The substance of light

by Dr Derek Pilgrim

LIGHT is a form of radiant energy. The velocity, *c*, of all electromagnetic waves is 2.998×10^8 ms^{-1} ms^{-1} *in vacuo*, (approximately 186,000 miles (300,000 km) per second, equivalent to encircling the earth about 7 times in one second). For all practical purposes it is the same in air. In other media it is: *c* x *n* where *n* is the refractive index, (the refractive index, *n*, is discussed in greater detail in the article *Refraction in water* in this series). In water, it is approximately:

$$c \times 3/4 = 2.25 \times 10^8 \text{ ms}^{-1}$$

Light is produced by, and propagated from, a luminous source, and the nature of this outward propagation of energy may be described and explained by two apparently disparate theories.

The dual nature of light

The two models used to describe the behavior of light are:

- the wave model, and
- the photon model

In fact these two models are entirely compatible and each is useful as a means of explaining particular optical phenomena. For example, it is through the wave model that we best understand such optical mechanisms as refraction and diffraction, and are able to describe the nature of colour. The photon model, however, is more appropriate when dealing with energetic photochemical processes such as photosynthesis

The wave model

In 1873 James Clark Maxwell (1831-1878) unified the known laws of electricity and magnetism into a single theory of electromagnetism. Fundamental to this theory is the existence of electromagnetic (*e-m*) waves, X-rays, visible light and radio waves, comprising electric and magnetic fields propagating as plane waveforms at right angles to each other, *(see Fig.1)*. Radiation, including light, may therefore be treated as a sinusoidal wave with a frequency, *v,* wavelength, λ , and velocity, *c*, related by:

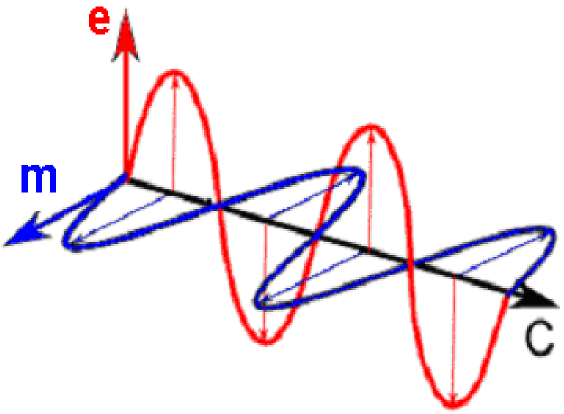

Fig.1 The e-m wave

$$c = \nu . \lambda \qquad \textit{(eqn.1)}$$

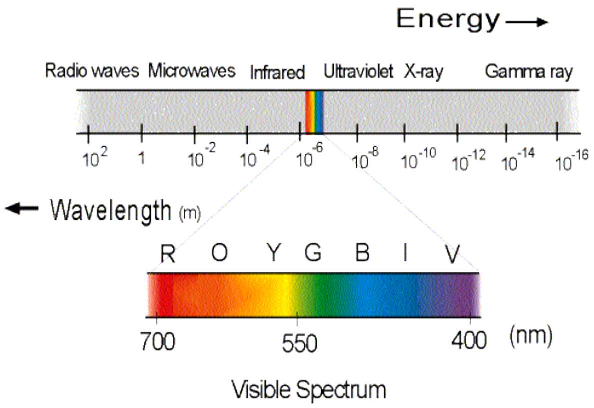

Fig.2 The visible spectrum

The spectrum of e-m radiation from 10^{-16} to 10^2 m is illustrated in *Fig.1.* The spectrum of visible light occupies an extremely small part of the total e-m spectrum. It will also be seen that different wavelengths within the visible spectrum are perceived as different colours, and that the longest wavelength (deep red, λ= 700 nm) is only about double that of the shortest (deep violet, λ = 350 nm). A halving of wavelength (or doubling of frequency) is equivalent to one octave in acoustics; it is therefore interesting to note that the whole spectrum of colour perceived by the human eye is contained within a bandwidth equivalent to just one octave in music!

The photon model

The great 17th century English physicist Isaac Newton (1642-1727) is credited with the discovery of much of what we understand about light and colour today; it was he, for example, who first split white light into its component colours *and then recombined these colours into white*. However, Isaac Newton did not perceive light in terms of waves, but as corpuscules, minute particles shot out by the luminous source. For example, Newton believed that these corpuscules were somehow deflected by a prism according to their size; the larger red ones being subjected to least deflection, and the smallest blue ones to the most. It is interesting to note, however, that Newton’s unlikely corpuscular theory came very close indeed to the modern photon model of light propagation as proposed by Max Planck (1858-1929). Consider the absorption of light by an atom. In an atom, electrons swarm around a core nucleus, those orbiting furthest from the nucleus possessing more energy than those orbiting closest. According to the quantum theory the electrons can have only certain energy levels so that *only certain orbitals are possible*, (see *Fig.3*). When light energy is absorbed, electrons are ‘excited’ to a higher orbital but the consequent increase in atomic energy is clearly quantisised since electrons must be promoted to particular orbitals; *they can not take up positions between orbitals.* When light energy is absorbed, electrons are 'excited' to a higher orbital but the consequent increase in atomic energy is clearly quantisised since electrons must be promoted to particular orbitals; they can not take up positions between orbitals. If sufficient energy is available to, say, raise an electron to beyond the next orbital but not to the orbital beyond that, then the electron will move only to the next orbital and one quantum of energy will be absorbed. This may be likened to the discrete increases in potential energy that would result from moving a mass from step to step up a staircase, (though in the atom, the steps – orbitals – are not evenly spaced). Of course, a molecule has a number of electronic energy levels associated with its component atoms; it also has quantisised vibrational and rotational energy levels. Vibrational energylevels are associated with oscillations in atom-atom bond distances; one may imagine atoms joined together by vibrating springs. Rotational energy levels arise from the energy involved in the rotation of molecules in space.

The *quantum* is defined as the smallest amount of energy by which the energy of a system may be changed. The *photon* is, simply, a quantum of light energy.

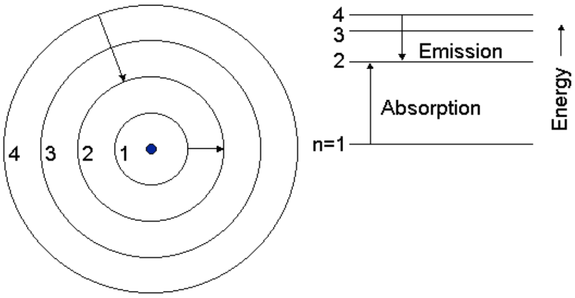

Fig.3 The quantum nature of light in absorption and emission in an atom

The energy, *e*, in one photon is expressedby:

$$e = h.\nu = \frac{h.c}{\lambda} \qquad \textit{(eqn.2)}$$

where h = *Planck's constant* = 6.626×10^{-34} *Js*
ν = *frequency* $[s^{-1}]$

Since the energy transition between any two levels involves the absorption of a simple photon then it follows that different transitions involve the absorption of photons of different energy content and hence, from e*qn.2*, *different frequencies*. That is to say that the particular configuration of electronic-vibrational-rotational energy levels for any particular molecule will preferentially absorb particular wavelengths or bands of wavelengths, *i.e. colours*.

This is, essentially, the connection between the wave and photon models: *the energy* *content of a photon is frequency dependent*. The two models are illustrated pictorially in *Fig.4*, in which the size of the photons (amplitude of the waves) indicate their relative energy content whilst the wavelength indicates colour. The blue photons comprise waves of highest amplitude and shortest wavelength, whilst the red photons comprise waves of lowest amplitude and longest wavelength. Clearly this is reminiscent of Newton's corpuscules!

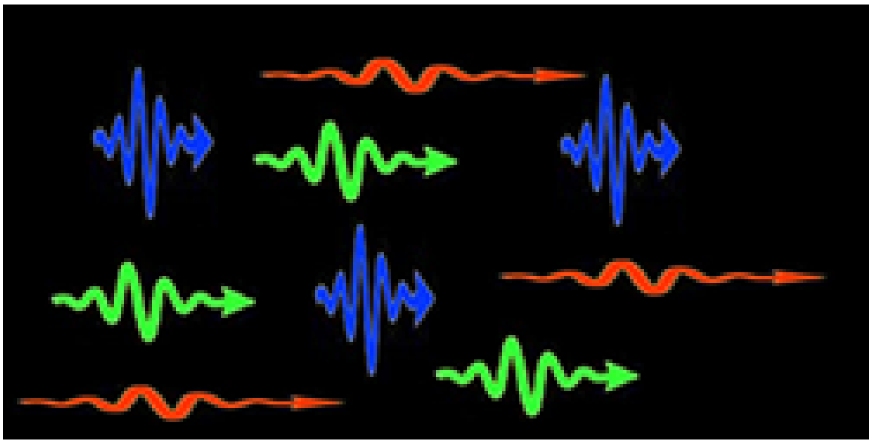

Fig.4 The two models of light propagation

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