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Physics, Chapter 36: Light and Its Measurement

Henry Semat
City College of New York

Robert Katz
University of Nebraska-Lincoln, rkatz2@unl.edu

Part Five

LIGHT

36

Light and Its Measurement

36-1 The Nature of Light

The word *light*, as commonly used, refers to the radiant energy which produces a visual effect. It was first shown by Maxwell that light is an electromagnetic radiation, propagated with a speed whose value was numerically determined by the relationship between electric and magnetic units. As we have seen in Section 31-3, the velocity of light in vacuum, represented by the symbol c, is given by the equation

$$c = (\epsilon_0\mu_0)^{-\frac{1}{2}},$$

where c has the numerical value of 3×10^8 m/sec, or 186,000 mi/sec. Light waves are now understood to be electromagnetic waves of shorter wavelength and higher frequency than the electromagnetic waves used in radio.

If light is propagated as an electromagnetic wave, its origin must ultimately be traced to electric charges. Thus an analysis of the light emitted by a substance may be used to determine the electronic constitution of that substance, and so to give information about the structure of nuclei, of atoms, and of aggregates of atoms. The emission of light by a source involves an interaction between matter and radiant energy. To explain the phenomena associated with the interaction of matter and radiant energy, it has been necessary to supplement Maxwell's electromagnetic theory of light by what is known as the *quantum theory of light*. Radiant energy, in its interaction with matter, behaves as though it consists of bundles of energy. The amount of energy $\mathcal{E}$ in each bundle, or *quantum*, is related to the frequency f by the equation

$$\mathcal{E} = hf, \tag{36-1}$$

where h is a universal constant called *Planck's constant* whose value is

$$h = 6.62 \times 10^{-27} \text{ erg sec.}$$

A quantum of light energy hf is also called a *photon*. We shall return to the quantum theory later in discussing the analysis of light and atomic structure. For the present we shall concern ourselves with the propagation of radiant energy, and shall emphasize particularly that form which produces a visual effect.

The normal human eye is capable of responding to those waves whose wavelengths lie in the range between 3.8×10^{-5} cm and 7.6×10^{-5} cm.
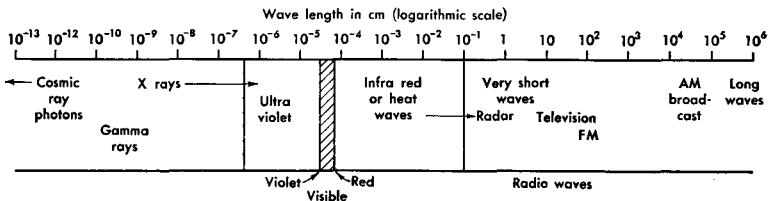

Fig. 36-1 The complete electromagnetic spectrum. Because of the wide range in wavelengths, the latter have been drawn to a logarithmic scale.

This is a very narrow region of the electromagnetic spectrum, corresponding roughly to that region of the solar spectrum which is transmitted by the earth's atmosphere. The electromagnetic spectrum is indicated in Figure 36-1, and ranges from waves of very short wavelength known as *x-rays* or *gamma rays*, to waves of very long wavelength used in radio broadcasting. The distinction between the terms "x-ray" and "gamma ray" lies in the origin of the radiation rather than in its wavelength; the term "gamma ray" is reserved for radiation emitted by the nucleus of an atom.

36-2 Sources of Light

Our principal source of light is the sun, but when sunlight is not available, other sources of light must be used. Before electric power became generally available, the sources of light widely used were the kerosene lamp, the candle, and illuminating gas. Light is emitted from these sources as a result of the chemical reactions in combustion. With the development of large sources of electric power, many new sources of light were developed to convert electric energy into light. Edison's incandescent electric light consisted of a carbon filament sealed into an evacuated glass bulb. The modern incandescent lamp contains a tungsten *filament* which may be heated to a temperature as high as 3000°C. The glass bulb is generally filled with an inert gas, such as argon, to retard evaporation of tungsten from the filament.

The *carbon arc* is frequently used as an intense source of light, as in searchlights or motion-picture projectors. The carbon arc consists of two carbon rods connected to a source of power through a resistor. The arc is started by momentarily touching the two carbon rods together. The rods are heated at the points of contact where the current density is very high. Some of the carbon vaporizes and becomes ionized, acting as the conducting
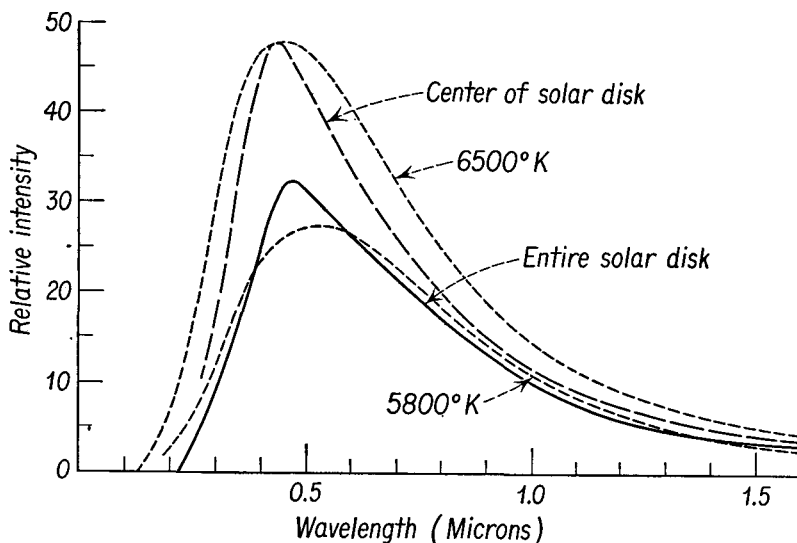
Fig. 36-2 Spectral distribution of solar radiation. The solid line shows the spectrum obtained from light from the entire solar disk, while the dashed line shows the spectrum of light from the center of the solar disk. Dotted lines indicate the spectrum of black body radiation at temperatures of 6500°K and 5800°K. (After R. N. Thomas, *The Scientific Monthly*, September, 1956.)

path for the current between the two electrodes. The positive terminal may reach a temperature of 3700°C, becoming white hot. This terminal is the principal source of light in the arc. Some carbon arcs, used primarily for spectroscopic or therapeutic purposes, have the cores of the positive electrodes filled with some material other than carbon. The light obtained from cored carbons is characteristic of the core material and is superimposed on the white light from the hot carbon.

Sunlight comes to us from a layer of the sun where the transition from opacity to transparency takes place. This layer is known as the *photosphere* and is at a temperature of about 6000°C. Sunlight is whiter than the light from either the tungsten lamp or the carbon arc. The hotter the source, the closer will the light it emits approach the color of sunlight. The mean-

ing of the temperature of the sun or of the photosphere is somewhat vague. One way of assigning a number to the temperature of the sun is to compare the solar spectrum to the radiation spectrum emitted by a black body.   If light from the entire solar disk is admitted to the spectroscope, we find that the spectrum is in approximate agreement with a black-body spectrum at a temperature of 5800°K, while the maximum intensity of the light from the center of the solar disk corresponds to a temperature of 6500°K, as shown in Figure 36-2.
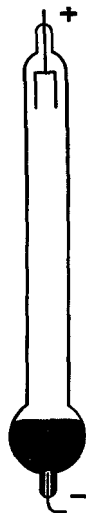
Another important source of light is the *mercury arc*.   In the low-pressure mercury arc a pool of mercury is placed at the bottom of a glass or quartz tube containing two metal electrodes sealed into the ends, as in Figure 36-3.   The mercury is in contact with one electrode, and mercury vapor at a low pressure fills the rest of the space in the tube.   To start the arc the tube is tilted so that liquid mercury makes momentary contact with both electrodes, and then the tube is returned to its vertical position.   The electric discharge through the ionized mercury vapor is similar to the electric discharge through a gas at low pressure; the light emitted is rich in blue, green, and violet light and is characteristic of the mercury.   A mercury arc also emits ultraviolet light; this is readily absorbed by ordinary glass but is transmitted by quartz.

Fig. 36-3 Mercury arc.

The high-pressure mercury arc contains a small amount of liquid mercury which is completely vaporized by the heat developed by the passage of current through the tube.   The pressure increases as the temperature of the vapor increases.   Pressures of 50 to 100 atm and temperatures of 5000°K are common in these arcs.   The high-pressure mercury arc is an intense source of illumination.

A *fluorescent* lamp is a low-pressure mercury arc in a long glass tube which has a coating of some fluorescent material on the inside surface. Some argon gas is also put into the tube to make it easier to start the lamp. Two filaments are built into the ends of the tube.   When heated, these filaments emit electrons which collide with and ionize the gas within the tube, thus starting the arc.   The construction of a typical fluorescent lamp is shown in Figure 36-4.   A special starting arrangement must be used with fluorescent lamps, similar to the schematic diagram in Figure 36-5.   When the lamp is switched on, alternating current flows through the two filaments in series, through the inductor L, and through the switch S.   After a short time the switch S is opened, producing a large induced emf across the filaments which now act as electrodes and start the arc in the tube.   The

starters built into fluorescent lamps automatically open and close the switch S through the use of a bimetallic strip.
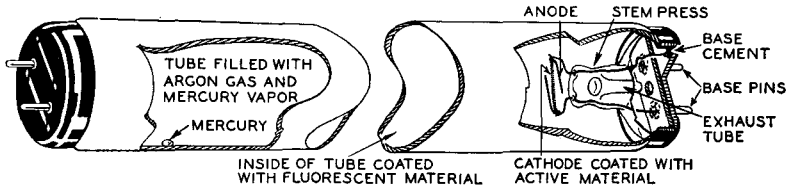
Fig. 36-4 Details of the construction of a fluorescent lamp. (Courtesy of Westinghouse Electric Company.)

There are essentially two sources of light in a fluorescent lamp. The mercury vapor emits green, blue, and violet light and, in addition, a large amount of ultraviolet radiation which is absorbed by the fluorescent coating

Fig. 36-5 Starting arrangement for a fluorescent lamp. S is the switch, F and F are filaments, and L is the inductance.
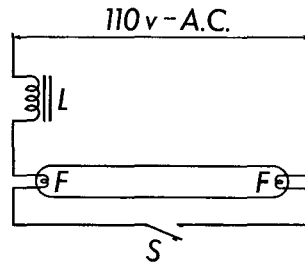
on the wall of the tube and is re-emitted as visible light. There are many substances which fluoresce under the action of ultraviolet light. These substances are called *phosphors*. By a suitable choice of phosphor, many different colors, such as red, orange, or yellow, can be added to the light from the mercury, so that the fluorescent lamp can have almost any desired color.

36-3   Electric Discharge through Gases

For the study of the passage of an electric current through a gas, let us put the gas into a very long glass tube which has a circular electrode sealed into each end, and which is provided with a small side tube which can be connected to a pumping system, as sketched in Figure 36-6.

Suppose that there is air in the tube, and that the two electrodes A and C are connected to the terminals of a source of high potential, say 50,000 volts. When the pressure of the air inside the tube is reduced to a few millimeters of mercury, the passage of electric current through the gas will be accompanied by the emission of light from the gas. At this pressure

the entire space between the electrodes will be filled with a pink or reddish glow. When the pressure of the air in the tube is reduced to about 0.1 mm, there is no longer a uniform glow between the electrodes but a series of dark and light regions, as shown in Figure 36-7. A bluish velvety glow, known as the *cathode glow*, covers the entire negative electrode, or cathode
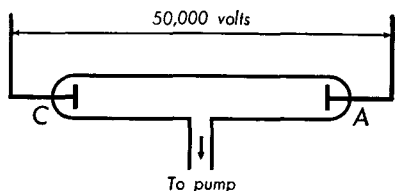

Fig. 36-6   A gas-discharge tube.

C. This is followed by a dark space called the *Crookes dark space* which ends at the *negative glow*. This is separated by the *Faraday dark space* from the luminous column, known as the *positive column*, which extends up to the anode. The positive column usually appears to be striated, consisting of a series of bright and dark regions, equally spaced. Covering the entire anode, or positive terminal *A*, is the *anode glow*.
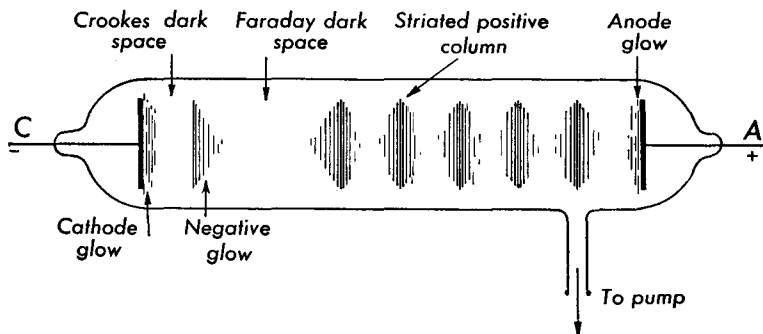

Fig. 36-7   Appearance of the electrical discharge when the pressure of the air in the tube is about 0.1 mm.

   Experiments show that there are always some ions present in the air. These ions may have been produced by the action of light, or as the result of collisions between molecules, or by ionizing agents, known as *cosmic rays*, which are always present at the earth's surface. Whatever the original source of these ions may be, when a potential difference of several thousand volts is placed across the electrodes *A* and *C*, the charged ions will be accelerated toward the appropriate electrode. Let us call the average distance between collisions of molecules with each other by the term *mean free path*. If the pressure of the gas is in the neighborhood of 1 atm, the

ions will have very short mean free paths and will acquire very little energy before making a collision. But when the pressure is reduced to about 1 mm of mercury, the mean free path is longer, and the ion may acquire sufficient kinetic energy to ionize the molecule with which it collides. This process is known as *ionization by collision*. As the pressure is lowered, a greater number of collisions result in the production of ions and electrons in the gas. At the same time some of the positive and negative charges recombine to form neutral atoms and molecules. When the pressure of the gas in the tube becomes very low, the mean free path may exceed the length of the tube, so that an ion may travel the entire length of the tube without collid-ing with a second molecule. At such low pressures, in the neighborhood of 0.001 mm of mercury, the positive ions reaching the cathode have a great deal of energy. One of the results is that the cathode may emit electrons under the bombardment of the positive ions. These electrons are called *cathode rays;* they leave the cathode in a direction at right angles to its surface, since the cathode is an equipotential surface and the electric field is perpendicular to it.

An electric discharge can be maintained through any gas at a low pressure. The light emitted is characteristic of the gas and comes prin-cipally from the positive column. The spectrum is a line spectrum, rather than a continuous spectrum, with the energy concentrated in very narrow wavelength intervals which appear as lines in the spectrometer. The color of the discharge is the visual impression of the combination of the intensity and wavelengths of the spectral lines. Thus neon appears red, argon ap-pears blue, and so forth. When examined on a spectroscope, the light yields information about the structure of the atoms and molecules of the gas. As sources of light, these gases are used chiefly for display purposes.

Another interesting aspect of electrical discharge in gases is the forma-tion of *free radicals*, such as the hydroxyl radical OH, the methyl radical CH_3, and so on. Free radicals are highly reactive and play an important part in maintaining chemical chain reactions. Thus, if a chlorine molecule is split in two, the chlorine radical may attach a hydrogen molecule H_2 in its vicinity, forming stable HCl and releasing a hydrogen atom as a free radical. The hydrogen radical then combines with a second chlorine molecule Cl_2, and so on. Most free radicals are short-lived at ordinary temperatures, lasting about 10^{-3} sec, but some free hydrocarbon radicals have lifetimes of many days. Recent research has shown that it is possible to maintain normally short-lived free radicals at low temperatures by trapping them in a chamber cooled with liquid helium. This study is of great interest in the field of low-temperature chemistry. The free radicals liberated in a gaseous discharge may serve to form unusual chemical com-pounds in the discharge tube.

36-4   Color Sensitivity of the Eye

The problem of color vision embraces three distinct fields—physics, psychology, and physiology.   Here we shall touch only upon a few important aspects of the subject.   The normal eye is sensitive to a short range of wavelengths.   It is customary to express wavelengths in Angstrom units (abbreviated A), where $1 \text{ A} = 10^{-8}$ cm, and in microns, where $1 \text{ } \mu = 10^{-6} \text{ m} = 10^{-4} \text{ cm} = 10^4 \text{ A}$.   The sensitivity of the normal human eye
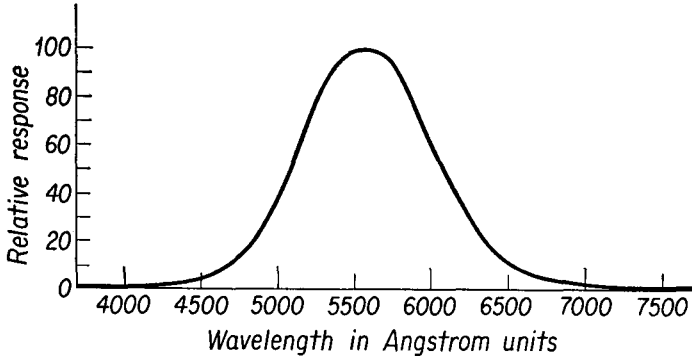
Fig. 36-8   Relative brightness sensitivity of the average human eye for daytime vision.

under normal daylight illumination is not constant over its range of sensitivity, ranging from 3,800 A to 7,600 A, as shown in Figure 36-8, but has a maximum response to light of 5,500 A, in the yellow-green region of the spectrum.   Daytime sensitivity coincides approximately with the radiation maximum of the sun; this is an adaptation.   In rod vision (see Section 39-3) the most sensitive wavelength is in the blue-green region.   Purely nocturnal creatures have only rods; purely diurnal creatures have only cones.

A very narrow band of wavelengths constitutes a spectral color.   The color identification ranges from violet for the shortest wavelengths to blue, green, yellow, orange, and red as the wavelength increases toward the maximum wavelengths visible.   Light of any given color can be analyzed into its component wavelengths by means of a spectroscope, and the intensity at each wavelength, or within each narrow band of wavelengths, can be measured with an appropriate instrument.   It must be emphasized that many problems within the field of vision are outside the realm of physics, for physics deals only with phenomena that may be observed by every observer.   While we may agree that the colors on two different cards match, and we may agree to call them orange, it is impossible for any one of us to be certain that the sense impression he receives is the same as the sense impression anyone else receives from the same card.

36-5   Intensity and Brightness of Light Sources

We may express the intensity of a source of light in terms of the rate at which it emits radiation, in units of power, or energy emitted per unit time. Since all sources emit some radiation to which the eye is not sensitive, and since the eye is not equally sensitive to all wavelengths emitted by the source, a special unit must be used to express the rate at which a source emits *visible* radiation. Commercially obtainable lamps are presently rated in terms of the electrical energy consumed by the lamp rather than in terms of light output. A 60-watt lamp is one which consumes 60 joules of electrical energy in each second. Only a small fraction of this energy is converted into light. If the energy radiated by a given lamp is known as a function of wavelength, the energy radiated as light can be determined by applying weighting factors in each wavelength interval from Figure 36-8 to the lamp's spectral distribution. This is a cumbersome procedure and is not generally followed. Instead, a light source of special construction has been adopted as standard, by international agreement, and other sources are visually compared to the standard source.

The present standard of light intensity is a black-body radiator at the temperature of molten platinum, at 2047°K, as shown in Figure 36-9. The unit of *luminous intensity* is called the *candela* (formerly called the *candle*), defined as the intensity of an opening in the standard source $1/60$ cm^2 in area, when observed in a direction normal to the plane of the opening, along the axis of the cylindrical tube which makes up the black body. This body is used as a practical approximation to a point source of light.

Fig. 36-9   Standard light source.

The rate at which visible radiation is emitted by a source is called the *luminous flux*, expressed in *lumens*. The luminous flux from a source of radiation may not be the same in all directions, so that it is necessary to specify the luminous flux emitted into a narrow cone whose axis is in a particular direction, expressed in *lumens per steradian*. The steradian is a unit of measuring the *solid angle*.

To describe the solid angle subtended by a cone, in steradians, we construct a sphere of arbitrary radius r centered at the apex of the cone.
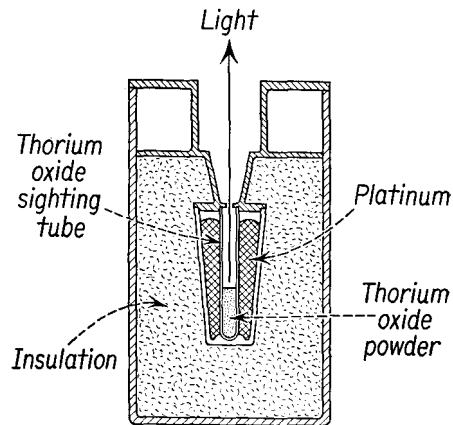
If the area of the sphere bounded by the cone is ΔA, the solid angle $\Delta \omega$ subtended by the cone is given by

$$\Delta \omega = \frac{\Delta A}{r^2} \text{ steradians.} \tag{36-2}$$

The definition of the steradian is analogous to the definition of the radian. Since the area of a sphere is $4\pi r^2$, the solid angle subtended by a sphere at its center is 4π steradians. As shown in Figure 36-10, if we wish to determine the solid angle subtended by a surface α at the point P, we draw a set of lines from P to the boundary of α, thus generating a conelike figure. From P as center, we describe a spherical surface of radius r and follow the procedure outlined above to find the solid angle subtended by this cone.
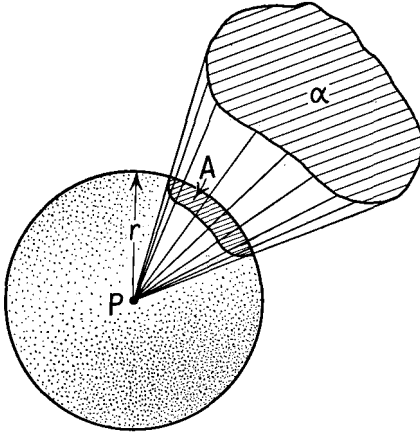
A point source of light of luminous intensity I which radiates uniformly in all directions is said to radiate a luminous flux of $4\pi I$ lumens. The luminous intensity I of an arbitrary source, when viewed from a particular direction, may be determined by measuring the light flux ΔF, expressed in lumens, which passes through an element of solid angle $\Delta \omega$, expressed in steradians, by the equation

Fig. 36-10

$$I = \frac{\Delta F}{\Delta \omega} . \tag{36-3}$$

From Equation (36-3) we see that a luminous intensity of 1 candela is equivalent to a luminous flux of 1 lumen/steradian, and that an isotropic source of luminous intensity 1 candela radiates a total luminous flux of 4π lumens. From the definition of the standard light source, we see that the lumen is the luminous flux emitted from $1/60$ cm² opening in the standard source, into a solid angle of 1 steradian.

Practical sources of light are not point sources but radiate light from an extended area, as in a fluorescent lamp or a tungsten filament. The *brightness* of an extended source is referred to technically as its *luminance*, and is expressed in units of luminous intensity per unit area, as *candelas per square meter*. Thus a source of unit luminance which is 1 m² in area has a luminous intensity of 1 candela. The luminous flux emitted normally from such a source is 1 lumen/steradian, when viewed from afar, so that the

source appears to be a point source. Many varied units of luminance are used. For example, the luminance of cathode-ray-tube screens is quoted by the manufacturer in units of foot lamberts, where a luminance of 1 foot lambert is equal to $1/\pi$ candela/ft^2.

Most diffuse radiating or reflecting objects appear equally bright visually from whatever direction they are viewed. Thus the sun and the full moon are seen as uniformly bright disks, in spite of the fact that they are spheres. This observation is formulated quantitatively as *Lambert's law* which states that the luminance, or brightness, B of an element of area ΔA in a direction making an angle θ with the normal to the element varies with the cosine of the angle θ. In other words, the radiant flux per unit solid angle radiated by the element of area varies with the angle in such a way that

$$\left(\frac{\Delta F}{\Delta\omega}\right)_\theta = \left(\frac{\Delta F}{\Delta\omega}\right)_0 \cos\theta. \quad \textbf{(36-4)}$$
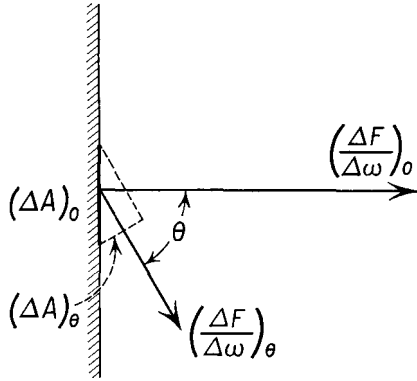

Fig. 36-11

From Figure 36-11 we see that the projected area $(\Delta A)_\theta$ of the source in the new direction is related to the actual area $(\Delta A)_0$ of the element by the equation

$$(\Delta A)_\theta = (\Delta A)_0 \cos\theta.$$

When we view the source from a direction making the angle θ with the normal, we calculate the luminance of the source by dividing the radiant flux per unit solid angle, as we see it, by the projected area of the source, as we see it. Thus the brightness at the angle θ, B_θ is given by

$$B_\theta = \frac{(\Delta F/\Delta\omega)_\theta}{(\Delta A)_\theta} = \frac{(\Delta F/\Delta\omega)_0 \cos\theta}{(\Delta A)_0 \cos\theta},$$

or
$$B_\theta = B_0;$$

that is, the apparent brightness of a source at an angle θ is equal to its brightness when viewed in the normal direction, provided that Lambert's law is obeyed. Thus the brightness of a diffuse source is independent of the direction from which it is viewed. Most commonly encountered light sources, such as the tungsten filament, the carbon arc, and so on, obey Lambert's law.

In optical projection systems the brightness of the source determines the brightness of the image. In efficiently designed optical systems, using a lamp of increased wattage does not appreciably increase the brightness

of the image, for the extra power consumption and increased light output are obtained by increasing the size of the filament rather than its brightness. It is for this reason that carbon arcs are used in theater projection systems.

Sources of illumination are rated as to their *luminous efficiency* in units of lumens per watt. The eye is most sensitive to light of wavelength 5,500 A. At this wavelength a lumen is equivalent to 0.00147 watt; that is, a source radiating 1 lumen of luminous flux at this wavelength radiates energy at the rate of 0.00147 joule/sec. From Figure 36-8 we note that the sensitivity of the eye at 5,000 A is only 0.4 of its sensitivity at 5,500 A, so that a source which radiates 1 lumen of luminous flux at 5,000 A radiates energy at the rate of 0.0037 watt. The brightness, luminous efficiency, and power consumption of a number of light sources are given in Table 36-1.

TABLE 36-1 POWER CONSUMPTION, LUMINANCE, AND EFFICIENCY OF LIGHT SOURCES

Source	Watts	Luminance (candelas/cm^2)	Luminous Efficiency (lumens/watt)
Tungsten lamp, gas filled	100	650	13
	1,000	1,100	19
Tungsten lamp, projection	100	1,800	23
	1,000	2,450	28
Carbon arc	1,500	15,000	16
	14,000	100,000	30
Fluorescent lamp (white)	40	0.6	58
Mercury arc			
10 atm	80	680	38
115 atm	1,000	48,000	60
Sodium vapor	45	9	55
Ideal monochromatic source (5,500 A)	1	—	680

36-6 Illuminance of an Illuminated Surface

The illumination of a surface is called the *illuminance E* and is the amount of luminous flux per unit area of the surface. Let us suppose that a point source of luminous intensity I is located a distance r from a surface of area ΔA, as shown in Figure 36-12, and that the line joining the point P to ΔA makes an angle θ with the normal to the area element. The solid angle $\Delta \omega$ subtended by ΔA at P is given by

$$\Delta \omega = \frac{\Delta A \cos \theta}{r^2}.$$

From Equation (36-3) the luminous flux ΔF radiated into a solid angle $\Delta \omega$

by a source of luminous intensity I is

$$\Delta F = I \; \Delta \omega.$$

Thus the luminous flux incident upon the area ΔA is

$$\Delta F = I \frac{\Delta A \cos \theta}{r^2},$$

and the illuminance of the surface is

$$E = \frac{\Delta F}{\Delta A} = \frac{I \cos \theta}{r^2}. \quad \text{(36-5)}$$

The illuminance of a surface which is perpendicular to the line of sight, that is, a surface for which $\theta = 0°$, will vary inversely with the square of the distance from the point source. The units of illuminance are lumens per square meter, termed *lux*. The British unit of illuminance is the lumen per square foot, formerly called the *foot candle*, for it is the illuminance of a surface located at a distance of 1 ft from a 1-candle source. Similarly, the lux was sometimes called the *meter candle*.
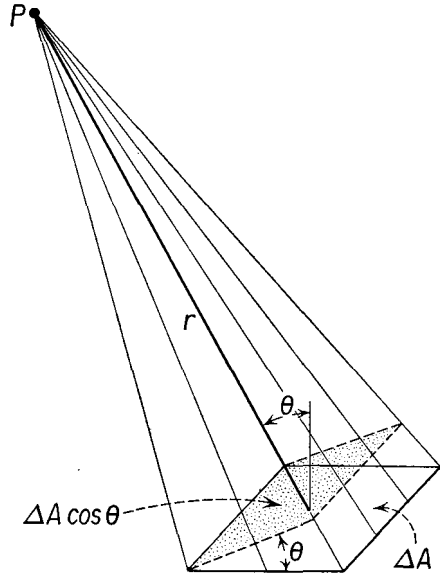
Fig. 36-12

   Proper illumination has come to be considered essential not only for comfort and enjoyment but also for safety and efficiency. For example, it is now considered desirable to have an illuminance of 10 lumens/ft² on library reading desks, and 75 lumens/ft² in hospital operating rooms. Although these values may be considered bright for artificial light, they are quite small when compared to the illumination provided naturally on an overcast day, when the illuminance is approximately 1,000 lumens/ft².

36-7   Photometry

The measurement of illuminance and luminous intensity is called *photometry*, and instruments used for such measurements are called *photometers*. A Bunsen photometer is simple in design and illustrates the principle used in many photometers for determining the intensity of a source of light. The Bunsen photometer has a screen S which consists of a white sheet of paper with a translucent grease spot G in its center, as shown in Figure 36-13. This screen is mounted in a box containing two mirrors MM, so arranged that both sides of the screen can be viewed simultaneously. The box is

mounted on an optical bench, and the two sources which are to be compared are mounted on the bench on opposite sides of the photometer. Most of the light which strikes the paper from each source is diffusely reflected, while most of the light which strikes the grease spot is transmitted through
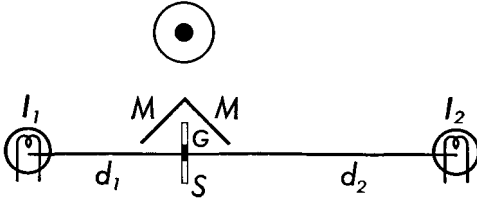

Fig. 36-13 Bunsen grease-spot photometer.

it. The experimental procedure is to move the screen S until the grease spot cannot be distinguished from the rest of the screen. In this case the illuminance of the photometer screen due to the source I_1 located a distance d_1 from the photometer is equal to the illuminance of the screen due to the source I_2 located a distance d_2 from the screen. From Equation (36-5) we have
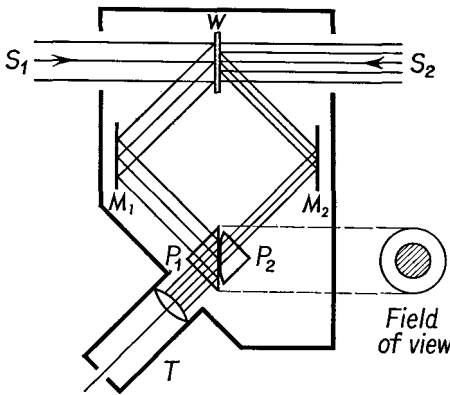
$$\frac{I_1}{d_1^2} = \frac{I_2}{d_2^2}.$$

(36-6)

If I_2 is the luminous intensity of a standard lamp, the luminous intensity of any other lamp can be determined with this photometer.

The Lummer-Brodhun photometer is an improvement on the Bunsen photometer, in which the grease spot is replaced by the photometer head shown in Figure 36-14. Light from the two sources S_1 and S_2, of intensities I_1 and I_2, respectively, falls on a diffuse white surface W. Some of the light which is scattered by this surface is reflected from the mirrors M_1 and M_2 into two right-angled prisms P_1 and P_2. Part of the base of prism P_2 is ground away so that only that portion of the light which strikes the surface of contact passes into the telescope T. The light striking the base of P_1 from M_1 is totally reflected into the telescope from the part of P_1 which is not in contact with P_2. The field of view seen through the telescope is sharply divided into two sections,

Fig. 36-14 Diagram of a Lummer-Brodhun photometer head.

one brighter than the other, except when their illuminations are equal, in which case the dividing line disappears.

Difficulties are encountered in visual photometry when two sources of different color, or two lamps at different temperatures, are compared. In this event a device called a *flicker photometer* is used, in which opposite sides of the photometer head are alternately illuminated. At sufficiently high

Fig. 36-15 A photoelectric tube used for measuring illuminance.
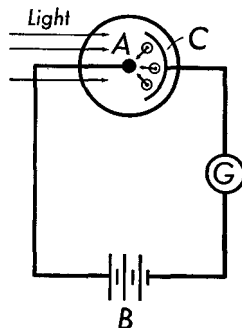
frequencies of alternation, the difference in appearance of the two sections of the photometer field which are due to color seems to disappear, and differences in intensity may be compared.

Besides the photometers which depend upon the visual matching of illuminated surfaces, other photometers are used which are based on some electrical effect resulting when light is incident upon a surface. In one type of *photoelectric effect*, light incident upon a metallic surface causes the ejection of electrons from the surface. When light falls on the cathode C of the photoelectric tube, shown connected to a simple circuit in Figure 36-15, electrons are ejected from the surface and are attracted to the anode A, because of the difference in potential between anode and cathode. The number of electrons emitted per second, and hence the current through the galvanometer, is proportional to the intensity of the incident light. The relative sensitivity of the surface to various wavelengths is different from the relative sensitivity of the eye, but, with the use of proper filters, such photocells can be used to measure illuminance. Filters have also been developed to match the sensitivity of photographic films for use of photoelectric cells as exposure meters. By use of appropriate filters, photoelectric cells have been used industrially to match color as well as intensity.

Another type of photoelectric effect which is widely used is the *photovoltaic effect*, in which a difference of potential is developed in an illuminated cell. For example, the Weston photronic cell consists of a very thin film of selenium formed on an iron plate. Light incident upon the selenium passes through it to the iron and produces an emf between the two substances, with the iron as positive terminal and the selenium as negative terminal.

The current through a galvanometer of internal resistance less than about 100 ohms is proportional to the illuminance of the surface. Such cells are widely used in photographic exposure meters, and similar cells are used in the newly developed *solar battery* which has recently been placed in service to charge storage batteries which power isolated telephone lines.

36-8   Speed of Light

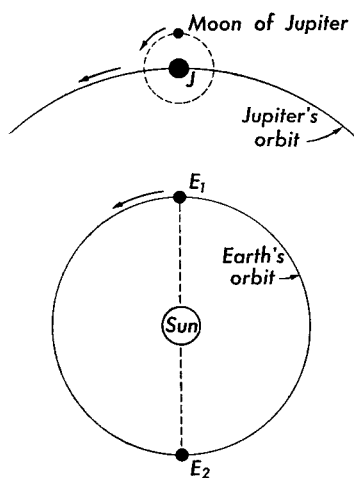The earliest determinations of the speed of light were based on astronomical observations. In 1675, Roemer, a Danish astronomer, observed that the time of occurrence of the eclipse of one of Jupiter's moons differed from that calculated on the assumption that light travels with infinite speed. He explained this discrepancy by assuming a finite speed of light and calculated this speed with the data then available. Referring to Figure 36-16, suppose that the time of occurrence of an eclipse of one of Jupiter's moons is observed when the earth is at E_1, and a calculation is then made as to the time of occurrence of an eclipse of this same moon of Jupiter 6 months later, when the earth is at E_2. If this calculation, which takes into consideration the motion of Jupiter as well as the earth, is made on the assumption that the speed of light is infinite, observation will show that the eclipse occurs about

Fig. 36-16 Roemer's method of determining the speed of light.

1,000 sec later than the calculated time. The diameter of the earth's orbit around the sun is about 186,000,000 mi. If the difference between the observed time and the calculated time is ascribed to the finite speed of light, we find the speed of light to be about 186,000 mi/sec.

One of the earliest terrestrial determinations of the speed of light was made in 1849 by Fizeau, who timed the passage of a beam of light a distance of 8.633 km from a source to a mirror and then back to the source. On its way from the source the light passed through the space between two teeth on a wheel whose speed was adjusted so that, on its return, the light failed to pass through this space but hit the adjacent tooth and was eclipsed. In this experiment the wheel had 720 teeth and the light was eclipsed when the speed was 12.6 rps. In 1850, Focault measured the speed of light using a rotating mirror instead of a toothed wheel.

Some of the best determinations of the speed of light were made by Albert A. Michelson (1852–1931), who began his experiments in about 1878 and continued them for about 50 years. In one of Michelson's experiments, a beam of light was sent from Mt. Wilson to Mt. San Antonio and back again, a distance of about 22 miles, measured very accurately by the U. S. Coast and Geodetic Survey. The essential arrangement for this experiment is shown in Figure 36-17. An octagonal mirror M_1 is mounted on the shaft of a variable-speed motor so that it rotates about an axis through its center. Light from a source S strikes mirror M_1 at an angle of

Fig. 36-17 Michelson's method for measuring the speed of light.
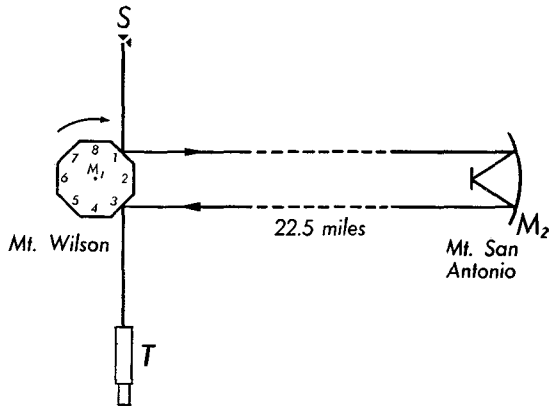
45° and is reflected from it to the distant mirror M_2 and back again, in such a way that when the octagonal mirror is stationary, the light is reflected from face 3 into the telescope. When the mirror is rotating, the image of the source is seen in the telescope when the time required for the light to traverse the path is equal to the time for face 2 to rotate into the position formerly occupied by face 3. In these experiments the angular speed of the mirror was about 530 rps. A measurement of the distance and the speed of the motor suffices to determine the velocity of light.

The speed of light in a material medium is less than its speed in vacuum. Focault placed a tube of water between the two mirrors and found that the speed of light in water is less than that in vacuum. Michelson used a tube 3 ft long and found the speed of light in carbon disulphide to be about four sevenths that of the speed of light in vacuum.

The presently accepted value for the velocity of light in vacuum is $c = 2.997923 \pm 0.000008 \times 10^{10}$ cm/sec. This is one of the most important constants of modern physics. Present-day methods for measuring the velocity of light use electronic devices rather than rotating mirrors to produce and detect very short bursts of light, but the basic concept in many of these experiments remains the same as that of Fizeau. In other methods

the velocity of light is inferred from the equation

$$c = \lambda f$$

and the measurement of λ and f of an electromagnetic wave. The precise knowledge of the velocity of light is used in radar, in which the distance of any object such as an airplane from a radar antenna is determined by measuring the time for a pulse of electromagnetic radiation to return to the antenna after reflection from the object. A very precise surveying instrument called the *geodimeter* is capable of measuring distances to an accuracy of 1 part in 1,000,000 by measuring the time interval between the radiation of a light beam modulated at a frequency of 10^7 cycles/sec and its detection after reflection from a distant mirror.

It is one of the cornerstones of Einstein's special theory of relativity that the velocity of light must have a constant value when measured by any observer, regardless of his velocity of translation. Near the turn of the last century, a number of experiments were conducted by Michelson, Morley, and many others in attempts to measure a difference in the velocity of light in the direction of the earth's motion and transverse to that motion. It was reasoned that light was propagated in a universal medium, called the *ether*, and that the velocity of light was a velocity with respect to the ether. In this case the velocity of light with respect to the earth would depend upon the velocity of the earth with respect to the ether. The velocity of light was found to be independent of its direction of propagation with respect to the earth or with respect to the stars. Einstein proposed his theory of relativity in an attempt to explain this result. If it were possible for an observer to find that the velocity of light, as he measured it, depended upon his own velocity, then the observer could determine his velocity simply by carrying out a measurement of the velocity of light, say in an airplane. Such a result would imply that motion was absolute rather than relative. To date, no such result has been obtained, and we must infer that all motion is relative motion.

Problems

36-1.   What is the solid angle subtended by a sphere 1 cm in radius at a distance of 5 m?

36-2. A distant object of circular outline subtends an angle of 1°. (a) What is the solid angle subtended by the object? (b) What is the cross-sectional area of the object if it is 3 m distant?

36-3. A sodium lamp emits essentially monochromatic light of wavelength 5,890 A. (a) What is the energy, in ergs, of one quantum of this radiation? (b) If the radiant power emitted by the lamp is 0.1 watt, what is the number of quanta radiated per second?

36-4. A point source of light whose luminous intensity is 2 candelas is placed 3 m above a horizontal table. The table is provided with a square hole of edge length 0.5 cm, whose center is 5 m from the light source. (a) Find the solid angle subtended by the hole at the light source. (b) Find the luminous flux passing through the hole.

36-5. A 25-watt tungsten-filament electric lamp operates at a luminous efficiency of 10.4 lumens/watt. (a) How many lumens of luminous flux does it radiate? (b) What is its efficiency in the production of light? (c) If we are sufficiently far away from the lamp that it may be approximated as a point source, what is its luminous intensity? (d) Assume that the bulb is spherical, 5 cm in diameter, and is perfectly diffusing, and neglect the area occupied by the base of the bulb. What is its luminance?

36-6. The bulb of Problem 36-5 is hung 4 ft above a desk top. What is the illuminance on the desk top at a point (a) directly beneath the lamp and (b) 5 ft from the lamp?

36-7. A lamp emits 100 lumens of luminous flux at a wavelength of 6,500 A. (a) What is the radiant power, in watts, emitted by the lamp? (b) The lamp is supplied with 500 watts of electrical power. What is its luminous efficiency?

36-8. Two sources of light are mounted 2 m apart on an optical bench, and a grease-spot photometer head is placed between them. One source is rated as 41.6 candelas. Determine the luminous intensity of the second source if the grease spot is observed to vanish when at a distance of 120 cm from it.

36-9. A lamp whose intensity is to be measured is placed 200 cm from a standard lamp rated at 450 lumens. Equal illuminances are produced by the two lamps when the Lummer-Brodhun photometer head is 60 cm from the standard source. Determine the luminous intensity of the test lamp.

36-10. Two lamps of luminous intensity 40 candelas and 60 candelas, respectively, are placed at opposite ends of a photometer bench 200 cm long. (a) Where will the photometer have to be placed to show equal illuminance from these two lamps? (b) Determine this illuminance.

36-11. A workbench 6 ft long and 3 ft wide is illuminated by two 100-watt tungsten lamps hung 3 ft above the center line of the bench, each lamp being 2 ft from the end of the bench, at the opposite ends. Compute the illuminance of the bench at a point (a) directly under one lamp, (b) at one corner of the bench, and (c) at the center of the bench.

36-12. The distance between Mt. Wilson and Mt. San Antonio is 35.426 km, and the angular speed of the motor in one of Michelson's experiments was 528.76 rps. Calculate the speed of light from these data.

36-13. If the price of electric power is 8 cents/kw hr, what is the daily cost of illuminating a room 20 ft long by 15 ft wide by 8 ft high with an average illumination of 10 lumens/ft^2 with (a) 100-watt tungsten lamps and (b) 40-watt fluorescent lamps? Assume that the room is illuminated 8 hrs a day, and that there is no reflection of light from the walls.