1.1 INTRODUCTION

1.1.1 Fundamental Nature of Light

Classically light is an electromagnetic wave consisting of waves of electric and magnetic fields. According to the Maxwell's equations of electricity and magnetism, the oscillating electric field induce oscillating magnetic field and oscillating magnetic field induce oscillating electric field. Due to mutual actions of oscillating electric and magnetic field the propagation of electromagnetic waves is self-sustaining and does not require a medium.

The electric and magnetic fields of an electromagnetic wave in vacuum are perpendicular to each other and perpendicular to the direction of the wave motion as shown in Fig. 1.1. These waves are also called transverse electromagnetic waves since the electric and magnetic fields oscillate in a plane perpendicular to the direction of the travel of the wave.

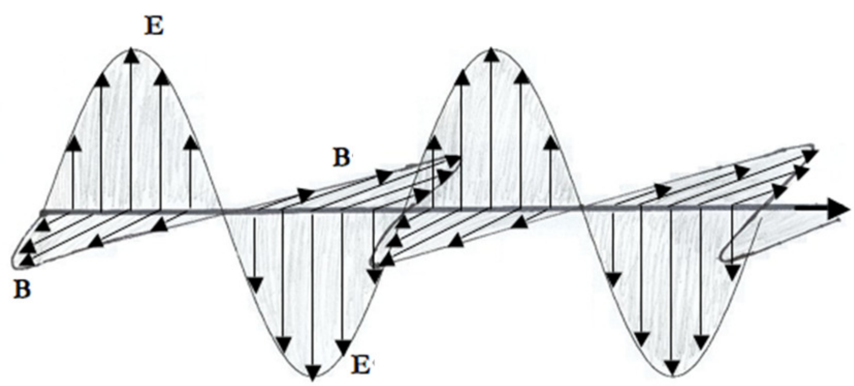

Figure 1.1: Plane Electromagnetic wave

Electromagnetic wave comes in a variety of frequencies as summarized in Fig. 1.2. Only a very small fraction of the wide range of the frequencies of electromagnetic spectrum is visible to the human eye where they produced the sensation of vision and color if the eye has the right receptors. Often the visible range of the electromagnetic spectrum is simply called light.

In the year 1900, Max Planck of Germany hypothesized that the energy contained in the electromagnetic waves is an integral multiple of a fundamental packet of energy energy for that light depending on the frequency. Planck hypothesized that each packet of energy in light of frequency f had energy equal to hf, where h is called the

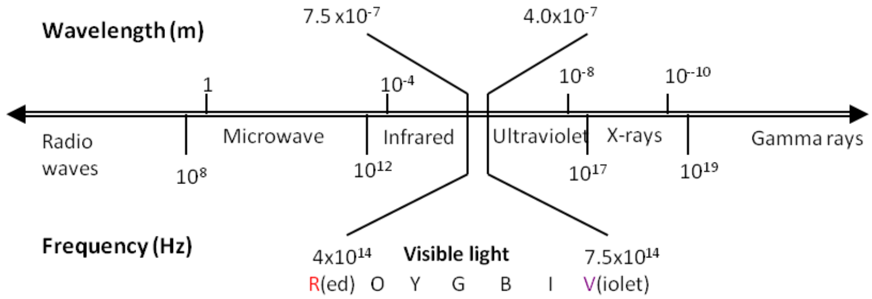

Figure 1.2: The electromagnetic spectrum. The wavelengths are for waves in vacuum.

Planck constant which has a value of 6.626×10^{-34} J.s.

$$E_{\text{packet}} = hf, \tag{1.1}$$

The energy in a beam of light wave of frequency f will be an integral multiple of

$$E = Nhf, \tag{1.2}$$

where N is a positive integer. Albert Einstein extended Planck's idea and reintroduced the particle picture of light. These particles of light, called corpuscles by Isaac Newton, are now called **photons**. Each photon carries energy $E = hf$ and momentum $p = hf/c$.

$$E_{\text{photon}} = hf, \tag{1.3}$$

$$p_{\text{photon}} = \frac{hf}{c}. \tag{1.4}$$

Since h is a small number, one photon has a very small amount of energy. Consequently, there are enormous number of photons in any reasonably macroscopic amount of energy. For instance, a 3-mW He-Ne red laser of frequency 4.74×10^{14} Hz emits approximately 10^{16} photons per second as the following calculation shows.

$$\begin{aligned} N &= \frac{\text{Power}}{\text{Energy of one photon}} = \frac{P}{hf} \\ &= \frac{3 \times 10^{-3}\ \text{J/s}}{6.626 \times 10^{-34}\ \text{J.s} \times 4.74 \times 10^{14}\ \text{Hz}} = 9.6 \times 10^{15}\ \text{per sec.} \end{aligned}$$

Due to the enormity of the number of photons in the ordinary light we do not perceive individual particles of light; instead, light appears to us as a continuum stream of energy. The subject of optics in which individual photons are important is called quantum optics and the subject in which there are too many photons and only an average effect is observed is called classical optics. In the present text, we will only study the classical aspects of light. The subject of classical optics is further divided into two parts: the ray optics and the wave optics.

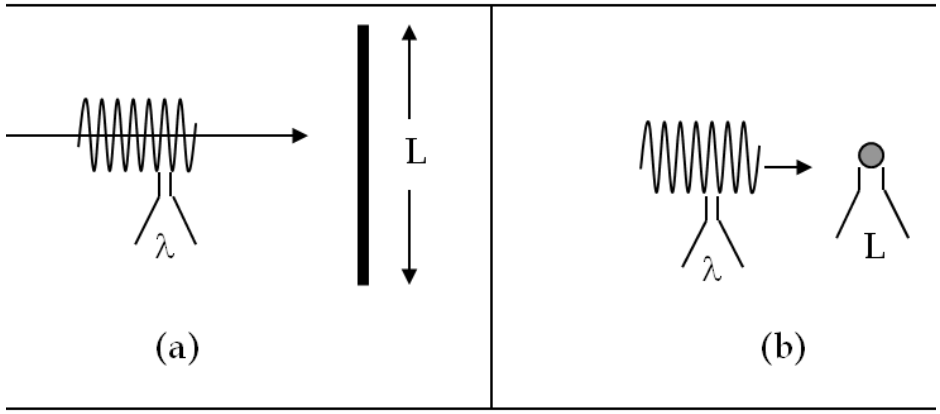

Figure 1.3: (a) Geometric optics situation applies when wavelength is much smaller than the dimensions of objects the light interacts with, and (b) Physical or wave optics situation applies when the wavelength of the light is of the same order as the dimension of the object.

1.1.2 Ray Optics and Wave Optics

What happens when an electromagnetic wave strikes an object? Light interacts with all ordinary matter through its electric and magnetic fields. Upon interaction with light, a material body re-radiates electromagnetic waves. To study these interactions it is important to divide the subject of optics into two categories depending upon the relative sizes of the wavelength of light (λ) and the smallest physical dimension of the material object (L) as shown in Fig. 1.3. If $\lambda << L$ then the wave can be treated as pencil rays. The domain of optics that falls in this range is called **geometric or ray optics**. Ray optics is very helpful in figuring out the direction of light beams but does not say anything about the intensity of light.

When light of wavelength is small compared to the dimensions of an opaque object, it forms a well-defined shadow behind the opaque object. On the other hand, if $\lambda \sim L$ or greater than L, then we cannot treat light as pencil rays any more and we must deal with the wave nature of light. The phenomena such as the diffraction of light arise in this domain and the subject is called **physical or wave optics**.

Although geometric optics can also be understood from the more fundamental subject of wave optics, it is far easier to apply, and when applicable, geometric optics is definitely preferred over the wave optics. Thus, when the red light of wavelength 700 nm strikes a lens of size 1 cm it is best to use rules of geometrical optics to figure out what will happen, but when the same light strikes a thin fiber of diameter 1000 nm you will have to use wave optics to understand what is going on.

1.1.3 Speed of Light

Perhaps the first attempt at measuring the speed of light was made by Galileo in early 1600s. Galileo and an assistant each carried a lantern with a shutter and placed themselves on different hilltops about a mile apart. They agreed beforehand that when Galileo opened the shutter, his assistant was to open his shutter as soon as he saw the light from Galileo's lantern. Galileo will then record the time for the round trip. He found no difference in the result from the result on the same experiment conducted with the lanterns only a few meters apart. From his experiments Galileo could not draw any conclusion about the speed of light because the speed of light is too great to be measured by his method. As a matter of fact, it takes only about 11 μs for light to travel the round trip between two hilltops separated by 1 mile while human reaction takes hundreds of milliseconds. Since the reaction time for Galileo and his assistant was of the order of hundreds of milliseconds, there was no way of determining the speed of light with the time measuring technique utilized by Galileo.

Of course if the distance for the travel of light in Galileo's experiment were large then we may be able to determine the speed of light by Galileo's method. Astronomical objects do provide large distances and could be used to deduce speed of light if we know the distance accurately. In 1675 the Danish astronomer **Ole Rømer** noticed something strange in the motion of the largest and brightest moon Io about the planet Jupiter. From his observations of the moon Io Rømer deduced that the time required for the light to travel a distance equal to the diameter of the orbit of the Earth about the Sun is equal to 16 minutes and 36 seconds.

The basic observations of Rømer are illustrated in Fig. 1.4. The moon Io goes behind the Jupiter in every orbit about the planet and an eclipse of Io is easily observed with good accuracy. The interval between the successive eclipses of Io gives a measure of its orbital time period. Rømer measured the time between successive eclipses to be 42 hours, 28 minutes and 36 seconds when Earth was at E in Fig. 1.4. He believed that from this period he would be able to make predictions about its position at any time. But the eclipse six months later, when Earth was at E$'$ appeared 16 minutes and 36 seconds later than predicted. Rømer interpreted this to mean that although the eclipse appeared at precisely the time he had predicted, light from

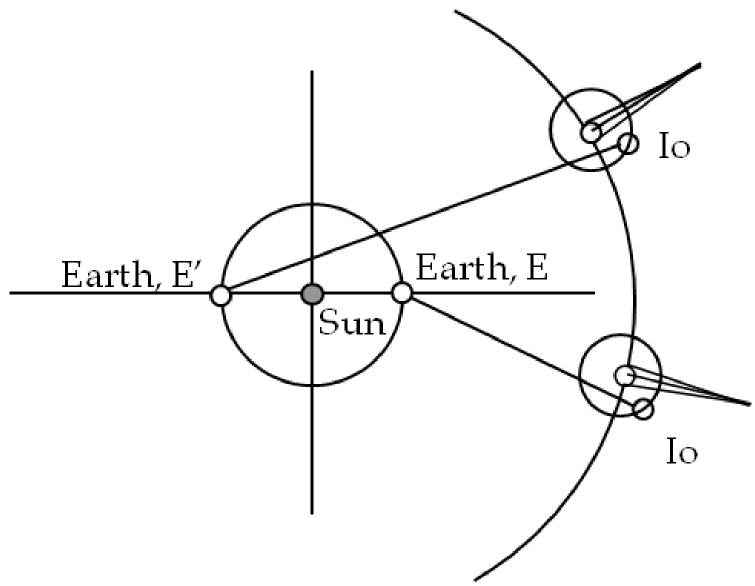

Figure 1.4: Illustrating Roemer's determination of speed of light based on observations made on Jupiter's moon Io.

Io took longer to get to E′ as compared to getting to E. Thus light traveled one whole diameter (EE′) of earth's orbit in 16 minutes and 36 seconds. From the estimate of the diameter of the orbit of Earth about Sun, which is approximately 280 million km, and Rømer's time delay, Christian Huygens estimated the speed of light (c) to be

$$c \approx \frac{280,000,000,000 \text{ m}}{996 \text{ s}} = 2.81 \times 10^8 \text{ m/s},$$

which is only about 6% off from the presently accepted value!

The first successful direct measurement of the speed of light was made by Armand Hippolyte Louis Fizeau (1819-1896) in 1849. Fizeau's experiment was similar in spirit to that of Galileo in that he measured time for a roundtrip for light. To be able to measure small time interval involved, Fizeau came up with an ingenious arrangement shown in Fig. 1.5. In **Fizeau's experiment**, light passed through a rotating cogwheel with toothed edges before being reflected off a mirror placed approximately five and half miles away. If the wheel was not rotating at the right speed, the returning light will strike a tooth in the wheel and will be blocked. But, if the cogwheel rotated at just the right speed, light would go out from one opening in the cogwheel and return though the next opening. From his measurements, Fizeau estimated the speed of light to be 3.13×10^8 m/s.

Jean Bernard Leon **Foucault** (1819-1868) improved on the apparatus of Fizeau by replacing the rotating cogwheel with a rotating plane mirror. A simple version of Foucault's experiment is shown in

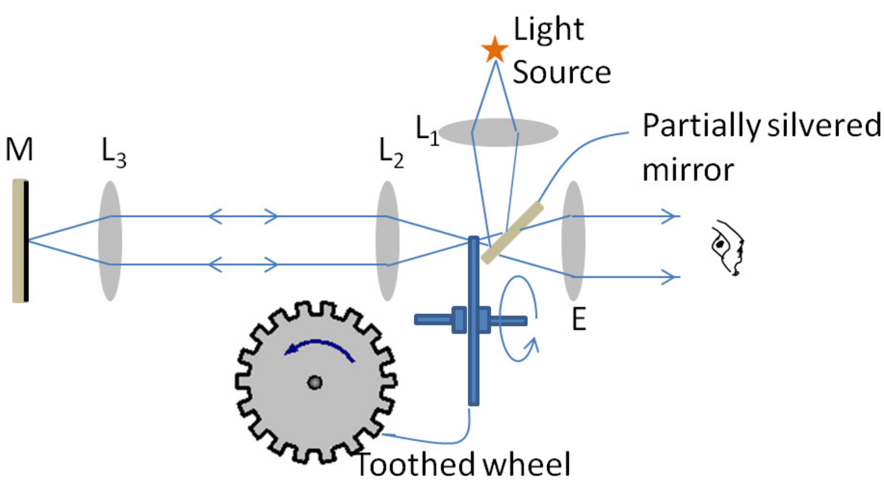

Figure 1.5: Schematic drawing of Fizeau's apparatus. The light from a source is focused on a toothed wheel by lens L_1 which is at the focal point of lens L_2 which makes the light paralell to the axis. The light then travels to the mirror M and reflected back. If the tooth is not blocking the ray, then the ray passes to the eyepiece E and to the eye. Let there be N teeth in the wheel. Let the total distance traveled by the light be $2d$. Suppose the light is leaving one opening in the toothed wheel makes it through the very next opening when the wheel rotates at the rate n revolutions per second. You can show that this will give the speed of light to be $2nNd$. In Fizeau's experiment values were $d = 8.63$ km, $N = 720$, $n = 25$ revs per second. This gave a value of 3.13×10^8 m/s for the speed of light.

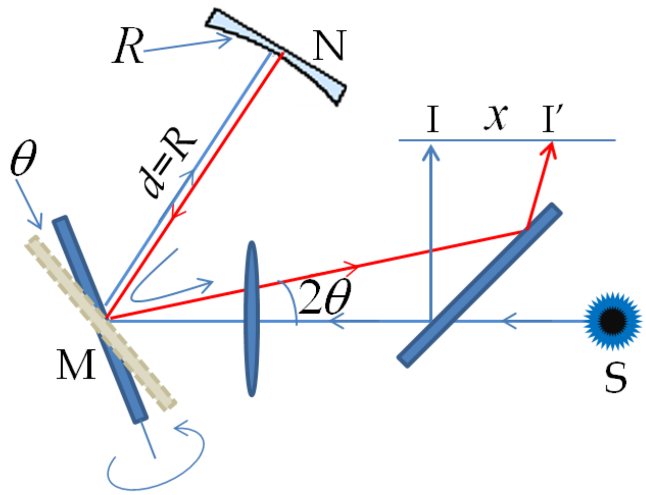

Figure 1.6: Foucault's apparatus.

Fig. 1.6. Light from a source S is is reflected from the rotating mirror M towards a concave mirror N. The reflected ray from N travels along the original path to M. If the mirror M is not rotating, then the return ray forms an image of the source at I. However, when the mirror M is rotating, then the reflected ray from the concave mirror finds the mirror M in a new orientation M′. The reflected ray from the new position of the plane mirror forms the image at I′. Foucault found that the mirror N with a radius of curvature of $R = 20$ m and a rate of rotation of 800 rev per sec for the mirror M, the image was displaced by $x = 0.7$ mm. This gave the speed of light 298,000 km/s, which is only 0.6% lower than the currently accepted value of 299,792,458 m/s.

In 1920's, **Albert Michelson** conducted experiments measuring the speed of light using a rotating prism as shown in Fig. 1.7. Michelson set his apparatus at Mount Wilson Observatory in Southern California and the reflecting mirror on the Lookout Mountain of Mount San Antonio, about 22 miles away. Careful measurements of Michelson led to a more precise value of the speed of light to be 299,796±4 km/s.

UNIT OF LENGTH

The measured speed of light in vacuum in the experiments mentioned above uses a standard meter for the distance traveled by light. The 1983 Conference Generale des Poids et Mesures turned the table around, and adopted an exact value of speed of light to be 299,792,458 m/s, and defined the unit of meter as the length of the path traveled by light in vacuum during a time interval of 1/299,792,458 of a

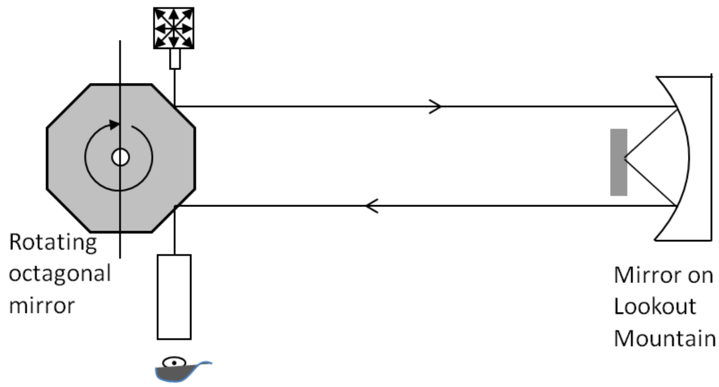

Figure 1.7: Michelson's apparatus on Mount Wilson observatory.

second.

$$\boxed{c = 299,792,458 \text{ m/s} \quad \text{(Exact)}} \tag{1.5}$$

With an exact value assigned to the speed of light, the unit of length now depends on the choice of the unit of time. Currently, the unit of time is defined in terms of the frequency of light emitted by an excited atom of Krypton.

1.1.4 Radiometry

Radiometry is the branch of optical physics that deals with the measurement of energy in light. The measurement of optical energy is an old subject and the physical quantities of interest and the methods for their measurements have evolved over time. Historically, the power of a light source was obtained by observing the brightness of the source. It turns out that the brightness perceived by the human eye depends upon the wavelength, i.e. the color of light, and differs from the actual energy contained in the light. Radiometry deals with the actual objective energy content rather than the subjective perception by a human.

Since the ordinary light has continuously flowing energy, the most basic quantity of interest is the amount of energy propagating per unit time, which is the power P of the light. We are often interested in power in a particular direction (Fig. 1.8). The amount of power emitted per unit solid angle of a light source is called its **radiant intensity** I_R. The SI unit of radiant intensity is Watts per steradian (W/sr). Let ΔP be the power of light in the solid angle $\Delta\Omega$, then the radiant intensity is given by

$$I_R = \frac{\Delta P}{\Delta \Omega} \quad \text{(Radiant Intensity)} \tag{1.6}$$

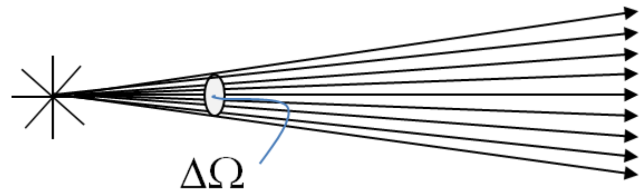

Figure 1.8: Radiant intensity is the power per unit solid angle.

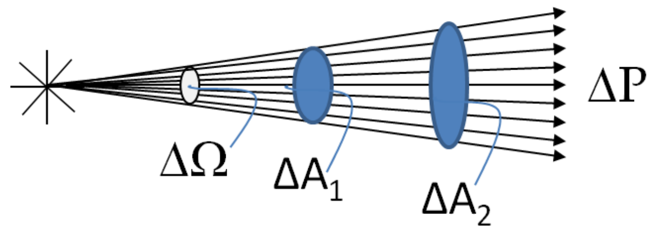

Figure 1.9: Irradiance at point is the power crossing a unit area perpendicular to light. Note the same power crosses may pass through two different areas corresponding to different irradiance at those locations.

If the source is isotropic, i.e., emits same power in all directions, then the total optical energy produced per second will be $4\pi I_R$.

The **intensity** of light I at a particular place, on the other hand, is the amount of average power that crosses a unit area perpendicular to the direction of the wave. The intensity of light is also called **radiant emittance** when light is emitted from a source and **irradiance** if light is incident upon a detector (Fig. 1.9).

Thus, if power ΔP is incident on a perpendicular area ΔA, then irradiance I is

$$I = \frac{\Delta P}{\Delta A} \quad \text{(Intensity or Irradiance)} \tag{1.7}$$

The unit of intensity in the SI system of units is Watts per square meter (W/m^2). Similarly, suppose light is emitted perpendicular to an area such that power ΔP is emitted from a perpendicular area ΔA, then the radiant emittance M of the source is defined as:

$$M = \frac{\Delta P}{\Delta A} \quad \text{(Emittance)} \tag{1.8}$$

From here on, we will use the same symbol I for both the irradiance and the radiant emittance. From the conservation of energy you can show that the intensity of light from a point source that emits light uniformly in all direction must drop off with the square of the distance from the source, since the same energy is spreading out over larger and larger areas as light moves out from the source.

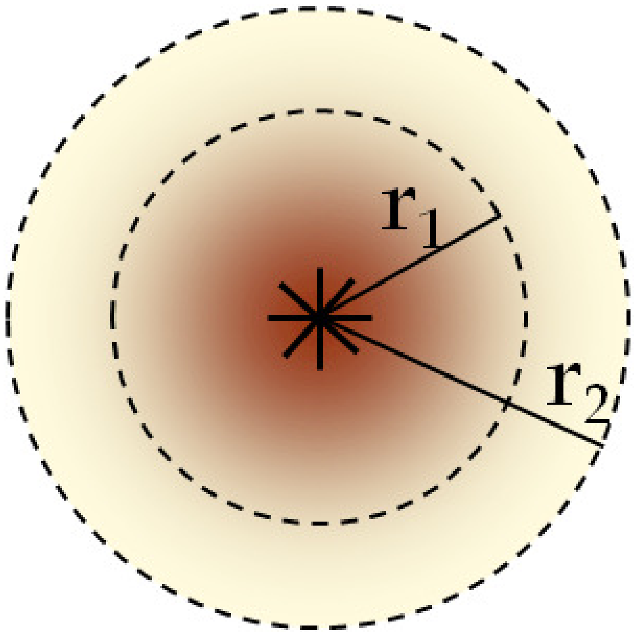

Figure 1.10: Intensity of light from a point source drops off as inverse square of distance.

Since the area of the spherical surface about a point source increases as the square the distance from the source, the intensity at distances r_1 and r_2 in Fig. 1.10 would be related by the following relation.

$$4\pi r_1^2 I_1 = 4\pi r_2^2 I_2 \implies \frac{I_2}{I_1} = \left(\frac{r_1}{r_2}\right)^2. \tag{1.9}$$

Most sources of light do not emit light equally in all directions; instead they emit more light in some directions than others. The quantity that gives both a measure of the intensity of light and its direction in space with respect to the source is called the **radiance**. The radiance is defined as the power per unit solid angle per unit normal area. It is usually denoted by the letter L.

$$L = \frac{\Delta P}{\Delta\Omega \Delta A} \quad \text{(Radiance)} \tag{1.10}$$

Light emitted by a source usually does not have the same power over different wavelength ranges. For instance, the sun emits more power in the blue-green color, of wavelength approx. 500 nm, than either blue or red. To study the wavelength-dependence of the intensity of a given light, one defines "density" of each quantity per unit wavelength. For instance, we define intensity of light in the range λ to $\lambda + d\lambda$ by

$$dI = I_\lambda d\lambda \tag{1.11}$$

where I_λ is the intensity per unit wavelength and dI is the intensity in the aforementioned range of wavelength. The total intensity is then obtained by integrating over wavelength. The quantity I_λ is important in spectroscopy where we study the distribution of light energy among different wavelengths, or alternately among different frequencies.

Example 1.1.1. The Irradiance of Sun. The irradiance of the sun light on earth is approximately 1.4 kW/m^2. (a) How much energy is incident on the Earth per day? (b) Find the intensity of light at the surface of the Sun. (c) Find the total energy in light emitted by the Sun in one earth day. Use the radius of earth $R_E = 6.37 \times 10^3$ km, the average Earth-Sun distance $r = 1.5 \times 10^8$ km and the radius of the Sun (R) equal to 6.96×10^5 km.

Solution. (a) The cross-section of Earth, which is a circle of radius R_E, collects light from the Sun. Since, the Earth is far away from the Sun, we can assume that all light is incident normally on the cross-section of Earth, which is a circle of radius R_E. Therefore, if we multiply the irradiance with the area of the circle, we will obtain the energy incident on the Earth per unit time. Hence, the energy incident on the Earth per day would be

$$\begin{aligned}\text{Energy} &= \pi R_E^2\ I\ T \quad (T = 1\ \text{day})\\ &= \pi \left(6.37 \times 10^6 \text{m}\right)^2 \times 1.4\ \text{kW/m}^2 \times 24 \times 3600\ \text{s} = 1.54 \times 10^{19} \text{kJ}.\end{aligned}$$

(b) Assuming the Sun to be isotropic source of light, the light intensity emitted by the Sun will drop as $1/r^2$ with r being the distance from the center of the Sun. Let I_0 and I be irradiance at the surface of the Sun ($r = R$) and a distance $r = r$ from the Sun respectively. Since, the light emitting from a spherical surface of radius R must pass through the spherical surface of radius r, we will have

$$I_0 R^2 = I r^2.$$

Now, we apply bthis to $r =$ the distance from the center of the Sun to Earth. This yields the irradiance at the surface of the Sun to be

$$I_0 = \left(\frac{r}{R}\right)^2 I = \left(\frac{1.5 \times 10^8\ \text{km}}{6.96 \times 10^5\ \text{km}}\right)^2 \times 1.4\ \text{kW/m}^2 = 6.5 \times 10^4\ \text{kW/m}^2.$$

(c) The energy leaving the Sun will be obtained by the intensity at the surface of the Sun and the total surface area of the Sun. Therefore, the energy of light leaving the Sun in all directions in time T will be

$$\text{Energy} = 4\pi R^2\ I_0\ T.$$

Putting in the numerical values we get the energy emitted in $T = 1$ Earth day to be

$$\begin{aligned}\text{Energy} &= 4\pi \left(6.96 \times 10^8 \text{m}\right)^2 \times 6.5 \times 10^4\ \frac{\text{kW}}{\text{m}^2} \times 24 \times 3600\ \text{s}\\ &= 3.4 \times 10^{28} \text{kJ}\end{aligned}$$

Extending the numerical example. You can show that the fraction of energy of the Sun received by the Earth is

$$\frac{R_E^2}{4r^2}.$$

1.1.5 Photometry

Radiometry gives us the objective measure of energy and power of light sources. However, human eye does not respond to all colors of light equally, and we perceive intensities differently than an objective instrument. For instance, experiments have shown that the eye is most sensitive to the yellow-green light than to the red and blue lights of the spectrum. Therefore, yellow-green light will appears brighter to our eyes than either the red or the blue light of the same intensity.

To take the difference into account, a new set of physical measures of light is defined for the visible light. These new measures are called photometric quantities. In photometry, power is weighted according to the human response by multiplying the corresponding quantity by a special function, called the $V(\lambda)$ function or the spectral luminance efficiency, whose value is between 0 and 1, and which tells us the approximate response of human eye to various wavelengths. The V-function was arrived at experimentally in 1924, and is an average response of a population of people in a wide range of ages. The astronomical instruments use a **V-filter** for photometry.

The units as well as the names of similar properties in photometry differ from those in radiometry. For instance, power is simply called power in radiometry, but it is called the luminous flux in photometry, and while the unit of power in radiometry is Watt, in photometry it is lumen. A lumen is defined in terms of a fundamental unit, called **candela**, which is one of the seven independent quantities of the SI system of units, viz. meter, kilogram, second, ampere, Kelvin, mole and candela. Candela is the SI unit of the photometric quantity called **luminous intensity** or **luminosity** that corresponds to the radiant intensity in radiometry. The following working definition was adopted for candela in 16th General Conference on Weights and Measures in 1979.

A monochromatic radiation source of frequency 540×10^{12} Hz is said to have a luminous intensity of one candela in a given direction if it emits $\dfrac{1}{683}$ watt of power per steradian in that direction.

Since there are 4π steradians in the full solid angle around a

Table 1.1: Radiometric and photometric quantities and units

	Radiometry		Photometry		
Definition	Name	Unit	Name	Unit	Unit Conversion
Power	Power	Watt (W)	Luminous flux Flux	Lumin (lm)	1 W = 683 lm
Power per unit unit solid angle	Radiant intensity	W/sr	Luminous intensity	Candela (Cd)	1 W/sr = 683 Cd
Power per unit area	Irradiance/ Emittance/ Intensity	W/m^2	Illuminance Illuminance	lm/m^2 = lux(lx)	1 W/m^2 = 683 lx
Power per unit area per unit solid angle	Radiance	W/(m^2 sr)	Luminance	Cd/m^2 = nit	1 W/m^{2}sr = 683 nit

source, the total power emitted by a one-candela source is $\frac{4\pi}{683}$ W, which is equal to 1 **lumen**, if the source emits radiation isotropically in all directions.

$$\boxed{1 \text{ lumen} = \frac{4\pi}{683} \text{ W.}}$$

Table 1.1 shows the units of radiometry and photometry side by side. Various sources of light are often labelled with **luminance**, which is the photometric term for the total power radiated per unit are per unit solid angle. Table 1.2 gives approximate luminance of several sources of light.

1.1.6 Optical Media

When light interacts with a material it can be absorbed, reflected, scattered or transmitted. If a significant part of light is transmitted such that a clear image can be seen through it then the material is called a **transparent medium** or simply the medium. On the other hand, if light passes through the medium but one cannot see a clear image, the medium is called **translucent**. In a translucent medium, light scatters around and takes a circuitous path. Finally, the medium is called **opaque** if light cannot pass through it at all. It is difficult to label a medium absolutely transparent or opaque, since the transparency depends on the wavelength of light. There are some media, such as glass and lucite, that are transparent to the visible light to a large extent, and they are often considered transparent

Table 1.2: Approximate luminances of various sources

(Ref: National Physical Laboratory, UK.)

Light Source	Luminance (nits)
Atomic fission bomb (0.1 millisecond after firing)	2×10^{12}
Lightning flash	8×10^{10}
Sunlight on the surface of Earth (at meridian)	1.6×10^{9}
Photoflash lamps	2.5×10^{8}
60 W bulb	1.2×10^{5}
Sperm candle flame	1×10^{4}
Clear blue sky	4×10^{3}
Moonlight on Earth	3×10^{3}
Starlit sky	5×10^{-4}

enough for optical devices.

The speed of light varies among transparent media. The ratio of the speed of light in vacuum (c) to the speed in a medium (v) is called the **refractive index** (n) of the medium.

$$\boxed{n = \frac{c}{v}.} \tag{1.12}$$

An important consequence of different speeds in different media is that, although the frequency of light does not change as light moves from one medium into another, the wavelength of the light will in general be different in different media as shown schematically in Fig. 1.11. If the wavelength is λ_1 in a medium of refractive index n_1 and the same light has a wavelength λ_2 in another medium of refractive index n_2, then

$$\boxed{n_1\lambda_1 = n_2\lambda_2.} \tag{1.13}$$

A transparent medium is often designated by its refractive index. For a quick reference, the refractive indices of some commonly occurring materials are given in Table 1.3.

Refractive index of a medium, however, is different for different color or frequency light. For instance, the refractive index of the flint glass for the red light is 1.62 while for the violet light it is 1.67. This difference is responsible for the separation of colors when sun light passes through a prism. The dependence of refractive index on frequency is called **dispersion** of light. The refractive index values given in Table 1 are for the yellow light.

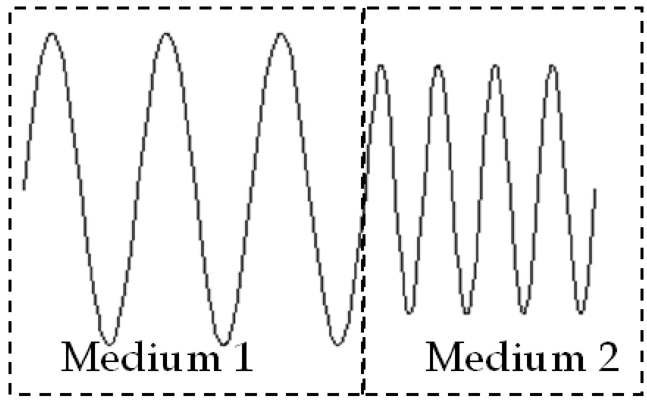

Figure 1.11: Different wavelength in different media for same light. The amplitude is shown smaller in the second medium to show that some of the incident light is reflected at the interface. The reflected wave is not shown here.

Table 1.3: Refractive indices of some common substances (λ= 589 nm, yellow light)

Material	Refractive index
Vacuum	1.00
Air	$\approx$ 1.00
Water	1.33
Plexiglas (plastic)	1.51
Crown glass	1.52
Flint glass	1.58

Example 1.1.2. Speed and wavelength of light in glass. Find (a) the speed and (b) the wavelength of light in glass if its wavelength in vacuum is 632.8 nm. Use $n = 1.55$ for the refractive index of glass for the given light.

Solution. (a) We divide the speed of light in vacuum by the refractive index to obtain the speed of light in the medium.

$$v = \frac{c}{n} = \frac{3 \times 10^8 \text{ m/s}}{1.55} = 1.94 \times 10^8 \text{ m/s}.$$

(b) To find the wavelength in the medium we note that frequency of light does not change when it passes from one medium into another. Let λ_0 be the wavelength of the light in vacuum and λ be the wavelength of the same light in the medium. The, we will have

$$f = \frac{c}{\lambda_0} = \frac{v}{\lambda}$$

Since $v = c/n$, we obtain

$$\lambda = \frac{\lambda_0}{n} = \frac{632.8 \text{ nm}}{1.55} = 408.3 \text{ nm}.$$