27-1 Planck Solves the Ultraviolet Catastrophe

By the end of the 19th century, most physicists were confident that the world was well understood. Aside from a few nagging questions, everything seemed to be explainable in terms of basic physics such as Newton's laws of motion and Maxwell's equations regarding electricity, magnetism, and light. This confidence was soon to be shaken, however.

One of the nagging questions at the time concerned the spectrum of radiation emitted by a so-called ***black body***. A perfect black body is an object that absorbs all radiation that is incident on it. Perfect absorbers are also perfect emitters of radiation, in the sense that heating the black body to a particular temperature causes the black body to emit radiation with a spectrum that is characteristic of that temperature. Examples of black bodies include the Sun and other stars, light-bulb filaments, and the element in a toaster. The colors of these objects correspond to the temperature of the object. Examples of the spectra emitted by objects at particular temperatures are shown in Figure 27.1.

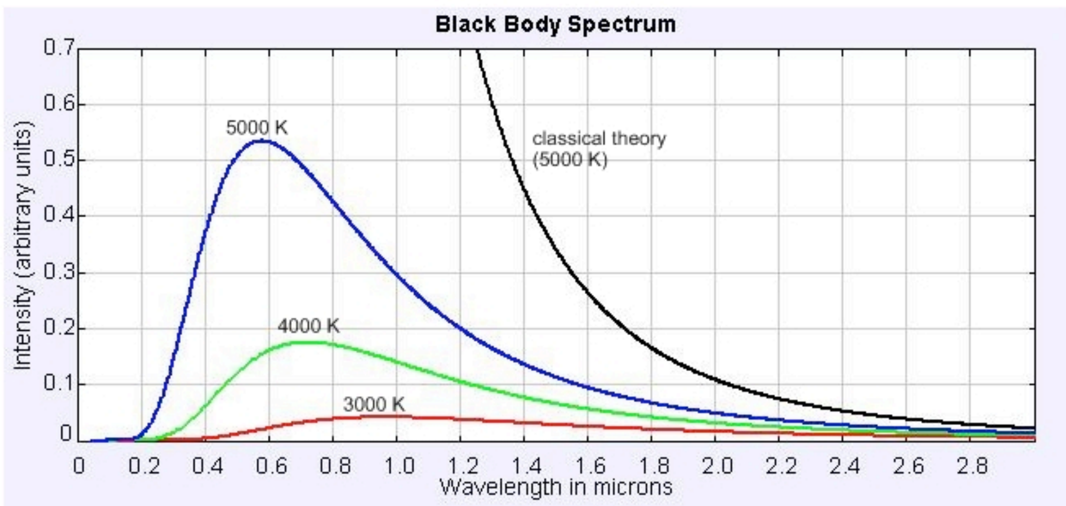

Figure 27.1: The spectra of electromagnetic radiation emitted by hot objects. Each spectrum corresponds to a particular temperature. The black curve represents the predicted spectrum of a 5000 K black body, according to the classical theory of black bodies.

At the end of the 19th century, the puzzle regarding blackbody radiation was that the theory regarding how hot objects radiate energy predicted that an infinite amount of energy is emitted at small wavelengths, which clearly makes no sense from the perspective of energy conservation. Because small wavelengths correspond to the ultraviolet end of the spectrum, this puzzle was known as the ***ultraviolet catastrophe***. Figure 27.1 shows the issue, comparing the theoretical predictions to the actual spectrum for an object at a temperature of 5000 K. There is clearly a substantial disagreement between the curves.

The German physicist Max Planck (1858 – 1947) was able to solve the ultraviolet catastrophe through what, at least at first, he saw as a mathematical trick. This trick, which marked the birth of quantum physics, also led to Planck being awarded the Nobel Prize for Physics in 1918. Planck determined that if the vibrating atoms and molecules were not allowed to take on any energy, but instead were confined to a set of equally-spaced energy levels, the predicted spectra matched the experimentally determined spectra extremely well. Planck determined that, for an atom oscillating with a frequency f, the allowed energy levels were integer multiples of the base energy unit hf, where Planck's constant h has the value 6.626×10^{-34} J s.

$E = nhf$, (Equation 27.1: **Allowed energy levels for an oscillator in a blackbody**)
where n is an integer.

Thus was born the idea of quantization, as applied to energy. If a quantity is quantized, it can take on only certain allowed values. Charge, as we discussed in chapter 18, is an example of something that is quantized, coming in integer multiples of the electronic charge e. Money is an example of an everyday item that is quantized, with quantities of money coming in integer units of a base unit, such as the penny in the United States and Canada.

Let us turn now to a second physical phenomenon that was puzzling scientists at the end of the 19^{th} century. This phenomenon is called the ***photoelectric effect***, and it describes the emission of electrons from metal surfaces when light shines on the metal. The photoelectric effect, or similar effects, have a number of practical applications, including the conversion of sunlight into electricity in solar panels, as well as the image-sensing systems in digital cameras.

Let's put the photoelectric effect experiment into context. First, recall that, beginning in 1801 with Thomas Young's double-slit experiment, physicists carried out a whole sequence of experiments that could be explained in terms of light acting as a wave. All these interference and diffraction experiments showed that light was a wave, and this view was supported theoretically by the prediction of the existence of electromagnetic waves, via Maxwell's equations. Then, in 1897, J.J. Thomson demonstrated that electrons exist and are sub-atomic particles. The stage was set for an explanation of the photoelectric effect in terms of light acting as a wave.

Predictions of the wave model of light regarding the photoelectric effect

The explanation for how light, as a wave, might interact with electrons in a metal to knock them out of the metal is fairly straightforward, based on the absorption of energy from the electromagnetic wave by the metal. Note that all metals have what is known as a ***work function***, which is the minimum energy required to liberate an electron from the metal. Essentially, the work function represents the binding energy for the most weakly bound electrons in the metal.

Remember that the intensity of an electromagnetic wave is defined as the wave's power per unit area. Predictions based on the wave model of light include:

- Light (that is, electromagnetic waves) of any intensity should cause electrons to be emitted. If the intensity is low, it will just take longer for the metal to absorb enough energy to free an electron.
- The frequency of the electromagnetic waves should not really matter. The key factor governing electron emission should be the intensity of the light.
- Increasing intensity means more energy per unit time is incident on a given area, and thus we might expect both more electrons to be emitted and that the emitted electrons would have more kinetic energy.

Amazingly, despite a century of success in explaining many experiments, the predictions of the wave model of light are completely at odds with experimental observations Again, as we will discover in Section 27-2, it took the intellect of Albert Einstein to explain what was going on.

Related End-of-Chapter Exercises: 1, 2, 36, 37.

Essential Question 27.1: In Figure 27.1, we can see that the intensity of light emitted by an object at 5000 K has a maximum at a wavelength of about 0.6 microns (600 nm). (a) What frequency does this correspond to? (b) What is difference between energy levels at this frequency?