37A

ASTRONOMICAL INSTRUMENTS

37.1 INTRODUCTION

We can see a number of objects in the sky like moon, the sun, the stars and several other shining objects, by our naked eye. However, there are several other heavenly bodies which cannot be seen by the naked eyes as they are too faint. For this purpose we have to use some instruments like an optical telescope which helps us in seeing such objects. The optical telescopes are the most important tool help in detailed study of the universe. Many of the principles employed in optical telescopes, are also used in instruments designed to operate in other parts of electro-magnetic spectrum.

In this lesson you will study about different types of telescopes and their use in the field of astronomy. You will also study about the resolving power of a telescope and the limitations of the telescopes due to the atmosphere.

37.2 OBJECTIVES

After studying this lesson, you should be able to:

- *describe the windows of electro-magnetic spectrum useful for earth-based astronomy;*
- *describe the principle and construction of different astronomical telescopes and their uses in astronomy;*
- *state and explain the Rayleigh's criterion for resolution of two close point sources of light;*
- *state limitations caused by atmosphere in seeing celestial objects and advantages of having a telescope above the atmosphere;*
- *state the meaning of light collecting power of a telescope and the factors on which its capacity to see faint stars depends;*
- *distinguish between an optical reflecting telescope and an infrared telescope; and*
- *describe the principle of working of X-ray telescope and radio-telescope.*

37.3 WINDOWS IN THE ELECTRO-MAGNETIC SPECTRUM

You know electromagnetic waves exist in a wide range of wave lengths from Υ-rays (wavelength less than 10^{-12} m) to radio waves of wave length several hundred milles. Self luminous celestial bodies emit all wave lengths and send information about themselves.

Unfortunately for astronomical observations, most of the wavelengths in the electro-magnetic spectrum are absorbed by the atmosphere. There are only two regions of spectrum which are allowed through the atmosphere. These are called **windows in the spectrum.** To an earth-based astronomer only these wavelength ranges are available to study celestial objects.

One of these is **optical window** which includes near ultra-violet (wavelengths longer than about 300 nm), visible light (400 nm to 700 nm) and some portions of infra-red upto about 30,000 nm (i.e. 0.03 mm) (Fig. 37.1). The other is the **radio-window,** which includes wavelength from about 1 mm to about 10 m. The long wavelength cut-off of the radio-window depends on the variable conditions of the ionosphere, i.e. the layer of ions high up in the atmosphere formed by ultra-violet light of the Sun. To study the entire spectrum received from celestial bodies, therefore, we have to send telescopes in space, in a low orbit around the earth outside the atmosphere.

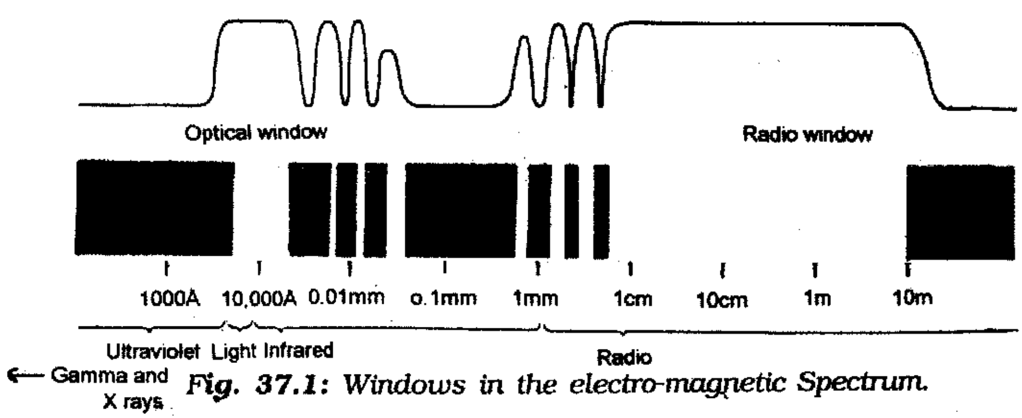


Fig. 37.1: Windows in the electro-magnetic Spectrum.

37.4 OPTICAL TELESCOPE

You have already studied about optical telescope in the Lesson 25 of book 4. However a brief review is given below:

37.4.1 The Simple Astronomical Telescope

As you already know, it consists of two simple convex lenses. The lens kept towards the object, called objective lens forms a real inverted image of the distant object (e.g. Moon), which is called the **primary image.** It is at adistance equal to focal length, f_o, from the lens. It lies in a plane perpendicular to the principal axis, which is called **primary focal plane.**

The eyepiece helps to observe fine details of primary image, *AB* formed by the objective lens (Fig.37.2). It is of shorter focal length f_e, and function in much in the same way as a magnifying glass to see tiny objects. It forms a magnified virtual image A'B', which is observed by the observer. **Angular magnification** or **magnifying power** of the telescope is defined as

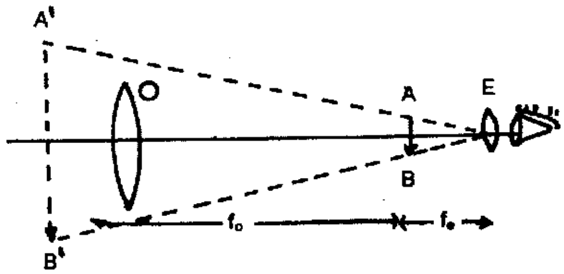


***Fig. 37.2** : Simple Astronomical Telescope*

$$m = \frac{\text{angle made by final image } A'B' \text{ at the eyepiece}}{\text{angle made by the distant object at the telescope}} \qquad \text{.....(37.1)}$$

You are already familiar with the relation

$$m = \frac{f_o}{f_e} \qquad \text{.....(37.2)}$$

which is valid if the final image is at a large distance and primary image is at the focal point of eyepiece.

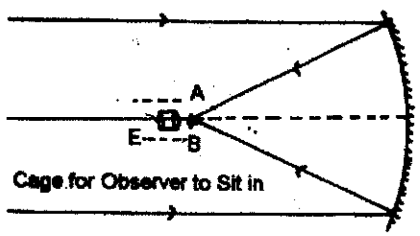
Because **final image seen in this telescope is inverted,** it is not usable for observing terrestrial objects. If you observe a person, or a building or any scenary, these are seen upside down, which no one likes. But surely no one would bother if one sees the Sun or Moon or a star upside down through the telescope.

37.4.2 Reflecting Telescope

As you already know, in concave mirror is used as objective in a reflecting telescope. The concave mirror used in a telescope is always **aluminised at the front surface.** Reflection at front surface **eliminates the basic problem of a mirror which is back aluminised viz. two reflecting surfaces,** the front one and the back one. This results in multiple reflections.

The objective mirror, *O* (Fig. 37.3), receives parallel rays from the distant object It focuses the rays to make a tiny inverted, real image *AB* with fine details at its primary focal plane. Point *F* in this plane and on principal axis of the mirror is called the **prime focus** of the telescope.

If the objective mirror is very large (like the 5.08 m mirror in the telescope at Mount palomer Observatory in U.S.A.), there is enough space for the observer to sit in a small cage (Fig. 37.3) for observation, or for photographing. This obstructs some of the incident light coming from the object being observed and which could get reflected by central poriton of objective mirror.



Figs. 37.3: *Large reflecting Telescope with observation cage at primary focus*

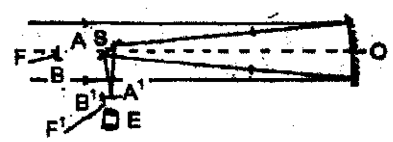


Fig. 37.4: *Newtonian Reflecting Telescope*

Will this method of observing the primary image be feasible if objective mirror is small, comparable to size of the observer or to size of his head? No, because the observer will blcok the entire (or a large portion of) light incident on the objective mirror. In such a telescope a small **secondary mirror** is placed in the path of the converging reflected beam (Fig. 37.4). It is a plane mirror placed between the mirror *O* and its prime focus *F*. It is a tiny mirror at and angle of 45° to the principal axis. It reflects the converging beam at an angle of 90° ar i forms the primary image A'B', which is real and inverted. F' is th new position of prime focus, which is usually about 2 cm outside the telescope tube. In this case

$$f_o = OS + SF' \qquad \text{..............(37.3)}$$

This primary image is observed by an eyepiece E placed on the side of the telescope tube. This design was the first successful design of the reflecting telescope. It was made by Sir Issac Newton and is popularly known as **Newtonian telescope.**

Like the simple refracting astronomical telescope, in both types of reflecting telescopes shown in Fig. 37.3 and 37.4, you directly look with the help of eyepiece at the real image made by the primary mirror. Hence the relation (1) for magnifying power is true for both of these reflecting telescopes also. For obtaining a large magnifying power, therefore, the focal length of objective lens/mirror has to be made large and thus telescope has to be quite long in all the three cases. Is it possible to make a telescope of short length and still get a large magnifying power?

37.4.3 The cassegranian Reflecting Telescope

This design of reflecting telescope is of **short length and still gives a large magnifying power.** It was developed by Cassegrain. It requires making a hole in the centre of the objective mirror (Fig.37.5).

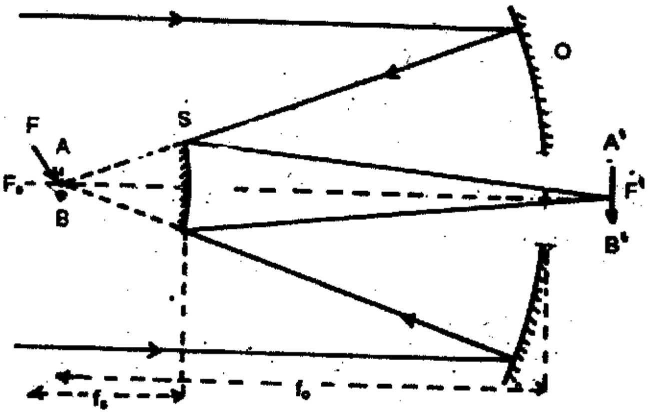


Fig. 37.5: Cassegranian Reflecting Telescope

The secondary mirror, in this case, is a convex mirror whose focal point F_s, is behind the prime focus F. The primary image AB which would have been formed in the absence of secondary mirror, acts as a **virtual object** for the secondary mirror, and forms a magnified real image A'B' at F', called the **cassegranian focus** of the telescope.

The enlargement of image by secondary mirror is SF'/SF. Thus the size of the real image **A'B'** made by the system consisting of a concave primary and a convex secondary mirror of focal length F_o.SF'/SF. This is called **effective focal length** of the *system which is much larger than the total length of the* system. When the image A'B' formed at the Cassegranian focus is observed by an eyepiece of focal length F_e magnifying power of the telescope is

$$m = f_o . SF' / f_e SF \qquad \text{.......... (37.4)}$$

This type of telescope, being small in size, is also light in weight. Thus, it is extremely convenient when an amateur astronomer, who adopts making astronomical observations a hobby, wants to carry it to far off places in search of better observation sites. Because of this advantage, this design was adopted for the telescope which was sent into space on 25 April, 1990. It was named as **Hubble Space Telescope** (HST) after the eminent astronomer Edwin Hubble, who discovered the phenomenon of expanding universe (see lesson 39). This telescope is orbiting the earth in a near-circular orbit at a height of 610 km, well above the earth's atmosphere.

The image at Cassegranian focus of HST is not observed by an eyepiece, as there is no human observer at the telescope. Instead, there are five instruments. There are two **cameras to photograph celestial objects.** Also there are two **spectrographs** and one **photometer to measure energy received at various wavelengths** from celestial objects. These instruments convert the image into useful digital data. This data is transmitted to Space Telescope Science Institute via, a system of geo-stationary satellites.

INTEXT QUESTIONS 37.1

1. *A refracting astronomical telescope has an objective of focal length 90 cm. A convex lens of focal length 5 cm is used as eyepiece. What is its magnifying power? Angular diameter of the Moon is 0.5°. What will be the angular diameter of its image seen in this telescope?*

 ....

 ....

 ....

2. *A Newtonian telescope has objective mirror of focal length 1.5 m. If the eyepiece has a focal length of 12.5 mm, what is its magnifying power? The angular diameter of Jupiter at a certain time is 50". What is the angular diameter of its image seen in this telescope?*

 ....

3. *The primary mirror of a Cassegrainian telescope is of focal length 50 cm. The secondary is of focal length 12.5 cm but is placed at 40 cm from the primary. Find the position of* Cassegranian focus *magnification produced by the secondary and the effective focal length of the system.*

 ....

4. *Why has the Hubble Space Telescope been designed as a* Cassegranian *telescope?*

 ....

37.5 THE RESOLVING POWER OF A TELESCOPE AND THE FACTORS WHICH LIMIT IT

Conceptually, resolving power of a telescope **is its ability to see fine details clearly**. If the light coming from a point in the object is focussed to a sharp point in the primary image, the image has find details. Then the telescope is said to have a high resolving power. If it spreads over an area, then the image gets blurred in which details are lost like an out of focus picture taken by a camera. Then the telescope is said to have a poor resoloution or low resolving power.

The **angular resolution** or **angle of resolution.** is measured in terms of **the smallest angular separation between two distant point sources of equal brightness whose images can just be seen as separate.** The smaller is the value of angle of resolution, the higher is said to be its **resolving power** or **resolution.**

37.5.1 Spherical Aberration

As you have studied earlier in book-4 the spherical aberration is a defect of the mirror due to its shape. This can cause blurring of an image and thus result in poor resolution of the telescope. Focal length of a spherical mirror is not the same for rays at different distances from the principal axis.

As you know a mirror whose surface is **paraboloidal** is completely free from spherical aberration. Therefore, all gooa reflecting telescopes are made with objective mirror of paraboloidal shape, rathor than of spherical shape. The primary mirror of the Hubble Space Telescope, too, is of paraboloidal shape.

It would appear from the above discussion that a telescope with paraboloidal mirror will produce a perfect image with finest details. In fact, we have not yet considered the wave nature of light. The wave nature of light places some limitation on seeing the objects clearly. What is that limitation? Let us now study this.

37.5.2 Diffraction Pattern by a Circular Aperture

Consider a small circular aperture illuminated by plane wavefronts, as we receive from a distance point source. You know that light bends at edges of small aperture due to its wave nature. This phenomenon is called diffraction. Thus on a screen behind this aperture, **a diffraction pattern** is formed (Fig.37.6). These are alternately bright and dark circular fringes. This pattern has **a central bright disc, called Airy disc.** This happen because the hole limits the boundary of the plane wavefronts that pass through it.

Similarly, when we focus the image of a star by a lens or a mirror having no spherical aberration, image should be a point, if light were not waves. In fact, we obtain a diffraction pattern similar to that shown in Fig.37.6. It is again, due to diffraction because the lens/mirror allows only as much part of plane wavefronts to refract/reflect through it as is its size.

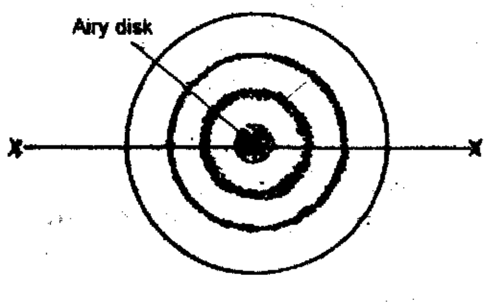


Fig. 37.6: Diffraction pattern of a star image in a telescope.

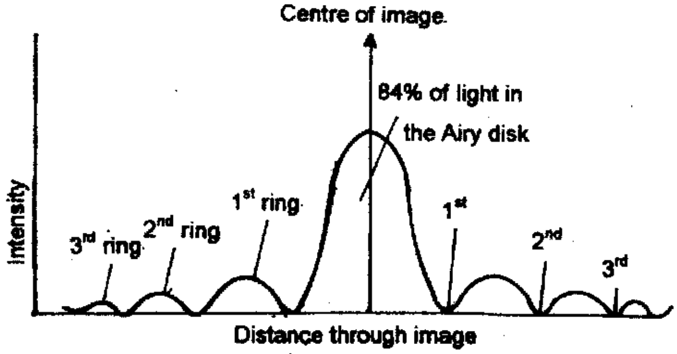


Fig. 37.7: Intensity distribution along the diameter of the diffraction pattern of a star

Consider any line XX passing through the centre of the Airy disc (Fig.37.6). If we plot the intensity of light along this line in the diffraction pattern, we get a graph as shown in Fig. 37.7. **Angular radius of first dark ring (i.e. angle subtended by the radius of first dark ring at the concerned small hole or lens or mirror) is**

$$\alpha_1 = \frac{1.22\lambda}{D} \quad ....(37.7)$$

where λ is the wavelength of incident light and D is the diameter of the hole/lens/mirror. Radii of other dark fringes, α_2, α_3, etc. can also be calculated, but do not concern us here. This formula was first given by Lord Rayleigh. First dark ring is treated as boundary of the Airy disc and equation (37.6) gives us the radius of the Airy disc.

37.5.3 Rayleigh's Criterion and Theoretical Limit of Resolution

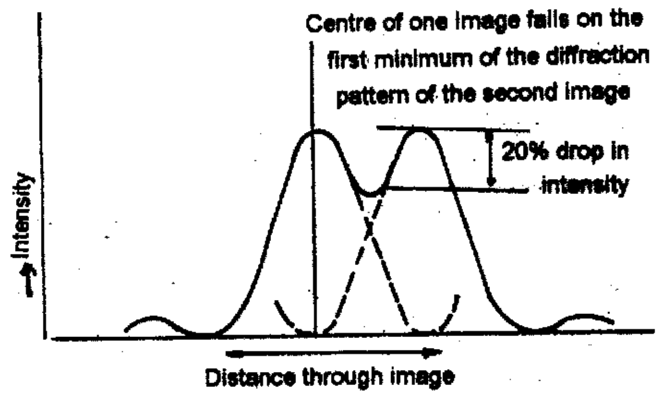


Fig. 37.8: Intensity distribution along line of centres of diffraction patterns of two stars just resolved

If angular separation of two distant point sources of equal brightness is equal to angular radius of Airy disc for the given lens/mirror, then the centre of Airy disc for one falls on the boundary of Airy disc for the other. Then the intensity scan in their super-imposed Airy discs along the line joining their centres is as shown in Fig.37.8. Since the intensity decreases a little (by about 20%) between the two images (which are in the form of Airy discs), the two images can be treated as resolved. This criterion for treating the images as resolved was first suggested by Lord Rayleigh and is known as **Rayleigh's criterion.**

According to Rayleigh's criterion, a perfect lens/mirror will resolve two stars if their angular separation (in radian) is

$$\alpha = \frac{1.22\lambda}{D} \quad ...(37.6)$$

This value is the theoretical limit of resolving power of a telescope. Actual resolving power of a given telescope is always somewhat less than this limit (i.e. value of angle of resolution is more) due to aberrations or imperfect polishing of the surface, etc.

Consider the Hubble Space Telescope with $D = 2.4$ m. If $\lambda = 550$ nm is taken as middle of visible part of electro-magnetic spectrum, then its angle of resolution according to Rayleigh's criterion is

$$\alpha = \frac{1.22 \times 550 \times 10^{-9}}{2.4} \text{ radian}$$
$$= 0.058 \text{ second of arc.}$$

Of course, in ultraviolet region with smaller wavelengths, the angle of resolution is still smaller.

It would be obvious that to achieve better angular resolution in a given wavelength range (i.e. smaller value of α), we need larger and larger mirrors. The largest optical telescope in India is the Vainu Bappu Telescope at Kavalur in Tamil Nadu being managed by Indian Institute of Astrophysics. It has an objective mirror of diameter 2.34 m. The telescope with best resolving power in the world is at Mount Palmoer Observatory in U.S.A., which has an objective mirror of diameter 5.08 m. The telescope with largest objective lens has a lens of diameter only 1 m. A lens of larger diameter is not suitable for telescopes, because

i) It becomes too thick and absorbs too much of light passing through it; and

ii) it becomes too heavy and being supported only at the edges, its shape gets distorted considerably when looking at different directions in the sky.

37.5.4 Atmospheric Limitations to Observation by Ground-Based Telescopes

The Earth's atmosphere is so vital to life. but it imposes several limitations upon the usefulness of ground based telescopes :

1) Clouds and rain, if present, are the most obvious limitation.

2) Even for visible wavelengths, for which atmosphere allows maximum fraction of incident energy to reach the Earth, some light is absorbed by the atmosphere. A star is seen brightest when it is overhead and becomes dimmer and dimmer as it goes down towards horizon. It is so because the incoming light rays have to travel a longer path through the atmosphere if the object is low in the sky.

3) Most of the electro-magnetic spectrum remains invisible to ground based telescopes, except the optical window and the radio-window, as mentioned earlier in article 37.3.

4) Why does the sky appear blue in day time? The air molecules scatter so much sunlight that the resulting blue sky hides all celestial objects except the Sun itself, the Moon and the brightest planet Venus. It is scattered preferentially in smaller wavelengths. At night too, a similar phenomenon occurs. Scattering of city light in and near the towns produces faint blue illumination in the sky, which hides fainter stars. Even starlight scattered by air molecules contributes to brightness of night sky and is capable of hiding very faint stars at places where scattered city light is negligible.

5) Air also emits light of its own. There is an air-glow all over the Earth, because atoms in the upper atmosphere are ionised during day time by ultra-violet light from the Sun. What you think could happen during night when ionised atoms slowly re-capture electrons separated from them? The attraction between an ion having positive charge and an electron having negative charge results in release of energy when they unite. This energy is emitted as a **photon,** i.e. a **packet of energy in the form of electro-magnetic waves.**

6) When air is unsteady, stars are seen twinkling by naked eye. The air column in our line of sight to a star irregularly converges or diverges or bends the incoming light rays (Fig. 37.9) It happens because temperature of air at any spot in the atmosphere randomly changes a little, which changes its refractive index. In a telescope, this irregular refraction of rays by unsteady air makes a star image to occupy a large area in the photograph, similar to blurring of image by being out of focus. Thus a ground based telescope may not be able to resolve star-separations less than 1 arc-second to 4 arc-second, depending on atmospheric conditions, even if its objective lens/mirror is large and perfect with angular resolution of 0.1 arc-second or less. Thus in terms of resolution, a ground based telescope with objective of diameter 2 m or 5 m cannot see significantly more details than the one of 0.1 m.

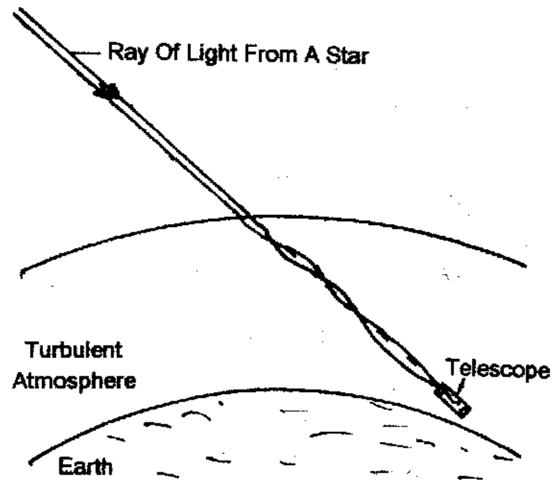


***Fig. 37.9** : Twinkling of a star by irregular refraction of light rays by small random changes of temperature of air*

Obviously, all the six limitations mentioned above are overcome by sending a telescope into space, like the Hubble Space Telescope. It enables us to achieve a resolution of about 0.1 arc-second, which we cannot achieve by the largest ground based telescopes at the best possible locations. It can also be used all the time irrespective of weather conditions on the Earth. It can collect informaton about celestial objects in the entire wavelength range from about 120 nm to about 1 mm.

37.5.5 Light Collecting Power of a Telescope

The above discussion of atmospheric limitations raises an obvious question, "what is the use of a ground based telescope with objective lens/mirror bigger than about 0.1 m if they cannot resolve better than about 1 arc-second?"

At night, while observing faint objects, the pupil of our eye expands to a diameter of about 7 mm. Thus it converges only as much energy coming from a star on our retina, as falls on a circular area of diameter 7 mm. With this light collecting power, the faintest stars that we are able to see are of brightness about 1/100 of the brightest group of stars in the sky, as you will study in Lesson 38.

When we look through a telescope whose objective lens/mirror is larger than 7 mm in diameter, it collects energy falling on an area larger than our pupil, and focusses it at a point on the retina. Thus it enables us to see fainter stars. If objective lens of a telescope is of diameter D, its light collecting power is larger than the eye by a factor

$$P_{CL} = \left(\frac{D}{7\,mm}\right)^2 \qquad ...(37.7)$$

assuming 100% transmission of light through the lenses of the telescope. This factor is called **light collecting power** of the telescope. The telescope enables us to see stars fainter by this factor.

Actually, the **transmission efficiency, (i.e. the percentage transmission of light)** through common refracting telescopes is about 75% and for reflecting telescopes is about 60%. Accordingly, the light collecting power is smaller, the smaller the transmission efficiency of the telescope.

Example 37.1 : *Diameter of the largest refracting telescope of the world is 1 metre. Find its light collecting power, if transmission efficiency of the telescope is 75%.*

Solution : Light collecting power is

$$P_{CL} = \left(\frac{1m}{7mm}\right)^2 \frac{75}{100} = \left(\frac{1000}{7}\right)^2 \frac{75}{100} = 15{,}000$$

times that of our eye.

The calculation given in the above example means that the 1 m telescope enables us to see stars fainter by a factor 15,000 when we look into it with our eyes. However, much fainter stars can be seen by the same telescope by using a detector more sensitive than our retina, e.g. photographic plate with long time exposure, or electronic devices. Sensitivity of detectors is an important factor in addition to objective diameter and transmission efficiency in deciding the capacity of a telescope to see faint objects in the sky.

Hubble Space Telescope can see objects fainter by a factor of about 50 compared to the ground based telescopes of more than twice the diameter, which have more than 4 times the light collecting power. It is due to darker sky background available to the space telescope. Similarly on the ground, if you move to outskirts of a town, you are able to see stars fainter by a factor of about 10 compared to what you can see in the town, using the same telescope.

INTEXT QUESTIONS 37.2

1. *You have an astronomical telescope with an objective mirror of diameter 6.25 cm and focal length 50 cm. Taking a wavelength of 500 nm find (a) the angular radius of its Airy disc, (b) linear radius of its Airy disc on a screen at the prime focus, and (c) theoretical limit of its angular resolution.*

   ....

2. *If the mirror of the above telescope has some defects, e.g. spherical aberration or imperfect polishing, will its actual angular resolution have a larger or small value compared to what you calculated in questions (3) above?*

   ....

3. *State four limitations caused by the atmosphere of the earth which prevent earth based telescopes to make good astronomical observations.*

   ....

4. *What is meant by light collecting power of a telescope? State the factors on which it depends.*

   ....

5. *Describe the various factors on which depends the capacity of a telescope to see faint stars.*

   ....

37.6 TELESCOPES FOR WAVELENGTHS OTHER THAN VISIBLE SPECTRUM

Having studied the various concepts and principles in respect of optical reflecting telescopes, let us now study about telescopes which are used to observe celestial objects by wavelengths other than visible. Do you think there is any concept or principles which will not be applicable to these telescopes? Surely not, but there has to be some difference due to a radically different wavelength range and consequent change in properties of the waves.

37.6.1 Infra-red Telescopes

Can you think of, how an infra-red telescope has to be different from an optical telescope? Obviously, as our eye is not sensitive to infra-red waves, the eyepiece is replaced by a detector capable of detecting infra-red radiations. Such a detector has to be cooled by liquid hydrogen or liquid helium when we are working at wavelengths longer than a few microns. Ground-based infra-red telescopes are used to study the celestial objects at radiation of wavelengths longer than 700 nm (the upper limit of visible spectrum) but within the optical window. These telescopes have been in use since long and have helped discover many infra-red emitting objects in the sky. A note worthy example is discovery of protostars, i.e., stars still in the process of formation, which have helped us understand the process of formation of stars, about which you will study in Lesson 38.

The Infra-red Astronomy Satellite (IRAS) was launched in 1983 to extend the range of the infra-red wavelengths. The Hubble Space Telescope itself is an infra-red space telescope as well as the optical telescope, capable of observing wavelengths upto 1 mm.

Another infra-red telescope in space is named **Cosmic Background Explorer** (COBE). It is working in the wavelength range around a millimetre and has led to better understanding of the cosmic background radiation. This electro-magnetic radiation is a diffuse black-body radiation at a temperature of about 3 K and pervades the entire universe. You will study more about this radiation in Lesson 39.

37.6.2 X-ray Telescope

This field of astronomy concerns the wavelengths in the range 0.01 nm to 10 nm, which are totally absorbed by the atmosphere. Only a space telescope can be used to study celestial objects at these wavelengths.

There are technical difficulties in the construction of an X-ray telescope. One is that they penetrate all matter. There is no material from the surface of which X-rays can reflect at any angle of incidence and with as much percentage reflection as light can reflect from a smooth parabolic mirror with aluminium coated surface.

Second difficulty is the extremely short wavelength. For reflection of a wavefront according to laws of reflection, surface of a mirror has to have such smoothness that any pits in it are not larger than a fraction of the wavelength of waves to be reflected. Sound waves with wavelength of the order of a metre can reflect from a brick wall, even if it is not plastered. For reflection of light a highly polished glass surface is necessary. Wavelength of X-rays are of the order of the size of atoms. Except a layer of atoms in a crystal, there can be no material surface with smoothness necessary to reflect X-rays. But it has been

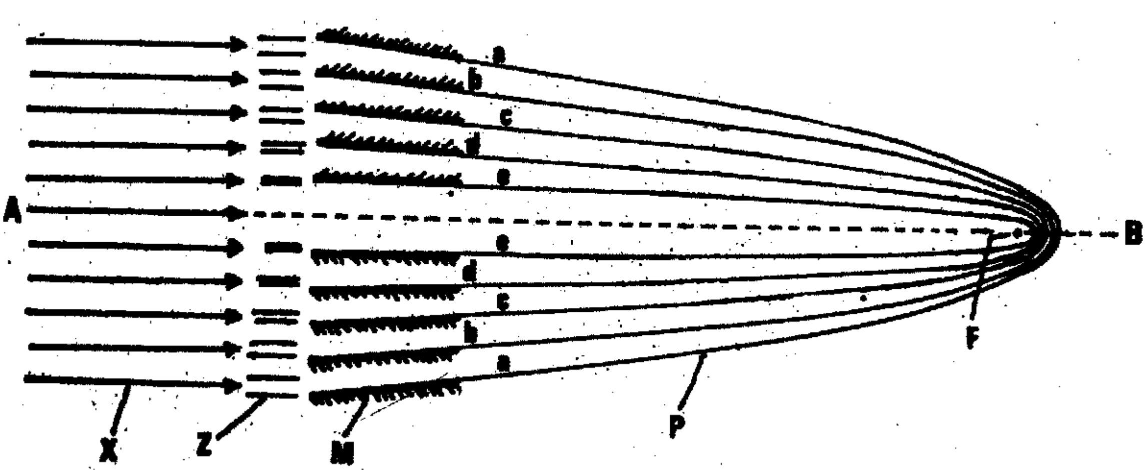


Fig. 37.10 : X-ray telescope

found that X-rays can be partially reflected from a very smooth metal surface at grazing incidence, even if pits in it are many times the size of the wavelength.

Space telescope named Einstein was the first true X-ray telescope launched into orbit by High Energy Astrophysical Observatory of U.S.A. Principle of its working can be understood with the help of figure 37.10. Consider a family of very long parabolas. All have the same focal point F and same principal axis. Clearly the surface of revolution about the principal axis for each curve (which is a paraboloid) is such that rays parallel to the principal axis reflected from it will come to a focus at F. We use only a small portion of these paraboloids at their open ends to make metallic reflecting surfaces M, which are shown by thick solid lines. Shape of the mirrors is, thus, roughly cylinderical, though precisely they are only the front parts of very long paraboloids. The difference in the diameters of any mirror at its two open ends is quite small. Thus these are called **cylinders.** A parallel beam of x-rays coming parallel to the common principal axis of these 'cylinders' reflects at grazing incidence from each and comes to a focus at F. The successful manufacture of mirrors of this type with accuracy and smoothness of surface required for x-rays is considered a great technological achievement.

This telescope has been used to provide data on extremely hot bodies where very violent processes are taking place, e.g. quasars, pulsars and nuclei of galaxies.

37.6.3 Radio-Telescopes

The wavelengths studied by radio-telescopes range from a few mm to about 10 m. These wavelengths can pass through our atmosphere even when sky is overcast by dense clouds. Television broadcasts are made in the same range of wavelengths. You can see television programmes quite clear even when entire city is full of dense fog and visibility is too little to drive your cycle or scooter or car, because these wavelengths travel quite unhindered from antenna of TV-station to your home antenna.

These wavelengths can also pass through dust cloud in our Milky Way Galaxy, which hide 95% of the galaxy from the optical view. Radio-reception from celestial objects is almost as effective in day time as in the night, except for greater man-made radio-noise during the day time.

A reflecting radio-telescope consists of a large paraboloidal reflector analogous to objective mirror of an optical telescope. The reflecting surface can be a thin continuous sheet of metal, or a fine mesh or wire with holes much smaller than the wavelength of electro-magnetic radiation to be observed. The reflecting paraboloid is often called a 'dish'.

Radio dishes are mounted so that they can be steered to point in any direction in the sky and collect the energy of radio waves coming from that direction on its entire area. The radio-waves are reflected to the focus of the paraboloid. An antenna is placed at the focus of the dish to detect the radio-signal.

Radio-energy emitted by most of the astronomical objects (e.g. Crab Nebula in constellation Taurus) is very small compared to the energy emitted in optical part of electro-magnetic spectrum. It is emitted due to the presence of specific molecules e.g. hydrogen (H_2), hydroxy (OH), water (H_2O), ammonia (NH_3), etc. Radio-telescopes help us to detect presence of such molecules.

In case of stars which are simply hidden by dust and thus have to be observed by radio-waves, the energy distribution with wavelength in their specturm is of the shape shown in Fig.37.11. On the long wavelength side of this curve, energy decreases rapidly with wavelength.

The basic reason for radio-energy being small is to be found in the following fact. The electro-magnetic energy is emitted by an atom or molecule in the form of a photon. Energy of a single photon of wavelength λ is hc/λ, where h is Plank's constant and c is the velocity of light. The larger the wavelength the smaller the energy of a single photon of that wavelength.

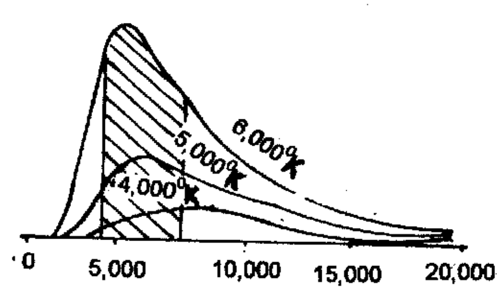


Fig. 37.11: Energy distribution in a radiation of a hot black body

Radio-dishes are usually built in large sizes for two reasons :

i) At radio-wavelengths most astronomical objects are extremely faint. The larger the area of the dish, the larger the amount of energy it collects from a certain source and the better is its ability to detect faint sources.

ii) The formula for angular resolution of a telescope :

$$1.22\lambda/D \qquad ...(37.8)$$

is applicable to a radio-dish also, provided its shape is accurate. Wavelengths of radio-waves that we study are far greater than those for visible light. Thus for large value of λ, the value of D must also be large, in order to have a respectable angular resolution.

Example 37.2 : *A typical wavelength of radio-waves is 21.1 cm which is emitted by neutral hydrogen and is frequently studied. Minimum aperture of the pupil of human eye in day time is 2 mm. Find the diameter of radio-dish which will have same angular resolution for 21.1 cm waves as the eye has for visible light (λ = 550 nm).*

Solution : If the diameter of required radio dish is d, then for same evalue of resolution in both causes :

$$\frac{21.1\,cm}{D} = \frac{550\,nm}{2\,mm}$$

$$\frac{21.1\,cm}{D} = \frac{550\,nm}{2\,mm}$$

The first radio-telescope was built at Jodrell Bank in England in 1957. It has a dish of diameter 76 metre. Its angular resolution for 21 cm waves is 10 times poorer than that for human eye. The largest steerable radio-dish in use today is of diameter 100 m used by Stockert Observatory of Bonn University in Germany. Larger dishes do not seem to be possible to build; using the materials and techniques of mechanical engineering available today.

Thus the largest radio-telescopes have far poorer resolving power than even the resolving power of the human eye. Consequently, it is not possible for a single radio-dish to determine accurately the position of radio-sources in the sky.

The following arrangement of several radio-dishes constitutes a radio-telescope which can map the sky with a resolution comparable with that obtained by the largest optical telescopes. It employs three rows of steerable dishes inclined to each other at about 120°. These rows are many kilometres in length and exact angles among them have to be planned according to features of land available. The three arms of the radio-telescope may not even be equal in length or be even straight lines themselves.

The radio-signal received at the focal point of each parabolic dish is conveyed to a central place. It is conveyed much in the same way as the signal received by your dish antenna is conveyed to your TV-set. Here all signals are combined by a computer technique called **aperture synthesis.** Thus we obtain a map of the region of sky at which all the radio-dishes are simultaneously pointed.

The Very Large Array (VLA) in use by National Radio-Astronomy Observatory of U.S.A. since 1980. It is a high resolution radio-telescope having three arms of length 21 km, 21 km and 18.9 km. Its resolving power is equivalent to a radio-dish of diameter 27 km. In India, a similar radio-telescope named "Giant Metrewave Radio Telescope (GMRT)" is under construction at a site 80 km north of Pune. It will have 30 fully steerable parabolic dishes, each of 45 m diameter. It will have a resolving power equivalent to a radio-dish of diameter 25 km.

INTEXT QUESTION 37.3

1. *State the main difference between an optical reflecting telescope and an infra-red telescope.*

   ....

2. *Describe briefly how an x-ray telescope brings the x-rays coming from a distant celestial object to a sharp focus.*

   ....

Why the parabolic reflector of a radio-telescope has to have a very large size?

....

Calculate the angle of resolution of a radio-dish of diameter 100 m for radio-waves of wavelength 21 cm.

....

Each radio-dish of GMRT near Pune is of 45 m diameter. The complete system is equivalent to a radio-dish of diameter 25 km. Find the angle of resolution of each dish and of the complete system for radio waves of wavelength 21.1 cm, the shortest wavelength for which it is used.

....

17.7 WHAT YOU HAVE LEARNT

- atmosphere absorbs e.m. radiations of all wavelengths coming from a celestial objects except for two narrow bands, the optical window and the radio window, by which ground based astronomers can study celestial objects;
- by using a simple astronomical telescope using a convex lens as objective or the Newtonian telescope using a concave mirror as objective, a celestial object appears to come closer by a factor f_o/f_e;
- in a Cassegranian reflecting telescope, the system consisting of concave objective mirror and convex secondary mirror has an effective focal length much longer than the length of the system itself and hence this is the design of Hubble Space Telescope;
- wave nature of light imposes a limit to resolving power of a telescope, which is $1.22\,\lambda/D$, due to the phenomenon of diffraction;
- atmosphere imposes several kinds of limitations to observing celestial objects due to which a telescope can neither resolve close stars nor see fainter stars nor use a wide range of wavelengths which it is capable of. These are overcome only by sending the telescope in space;
- a ground-based telescope with objective larger than 0.1 m may not be useful in terms of resolving power due to atmospheric terbulance, but is useful for seeing faint stars as it collects more light than eye by a factor $(D\ /7\text{mm})^2$ x transmission efficiency;
- telescopes sent in space which can observe in far infra-red wavelengths (IRAS and COBE) have helped discover infra-red emitting objects better understand the process of formation of stars and the 3K cosmic background radiation;
- inspite of their property to penetrate all matter and wavelength of the order of size of atoms, x-rays can be reflect partially from a

very smooth metal surface at grazing incidence. Using this property an array of paraboloidal mirrors with common focal point can be used to make an x-ray telescope. Such a telescope in space has helped understand the nature of quaress, pulsars and nuclei of galaxies;

- radio-window is useful for observing celestial objects even through clouds in our atmosphere or through dust clouds in space;
- the concave paraboloidal mirror to make a radio-telescope (radio-dish) has to be large because (i) a photon at radio-wavelength has very small energy hc/λ and hence energy coming from a celestial object has to be collected over a large area, and (ii) for good angular resolution $1.22\lambda/D$, D has to be large when λ is large;
- for achieving an angular resolution similar to a big optical telescope, a radio telescope has to have an effective diameter of tens of kilometers which is achieved by having many radio-dishes in three rows to make Y-shape and combining their signals by the technique of aperature synthesis.

37.8 TERMINAL QUESTIONS

1. An achromatic refracting telescope has an objective lens of focal length 50.0 cm. It can be used with any of three eye pieces of focal lengths (a) 4.0 cm, (b) 2.5 cm and (c) 1.25 cm. What is the magnifying power of the telescope with each eyepiece?
2. A Newtonian reflecting telescope has objective mirror of diameter 122 mm and focal length 1.50 m. What is its angular resolution by Rayleigh's criterion?
3. If in the above reflecting telescope (Q No.2), one can use any of three eye pieces of focal lengths (a) 4.0 cm, (b) 2.5 cm and (c) 1.25 cm, what is its magnifying power with each eyepiece.
4. In a Cassegranian telescope focal length of objective is 50 cm. The secondary mirror gives a magnification of 4. What is the effective focal length of the system? What are its magnifying powers with eyepieces of focal lengths (a) 40 mm, (b) 25 mm and (c) 12.5 mm?
5. What is Rayleigh's criterion for considering two star images as resolved?
6. In what respects is Hubble space Telescope superior to even larger ground-based telescopes?
7. What is meant by angular resolution of a telescope? The angular resolution of the common Newtonian telescope with a mirror of 15 cm diameter is 1.5 arc — second (because mirror has some imperfections). The angular resolution of Hubble Space Telescope is 0.1 arc — second. Which of the two will be said to have higher resolution and how many times?

8. In what respects is a radio-telescope (single dish) similar to a reflecting optical telescope?

   Why is the resolving power of such a radio-telescope much smaller than an optical telescope?

9. Why do we need to make radio-telescopes with effective aperture as high as 27 km? How do we achieve it? State essential features of GMRT under construction in India.

10. Describe the shape of any one mirror of an x-ray telescope. Why must it have many such mirrors? Why is each mirror called a *cylinder?*

11. What is the wavelength range studied by radio-telescopes? How is this wavelength range specially useful in observation of celestial objects.

12. How does the secondary mirror of a cassegranian telescope help in making the effective focal length long though the system is of short length? How is this helpful to amateur astronomers?

CHECK YOUR ANSWERS

INTEXT QUESTIONS 37.1

1. $m = f_o / f_e$ = 90 cm/5 cm = 18..

   Angular diameter of image of Moon seen in the telescope
   = m x 0°.5 = 18 x 0°.5 = 9°

2. $m = f_o / f_e$ = 1.5 m/12.5 mm = 120

   Angular diameter of Jupiter seen in the telescope
   = m x 50" = 120 x 50" = 6000" = 1°40'

3. It would be clear from figure 37.5 that

   FS = 10 cm, but f_s = 12.5 cm.

   Using convention of signs :

   Therefore u = −10 cm f_s = −12.5 cm.

   Using mirror formulae

   $1/v + 1/u = 1/f$

   $1/v = (1/-12.5) - (1/-10)$

   $= 1/10 - 1/12.5 = 1/50$

   $v = +50$ cm.

   Magnification produced by secondary = 50/10 = 5

   Therefore, effective focal length of the system = f_o. SF'/SF = 50 x 5 = 250 cm.

4. Cassegrainian telescope is small in size compared to its effective focal length. Thus it is also lighter than a Newtonina telescope of same focal length. (See article 37.43)

In t Questions 37.2

1.) α_r = $1.22\lambda / D$

   = 1.22 x 500 nm/5.0 cm (Because λ = 500 nm, D = 5 cm)

   = 1.22 x 10^{-5} radian

   = 2.4 arc-second.

   (b) Linear radius of Airy disc = $f_o.\alpha_1$

   = 50 cm x 1.22 x 10^{-5} = 6.1 μm

   (c) Theoretical limit of angular resolution is 2.4 arc-second as it is same as angular radius of Airy disc.

2. If the mirror has defects it causes, blurring of image. Thus diameter of disc image of a point object is more than that of the Airy disc. Hence value of angular resolution is larger.

3. See article 37.5.4

4. See article 37.5.4

5. See article 37.5.4

Intext Questions 37.3

1. See article 37.6.1

2. See article 37.6.2

3. See article 37.6.3

4. α = $1.22\lambda / D$ = 1.22 x 21 x 10^{-2}/100 radian

   = 1.22 x 21 x 10^{-2} x 57.3 x 60/100 arc-minute

   = 8.8 arc-minute

5. Angle of resolution of each dish of 45 m for λ = 21.1 cm.

$$= \frac{1.22\lambda}{D} = \frac{1.22 \times 21.1 \times 10^{-2} \times (57.3 \times 60)}{45} \, arc\ min.$$

= 20 arc min

Angles of resolution of complete system with equivalent D of 25 km is

$$= \frac{1.22\lambda}{D} = \frac{1.22 \times 21.1 \times 10^{-2} \times (57.3 \times 60)}{25000} \, arc-min.$$

= 3.5 x 10^{-2} arc – minute