

Unit 20

ELECTROMAGNETIC WAVES

Is the wavelength the distinguishing characteristic of color?

STUDENT LEARNING OUTCOMES



The students will:

- ✓ [SLO: P-10-E-94] state the main regions of the electromagnetic spectrum in order of frequency and in order of wavelength
- ✓ [SLO: P-10-E-95] state that the speed of all electromagnetic waves in: (a) a vacuum is 3.0×10^8 m/s
- ✓ (b) air is approximately the same as in a vacuum.
- ✓ [SLO: P-10-E-96] Describe the applications of electromagnetic waves in society.
- ✓ [SLO: P-10-E-97] Describe the damage caused by electromagnetic radiation.
- ✓ [SLO: P-10-E-98] Explain qualitatively, how scattering of light by molecules in the air give the sky its blue color during the day and its shades of red during sunset.
- ✓ [SLO: P-10-E-99] State that theoretically light can also considered to be made of massless particles that carry energy and momentum called 'photons'.

Electromagnetic waves are essential to our lives. The exploration of these waves started with the work of Michael Faraday and James Clark Maxwell. Their experiments showed the link between electricity and magnetism, forming a key theory of electromagnetic waves in Physics. Since then, electromagnetic waves have played a vital role in human progress and advancement in technology, from sending wireless information to studying the far off galaxies. They connect everything, bridging what we can see and what we cannot. It is now our duty to explore these waves, for helping us to gain a better understanding of the universe and ourselves.

20.1 ELECTROMAGNETIC SPECTRUM

Electromagnetic waves are transverse waves generated by the oscillations of electric and magnetic fields that are mutually perpendicular to each other, as illustrated in Figure 20.1. These

waves do not require a medium for propagation, enabling them to travel through the vacuum of space. The direction of wave propagation is perpendicular to the vibrations of both the electric and magnetic fields. Electromagnetic waves are categorized into different types based on their frequency, wavelength, or energy levels, collectively forming the electromagnetic spectrum.

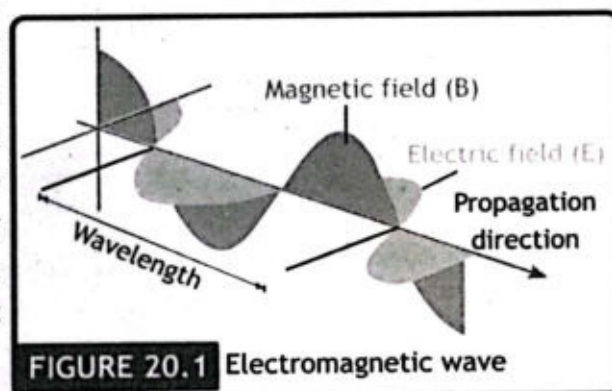


FIGURE 20.1 Electromagnetic wave

The electromagnetic spectrum can be defined as:

'The range of different frequencies and wavelengths of electromagnetic waves is called the electromagnetic spectrum'. This includes radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays as given in table 20.1.

TABLE 20.1 SPECTRUM OF ELECTROMAGNETIC WAVES

Type of radiation	Wavelength range	Frequency range (Hz)
Radio	$> 1 \text{ mm}$	$< 3 \times 10^{11}$
Microwave	$1 \text{ mm} - 25 \text{ } \mu\text{m}$	$3 \times 10^{11} - 3 \times 10^{13}$
Infrared	$25 \text{ } \mu\text{m} - 2.5 \text{ } \mu\text{m}$	$10^{13} - 4 \times 10^{14}$
Visible	$750 \text{ nm} - 400 \text{ nm}$	$4 \times 10^{14} - 7.5 \times 10^{14}$
Ultraviolet	$400 \text{ nm} - 1 \text{ nm}$	$10^{15} - 10^{17}$
X-Rays	$1 \text{ nm} - 1 \text{ pm}$	$10^{17} - 10^{20}$
Gamma Rays	$< 10^{-12}$	$10^{20} \times 10^{24}$

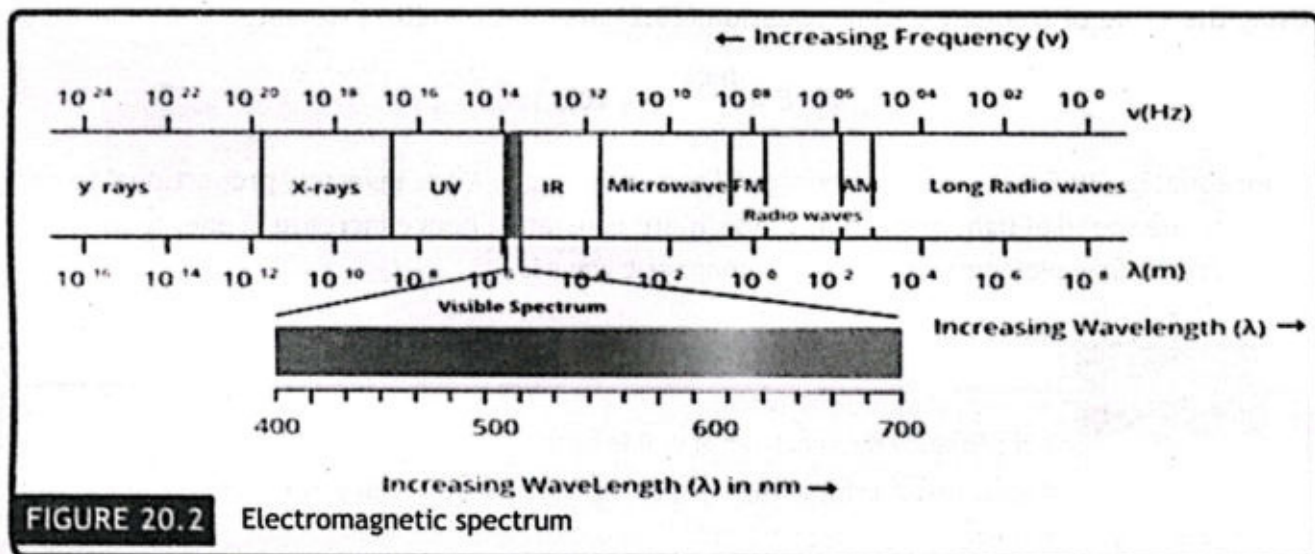


FIGURE 20.2 Electromagnetic spectrum

In a vacuum, electromagnetic waves travel at the speed of light. The speed of light in the vacuum is a universal constant and is denoted by 'c' whose value can be given as ' $c = 3 \times 10^8$ m/s'. The speed of light does not remain the same in mediums as it slows down due to interaction of light with the its particles, however in air it is approximately same as that of vacuum.

The electromagnetic spectrum consists of a span of all electromagnetic radiations (waves) which further contains many sub ranges which are commonly known as portion of the electromagnetic radiation as shown in figure 20.2. The visible light which is a portion of electromagnetic spectrum is divided into sub ranges i.e. the colors of light like red, orange, yellow, green, blue and violet etc. We can study the spectrum of light with the help of a prism or diffraction grating.

The relation between energy 'E' frequency 'f' and the wavelength ' λ ' can be found by Max Plank's equation:

$$E = hf \quad \text{--- (20.1)}$$

Here 'h' is the Plank's constant whose value is ' 6.63×10^{-34} Js'.

From the equation 20.1 it is clear that frequency 'f' and energy 'E' are directly proportional to each other hence increase in frequency will result in an increase in energy of the electromagnetic waves. As we know that speed, wavelength and frequency are related as:

$$c = f\lambda \quad \text{or} \quad f = \frac{c}{\lambda} \quad \text{--- (20.2)}$$

Here 'c' is the speed of light whose value is ' 3×10^8 m/s'.

Equation 20.2 shows that frequency 'f' and wavelength ' λ ' are inversely proportional to each other as the speed of light is constant in vacuum, hence increase in frequency will result in a decrease in wavelength of the electromagnetic waves.

Using the value of frequency from equation (20.2) in equation (20.1) we get:

$$E = \frac{h \cdot c}{\lambda} \quad \text{--- 20.3}$$

From equation 20.3 it is clear that energy 'E' and wavelength 'λ' are inversely proportional to each other as the speed of light in vacuum 'c' and 'h' are constants, hence increase in energy will result in a decrease in wavelength of the electromagnetic waves.

MINI LAB



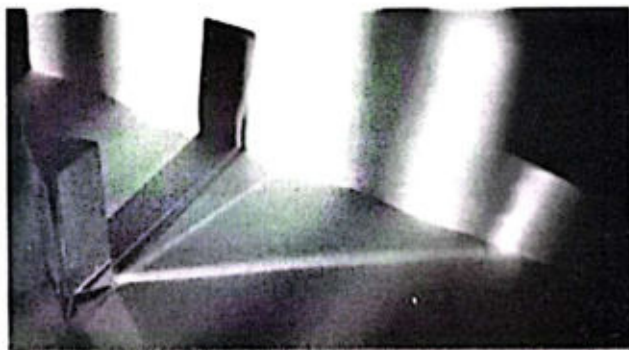
Aim: To study the spectrum of visible light.

Apparatus: A prism, white paper, light coming through a window or a white light source.

Performance: To perform the activity for studying the spectrums of visible light, you have to do the following tasks:

- Take a prism which has two triangular faces and three rectangular faces as shown below in the figure.
- Cover the window of your room such that the covering has a small portion from which light can enter into the room.
- The sunlight from that small portion coming into the room is white light (which is not a pure color but a mixture of many colors).
- If you do not have the facility of light coming from the window you can use some artificial source of white light like a torch.
- The spectrum of white light can be seen by placing a prism in the path of the light such that one of its rectangular faces is facing towards the incident light.
- You will observe that after passing through the prism the white light splits into its component colors, as the prism has the property of bending the light from its straight line path due to difference of speed of light in air and in glass and also due to difference of wavelengths of the components of the white light.
- The spectrum of the sunlight is shown here:

Conclusion: from the above project we learnt that the white light coming from the Sun is actually a mixture of different wavelengths of different colors. Due to different wavelengths each component after passing through the prism deviates at different extent which splits all the constituent colors of white light.



Example 20.1

Find the energy range for the infrared, visible and ultra-violet for their corresponding maximum and minimum wavelengths.

GIVEN: From table 20.1:

For Infrared radiation:

Maximum Wavelength ' λ_L ' = 250 μm ,

Minimum Wavelength ' λ_S ' = 2.5 μm

For visible radiation:

Maximum Wavelength ' λ_L ' = 750 nm,

Minimum Wavelength ' λ_S ' = 400 nm

For ultraviolet radiation:

Maximum Wavelength ' λ_L ' = 400 nm,

Minimum Wavelength ' λ_S ' = 1 nm

REQUIRED:

For Infrared radiation:

Maximum Energy ' E_{max} ' = ?,

Minimum Energy ' E_{min} ' = ?

For visible radiation:

Maximum Energy ' E_{max} ' = ?,

Minimum Energy ' E_{min} ' = ?

For ultraviolet radiation:

Maximum Energy ' E_{max} ' = ?,

Minimum Energy ' E_{min} ' = ?

SOLUTION:

To find the value of energy we use the equation:

$$E = \frac{h c}{\lambda}$$

For Infrared radiation:

The maximum energy corresponds to smallest wavelength hence:

$$E_{\text{Max}} = \frac{h c}{\lambda_S} = \frac{(6.63 \times 10^{-34} \text{ Js}) (3 \times 10^8 \text{ ms}^{-1})}{(2.5 \times 10^{-6} \text{ m})}$$

$$E_{\text{Max}} = 7.96 \times 10^{-20} \text{ J} \quad \text{ANSWER}$$

The minimum energy corresponds to largest wavelength hence:

$$E_{\text{min}} = \frac{h c}{\lambda_L} = \frac{(6.63 \times 10^{-34} \text{ Js}) (3 \times 10^8 \text{ ms}^{-1})}{(250 \times 10^{-6} \text{ m})}$$

$$E_{\text{min}} = 7.96 \times 10^{-22} \text{ J} \quad \text{ANSWER}$$

For visible radiation:

The maximum energy corresponds to smallest wavelength hence:

$$E_{\text{Max}} = \frac{h c}{\lambda_S} = \frac{(6.63 \times 10^{-34} \text{ Js}) (3 \times 10^8 \text{ ms}^{-1})}{(400 \times 10^{-9} \text{ m})}$$

$$E_{\text{Max}} = 4.97 \times 10^{-19} \text{ J} \quad \text{ANSWER}$$

The minimum energy corresponds to largest wavelength hence:

$$E_{\text{min}} = \frac{h c}{\lambda_L} = \frac{(6.63 \times 10^{-34} \text{ Js}) (3 \times 10^8 \text{ ms}^{-1})}{(750 \times 10^{-9} \text{ m})}$$

$$E_{\text{min}} = 2.65 \times 10^{-19} \text{ J} \quad \text{ANSWER}$$

For ultraviolet radiation:

The maximum energy corresponds to smallest wavelength hence:

$$E_{\text{Max}} = \frac{h c}{\lambda_S} = \frac{(6.63 \times 10^{-34} \text{ Js}) (3 \times 10^8 \text{ ms}^{-1})}{(1 \times 10^{-9} \text{ m})}$$

$$E_{\text{Max}} = 1.99 \times 10^{-16} \text{ J} \quad \text{ANSWER}$$

The minimum energy corresponds to largest wavelength hence:

$$E_{\text{min}} = \frac{h c}{\lambda_L} = \frac{(6.63 \times 10^{-34} \text{ Js}) (3 \times 10^8 \text{ ms}^{-1})}{(400 \times 10^{-9} \text{ m})}$$

$$E_{\text{min}} = 4.97 \times 10^{-19} \text{ J} \quad \text{ANSWER}$$

These are the energy ranges in joules for the infrared, visible and ultra-violet for their corresponding maximum and minimum wavelengths.

UNIT OPENER



Every primary color has its unique wavelength. You can say that the wavelength is the finger print of every primary color. A color can be recognized by its wavelength and no two (different) colors have the same wavelength.

But in case of secondary colors like white which is you can say a mixture of different colors do not have particular wavelength. In spite of it such colors have many wavelengths in them which can be separated with the help of prism or raindrop into its constituent colors to form a rainbow as shown in the figure.



20.2 APPLICATIONS OF ELECTROMAGNETIC WAVES

The electromagnetic spectrum has a wide range of electromagnetic waves from very long radio waves to the very short gamma rays. These incredible waves play an essential role in various scientific, medical and technological applications in our everyday lives.

20.2.1 APPLICATIONS OF RADIO WAVES

Radio waves have the longest wavelengths in the electromagnetic spectrum. Without radio waves it would not be possible to send and receive information as easy as it is. Radio Waves are used in the working of television, mobile phones, wireless network, GPS receivers, wireless clocks and even small items like small door openers.

A. Radio and Television Broadcasting: Radio and television broadcasting are essential components of modern communication, utilizing radio waves to transmit audio and video signals from broadcasting stations directly into our homes. The radio waves carry coded information (like

POINT TO PONDER



At atomic and subatomic levels and even for the energy of electromagnetic radiation we do not use the joule as the unit for energy. We need some small unit for measuring energy at those levels. Electron-volt is a smaller unit of energy which can be used for energy of electromagnetic radiations.

We can convert energy from joules 'J' into electron-volts 'eV' by simple dividing the energy by the magnitude of charge on single electron as:

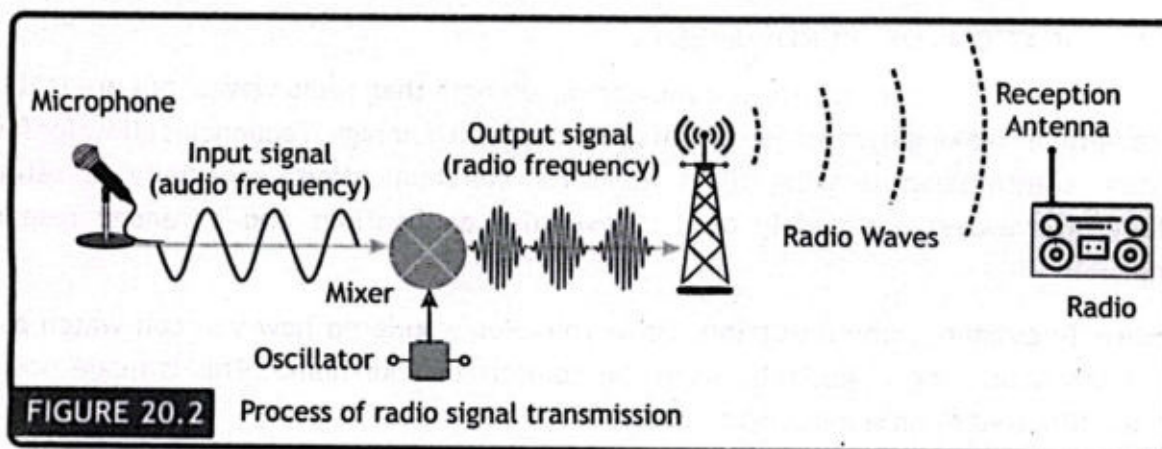
$$1 \text{ J} = \left(\frac{1}{1.6 \times 10^{-19}} \right) \text{ eV} = 6.25 \times 10^{18} \text{ eV}$$

audio and video signals) from broadcasting antennas to our devices, which then decode and show the content.

This process starts with the generation of content at radio and TV stations, ranging from news and music to entertainment and educational content. Once the content is ready, it is encoded into a format suitable for transmission. This encoding process involves converting the audio and video signals into a series of coded information.

The encoded signals are then transmitted from broadcasting antennas, which are strategically located to cover wide geographical areas. These antennas emit radio waves, as the radio waves propagate, they can be received by various devices, such as radios, televisions, and smartphones. Each of these devices is equipped with a tuner that can detect specific frequencies corresponding to the broadcasting station as illustrated in figure 20.2.

When such a device picks up these radio waves, it involves decoding the received signals. This process is carried out by the device's internal circuitry, which interprets the coded information and converts it back into audio and video formats.



B. Astronomy: Astronomical objects with changing magnetic fields can emit radio waves. The study of these radio waves from space is known as radio astronomy. By analyzing the radio waves from these sources, scientists can gain valuable insights into the composition, structure, and motions of celestial bodies in the universe.

You may be familiar with the sighting of the moon for Ramadan or eid using optical telescopes. However, sometimes the moon cannot be observed due to



FIGURE 20.3 Radio telescope

POINT TO PONDER

Have you ever wondered how scientists uncover the secrets of substances without even touching them? Spectroscopy makes this possible! It demonstrates how electromagnetic waves interact with matter, allowing us to understand the hidden structures and behaviors of atoms and molecules.

Why do only specific waves get absorbed while others pass through? Consider how energy differences between electronic states lead to this unique interaction—an amazing process that helps us uncover the secrets of the universe!

obstacles like clouds or bright sunlight. In such cases, radio telescopes offer a significant advantage, as their observations are unaffected by sunlight, clouds, or rain. One limitation of radio telescopes, however, is that radio waves are much longer than visible light waves. To achieve image resolutions comparable to those of optical telescopes, radio telescopes (like the one shown in Figure 20.3) need to be significantly larger in size.

20.2.2 APPLICATIONS OF MICROWAVES

Microwaves have a higher frequency and shorter wavelength than radio waves, but are still low-energy radiations, making them generally safe for humans. Their high frequencies allow for faster information transmission, making them ideal for communication, especially in satellite technology. Microwaves are widely used in everyday applications and advanced research, including:

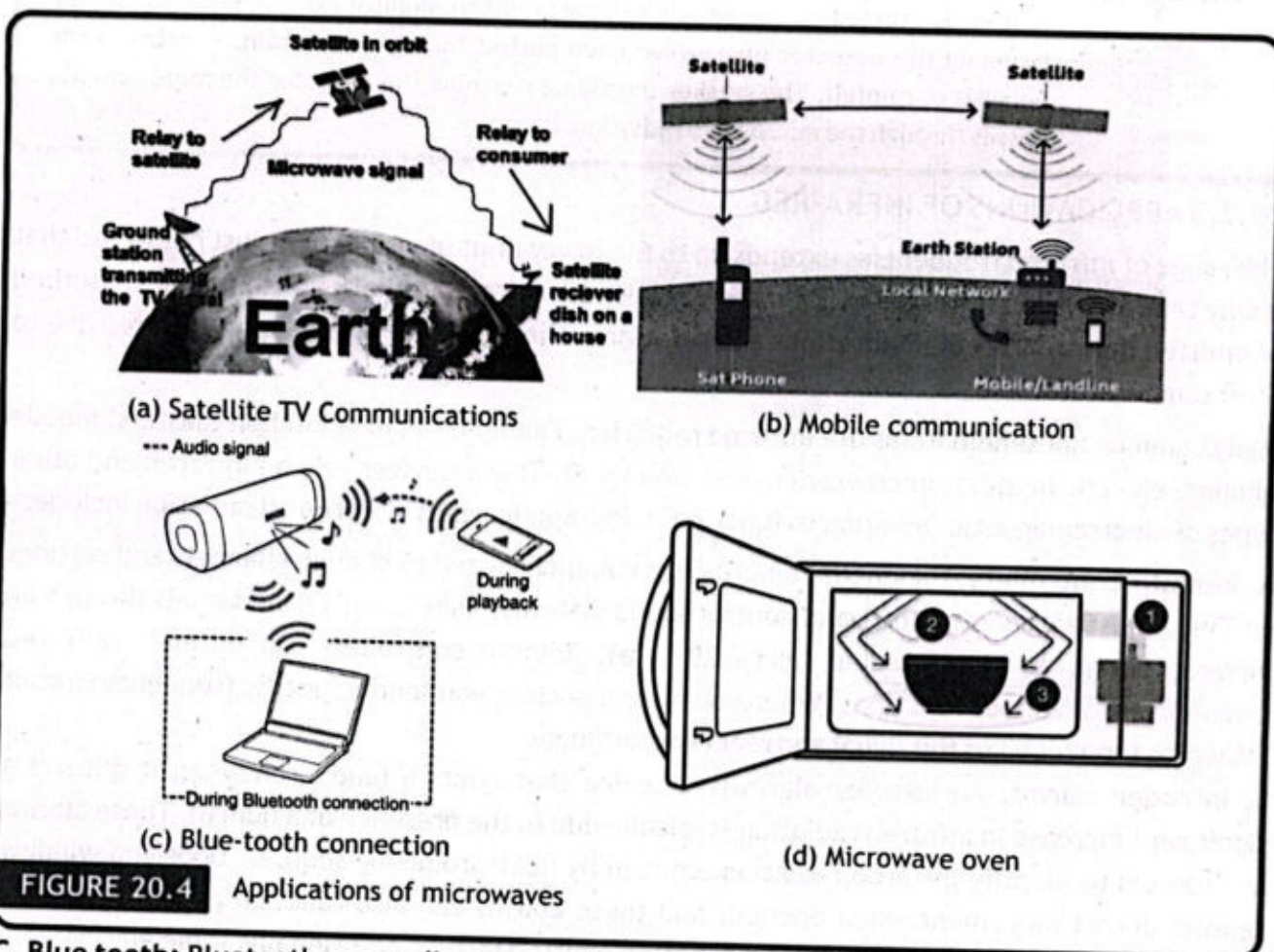
A. Satellite Television Communication: Have you ever wondered how you can watch a live cricket match happening in Australia from the comfort of your home? This is made possible through satellite television communication.

Microwaves, with their high frequency and shorter wavelength, can easily travel through the Earth's atmosphere. In satellite communication, television signals are transmitted via microwaves to a satellite in space. The satellite amplifies these signals and retransmits them back to Earth, enabling coverage in areas where terrestrial transmission cannot reach. Dishes and other receiving antennas then pick up these signals, as illustrated in Figure 20.4 (a).

It is important to note that satellite television communication often requires more than one satellite to ensure uninterrupted coverage across different regions.

B. Mobile Phones: Mobile phones communicate to a mobile phone tower using radio waves then mobile phone towers communicate with satellites using microwaves. Microwaves are used as they can pass through the atmosphere. The signal can be sent to a satellite and used to communicate around the world. The mobile signals are sent to the satellite by microwaves and

these signals are interchanged between satellites and on Earth stations as shown in figure 20.4 (b).



C. Blue tooth: Bluetooth uses radio waves and microwaves to transmit information between two devices directly. It uses weaker waves which use less power to generate them and makes the Bluetooth a particularly useful technology for battery powered devices. Those weaker waves also mean that Bluetooth typically works only over short distances less than 30 feet or 9 meters. A typical Bluetooth connection is shown in figure 20.4 (c). Bluetooth connection between two devices will stay active as long as they remain within range without the need for a router or any other intervening device.

D. Microwave Oven: Microwave ovens are used to cook and heat the food evenly and efficiently. They are called microwave oven as they use microwave in their working. Microwaves cause the molecules in food to vibrate which create heat to cook the food. The different parts of microwave work together to cook food properly. A typical consumer microwave oven uses 2.45 GHz frequency and the wavelength of 12.2 cm and can be shown in figure 20.4 (d).

SCIENCE
TIDBITS

Microwaves traversed through the atmosphere will be absorbed by the water. This process is utilized by the weather department to monitor rain. If weak signals are reaching the detector microwave have passed through more rain. It helps in the analysis of rainfall. The weaker the signal reaching the detector the more rain has passes through the microwave radiation.

20.2.3 APPLICATIONS OF INFRA-RED

The range of infrared frequencies extends up to the lower limit of visible light just below red that is why they are called infra-red which means below red. Infrared radiation is commonly absorbed or emitted during molecular vibrations and rotations. Therefore, all objects emit infrared due to their temperature.

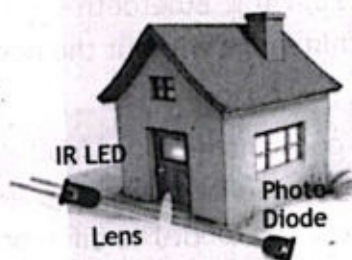
Many common household items use infrared radiation. Examples include kitchen toasters, mobile phones, electric heaters, microwave ovens, and Wi-Fi. These devices rely on infrared and other types of electromagnetic radiation to function. Some applications of infra-red radiation include:

A. Remote Controllers: Handheld 'remotes' are commonly used to change channels and settings on TVs, adjust air conditioners, and control sound systems. They usually send signals through an infrared beam, as illustrated in figure 20.5 (a). Remote controllers use different infrared frequencies for various functions. When you press a button, you send a specific frequency to your TV, which then receives the signal and reacts accordingly.

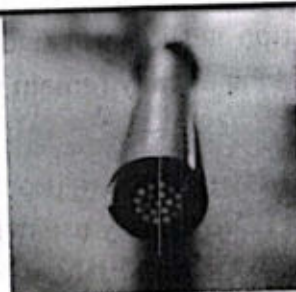
B. Intruder alarms: An intruder alarm is a device that emits a loud siren when it detects a significant increase in infrared radiation, typically due to the presence of a human. These alarms use sensors to identify infrared radiation emitted by heat-producing sources. Door and window sensors detect movement when opened, and these alarms can also function as fire alarms by detecting the large amounts of infrared radiation emitted by fire. Additionally, some alarms work using an LED and photodiode circuit, where the continuous infrared beam is disrupted by movement, breaking the circuit and triggering the alarm, the setup for such an alarm is shown in figure 20.5 (b).



(a) Remote controller



(b) Intruder alarm



(c) IR Optical fiber



(d) Thermal imaging

FIGURE 20.5 Applications of infra-red radiations

POINT TO PONDER



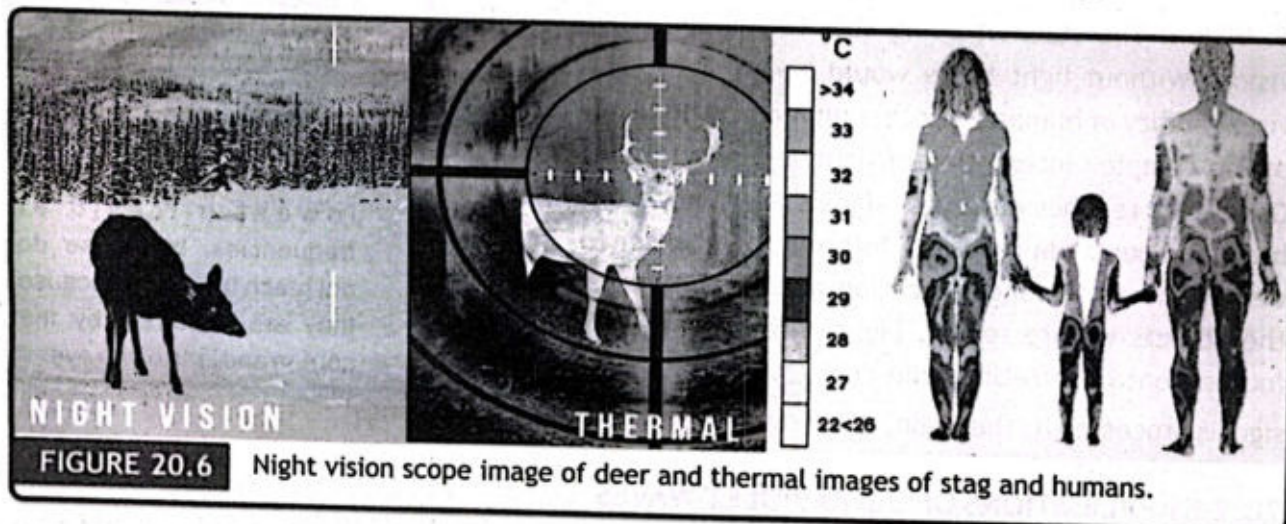
Reconnaissance satellites can detect buildings, vehicles and even individual humans by their infrared emission. Such satellites were used for military purposes in Afghan war. More mundanely we use infrared lamps which are also called as quartz heaters to warm us because we human absorb infrared better than our surroundings.



C. Optical Fibers: Optical fibers are thin strands of glass or plastic with double refractive indices. Light or infrared radiation entering the core reflects from the core-cladding boundary due to total internal reflection, allowing it to travel through the core at the speed of light. Ordinary light, laser light, and infrared radiation are used in optical fibers. Infrared radiation is particularly advantageous because its wavelength has low absorption in glass optical fibers, enabling long-distance data transmission with minimal power loss as shown in figure 20.5 (c).

D. Thermal Imaging: Thermal imaging involves converting infrared radiation (heat) emitted by objects into visible images using a thermal camera. This technology is highly effective in penetrating smoke, dust, aerosols, and clouds, making it useful in various conditions both during the day and at night as shown in figure 20.5 (d).

E. Night Vision: Infrared radiation makes the night vision possible as the night vision scopes can detect the infrared emitted by various warm objects including humans and converts it to visible light as shown in figure 20.6. The Sun radiates with a 6000 K surface temperature in which about half of the solar radiations reaching on the Earth is in the infrared region with most of the rest in the visible part of the spectrum and a relatively small amount in the ultraviolet region.



20.2.4 APPLICATIONS OF VISIBLE LIGHT

Visible light is the narrow segment of the electromagnetic spectrum to which the normal human eye responds. The part of spectrum which is known as visible light with the colors associated with pure wavelengths is shown in figure 20.7.

Red light has the lowest frequency and longest wavelength while violet has the highest frequency and smallest wavelength in visible spectrum. Visible light is the most prominent aspect of electromagnetic radiation in our lives and we enjoy

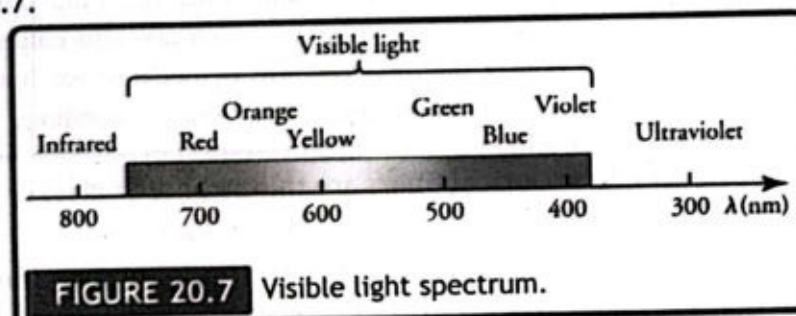


FIGURE 20.7 Visible light spectrum.

the beauty of nature through visible light. Among many uses we are discussing only two uses of visible light spectrum as:

A. Photography: In photography, visible light plays a pivotal role in capturing images. Cameras are designed to mimic the human eye's ability to detect and focus on visible light. Photographic sensors and film capture the light reflected or emitted by the subject, which is then processed to create an image. Different wavelengths of visible light are responsible for the colors we see in photographs. Advances in photographic technology have enabled high-resolution, color-accurate images that are used in everything from art and media to scientific research and documentation. A visible light camera is shown in figure 20.17.

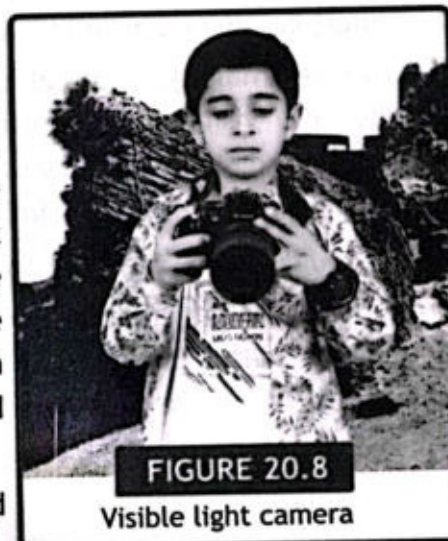


FIGURE 20.8

Visible light camera

B. Vision: The state of being able to see something is called vision. Without light there would be no sight. The visual ability of human and other animals is the result of the complex interaction of light, eyes and brain. Once light reaches our eyes, signals are sent to our brain and our brain reads the information in order to detect the appearance, location and movement of the objects we are seeing. Light enters the eye, is focused onto the retina, and converted into neural signals processed by the brain, allowing us to perceive our surroundings!

POINT TO PONDER



The retina of our eyes actually responds to the lowest ultraviolet frequencies, but these do not reach the retina because they are absorbed by the cornea and lens of the eye.

20.2.5 APPLICATIONS OF ULTRAVIOLET WAVES

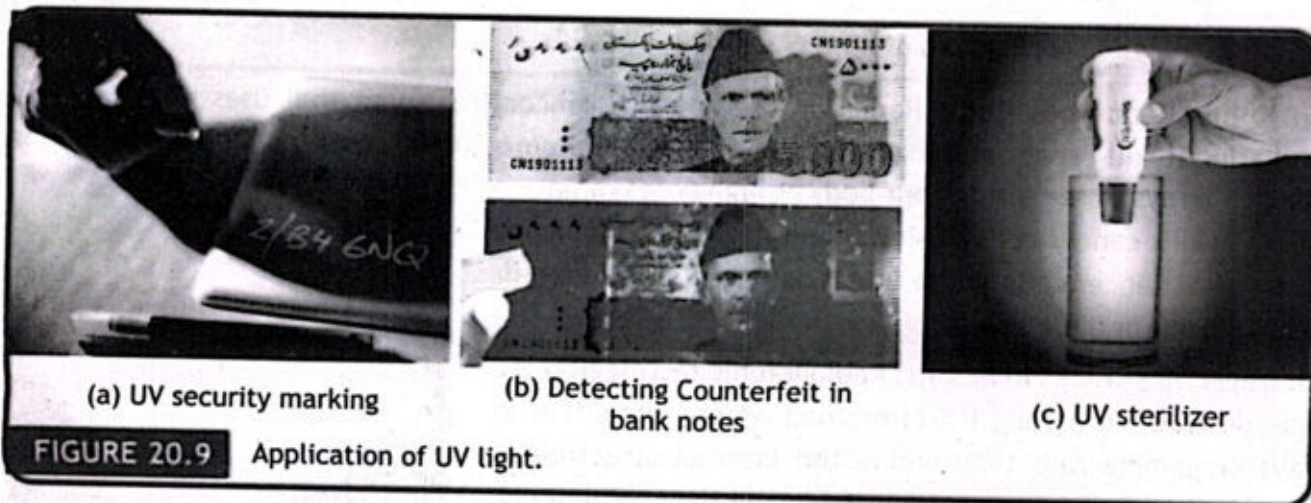
Ultraviolet means 'above violet'. The frequency of ultraviolet radiations extends upward from

violet the highest frequency in visible spectrum. Solar ultraviolet are further subdivided into three regions ultraviolet-A from 320 to 400 nm, ultraviolet-B from 290 to 320 nm and ultraviolet-C from 220 to 290 nm ranked from long to short wavelengths. Most ultraviolet-B and all ultraviolet-C are absorbed by the ozone (O_3) molecules in the upper atmosphere resulting 99% of the solar ultraviolet radiations reaching the Earth's surface are ultraviolet-A. Some practical applications of UV light are:

A. Security Marking: An ultraviolet watermark is included on many sensitive documents like credit cards, driver's licenses and passports to help prevent frauds. The watermark can only be seen when viewed under ultraviolet emitting light source. The ink used in this process do the fluorescence (a process in which any material absorbs radiations of high energy and frequency like ultraviolet and re-emit low energy radiations like visible light). The ink absorbs ultraviolet radiations and then emits visible light which can be seen by human eye as shown in figure 20.9 (a).

B. Detecting Counterfeit Bank Notes: Currencies of various countries including Pakistan's bank notes have an image as well as many multicolor fibers that are visible only under ultraviolet light to thwart counterfeiters. The whole process in this system is the same as in security marking by fluorescence we can see the fibers and images on the bank notes to check their reliability as shown in figure 20.9 (b).

C. Sterilizing Water: Sterilizing water means to purify the water from harmful microorganisms like bacteria and viruses etc. An ultraviolet purifier treats micro-biologically unsafe water with germ killing ultraviolet light. An ultraviolet sterilizer is shown in figure 20.9 (c). Ultraviolet sterilization is considered to be one of the most effective water treatment methods for disinfection. It quickly sterilizes the water and not any need of additional chemicals, it is cost effective and there is no danger of overdosing.

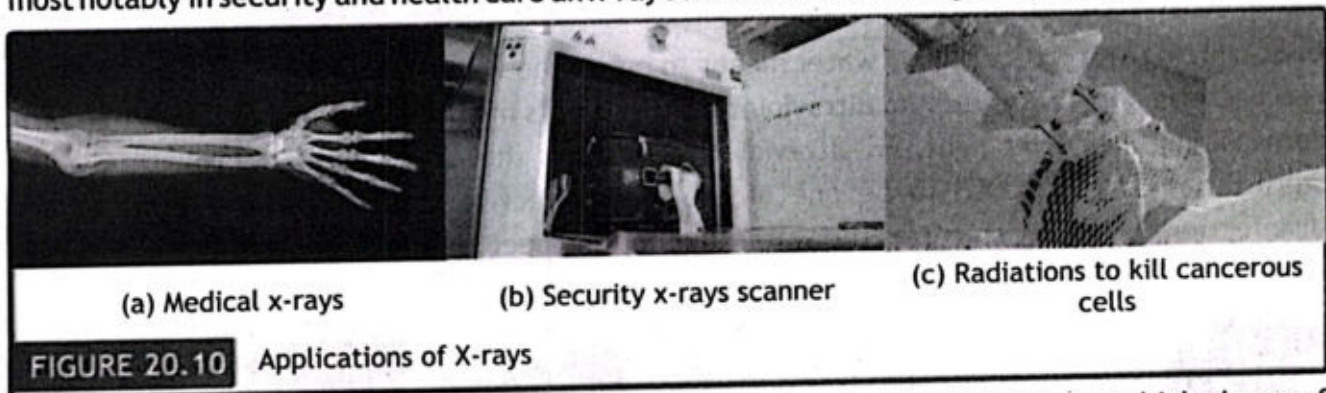


20.2.6 APPLICATIONS OF X-RAYS

The low range of x-rays overlaps with the ultraviolet and high energy x-rays overlaps gamma rays (in low energy region). X-rays have many medical, technological and social applications some of them are:

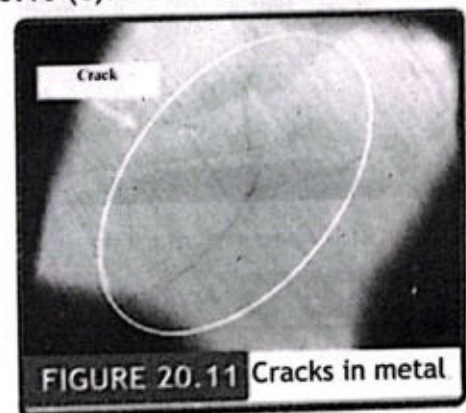
A. Medical Imaging: The widest use of x-rays is for imaging objects that are opaque to visible light such as human body. The ability of x-rays to penetrate matter depends on density, so an x-ray image can reveal very detailed density information. The fracture of bones can be found by using x-rays as shown in figure 20.10 (a). The use of x-rays technology in medical science is called radiology. X-rays are widely available and used extensively in medical diagnostics. An x-rays can affect a photographic film. When a person stands in front of a photographic film x-ray is bombarded on his/her body to form an image.

B. Security Scanners: X-rays scanners are used to detect threats such as weapons or explosives that a person could be carrying under their clothing, the scanners used for this purpose use very low energy x-rays that are reflected back to the scanner which shows any metal object. Along with this x-rays scanning technology is also used in many industrial and commercial applications most notably in security and health care an x-ray scanner is shown in figure 20.10 (b).



C. Killing Cancerous Cells: Radiation therapy is a cancer treatment that uses high doses of radiation to kill cancer and shrink tumors as shown in figure 20.10 (c). At low doses radiation is used in x-rays to see inside your body. At high doses radiation therapy kills cancer cells or slows their growth by damaging their DNA. Cancer cells whose DNA is damaged beyond repair stop dividing or die.

D. Detecting Cracks in Metals: Radiographic testing (RT) is a non-destructive testing (NDT) method which uses either x-rays or gamma rays to examine the internal structure of manufactured components identifying any flaws or defects. In the radiographic testing the test part is placed between the



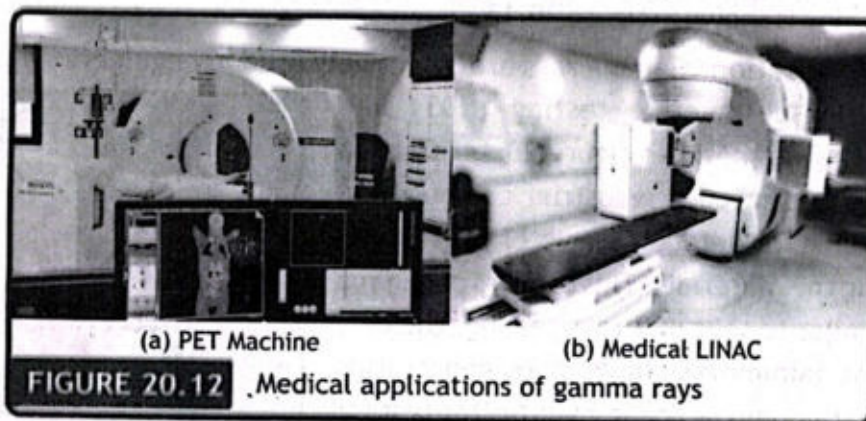
radiation source and the film (or detector). Because x-rays are hardly scattered at the crack, a region where the crack exists is dark and that region where the crack does not exist is light on the image of the scattered x-rays. The crack can be detected from the dark and light regions on the image. As cracks make the portion of metal thinner as compared to other regions and hence more x-rays will pass through the cracks to form an image illustrating the exact size and location of the crack as shown in figure 20.11.

20.2.7 APPLICATIONS OF γ -RAYS

Gamma rays are the most energetic form of electromagnetic radiation, possessing the shortest wavelength. As a type of nuclear radiation, they are emitted from the nucleus of a heavy atom. Due to their high energy, gamma rays are highly penetrating, capable of passing through many materials that block other types of radiation. Few applications of gamma rays are:

B. Medical Treatment: Gamma rays are really useful in medicine for both diagnosing and treating diseases. In the realm of nuclear medicine, healthcare professionals utilize radioactive materials that emit gamma rays. These materials are often introduced into the body through injections or ingested in small amounts. Once inside, the radioactive substances accumulate in specific organs or tissues, depending on their chemical properties.

Specialized imaging equipment, such as gamma cameras or positron emission tomography (PET) scanners, is then employed to detect the gamma rays emitted from these radioactive materials. This imaging technique allows doctors to visualize the internal structures of the body in real-time, providing critical insights into the functioning of various organs.



In addition to diagnostic applications, gamma rays are also pivotal in the treatment of cancer through a process known as radiation therapy. In this context, high-energy gamma rays are precisely targeted at cancerous cells to destroy them or inhibit their growth. This treatment can be administered externally, using machines that generate gamma rays, or internally, through a method called brachytherapy, where radioactive sources are placed directly within or near the tumor. The ability of gamma rays to penetrate tissues makes them particularly effective in targeting tumors while minimizing damage to surrounding healthy cells.

C. Sterilizing Food and Medical Equipment: Gamma rays are effectively used for sterilizing both medical equipment and food. Gamma radiation sterilization involves exposing medical products to gamma rays. The radiation source typically used is the Cobalt-60 isotope which emits gamma radiations in

POINT TO PONDER



Gamma Knife is a non-invasive brain surgery that uses targeted gamma radiation to treat tumors, lesions, and abnormal tissues. This method effectively eliminates or reduces these tissues while protecting surrounding healthy tissue, making it a safer treatment option.

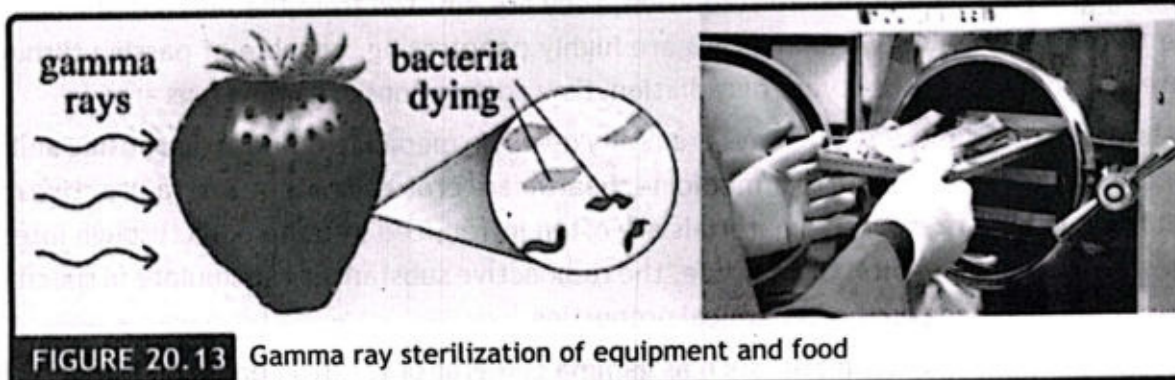


FIGURE 20.13 Gamma ray sterilization of equipment and food

the process to destroy any microorganism present. Similarly for food sterilization we again use Cobalt-60 which is used to kill bacteria, mold, parasite and insects in the food. The most important aspect of this process is that the food itself does not become radioactive. A gamma ray sterilization machine is shown in figure 20.13.

D. Engineering Application: Gamma rays are effectively used in engineering for many purposes particularly in non-destructive testing (NDT) and radiographic testing as shown in figure 20.14. Gamma rays are employed to inspect industrial components, welds and structures for defects, cracks or other flaws without damaging the materials. This process of gamma rays testing is similar to that of x-rays testing, the only difference is that gamma rays have more penetrating power than the x-rays and hence it gives better test for hard materials. In radiography gamma rays penetrate the materials to reveal hidden flaws.



FIGURE 20.14

Gamma ray radiographic testing

20.3 RISKS ASSOCIATED WITH ELECTROMAGNETIC WAVES

The electromagnetic waves along with their many applications have some hazards associated with them. Every type of electromagnetic waves has its particular hazards. Normally majority of the electromagnetic waves in smaller amounts are safe to human and the atmosphere but their

higher intensities can produce damages for the living organism on Earth and its atmosphere. Some of the hazards of electromagnetic spectrum are listed in table 20.2.

TABLE 20.2 ELECTROMAGNETIC WAVES: A HAZARD ANALYSIS

EM wave	Potential Hazards
Radio waves	- High-energy radio waves can cause tissue heating, leading to burns or heat-related injuries. - Continuous exposure can interfere with biological systems and medical devices like pacemakers and hearing aids.
Microwaves	- Microwaves can cause tissue damage, especially in sensitive organs like the eyes, potentially leading to cataracts. - Exposure to high-powered microwaves may result in burns or heat stress and can interfere with implanted medical devices.
Infrared	- Prolonged exposure to infrared waves can cause thermal damage, resulting in burns or overheating. - High-intensity infrared radiation over time can cause eye damage, skin aging, and diseases.
Visible light	- Direct viewing of intense visible light over extended periods can cause eye strain and retinal damage. - Long exposure to bright artificial lighting can disrupt biological rhythms and, in extreme cases, cause burns or permanent eye injuries.
Ultraviolet	- Long-term exposure to UV waves damages skin cells, causing sunburn and increasing the risk of skin cancers. - UV radiation can harm the eyes, leading to cataracts and other vision impairments, and weaken the immune system.
X-rays	- X-rays cause ionization that can lead to tissue damage, cell mutations, and a high risk of cancer. - Frequent or high-dose exposure can cause burns, cataracts, and acute radiation sickness affecting overall health.
γ -rays	- Gamma rays cause cell mutations, leading to cancer or death due to their penetrative and ionizing nature. - Prolonged exposure leads to acute radiation sickness and poses environmental and health threats through nuclear accidents or improper disposal.

Ionizing radiation refers to electromagnetic waves that have enough energy to remove tightly bound electrons from atoms, creating ions. This can lead to various chemical and biological changes in living tissues. Among the electromagnetic (EM) spectrum, ultraviolet (UV) rays, X-rays, and gamma rays are ionizing radiation, differing primarily in their energy levels and wavelengths.

UV rays occupy the part of the EM spectrum with wavelengths shorter than visible light but longer than X-rays. Prolonged exposure to UV radiation can cause skin cancer, cataracts, and other health issues. X-rays have shorter wavelengths and higher energy compared to UV rays. The ionizing power of X-rays can cause cellular damage, increasing the risk of cancer with excessive exposure.

Gamma rays are at the high-energy end of the EM spectrum, with the shortest wavelengths and highest frequencies. Gamma rays have significant ionizing power, capable of penetrating almost any material. This makes them both a powerful tool in medical treatments, such as radiotherapy for cancer, and a considerable hazard in terms of radiation exposure. The intense ionizing effect of gamma rays can cause severe cellular and DNA damage, necessitating strict safety protocols in environments where gamma rays are present.

Lower-energy radiation such as visible light, infrared, microwaves, and radio waves lack sufficient energy to ionize atoms and are generally considered non-ionizing. Thus, they are less harmful in terms of causing immediate biological damage. It is essential to protect oneself from excessive exposure to ionizing radiation, especially X-rays and gamma rays. Shielding, limiting exposure time, and maintaining a safe distance from radiation sources are crucial preventive measures.

20.4 SCATTERING OF LIGHT

Light scattering occurs when light waves bounce off particles in a medium in different directions. The amount of scattering depends on the particle size and the light's wavelength; shorter wavelengths scatter more, while longer wavelengths scatter less and travel straighter. For effective interaction, the light's wavelength must be similar in size to the particles. Sunlight contains almost all wavelengths in the visible spectrum, including shorter wavelengths like blue and violet, as well as longer wavelengths like orange and red.

20.4.1 BLUE COLOR OF SKY

The light coming from the Sun has many wavelengths among them the blue color is present in the major percentage of the lower wavelengths. With the wavelength of the light the scattering efficiency of the small molecules in the atmosphere decreases. The Sun radiates its light which when enters into the atmosphere of the Earth scattered due to the air molecules, dust particles

and water vapors. The major components in the atmosphere are the gases like Oxygen and Nitrogen which cause the major scattering of light. As the sizes of molecules of these gases are small and are comparable to the size of region of smaller wavelengths mainly blue with indigo and violet hence these wavelengths suffers the most interactions with the molecules of the gases and reflect around due to scattering. While the region of larger wavelengths of visible light do not suffer such scattering as their wavelengths are larger than the molecules of the gases and they pass straight through the atmosphere. In upper atmosphere we see scattering of smaller wavelengths which give the appearance of blue color in upper atmosphere which is known as blue sky. This phenomenon is shown in figure 20.15. From figure it can be seen that larger wavelengths (red, orange, yellow etc.) pass through the atmosphere without scattering appreciably while the smaller wavelength (blue, indigo, violet etc.) of light

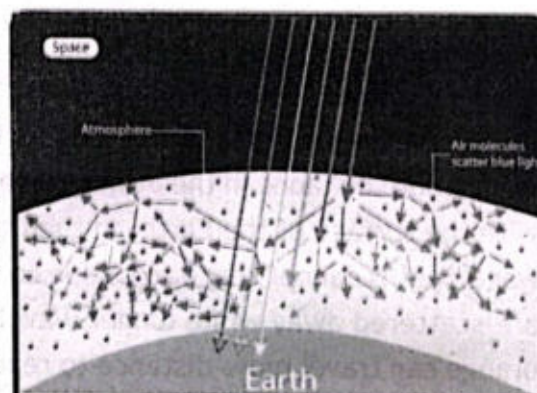


FIGURE 20.15 Blue color of sky

CASE STUDY

A Clear Summer Day and a Beautiful Sunset:

Imagine a summer day at the beach. The sky is bright blue and looks clear and vibrant. But as the sun sets, the sky turns shades of orange, pink, and red, creating a beautiful, colorful scene.

Can you think why does this happen?

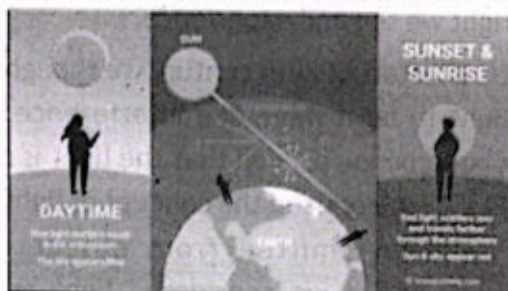
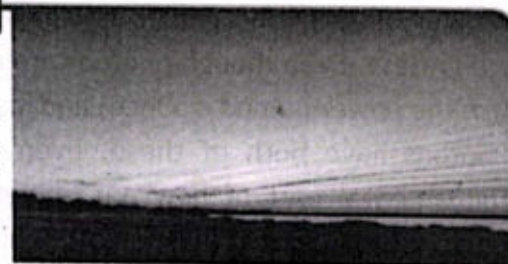
Explanation

This color change is due to the way sunlight interacts with the atmosphere of the Earth. Sunlight contains all colors, which means it is a mix of different wavelengths of light.

1. **During the Day:** When sunlight reaches Earth's atmosphere, it interacts with the tiny gas molecules in the air. These molecules scatter the sunlight in all directions. Blue light, with its shorter wavelength, scatters more than other colors like red and green. This scattered blue light reaches our eyes from all directions, making the sky appear blue.

2. **At Sunset:** As the sun moves lower on the horizon, sunlight has to pass through more of the atmosphere to reach us. By the time it gets to our eyes, most of the blue and violet light has scattered out in different directions. This leaves behind more of the red and orange wavelengths, which are longer and scatter less, creating the warm colors of sunset.

This effect, known as Rayleigh scattering, explains why we see different colors in the sky at various times of the day. It's a perfect example of how the behavior of light changes what we see in the natural world.



scattered in all directions filling the sky with a blue hue.

20.4.2 RED SKY AT DUSK

In the evening and in the morning as the Sun light has to travel more distance in the atmosphere due to its low angle with the surface of the Earth. In such situation the smaller wavelengths cannot reach to us due to more scattering and are scattered away while longer wavelengths like red and orange can travel more distance to reach us. This results in

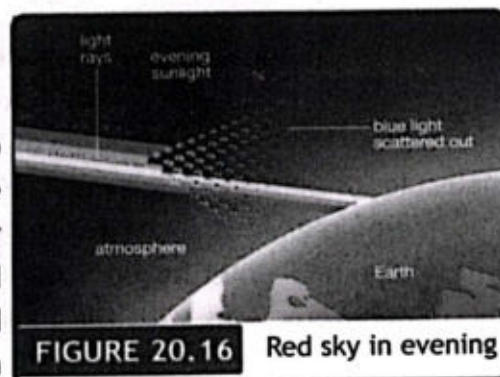


FIGURE 20.16 Red sky in evening

the warmth. Reddish hues we see during sunset as the Sun's light passes through more air molecules before reaching our eyes. The phenomenon of red sky in evening is shown in figure 20.16, which shows at smaller angles blue light scattered out and red light reaches to us. The same phenomenon is the early morning's sunrise time the sky appears reddish.

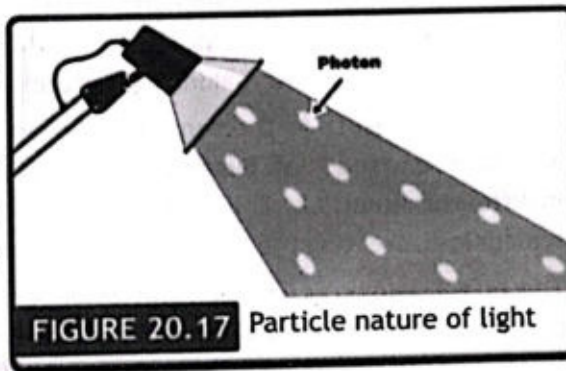
20.5 NATURE OF LIGHT

Imagine light as a stream of tiny, super-fast bullets. These "bullets" are called photons. Unlike regular bullets, photons do not have any mass. That means they are incredibly light, almost weightless. Even though photons are massless, they still carry energy and momentum. Energy is like the power behind a punch, and momentum is like the force that keeps a moving object going. Photons have both of these, even without any mass. This might seem strange, but it's a fundamental part of how our universe works. Scientists have done experiments that prove photons behave like particles with energy and momentum. So, light might seem like a continuous wave, but it's actually made up of these tiny, massless particles called photons (as shown in figure 20.17). They're like the building blocks of light, carrying energy and momentum that make up the light we see and experience.

Up till start of 20th century we thought light as a wave only because we got many evidences about light to be a wave like interference, reflection, refraction, diffraction and polarization, such phenomenon proved that the light is a wave. However, at the beginning of the 20th century, Max Planck introduced the concept of light having a particle nature. He suggested that the behavior of radiation emitted from objects could only be explained if we considered light as tiny packets of energy, which he called "quanta of light."

He explained the light to be composed of tiny massless particles called "photons" which carry some energy and momentum but no charge. The energy of photon can be given by equation 20.1 as:

$$E = hf$$



Similarly the momentum of a photon can be given by the equation 20.1 as:

$$p = \frac{h}{\lambda} = \frac{h f}{c} \quad \text{--- 20.4}$$

A photon is a fundamental particle and quantum of the electromagnetic field, carrying energy and momentum without mass, always traveling at light speed in a vacuum. As the basic building blocks of light, photons are classified as elementary particles. This raises the question of whether light is a wave or a particle, a puzzle addressed by Louis De Broglie's theory of light's dual nature, which states that light exhibits both properties.

Example 20.2

You are using a radiation monitor which gives you a signal of some radiations received. The wavelength of those radiations was 200 nm. Find the frequency, momentum and energy of the radiation signals.

GIVEN:

Wavelength ' λ ' = 200 nm

REQUIRED:

Frequency ' f ' = ?, Momentum ' p ' = ? and Energy ' E ' = ?

SOLUTION:

To find the value of frequency first we use the equation: $f = \frac{c}{\lambda}$

putting values $f = \frac{3 \times 10^8 \text{ ms}^{-1}}{200 \times 10^{-9} \text{ m}}$ or $f = 1.5 \times 10^{15} \text{ Hz}$ --- **ANSWER**

To find the momentum of radiations we use: $p = \frac{h f}{c}$

putting values $p = \frac{(6.63 \times 10^{-34} \text{ Js}) (1.5 \times 10^{15} \text{ s}^{-1})}{3 \times 10^8 \text{ ms}^{-1}}$

Therefore $p = 3.315 \times 10^{-27} \text{ kg m s}^{-1}$ --- **ANSWER**

Now the energy of radiations can be found by the relation as: $E = \frac{h c}{\lambda}$

using values $E = \frac{(6.63 \times 10^{-34} \text{ Js}) (3 \times 10^8 \text{ ms}^{-1})}{200 \times 10^{-9} \text{ m}}$ or $E = 9.945 \times 10^{-19} \text{ J}$ --- **ANSWER**

As frequency of the received radiation lays in the region of ultra violet radiations hence the radiation detected by the radiation monitor are ultra violet radiations.



20.5.1 RADIATION PRESSURE

Imagine tossing a tennis ball; it has weight and you can feel it. Now, think of a tiny, fast bullet made of energy—This bullet doesn't have any weight, but it can still push things around. Photons, which are the particles that make up light, are like these energy bullets. They don't have mass,

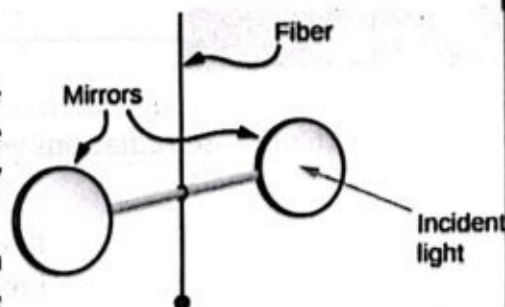
PROJECT

Title: to study the radiation pressure.

Apparatus: Two concave mirrors of very light weight, an inextensible and light weight fiber, a very light pipe and a source of intense light.

Performance: To perform the activity for studying radiation pressure, you have to do the following tasks:

- Take two concave shaped mirrors and connect them by a light rod or pipe.
- Hang the mirror and pipe system by an inextensible light string as shown in figure here.
- Bring the whole apparatus in stationary state.
- Make sure that there is no wind in the room.
- Now take torch which can give you an intense light and strike the light on one mirror you will notice that the whole assembly will rotate a little due to the pressure exerted by the light.
- Change the intensity of light and note the extent of rotation and guess the relation between intensity of light and the radiation pressure.



Conclusion: from the above project we learnt that the when we strike a light of particular intensity we moved the mirrors assembly which can only be possible if the incident light has some pressure i.e. light exerted some force on unit area of the mirror. By changing the intensity of light we noticed that the mirrors assembly moved larger distance which shows that the radiation pressure is directly proportional to the intensity of light.

but they carry energy and momentum. That's why sunlight can warm your skin and why solar sails can move spacecraft.

Despite having no mass, photons significantly interact with matter. Due to transfer of momentum

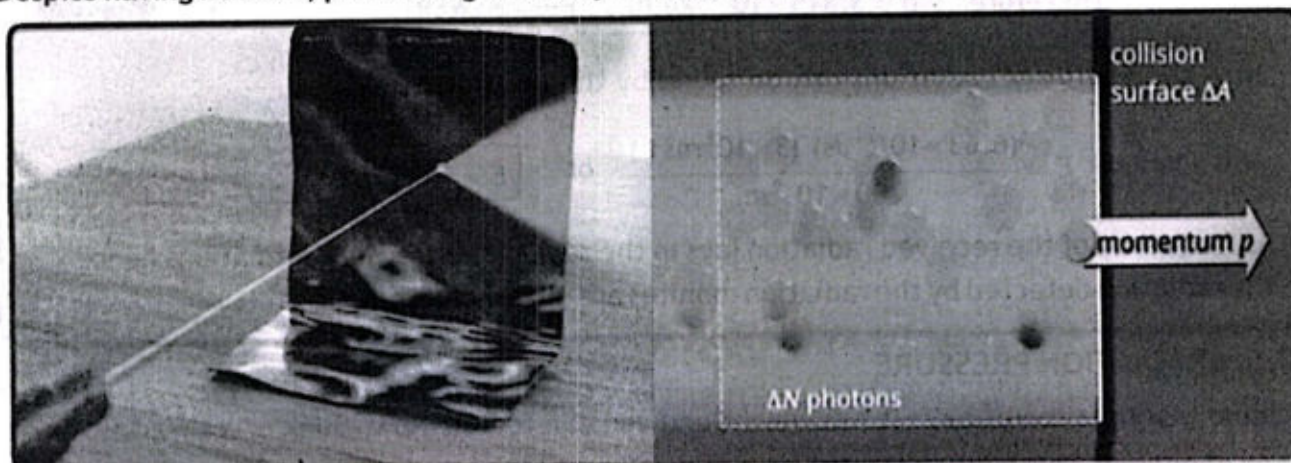


FIGURE 20.18 Radiation's pressure due to collision of photons on the surface where light strikes

light can exert pressure on objects and this phenomenon is known as “radiation pressure” as shown in figure 20.18. This pressure depends on the surface type and light intensity. For instance, sunlight warms your hands by transferring tiny momentum, which is imperceptible due to the high speed of light.

While often too small to notice with regular light, radiation pressure is crucial in astronomical contexts, such as balancing gravitational forces in stars or pushing dust in comet tails. It also has practical applications, like laser cooling and trapping, which manipulate atoms and small objects.

20.5.2 SOLAR SAILS:

With many other applications of radiation pressure one is the “solar sails”. The solar sail is a spacecraft propulsion method that utilizes the momentum of photons. These particles of light have no mass yet when they strike something they can impart momentum and provide a tiny push. Solar sails use large but light weight reflective materials to capture and reflect solar radiations providing a continuous thrust. Imagine it like a sailing boat in space where sunlight acts as the wind pushing against the sail propelling the spacecraft forward. The incident photons hit the sail and transfer their momentum to the sail and reflect at some angle which gives a thrust to the sail as shown in figure 20.19.

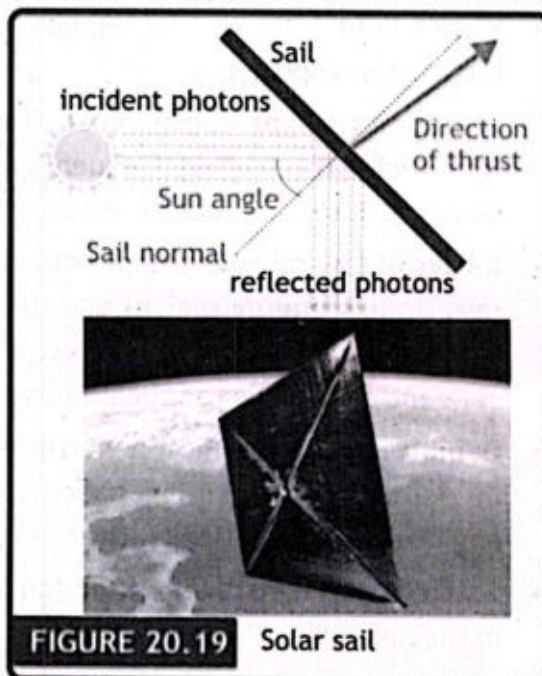


FIGURE 20.19 Solar sail

SUMMARY

- **Electromagnetic waves** are the waves which do not require a material medium for their production and propagation.
- **Electromagnetic Spectrum** is the range of different wavelengths of electromagnetic waves is called the spectrum of the electromagnetic waves.
- The **speed of light** in the vacuum is a universal constant and is denoted by ' c ' whose value can be given as 3×10^8 m/s.
- **Spectroscopy** is the branch of Physics which is used to study the ways different electromagnetic waves interact with matter.
- **Radio waves** are the range of longest wavelengths in the family of electromagnetic waves is the radio waves and can travel at the speed of light and can be used in radio transmission, television transmission and in astronomy.

- **Microwaves** have a higher frequency and lower wavelength than radio waves, but they are still generally thought of as low energy radiations and are used by some radars, Bluetooth, headphones, speakers and even Wi-Fi.
- **Infrared radiations** are in general produced by thermal motion, the vibration and rotation of atoms and molecules and have applications in household electrical appliances, remote controllers, intruder alarms, thermal imaging and optical fibers.
- **Visible light** is the narrow segment of the electromagnetic spectrum to which the normal human eye responds.
- **Ultraviolet** means 'above violet'. The frequency of ultraviolet radiations extends upward from violet the highest frequency in visible spectrum and have applications in security marking, detecting counterfeit bank notes and sterilizing water.
- **X-rays** of low range overlaps with the ultraviolet and high energy x-rays overlaps gamma rays (in low energy region) and its applications are in medical, technological and social applications some of them are use in medical imaging, security scanners, killing cancerous cells and engineering applications such as detecting cracks in metal etc.
- **Gamma rays** are the most penetrating nuclear radiations and are used in medical treatment in detecting and killing cancerous cells, sterilizing food and medical equipment, engineering applications such as detecting cracks in metal etc.
- **Scattering of light** is the reflection of light waves in different directions from the particles of the medium.
- **Blue sky** is the phenomenon in upper atmosphere, where scattering of smaller wavelengths of light gives the appearance of blue color in upper atmosphere.
- **Nature of light** have two aspects a wave like and a particle like.
- **Photon** is a tiny massless particle from which the light is composed of.
- **Radiation pressure** is the phenomenon in which due to transfer of momentum light can exert pressure on objects.
- **Solar sail** is a spacecraft propulsion method that utilizes a curious quirk of photons.

EXERCISE



MULTIPLE CHOICE QUESTIONS

Q1. Choose the best possible option in the following questions.

1. Identify the electromagnetic wave with the greatest ability to penetrate matter.
A. Radio waves B. Ultraviolet C. X-rays D. Gamma rays
2. Which type of radiation primarily carries heat energy?
A. Radio waves B. Ultraviolet C. Infrared D. Visible light
3. The wavelength of 10 cm is corresponding to spectrum of:
A. Microwaves B. Ultraviolet C. Infrared D. X-rays
4. The atomic structure of solids or cracks in solid structure can be investigated by:
A. Microwaves B. Ultraviolet C. Gamma rays D. X-rays
5. Which waves are used for treating muscle aches in physiotherapy?
A. Microwaves B. Ultraviolet C. Infrared D. X-rays
6. X-rays have a higher energy than visible light, because of its:
A. Shorter wavelength B. Longer wavelength C. Lower frequency D. Higher speed
7. Electromagnetic waves are produced due to the motion of which of the following?
A. Neutral particles B. Charged particles
C. Accelerating neutral particles D. Accelerating charged particles
8. If the frequency of an electromagnetic wave is 2×10^{18} Hz, to which spectrum it belongs to?
A. Microwaves B. Ultraviolet C. Infrared D. X-rays
9. Light with longest wavelength in visible spectrum is:
A. Green B. Violet C. Orange D. Red
10. Electromagnetic waves exhibit particle-like behavior in quantum mechanics. These particles are called:
A. Atom B. X-ray C. Electron D. Photon
11. The energy of an electromagnetic wave depends directly on its:
A. Wavelength B. Amplitude C. Frequency D. Speed
12. When an electromagnetic wave enters from one medium into the other which quantity does not change?
A. Wavelength B. Speed C. Frequency D. Energy

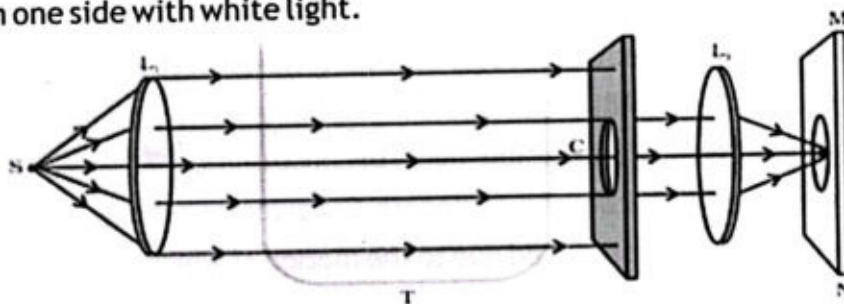
13. On halving the area of a totally reflecting surface, the radiation pressure will:
 A. Remain the same B. Double C. Halve D. Quadruple
14. Solar sails are preferred for deep-space missions because they require:
 A. Electric energy B. Fuel C. Chemical energy D. No fuel
15. Which of these electromagnetic waves has the least momentum?
 A. Gamma rays B. Ultraviolet C. Infrared D. Radio waves

CONSTRUCTED RESPONSE QUESTIONS

QII. Follow the directions to respond to the following questions.

Take some colloidal solution of sulphur from your Chemistry lab and fill the solution in some transparent beaker.

Assemble the beaker between a light source 'S' and slit 'C' as shown in figure and illuminate the beaker from one side with white light.



- Q.1: What color of the solution appears if seen from above? Why?
- Q.2: What color spot appears on the screen 'N-M' after the light passes through the whole beaker?
- Q.3: What phenomenon is observed in this activity?

SHORT RESPONSE QUESTIONS

QIII. Give a short response to the following questions.

1. A leak microwave oven in a home can sometimes cause interference with home's Wi-Fi system. Why?
2. Give an example of energy carried by an electromagnetic wave.
3. Your friend says that more patterns and colors can be seen on the wings of birds if viewed in ultraviolet light. Would you agree with your friend? Explain.

4. Can human body detect electromagnetic radiations that are outside the visible region of the spectrum?
5. What property of light corresponds to loudness in sound?
6. Certain orientations of a television antenna give better reception than others for a particular station. Explain.
7. Why microwaves are used for satellite TV and radio waves are used for terrestrial TV?
8. Can we use x-rays and gamma rays for broadcasting radio and TV signals?
9. When you stand outdoors in the sunlight, why can you feel the energy that sunlight carries but not the momentum it carries?
10. A newscaster in the studio speaks to a reporter from some remote place the voice of reporter is sometimes delayed. What causes this delay?
11. Is the visible region a major portion of the electromagnetic spectrum? Explain.
12. As the light passes through the atmosphere it scatters. Does the same happen with infrared light and radio waves? Explain.
13. Why the radiation pressure of an electromagnetic wave is greater when it is perfectly reflected as compared to when it is absorbed by the surface?
14. How are the photons produced?
15. Explain the reason that why clouds appear white in color?

LONG RESPONSE QUESTIONS

QIV. Give a detailed response to the following questions.

1. Break down the electromagnetic spectrum in terms of wavelength and frequency. Why is the speed of electromagnetic waves in air nearly the same as in vacuum?
2. Evaluate the importance of radio waves in communication systems and astronomy compared to other electromagnetic waves. Why are they uniquely suited for this purpose?
3. Compare the use of microwaves in household applications versus industrial or scientific uses. How do their characteristics make them versatile?
4. What are infrared radiations and how they can be produced? Write their characteristics?
5. What is visible light? Why is visible light crucial for life on Earth?
6. Ultraviolet radiation has both beneficial and harmful effects. Discuss its characteristics, applications, and risks. How can we balance its advantages (e.g., sterilization) with its dangers (e.g., skin cancer)?
7. How x-rays are different from the rest of electromagnetic radiations? Discuss in details.

8. Gamma rays are the most energetic. How do their properties make them suitable for applications in nuclear science and astrophysics?
9. What potential hazards are associated with various parts of the electromagnetic spectrum? Compare the risks posed by ionizing and non-ionizing radiation, and evaluate why ionizing radiation is more dangerous in terms of its impact on living tissues and biological systems.
10. Explain the scattering of light from the atmosphere and why the color of sky appears different at different times in a day?
11. Compare radiation pressure propulsion with chemical propulsion in space exploration. Which is more viable for long-term missions, and why?

NUMERICAL RESPONSE QUESTIONS

QV. Solve the questions given below.

1. Calculate the wavelength of an electromagnetic wave with a frequency of 5.0×10^{14} Hz.
(Ans. 600 nm)
2. A gamma ray photon has a frequency of 2.0×10^{20} Hz. Calculate its energy.
(Ans. 1.33×10^{-13} J)
3. A laser emits light with a frequency of 4.0×10^{14} Hz. What is the momentum of each photon?
(Ans. 8.84×10^{-28} kg m/s)
4. What will be the momentum and energy of the photon from the radio waves with wavelength 100 nm?
(Ans. 6.63×10^{-33} kg m/s, 1.24×10^{-5} eV)
5. The surface of Earth is hit by many radiations of different frequency and wavelength at all the times mainly during the day times. The maximum energy of radiations received in your room during a sunny day is 4.7 eV. Find the frequency and wavelength of this radiation also tell the type of radiation.
(Ans. 1.13×10^{15} Hz, 265 nm, UV)
6. Find the momentum and energy of the photon from the visible light of the smallest wavelength.
(Ans. 3.27 eV, 1.74×10^{-27} kg ms⁻¹)