Light, Atoms, the Electromagnetic Spectrum

Light

What is light? From the time of Issac Newton (1642 - 1727) to the beginning of the 20th century the fundamental nature of light was a topic of hot debate among scientists. Newton proposed in his book *Opticks*, published in 1704, that light consisted of a stream of particles. This was known as the *corpuscular* theory of light, and with it Newton was able to explain many common phenomena involving light such as reflection and refraction. Most scientists of this period accepted the corpuscular theory, both because it seemed to explain known phenomena and because Newton was its architect. During Newton's lifetime, however, Dutch physicist and astronomer, Christian Huygens[1] (1629 - 1695), proposed an alternative theory that also explained reflection and refraction. In Huygen's theory light consisted of waves. Wave theory was also useful in explaining a phenomenon known as *diffraction*, or the bending of light around sharp edges. In spite of its successes, Huygen's theory did not receive wide acceptance. All waves known to scientists at the time (sound, water, etc.) traveled through a medium of some sort. Light, on the other hand, travels to us from the sun, moon and stars through the vacuum of space.

In 1801, Thomas Young conducted an experiment that demonstrated another phenomena that could only be explained by the wave theory of light, that of *interference*. Interference occurs when light waves combine in such a manner that they either add together to form a bigger wave or cancel each other out. Figure 1 shows the case of both *constructive* and *destructive* interference. In constructive interference identical light waves that are *in phase* with (i.e., the crests and troughs of each wave correspond with the other) add in such a manner that the combined wave has an *amplitude* (A) that is twice that of either individual light wave. In destructive interference waves that are exactly out of phase (i.e., the crest of one wave corresponds with the trough of the other) cancel each other out when added together. Such behavior could not be explained by the corpuscular theory since at the time no known mechanism could explain how particles could combine so as to cancel each other out. Later work by Maxwell demonstrated that light was actually a high frequency electromagnetic wave (like radio or television waves) that traveled through space with a speed of 3×10^8 m/s. By the dawn of the 20th century, the wave theory of light was firmly entrenched in scientific dogma.

- *interference* – combining light waves or any e/m wave together in such a manner as to cause either constructive (bright) or destructive (dark) patterns to result
- *diffraction* – bending of light or any e/m waves as they pass through narrow openings or around sharp corners
- *refraction* – the change of speed and direction that occurs when light goes from one medium to another.
- *scattering* – what happens, in general, when light or any e/m waves interact with matter.
- *reflection* - a form of scattering that may be described with a simple geometric relationship, i.e. angle of incidence equals angle of reflection.

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[1] Christian Huygens chief accomplishment as a physicist was the wave theory of light. As an astronomer, Huygens was the first to recognize the rings of Saturn (1655) and discovered Titan, a moon of Saturn.

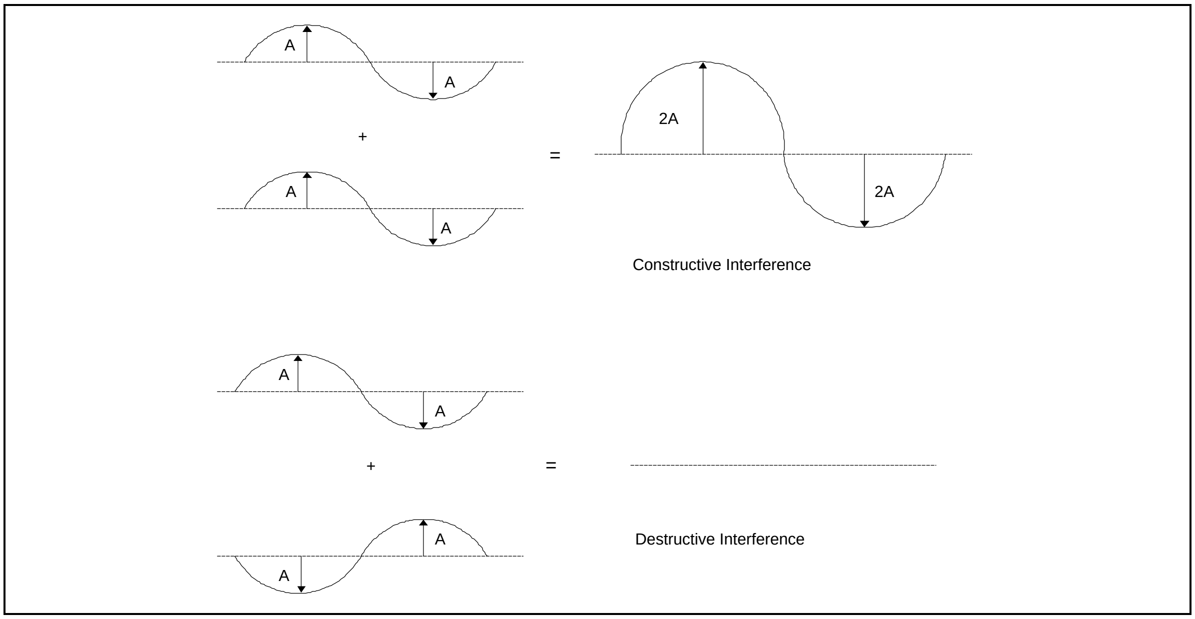

Figure 1. Interference in waves.

As resounding as the evidence for the wave behavior of light was, there were still experiments that gave results that could not be explained by the wave theory. One such result is the *photoelectric effect*. The photoelectric effect is a phenomenon whereby electrons are ejected from a metallic surface that has been exposed to light. This phenomenon cannot be reasonably explained with the wave theory.

An explanation of the photoelectric effect was proposed by Albert Einstein in 1905. Einstein, drawing upon the earlier work of Max Planck (1858 - 1947) proposed that light was composed of discrete bundles of energy called *photons* and that the energy (E) of each photon was proportional to the frequency (f) of the light wave: $\boldsymbol{E = hf}$, where $h = 6.63 \times 10^{-34}$ J · s is *Planck's constant*. Notice that Einstein's explanation of the photoelectric effect contains elements of both the particle (energy of a single photon) and wave (frequency) theories of light.

This is the essential nature of light. At times it exhibits particle-like properties and at other times it exhibits wave-like properties. The best answer to the puzzle "What is light?" is that it is both particles and waves: sometimes the particle properties dominate and sometimes the wave properties dominate.

For most purposes we may assume that the wave properties of light dominate. The wavelength of light (λ) is related to its color. In the visible spectrum which extends from approximately 400 - 700 *nanometers* (a nanometer is 10^{-9} meters), longer wavelengths correspond to red and orange and shorter wavelengths correspond to violet and blue. When all of the colors of the visible electromagnetic spectrum are combined the result is white light. You have probably heard about *ultraviolet* light and its associated dangers in relationship to the depletion of the earth's ozone layer. This is light with wavelengths in the 100 to 400 nanometer range. Wavelengths from 1 millimeter to 10 microns (10^{-3} to 10^{-7} meters) are known as *infrared* light.

The frequency of a light wave (*f*) is equal to the speed of light (*c*) divided by its wavelength (λ): ***f* = *c*/λ.** Since the speed of light in free space is constant (c = 3 x 10^8 m/s) the longer the wavelength the lower the frequency. All visible light waves have frequencies of around 10^{15} Hz.

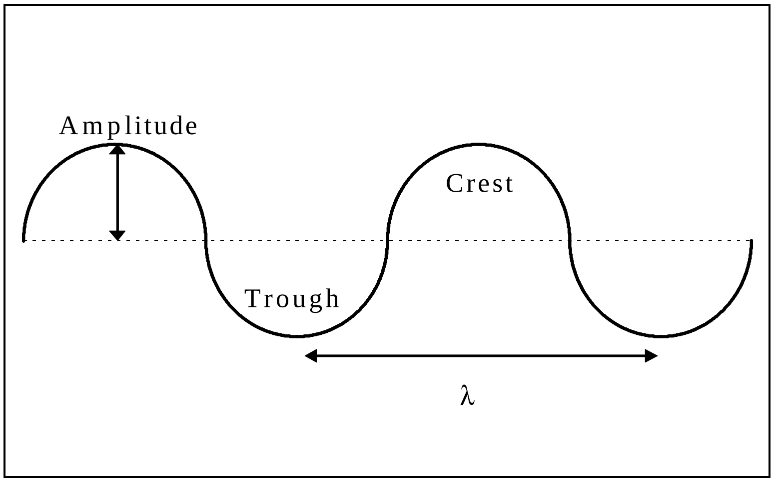

Figure 2. Characteristics of a light wave.

Spectroscopy

Spectroscopy is an extremely useful analytic technique that involves analyzing the light given off by an object. All objects emit electromagnetic radiation. If the object is hot enough this radiation is in the visible region. A spectrometer is a device that uses diffraction and interference to separate the light given off from an object into different colored lines known as a spectrum. Each spectral line corresponds to light of a different wavelength. Every element in the universe (e.g. Hydrogen, Helium, etc.) has a unique spectrum. By carefully analyzing the spectra given off by an object such as a star, one may gain insight as to its composition.

Let us consider the various types of spectra and their origin. There are three types of spectra: (1) bright line or emission line spectra, (2) continuous spectra, (3) dark line or absorption line spectra.

A bright line or emission spectra is produced by a low-density glowing gas which radiates energy at specific wavelengths characteristic of the element or elements that make up the gas. The spectrum consists of a number of bright lines against a dark background. Each bright line has a color that represents a specific wavelength.

A continuous spectrum is produced by a solid, liquid or dense gas. The spectrum appears as a smooth transition of all colors in the visible spectrum from the shortest or the longest wavelength without any gaps between the colors.

A dark line or absorption spectrum is produced when a cooler gas absorbs specific wavelengths of light passing through it. The wavelengths absorbed are determined by the elements that compose the gas. Since no two elements absorb the exact same wavelengths, it is possible to determine the elemental composition of the gas by examining the spectra. A dark line or absorption spectrum appears as a continuous spectrum of all colors with a number of dark lines through it. The K and H lines in the solar spectrum, for instance, are due to ionized calcium in the outer layers of the sun's atmosphere. If the dark lines are closely spaced in some parts the clumps of dark lines are known as bands.

Wien's Law

All objects emit some electromagnetic radiation. When objects are heated to any temperature above absolute zero they emit a spectrum of wavelengths but emit most strongly in a narrow region of wavelengths closely associated with a particular temperature. When this radiation is in the visible region the relationship between intensity, temperature and color is known as Wien's Law and says, essentially, that hotter objects emit more strongly in the shorter wavelength region. Wien's law applies perfectly only to a class of objects known as *blackbodies*.

Blackbodies

A blackbody is any object that is 100% efficient at absorbing all of the electromagnetic radiation that falls on it. Because such an object reflects no light it appears to be black (unless it is heated), hence the *Nom de Guerre*. When blackbodies get hot, either through efficiently absorbing radiation or other external means they are also very efficient radiators of energy. Most blackbodies are high-density materials such as solids.

There are very few *perfect* blackbodies, but many objects are close enough that we may assume that they are essentially blackbody radiators. Under this assumption Wien's law may be applied to a variety of objects without significant error.

When an object is a selective absorber and emitter of electromagnetic radiation it obeys Kirchoff's Laws.

Origin of E/M Radiation

Visible, ultraviolet and infrared light originates from electronic transitions in atoms. Gamma rays originate from similar events in the nuclei of atoms. X rays may form in any of several ways but most commonly from the rapid acceleration of atoms. At the other end of the spectrum, radio waves result from the oscillations of large numbers of charged particles.

Doppler Shift

Any relative motion between an observer and a source of light or any form of e/m radiation results in a *Doppler Shift*, i.e., a shifting of spectral lines toward either shorter or longer wavelengths. Objects moving towards an observer undergo a blue shift and objects moving away from an observer undergo a red shift.