15.6: An Alternate View of Electromagnetic Energy

Physicists soon realized that there were problems with the electromagnetic wave model. While it explained many phenomena such as radio communication, RADAR and large scale energy transfers, there were problems. The relationship between temperature and the color of the light that was emitted by the object didn't match what the models predicted. Different physicists worked on this problem, but couldn't resolve the issue. Some were able to create a model that matched the long wavelength data, but failed to match the short wavelength data. Others were able to match the short wavelengths, but not the long. This problem became known as the *Ultraviolet Catastrophe*. Since the models predicted that all waves should get shorter and shorter then all red light should becomes ultraviolet. Since this clearly did not happen, it pointed out that there was something fundamental that physicists did not understand about how electromagnetic energy behaved.

Planck's Hypothesis

In 1900, Max Planck decided to tackle the problem. He used almost the same approach as the others before him, treating waves as the result of charges performing simple harmonic motion. If you recall the section on transverse waves, we showed that the kinetic energy of a mass-spring system depended on the oscillation frequency. Planck added his own innovation and proposed that the charges could only oscillate at certain fixed frequencies. This meant that each oscillating charge could only have certain energy values. That meant that those oscillating charges could only change their energy by fixed amounts. This goes completely against the Newtonian model which says that masses can oscillate at any frequency, and can change their energy by any amount.

Planck's hypothesis of discrete energies (which he called *quanta*) meant that the oscillating charges had *quantized energies*. A particular oscillator could only oscillate in certain ways, though there might be a large number of allowed ways to oscillate. We choose 'n' to list the allowed energies. n = 1 is the first allowed oscillation energy and n = 5 is the fifth allowed energy. We say the oscillator is in a different *energy state* for each value of n. n = 1 is the first energy state, and n = 5 is the fifth energy state. n is called the *quantum number*. Planck's hypothesis is written as:

$$E_n = nhf \; (n = 1,2,3,4...)$$

If this model were true, then the oscillator could only change its energy in multiples of hf, where f is the oscillator frequency and h is a proportionality constant called Planck's Constant. $h = 6.626 \times 10^{-34}$ Joule-seconds = 4.136×10^{-15} electron-Volt-seconds. An oscillator in the n = 2 state would have energy of 2hf.

The model predicts that an oscillating charge (representing an atom in some material) can absorb energy from an incoming electromagnetic wave, but the amount of energy absorbed must be a multiple of hf. By absorbing energy of 3hf, the oscillating charge would move from the n = 2 state to the n = 5 state. If the absorbed energy were to be 3.25hf, the oscillator would 'ignore' the wave and not absorb **any** energy. The oscillator could also emit energy, as long as it was a multiple of hf. The n = 5 oscillator could emit 2hf worth of energy and become an n = 3 oscillator with energy of 3hf.

Planck was able to use this hypothesis to construct a model that exactly followed the experimental relationship between the temperature and the color (electromagnetic wavelength) of the hot object. Planck was also able to show that the Wien Law followed from his hypothesis, as well as another experimental relationship called Stefan's Law, which related the energy emitted by stars and their temperature.

Because this idea went against everything that physicists believed to be true about the way that energy is transferred between objects, even Planck himself did not fully believe that energy behaved this way. He considered quantization a mathematical trick that happened to produce a model that fit well with the experimental evidence. It would be the work of Albert Einstein that lifted this idea to prominence.