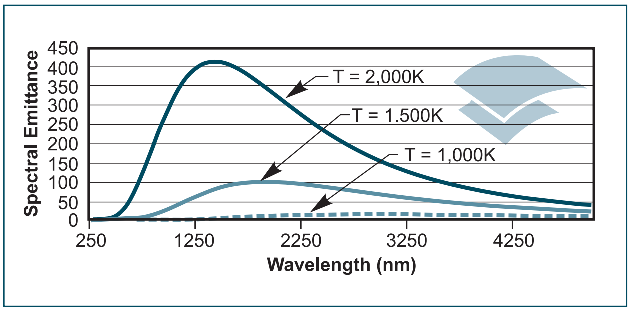

Figure 43 - black body radiation curves at different temperatures

Artificial sources in general do not have the same spectral distribution as a perfect black body but for our purposes we shall consider them equal. Figure 43 depicts the spectral radiance of several black body radiators.

If we consider the Photopic evaluation of a black body radiation at a temperature of T=2045K

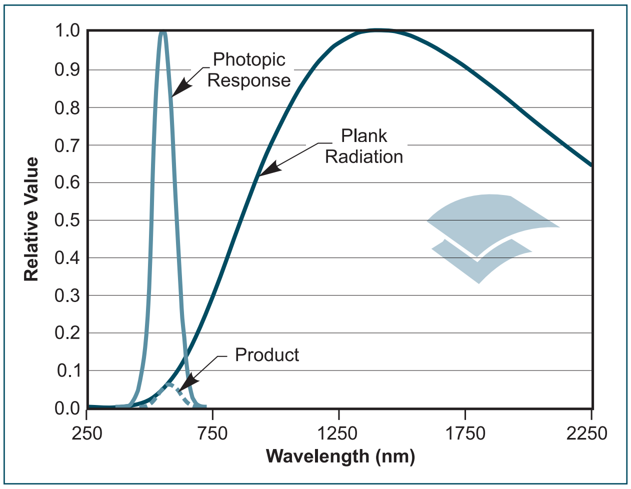

Figure 44a - Photopic evaluation of a black body radiation at T=2,045K

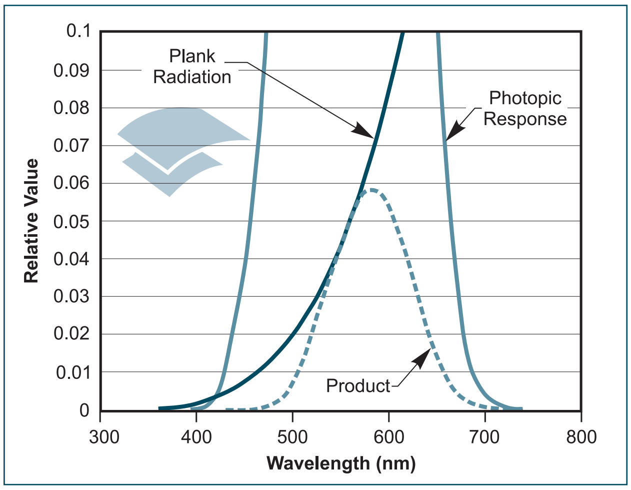

Figure 44b - Enlargment of Photopic evaluation of a Black Body radiation at T=2,045K

Integration of the product of the light emittance by the Photopic function provides the conversion from a Radiometric signal to a Photometric.