3.3 The Wave Nature of Light

Much of the history of physics is concerned with the evolution of our ideas about the nature of light. The speed of light was first measured with some accuracy in 1675, by the Danish astronomer Ole Roemer (1644-1710). Roemer observed the moons of Jupiter as they passed into the giant planet's shadow, and he was able to calculate when future eclipses of the moons should occur by using Kepler's laws. However, Roemer discovered that when Earth was moving closer to Jupiter, the eclipses occurred earlier than expected. Similarly, when Earth was moving away from Jupiter, the eclipses occurred behind schedule. Roemer realized that the discrepancy was caused by the differing amounts of time it took for light to travel the changing distance between the two planets, and he concluded that 22 minutes was required for light to cross the diameter of Earth's orbit.6 The resulting value of 2.2×10^{10} cm s^{-1} was close to the modern value of the speed of light. In 1983 the speed of light *in vacuo* was recognized as a fundamental constant of nature whose value is, *by definition*, $c = 2.99792458 \times 10^{10}$ cm s^{-1}.

Even the fundamental nature of light has long been debated. Isaac Newton, for example, believed that light must consist of a rectilinear stream of particles, because only such a stream could account for the sharpness of shadows. Christian Huygens (1629-1695), a contemporary of Newton, advanced the idea that light must consist of waves. According to Huygens, light is described by the usual quantities appropriate for a wave. The distance between two successive wave crests is the **wavelength** λ, and the number of waves per second that a point in space is the **frequency** ν of the wave. Then the speed of the light wave is given by

$$c = \lambda\nu. \tag{3.10}$$

Both the particle and wave models could explain the familiar phenomena of the reflection and refraction of light. However, the particle model of light prevailed, primarily on the strength of Newton's reputation, until its wave nature was conclusively demonstrated by Thomas Young's (1773-1829) famous double-slit experiment.

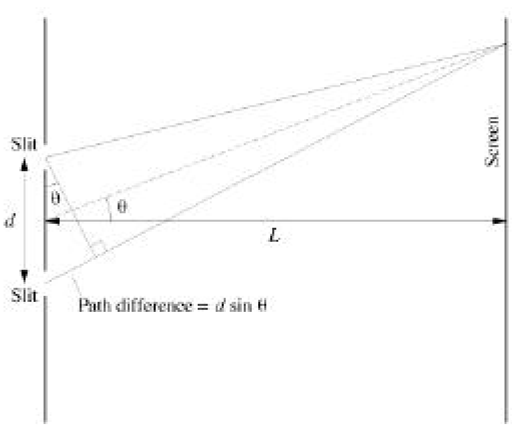

Figure 3.3

In a double-slit experiment, monochromatic light of wavelength λ from a single source passes through two narrow, parallel slits that are separated by a distance d. The light then falls upon a screen a distance L beyond the two slits (see Fig. 3.3). The series of light and dark *interference fringes* that Young observed on the screen could be explained only by a wave model of light. As the light waves pass through the narrow slits, they spread out (diffract) radially in a succession of crests and troughs. Light obeys a *superposition principle,* so when two waves meet, they add algebraically; see Fig. 3.4. At the screen, if a wave crest from one slit meets a wave crest from the other slit, a bright fringe or maximum is produced by the resulting **constructive interference.** But if a wave crest from one slit meets a wave trough from the other slit, they cancel each other, and a dark fringe or minimum results from this **destructive interference.**

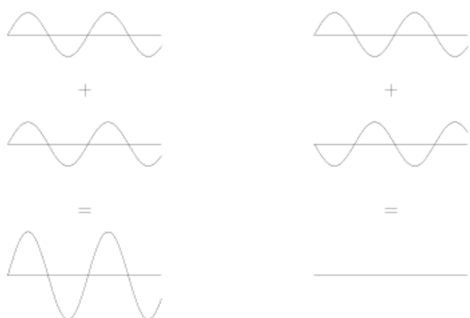

Figure 3.4

The interference pattern observed thus depends on the difference in the lengths of the paths traveled by the light waves from the two slits to the screen. As shown in Fig. 3.3, if $L \sim d$, then to a good approximation this path difference is $d\sin\theta$. The light waves will arrive at the screen *in phase* if the path difference is equal to an integral number of wavelengths. On the other hand, the light waves will arrive 180° out *of phase* if the path difference is equal to an odd integral number of half-wavelengths. So for $L \sim d$, the angular positions of the bright and dark fringes for **double-slit interference** are given by

$d\sin\theta$ = $n\lambda$ (n = 0, 1, 2, for bright fringes) (3.11)

$(n-1/2)\lambda$ .... (n = 1, 2, 3, for dark fringes).

In either case, *n is* called the **order** of the maximum or minimum. From the measured positions of the light and dark fringes on the screen, Young was able to determine the wavelength of the light. Measured in units of **angstroms,** abbreviated A, Young obtained a wavelength of 4000 A for violet light, and 7000 A for red light. The diffraction of light goes unnoticed under everyday conditions for these short wavelengths, thus explaining Newton's sharp shadows.

The nature of these waves of light remained elusive until the early 1860s, when the Scottish mathematical physicist James Clerk Maxwell (1831-1879) succeeded in condensing everything known about electric and magnetic fields into the four equations that today bear his name. Maxwell found that his equations could be manipulated to produce wave equations for the electric and magnetic field vectors E and B. These wave equations predicted the existence of *electromagnetic waves* that travel through a vacuum with a speed $v = 1/\sqrt{em}$. Upon inserting the values of ε and μ, Maxwell was amazed to discover that electromagnetic waves travel at the speed of light. Furthermore, these equations implied that electromagnetic waves are *transverse* waves, with the oscillatory electric and magnetic fields perpendicular to each other *and* to the direction of the wave's propagation (see Fig. 3.5); such waves could exhibit the polarization known to occur for light. Maxwell wrote that "we can scarcely avoid the inference that light consists in the transverse modulations of the same medium which is the cause of electric and magnetic phenomena."

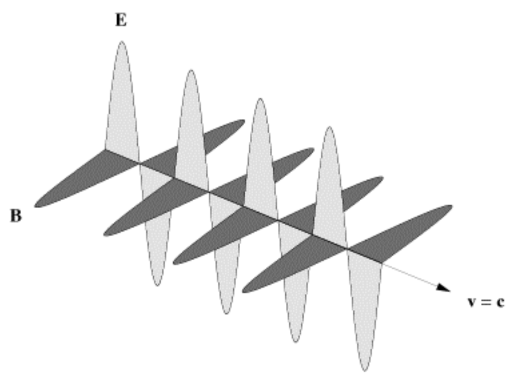

Figure 3.5

Maxwell did not live to see the experimental verification of his prediction of electromagnetic waves. Ten years after Maxwell's death, the German physicist Heinrich Hertz (1857-1894) succeeded in producing radio waves in his laboratory. Hertz determined that these electromagnetic waves do indeed travel at the speed of light, and he confirmed their reflection, refraction, and polarization properties. In 1889, Hertz wrote:

What is light? Since the time of Young and Fresnel we know that it is wave motion. We know the velocity of the waves, we know their lengths, and we know that they are transverse; in short, our knowledge of the geometrical conditions of the motion is complete. A doubt about these things is no longer possible; a refutation of these views is inconceivable to the physicist. The wave theory of light is, from the point of view of human beings, certainty.

Region	Wavelength
Gamma ray	$\lambda < 0.1$ A
X-ray	0.1A< $\lambda <$ 100A
Ultraviolet	100 A < $\lambda <$ 4000 A
Visible	4000A < $\lambda <$ 7000 A
Infrared	7000 A < $\lambda <$ 1 mm
Microwave	1 mm < $\lambda <$ 10 cm
Radio	10 cm < λ

Table 3.1 The Electromagnetic Spectrum.

Today, astronomers utilize light from every part of the **electromagnetic spectrum.** The total spectrum of light consists of electromagnetic waves of all wavelengths, ranging from very short wavelength gamma rays to very long wavelength radio waves. Table 3.1 shows how the electromagnetic spectrum has been arbitrarily divided into various wavelength regions.

Like all waves, electromagnetic waves carry both energy and momentum in the direction of propagation. The amount of energy carried by a light wave is described by the **Poynting vector, S.** The Poynting vector points in the direction of the electromagnetic wave's propagation and has a magnitude equal to the amount of energy per unit time that crosses a unit area oriented perpendicular to the direction of the propagation of the wave. Because the magnitudes of the fields E and B vary harmonically with time, the quantity of practical interest is the *time-averaged* value of the Poynting vector over one cycle of the electromagnetic wave. In a vacuum the magnitude of the timeaveraged Poynting vector, (S), is

$$S = \frac{c}{8p} EB \quad \text{(cgs units: ergs/cm}^2\text{/sec)}$$

where E and B are the maximum magnitudes (amplitudes) of the electric and magnetic fields. The time-averaged Poynting vector thus provides a description of the radiant flux in terms of the electric and magnetic fields of the light waves. However, it should be remembered that the radiant flux discussed in Section 3.2 involves the amount of energy received *at all wavelengths* from a star, whereas E and B describe an electromagnetic wave of a specified wavelength.

Because an electromagnetic wave carries momentum, it can exert a force on a surface hit by the light. The resulting **radiation pressure** depends on whether the light is reflected from or absorbed by the surface. If the light is completely absorbed, then the force due to radiation pressure is in the direction of the light's propagation and has magnitude

$$F_{rad} = \frac{\langle S \rangle A}{c} \cos\theta \qquad \text{(absorption)} \qquad (3.13)$$

where θ is the angle of incidence of the light as measured from the direction perpendicular to the surface of area A (see Fig. 3.6). Alternatively, if the light is completely reflected, then the radiation pressure force must act in a direction perpendicular to the surface; the reflected light cannot exert a force parallel to the surface. Then the magnitude of the force is

$$F_{rad} = \frac{2\langle S \rangle A}{c} \cos\theta \qquad \text{(reflection)} \qquad (3.14)$$

Radiation pressure has a negligible effect on physical systems under everyday conditions. However, radiation pressure may play a dominant role in determining some aspects of the behavior of extremely luminous objects such as early main-sequence stars, red supergiants, or accreting compact stars. It may also have a signficant effect on the small particles of dust found throughout the interstellar medium.

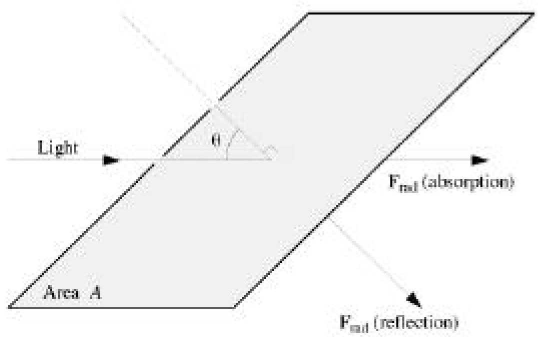

Figure 3.6