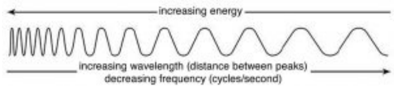
2.1: Light and Getting Quantum Mechanical

While Rutherford and his colleagues worked on the nature of atoms, other scientists were making significant progress in understanding the nature of electromagnetic radiation, that is, light. Historically, there had been a long controversy about the nature of light, with one side arguing that light is a type of wave, like sound or water waves, traveling through a medium like air or the surface of water and the other side taking the position that light is composed of particles. Isaac Newton called them corpuscles. There was compelling evidence to support both points of view, which seemed to be mutually exclusive, and the attempt to reconcile these observations into a single model proved difficult.



By the end of the 1800s, most scientists had come to accept a wave model for light because it better explained behaviors such as interference[2] and diffraction,[3] the phenomena that gives rise to patterns when waves pass through or around objects that are of similar size to the wave itself. James Clerk Maxwell (1831–1879) developed the electromagnetic theory of light, in which visible light and other forms of radiation, such as microwaves, radio waves, X-rays, and gamma rays, were viewed in terms of perpendicular electric and magnetic fields. A light wave can be described by defining its frequency (ν) and its wavelength (λ). For all waves, the frequency times its wavelength equals the velocity of the wave. In the case of electromagnetic waves, $\lambda\nu = c$, where c is the velocity of light.

Although the wave theory explained many of the properties of light, it did not explain them all. Two types of experiments in particular gave results that did not appear to be compatible with the wave theory. The first arose during investigations by the German physicist Max Planck (1858–1947) of what is known as black body radiation. In these studies, an object heated to a particular temperature emits radiation. Consider your own body, which typically has a temperature of approximately $98.6^{\circ}\mathrm{F}$ or $36^{\circ}\mathrm{C}$. Your body emits infrared radiation that can be detected by some cameras.[4] Some animals, like snakes, have infrared detectors that enable them to locate their prey—typically small, warm-blooded, infrared-light-emitting mammals.[5] Because mammals tend to be warmer than their surroundings, infrared vision can be used to find them in the dark or when they are camouflaged.

Planck had been commissioned by an electric power company to produce a light bulb that emitted the maximum amount of light using the minimum amount of energy. In the course of this project he studied how the color of the light emitted (a function of its wavelength) changed as a function of an object's (such as a light bulb filament) temperature. We can write this relationship as $\lambda\,(\mathrm{wavelength}) = f(t)$ where $t =$ temperature and f indicates "function of." To fit his data Planck had to invoke a rather strange and non-intuitive idea, namely that matter absorbs and emits energy only in discrete chunks, which he called quanta. These quanta occurred in multiples of $E\,(\mathrm{energy}) = h\nu$, where h is a constant, now known as Planck's constant, and ν is the frequency of light. Planck's constant is considered one of the fundamental numbers that describes our universe.[6] The physics that uses the idea of quanta is known as quantum mechanics.

One problem with Planck's model, however, is that it disagreed with predictions of classical physics; in fact as the frequency of the light increased, his measurements diverged more and more from the predictions of the then current, wave-based theory.[7] This divergence between classical theory and observation became known, perhaps over-dramatically, as the ultraviolet catastrophe. It was a catastrophe for the conventional theory because there was no obvious way to modify classical theories to explain Planck's observations; this was important because Planck's observations were reproducible and accurate. Once again, we see an example of the rules of science: a reproducible discrepancy, even if it seems minor, must be addressed or the theory must be considered either incomplete or just plain wrong.

The idea that atoms emit and absorb energy only in discrete packets is one of the most profound and revolutionary discoveries in all of science, and set the stage for a radical rethinking of the behavior of energy and matter on the atomic and subatomic scales. Planck himself proposed the idea with great reluctance and spent a great deal of time trying to reconcile it with classical theories of light. In the next section we will see how this property can be used to identify specific types of atoms, both in the laboratory and in outer space.

Questions

Questions to Answer

- What is a constant? What is a function?
- What happens to the energy of a photon of light as the frequency increases? What about as the wavelength increases? (remember: $\lambda\nu = c$)
- Why is it difficult to detect cold-blooded animals using infrared detectors?

Questions to Ponder

- How can the phenomena of diffraction and interference be used as evidence that light behaves like it a wave?
- How can light be both a wave and a particle?
- Is light energy?
