Boltzmann,[1] and Gibbs, uses the methods of probability theory to calculate averages and fluctuations from the average for systems containing many particles or modes of vibration. It is interesting that quantum physics started not with a breakdown of Maxwell's or Newton's laws applied to the atom, but with a problem of classical statistical mechanics—that of calculating the intensity of radiation at a given wavelength from a heated cavity. The desperate solution to this radiation problem was found by a thoroughly classical thermodynamicist, Max Planck, in 1900. Indeed, it is significant that both Planck and Einstein returned again and again to the simple and general foundation of thermodynamics and statistical mechanics as the only certain bases for the new quantum theory. Although we shall not follow the original thermodynamic arguments completely, we shall see in this chapter how Planck arrived at the correct spectral distribution for cavity radiation by allowing only certain energies for the radiation-emitting oscillators in the cavity walls. We shall also see how Einstein extended this quantization of energy to light itself, thereby brilliantly explaining the photoelectric effect. We conclude our brief history of the quantum theory of light with a discussion of the scattering of light by electrons (Compton effect), which showed conclusively that the light quantum carried momentum as well as energy. Finally, we describe the pull of gravity on light in Section 3.7.

3.1   HERTZ'S EXPERIMENTS—LIGHT AS AN ELECTROMAGNETIC WAVE

It is ironic that the same experimentalist who so carefully confirmed that the "newfangled" waves of Maxwell actually existed and possessed the same properties as light also undermined the electromagnetic wave theory as the complete explanation of light. To understand this irony, let us briefly review the theory of electromagnetism developed by the great Scottish physicist James Clerk Maxwell between 1865 and 1873.

Maxwell was primarily interested in the effects of electric current oscillations in wires. According to his theory, an alternating current would set up fluctuating electric and magnetic fields in the region surrounding the original disturbance. Moreover, these waves were predicted to have a frequency equal to the frequency of the current oscillations. *In addition, and most importantly, Maxwell's theory predicted that the radiated waves would behave in every way like light:* electromagnetic waves would be reflected by metal mirrors, would be refracted by dielectrics like glass, would exhibit polarization and interference, and would travel outward from the wire through a vacuum with a speed of 3.0×10^8 m/s. Naturally this led to the unifying and simplifying postulate that light was also a type of Maxwell wave or electromagnetic disturbance, created by extremely high frequency electric oscillators in matter. At the end of the 19th century the precise nature of these charged submicroscopic oscillators was unknown (Planck called them resonators), but physicists assumed that somehow they were able to emit light waves whose frequency was equal to the oscillator's frequency of motion.

Even at this time, however, it was apparent that this model of light emission was incapable of direct experimental verification, because the highest

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[1]On whose tombstone is written $S = k_\mathrm{B} \log W$, a basic formula of statistical mechanics attributed to Boltzmann.

electrical frequencies then attainable were about 10^9 Hz and visible light was known to possess a frequency a million times higher. But Heinrich Hertz (Fig. 3.1) did the next best thing. In a series of brilliant and exhaustive experiments, he showed that Maxwell's theory was correct and that an oscillating electric current does indeed radiate electromagnetic waves that possess every characteristic of light except the same wavelength as light. Using a simple spark gap oscillator consisting of two short stubs terminated in small metal spheres separated by an air gap of about half an inch, he applied pulses of high voltage, which caused a spark to jump the gap and produce a high-frequency electric oscillation of about 5×10^8 Hz. This oscillation, or ringing, occurs while the air gap remains conducting, and charge surges back and forth between the spheres until electrical equilibrium is established. Using a simple loop antenna with a small spark gap as the receiver, Hertz very quickly succeeded in detecting the radiation from his spark gap oscillator, even at distances of several hundred meters. Moreover, he found the detected radiation to have a wavelength of about 60 cm, corresponding to the oscillator frequency of 5×10^8 Hz. (Recall that $c = \lambda f$, where λ is the wavelength and f is the frequency.)

In an exhaustive tour de force, Hertz next proceeded to show that these electromagnetic waves could be reflected, refracted, focused, polarized, and made to interfere—in short, he convinced physicists of the period that Hertzian waves and light waves were one and the same. The classical model for light emission was an idea whose time had come. It spread like wildfire. The idea that light was an electromagnetic wave radiated by oscillating submicroscopic electric charges (now known to be atomic electrons) was applied in rapid succession to the transmission of light through solids, to reflection from metal surfaces, and to the newly discovered Zeeman effect. In 1896, Pieter Zeeman, a Dutch physicist, discovered that a strong magnetic field changes the frequency of the light emitted by a glowing gas. In an impressive victory for Maxwell, it was found that Maxwell's equations correctly predicted (in most cases) the change of vibration of the electric oscillators and hence, the change in frequency of the light emitted. (See Problem 1.) Maxwell, with Hertz behind the throne, reigned supreme, for he had united the formerly independent kingdoms of electricity, magnetism, and light! (See Fig. 3.2.)

A terse remark made by Hertz ends our discussion of his confirmation of the electromagnetic wave nature of light. In describing his spark gap transmitter, he emphasizes that "it is essential that the pole surfaces of the spark gap

Figure 3.1 Heinrich Hertz (1857–1894), an extraordinarily gifted German experimentalist. (©*Bettmann/Corbis*)
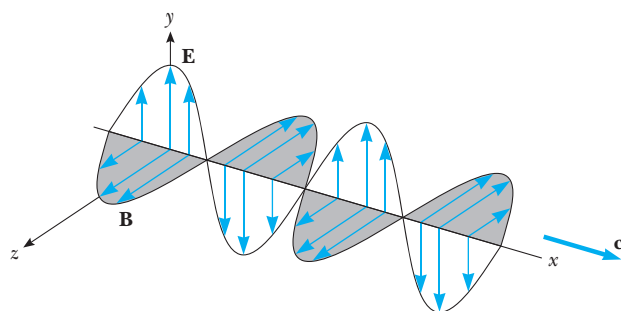

Figure 3.2   A light or radio wave far from the source according to Maxwell and Hertz.

should be frequently repolished" to ensure reliable operation of the spark.[2] Apparently this result was initially quite mysterious to Hertz. In an effort to resolve the mystery, he later investigated this side effect and concluded that it was the ultraviolet light from the initial spark acting on a clean metal surface that caused current to flow more freely between the poles of the spark gap. In the process of verifying the electromagnetic wave theory of light, Hertz had discovered the photoelectric effect, a phenomenon that would undermine the priority of the wave theory of light and establish the particle theory of light on an equal footing.
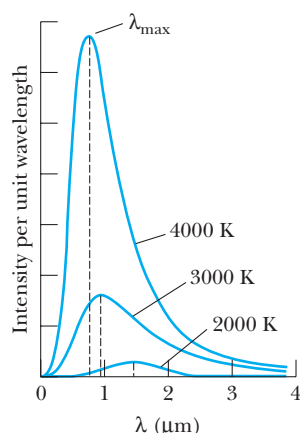
3.2   BLACKBODY RADIATION

The tremendous success of Maxwell's theory of light emission immediately led to attempts to apply it to a long-standing puzzle about radiation—the so-called "blackbody" problem. The problem is to predict the radiation intensity at a given wavelength emitted by a hot glowing solid at a specific temperature. Instead of launching immediately into Planck's solution of this problem, let us develop a feeling for its importance to classical physics by a quick review of its history.

Thomas Wedgwood, Charles Darwin's relative and a renowned maker of china, seems to have been the first to note the universal character of all heated objects. In 1792, he observed that all the objects in his ovens, regardless of their chemical nature, size, or shape, became red at the same temperature. This crude observation was sharpened considerably by the advancing state of spectroscopy, so that by the mid-1800s it was known that glowing solids emit continuous spectra rather than the bands or lines emitted by heated gases. (See Fig. 3.3.) In 1859, Gustav Kirchhoff proved a theorem as important as his circuit loop theorem when he showed by arguments based on thermodynamics that for any body in thermal equilibrium with radiation[3] the emitted power is proportional to the power absorbed. More specifically,

$$e_f = J(f, T)A_f \tag{3.1}$$

where e_f is the power emitted per unit area per unit frequency by a particular heated object, A_f is the absorption power (fraction of the incident power absorbed per unit area per unit frequency by the heated object), and $J(f, T)$ is a universal function (the same for all bodies) that depends only on f, the light frequency, and T, the absolute temperature of the body. A *blackbody* is defined as an object that absorbs all the electromagnetic radiation falling on it and consequently appears black. It has $A_f = 1$ for all frequencies and so Kirchhoff's theorem for a blackbody becomes

Blackbody

$$e_f = J(f, T) \tag{3.2}$$

Figure 3.3 Emission from a glowing solid. Note that the amount of radiation emitted (the area under the curve) increases rapidly with increasing temperature.

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[2]H. Hertz, *Ann. Physik* (Leipzig), 33:983, 1887.

[3]An example of a body in equilibrium with radiation would be an oven with closed walls at a fixed temperature and the radiation within the oven cavity. To say that radiation is in thermal equilibrium with the oven walls means that the radiation has exchanged energy with the walls many times and is homogeneous, isotropic, and unpolarized. In fact, thermal equilibrium of radiation within a cavity can be considered to be quite similar to the thermal equilibrium of a fluid within a container held at constant temperature—both will cause a thermometer in the center of the cavity to achieve a final stationary temperature equal to that of the container.