Chapter 1 Telescopes

1.1 Lenses

Learning objectives:

- What is a converging lens and what is its focal length?
- How does a converging lens form an image?
- How can we predict the position and magnification of an image formed by a converging lens?

The converging lens

Lenses are used in optical devices such as the camera and the telescope. A lens works by changing the direction of light at each of its two surfaces. Figure 1 shows the effect of a converging lens and of a diverging lens on a beam of parallel light rays.

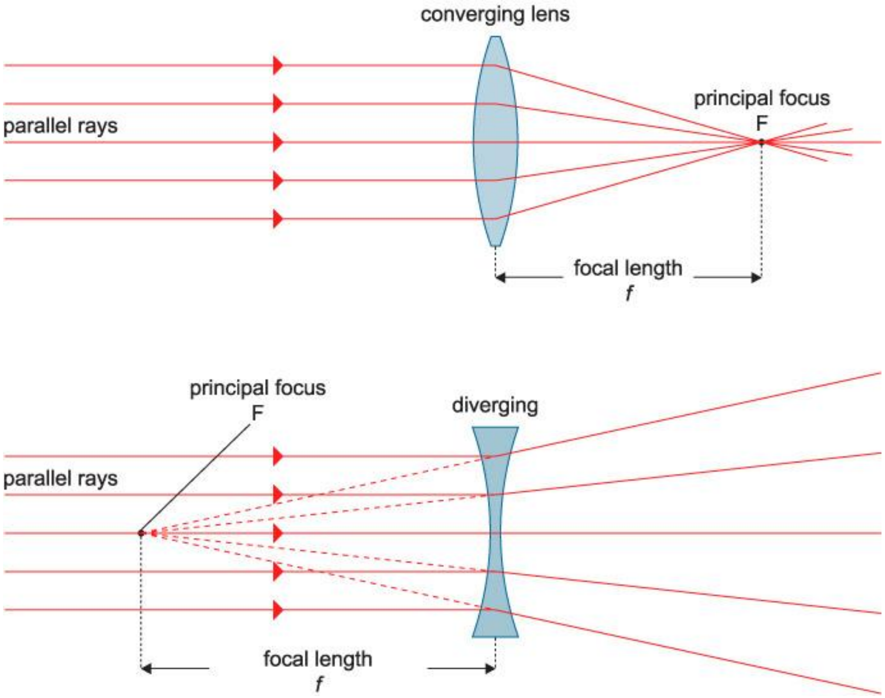


Figure 1 *Focal length*

- A **converging lens** makes parallel rays converge to a focus. The point where parallel rays are focused to is called the **principal focus** or the **focal point** of the lens.
- A **diverging lens** makes parallel rays diverge (i.e. spread out). The point where the rays appear to come from is the principal focus or focal point of this type of lens.

In both cases, the distance from the lens to the principal focus is the **focal length** of the lens. In this option, we consider the converging lens only.

Note

The plane on each side of the lens perpendicular to the principal axis containing the principal focus is called the **focal plane**.

Investigating the converging lens

The arrangement in Figure 2 can be used to investigate the image formed by a converging lens. Light rays illuminate the crosswires which form the object. These light rays are refracted by the lens such that the rays form an image of the crosswires.

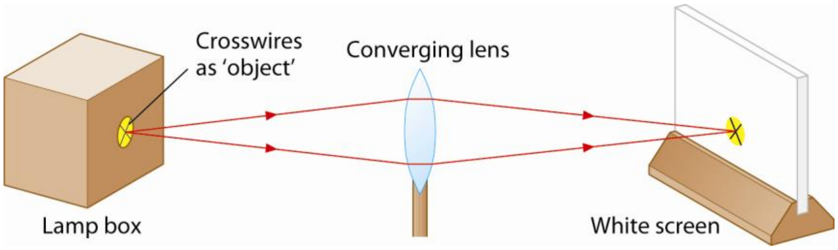


Figure 2 *Investigating images*

1 **With the object at different distances beyond the principal focus of the lens**, the position of the screen is adjusted until a clear image of the object is seen on the screen. The image is described as a real image because it is formed on the screen where the light rays meet. If the object is moved nearer the lens towards its principal focus, the screen must be moved further from the lens to see a clear image. The nearer the object is to the lens, the larger the image is.

2 **With the object nearer to the lens than the principal focus**, a magnified image is formed. The lens acts as a magnifying glass. But the image can only be seen when you look into the lens from the other side to the object. The image is called a **virtual image** because it is formed where the light rays appear to come from.

Ray diagrams

The position and nature of the image formed by a lens depends on the focal length of the lens and the distance from the object to the lens.

If we know the focal length, f, and the object distance, u, we can find the position and nature of the image by drawing a ray diagram to scale in which:

- the lens is assumed to be thin so it can represented by a single line at which refraction takes place
- the straight line through the centre of the lens perpendicular to the lens is called the principal axis
- the principal focus F is marked on the principal axis at the same distance from the lens on each side of the lens
- the object is represented by an 'upright' arrow as shown in Figure 3.

Note that the 'horizontal' scale of the diagram must be chosen to enable you to fit the object, the image and the lens on the diagram.

Formation of a real image by a converging lens

To form a real image, the object must be beyond the principal focus F of the lens. The image is formed on the other side of the lens to the object.

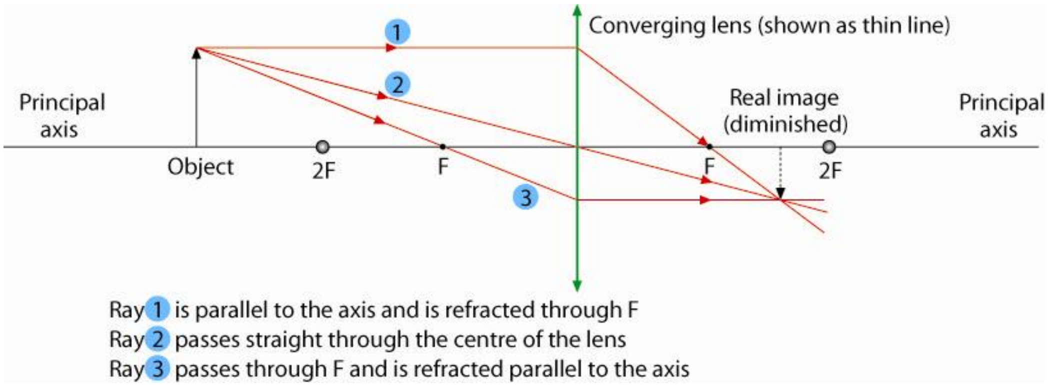


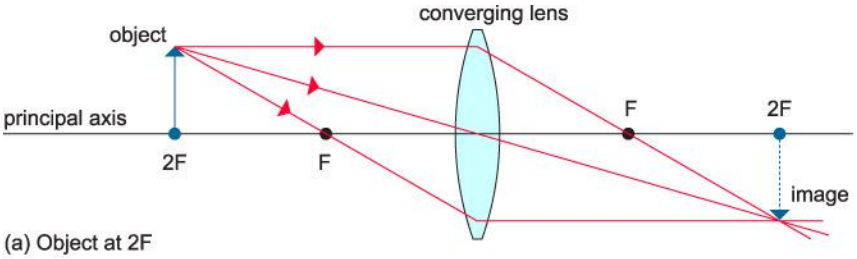
Figure 3 *Formation of a real image by a converging lens*

To locate the tip of the image, three key ‘construction’ rays from the tip of the object are drawn, through the lens. The tip of the image is formed where these three rays meet. The image is real and inverted.

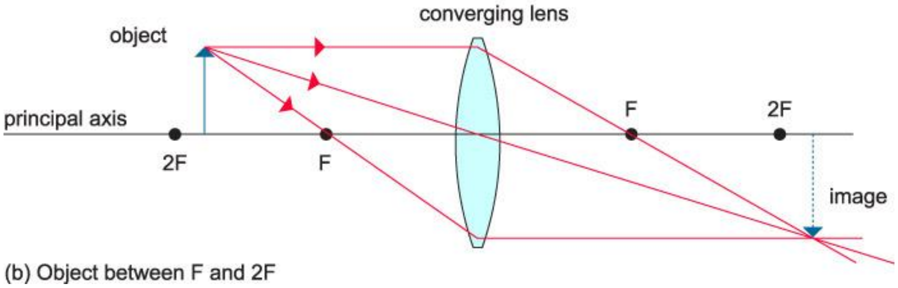
1. Ray 1 is drawn parallel to the principal axis before the lens so it is refracted by the lens through F.
2. Ray 2 is drawn through the lens at its centre without change of direction. This is because the lens is thin and its surfaces are parallel to each other at the axis.
3. Ray 3 is drawn through F before the lens so it is refracted by the lens parallel to the axis.

Figure 4(a) and 4(b) show ray diagrams for the object at 2F and between F and 2F respectively. The results for Figures 3 and 4 are described in the table below. Notice that the image is:

- diminished in size when the object is beyond 2F as in Figure 3
- the same size as the object when the object is at 2F as in Figure 4(a)
- magnified when the object is between F and 2F as in Figure 4(b).



(a) Object at 2F



(b) Object between F and 2F

Figure 4 *Using ray diagrams to locate an image*

Formation of a virtual image by a converging lens

The object must be between the lens and its principal focus, as shown in Figure 5. The image is formed on the same side of the lens as the object.

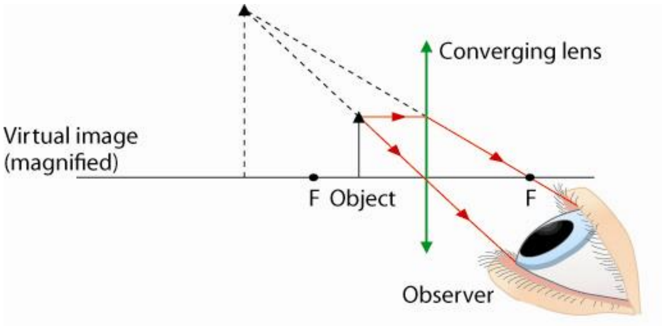


Figure 5 *Virtual image by a converging lens*

Figure 5 shows that the image is virtual, upright and larger than the object. The image is on the same side of the lens as the object and can only be seen by looking at it through the lens. This is how a **magnifying glass** works.

If the object is placed in the focal plane, light rays from any point on the object are refracted by the lens to form a parallel beam. A viewer looking at the object through the lens would therefore see a virtual image of the object at infinity.

Object position	Image position	Nature of image	Magnified or diminished	Upright or inverted	Application
beyond 2F	between F and 2F	real	diminished	inverted	camera
2F	2F	real	same size	inverted	inverter
between F and 2F	beyond 2F	real	magnified	inverted	projector
< F	same side as object	virtual	magnified	upright	magnifying lens

Table 1 *Image formation by a converging lens*

Note

$$\text{The linear magnification of the image} = \frac{\text{height of the image}}{\text{height of the object}}$$

$$\text{It can be shown that this ratio is equal to } \frac{\text{the image distance}}{\text{the object distance}}$$

The image is said to be **magnified** if the image height is greater than the object height and **diminished** if it is smaller.

AQA Examiner's tip

When you draw a ray diagram, make sure you choose a suitably large scale that enables you to fit the object and the image on your diagram – and use a ruler to make sure your lines are straight!

The lens formula

For an object on the principal axis of a thin lens of focal length f at distance u from the lens, the distance, v, from the image to the lens is given by

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$$

Notes

1 Proof of the lens formula is not required for this specification.

2 When numerical values are substituted into the formula, the sign convention

real is positive; virtual is negative

is used for the object and image distances. The focal length, f, for a converging lens is always assigned a positive value. A diverging lens is always assigned a negative value.

Worked example

An object is placed on the principal axis of a convex lens of focal length 150 mm at a distance of 200 mm from the centre of the lens.

a Calculate the image distance.

b State the properties of the image.

Solution

a $f = +0.150\,\text{m}$, $u = +0.200\,\text{mm}$

Using the lens formula $\frac{1}{u}+\frac{1}{v}=\frac{1}{f}$ gives $\frac{1}{0.200}+\frac{1}{v}=\frac{1}{0.150}$

Hence $\frac{1}{v}=\frac{1}{0.150}-\frac{1}{0.200}=6.67-5.00=1.67$

Therefore $v = +0.600\,\text{m}$

b The image is real (because v is positive), inverted and magnified (because $v > u$).

Summary questions

1 a i Copy and complete the ray diagram in Figure 6 to show how a converging lens in a camera forms an image of an object.

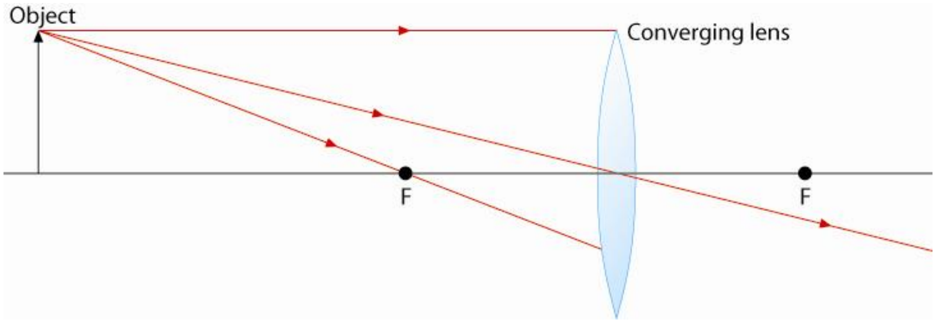


Figure 6

ii State whether the image in Figure 6 is real or virtual, magnified or diminished, upright or inverted.

b **i** Draw a ray diagram to show how a converging lens is used as a magnifying glass.

ii State whether the image in your diagram is real or virtual, magnified or diminished, upright or inverted.

2 An object is placed on the principal axis of a thin converging lens at a distance of 400 mm from the centre of the lens. The lens has a focal length of 150 mm.

a Draw a ray diagram to determine the distance from the image to the lens.

b State whether the image is:

i real or virtual

ii upright or inverted.

c Use the lens formula to check the accuracy of your ray diagram.

3 An object is placed on the principal axis of a thin converging lens at a distance of 100 mm from the centre of the lens. The lens has a focal length of 150 mm.

a Draw a ray diagram to determine the distance from the image to the lens.

b State whether the image is:

i real or virtual

ii upright or inverted.

c Use the lens formula to check the accuracy of your ray diagram.

4 An object of height 10 mm is placed on the principal axis of a converging lens of focal length 0.200 m.

a Calculate the image distance and the height of the image for an object distance of:

i 0.150 m

ii 0.250 m.

b In each case above, calculate the distance between the object and the image and state whether the image in each case is real or virtual and upright or inverted.

$$\text{The linear magnification of the image} = \frac{\text{height of the image}}{\text{height of the object}} = \frac{\text{image distance}}{\text{object distance}}$$

1.2 The refracting telescope

Learning objectives:

- What is a refracting telescope?
- What do we mean by angular magnification?
- How does the angular magnification depend on the focal lengths of the two lenses?

The astronomical telescope consisting of two converging lenses

To make a simple refracting telescope, two converging lenses of differing focal lengths are needed. The lens with the longer focal length is referred to as the objective because it faces the object. The viewer needs to look through the other lens, the eyepiece, as shown in Figure 1. Light from the object enters his or her eye after passing through the objective then through the eyepiece into the viewer's eye. By adjusting the position of the inner tube in the outer tube, the distance between the two lenses is altered until the image of the distant object is seen in focus. If the telescope is used to view a distant terrestrial object, the viewer sees an enlarged, virtual and inverted image.

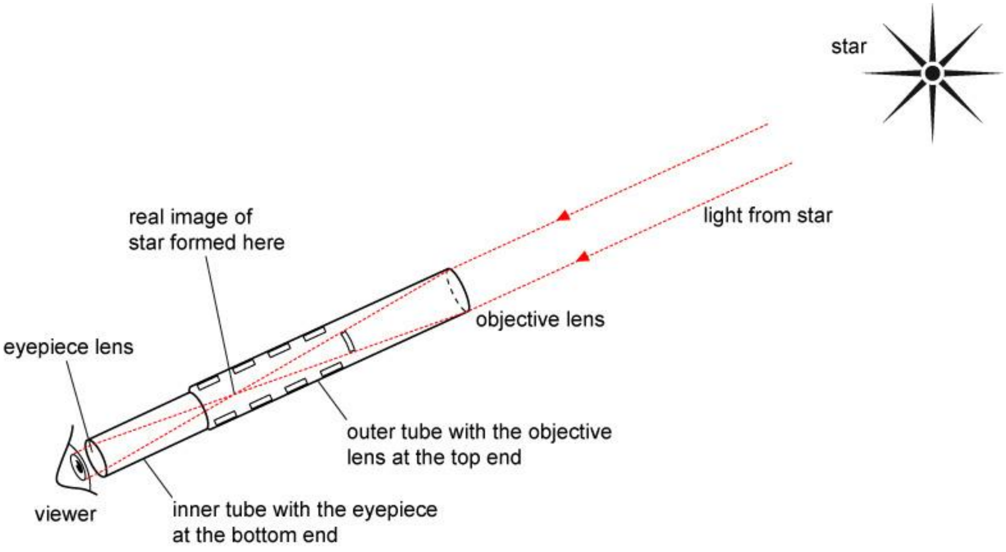


Figure 1 *The simple refracting telescope*

To understand why the viewer sees a magnified virtual image, consider the effect of each lens on the light rays from the object that enter the telescope:

- The objective lens focuses the light rays to form a real image of the object. This image is formed in the same plane as the principal focus of the objective lens which is where the light rays cross each other after passing through the objective lens. If a 'tracing paper' screen is placed at this position, as shown in Figure 2, the real image formed by the objective can be seen directly on the paper without looking through the eyepiece.

- The eyepiece gives the viewer looking through the telescope a magnified view of this real image with or without the tracing paper present. If the tracing paper is removed, the viewer sees the same magnified view of the real image except much brighter. This magnified view is a virtual image because it is formed where the rays emerging from the eyepiece appear to have come from.

The virtual image is inverted compared with the distant object. This is because the real image formed by the objective is inverted and the final virtual image is therefore inverted compared with the distant object.

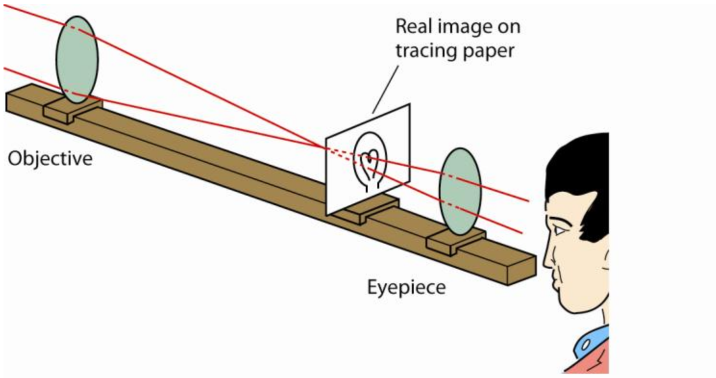


Figure 2 *Investigating the simple refracting telescope*

The ray diagram in Figure 3 shows in detail how the viewer looking through the eyepiece sees the final virtual image. The diagram shows the telescope in **normal adjustment** which means the telescope is adjusted so the virtual image seen by the viewer is at infinity. In this situation, the principal focus of the eyepiece is at the same position as the principal focus of the objective. In other words, in normal adjustment:

the distance between the two lenses is the sum of their focal lengths

This is because:

- the real image of the distant object is formed in the focal plane of the objective (because the light rays from each point of the object are parallel to each other before entering the objective lens)
- the eyepiece is adjusted so its focal plane coincides with the focal plane of the objective. As a result, the light rays that form each point of the real image leave the eyepiece parallel to one another. To the viewer looking into the eyepiece, these rays appear to come from a virtual image at infinity.

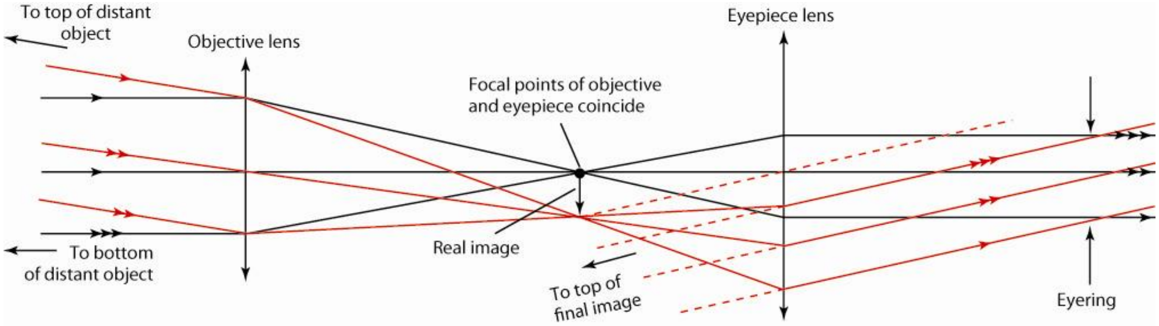


Figure 3 *Ray diagram for a simple refracting telescope in normal adjustment*

Notes

1 The light rays from each point of the distant object:

- are effectively parallel to each other by the time they reach the telescope
- leave the telescope as a parallel beam which therefore appears to the viewer to come from a distant point.

2 The real image formed by the objective lens is inverted and diminished in size. The eyepiece in effect acts as a magnifying glass with the real image being viewed by it. The viewer sees a magnified virtual image which is 'upright' compared with the real image and therefore inverted compared with the distant object.

3 Notice that all the light rays from the object that pass through the eyepiece all pass through a circle referred to as the 'eye-ring'. This is the best position for the viewer's eye as the entire image can be seen by the eye at this position.

Angular magnification

Application

Investigating the simple refracting telescope

Use two suitable converging lenses in holders to make a simple refracting telescope. Adjust the position of the eyepiece so an image of a distant object is seen in focus. The image of the object is inverted and it should be magnified.

Place a 'tracing paper' screen between the lenses and locate the real image of the distant object formed by the objective lens. Observe the image directly and through the eyepiece to see that the eyepiece gives a magnified virtual image of the real image. The virtual image becomes brighter if the screen is removed.

View the distant object directly with one eye and through the telescope with the other eye, as in Figure 4. You should be able to estimate how large the image appears to be compared with the object viewed directly (i.e. without the aid of the telescope). This comparison is referred to as the angular magnification (or magnifying power) of the telescope.

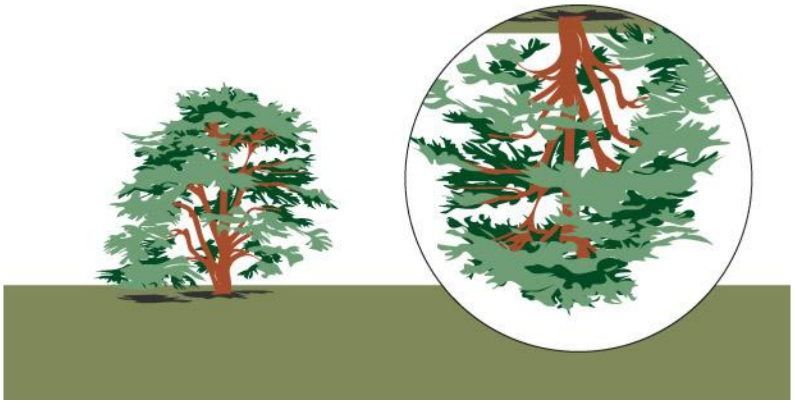


Figure 4 *A telescope test*

Suppose a telescope in normal adjustment makes a distant object appear to be three times larger. Its angular magnification would therefore be 3. If the angle subtended by the distant object to the 'unaided' eye is 1°, the angle subtended by the telescope image to the eye would be 3°. Figure 5 shows the idea. The diagram shows only one light ray from the top of the object entering the telescope at the objective lens and leaving in a direction as if it was from the tip of the virtual image seen by the viewer. The distant object and the image are meant to be at infinity so the angle subtended by the distant object to the unaided eye is effectively the same as the angle subtended by the object to the telescope.

- The angle subtended by the final image at infinity to the viewer = β
- The angle subtended by the distant object to the unaided eye = α

The angular magnification of the telescope in normal adjustment =

$$\frac{\textbf{angle subtended by the final image at infinity to the viewer}}{\textbf{angle subtended by the distant object to the unaided eye}} = \frac{\beta}{\alpha}$$

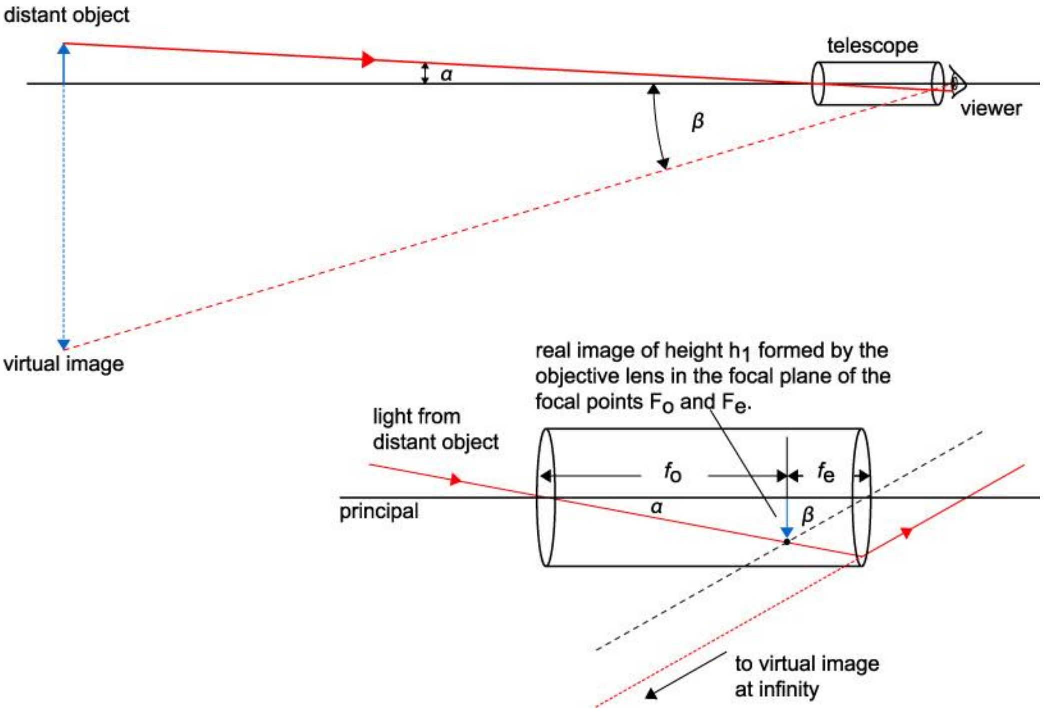


Figure 5 *Angular magnification*

From the inset diagram in Figure 5, it can be seen that $\tan\alpha = \dfrac{h_1}{f_o}$ and $\tan\beta = \dfrac{h_1}{f_e}$, where h_1 is the height of the real image and f_o and f_e are the focal lengths of the objective and eyepiece lenses respectively.

Combining these two equations to eliminate h_1 gives $\dfrac{\tan\beta}{\tan\alpha} = \dfrac{h_1 / f_e}{h_1 / f_o} = \dfrac{f_o}{f_e}$

Assuming angles α and β are always less than about 10°, applying the small angle approximation

$\tan\alpha = \alpha$ in radians and $\tan\beta = \beta$ in radians gives $\dfrac{\beta}{\alpha} = \dfrac{f_o}{f_e}$

Therefore:

the angular magnification of a telescope in normal adjustment = $\frac{f_o}{f_e}$

Notes

1 The height h_1 of the real image = $f_o \tan \alpha = f_o \times$ (α in radians)
Remember 360° = 2π radians.

2 The objective is the lens with the longer focal length. If you use a telescope the wrong way round, you will see a diminished image!

AQA Examiner's tip

Always check your calculator is in the correct 'angle' mode when carrying out calculations involving angles.

Worked example

A refracting telescope consists of two converging lenses of focal lengths 0.840 m and 0.120 m.

a If the telescope is used in normal adjustment, calculate:

  i its angular magnification

  ii the distance between its lenses.

b The telescope in normal adjustment is used to observe the Moon when the angle subtended by the lunar disc is 0.40°. Calculate:

  i the angle subtended by the image of the lunar disc

  ii the diameter of the real image of the lunar disc formed by the objective lens.

Solution

a i The objective is the lens with the longer focal length.

$$\text{Angular magnification} = \frac{f_o}{f_e} = \frac{0.840}{0.120} = 7.0$$

ii Distance between the lenses = $f_o + f_e = 0.840 + 0.120 = 0.960$ m

b i angular magnification = $\frac{\beta}{\alpha}$ where $\alpha = 0.40°$

Therefore $\beta = \alpha \times$ angular magnification $= 7\alpha = 2.8°$

ii $h_1 = f_o \tan \alpha = 0.840 \times \tan 0.40° = 5.9 \times 10^{-3}$ m

Image brightness

A star is so far away that it is effectively a point object. When viewed through a telescope, a star appears brighter than when it is viewed by the unaided eye. This is because the telescope objective is wider than the pupil of the eye so more light from a star enters the eye when a telescope is used than when the eye is unaided.

The pupil of the eye in darkness has a diameter of about 10 mm. The light entering the eye pupil or the objective is proportional to the area in each case and the area is proportional to the square of the diameter. Therefore, in comparison with the unaided eye, a telescope with an objective lens:

- of diameter 60 mm would collect 36 times $\left(=\left(\frac{60}{10}\right)^2\right)$ more light per second from a star
- of diameter 120 mm would collect 144 times $\left(=\left(\frac{120}{10}\right)^2\right)$ more light per second from a star.

This is why many more stars are seen using a telescope than using the unaided eye. The greater the diameter of the objective of a telescope, the greater the number of stars that can be seen.

Planets and other astronomical objects in the solar system are magnified using a telescope (unlike stars which are point objects and are seen through telescopes as point images no matter how large the magnification of the telescope is). Yet the image of a planet viewed using a telescope is not significantly brighter than the planet when it is viewed directly. This is because, although more light per second enters the eye when a telescope is used, the virtual image is magnified so is spread over a larger part of the field of view. As a result, the amount of light per second per unit area of the virtual image is unchanged.

Warning! Never view the Sun using a telescope or directly. The intensity of sunlight entering the eye would damage the retina of the eye and cause blindness.

How science works

Galileo on trial

Although the telescope was first invented by the English astronomer Thomas Digges, it was not generally known about until after its rediscovery in 1609 by the Dutch lens-maker Hans Lippershey. When Galileo first heard about it, he rushed to make his first telescope so he could demonstrate it before anyone else to his patrons in Venice – observing incoming ships would enable them to buy the ships' cargoes before their competitors could! After being rewarded accordingly, Galileo went on to make more powerful telescopes and used them to observe the stars and the planets.

His discoveries of craters on the lunar surface and of the four inner moons of Jupiter (now referred to as the Galilean moons Io, Callisto, Ganymede and Europa) convinced him that the Copernican model of the solar system published by Copernicus more than seventy years earlier was correct – the planets orbit the Sun and the Earth itself is a planet. After Galileo published his discoveries in 1610, his support for the Copernican model was challenged by members of the Inquisition and he had to rely on his friends in the Church to defend him. As a result of a further publication 'Dialogue on the Two Chief World Systems' which he wrote in 1629, Galileo was tried by the Inquisition for heresy and forced to confess. He was sentenced to life imprisonment which his friends in the Church managed to reduce to confinement at his home in Tuscany. However, before he died in 1642, he wrote a textbook on his scientific theories and experiments in which he established the scientific method – used by scientists worldwide ever since.

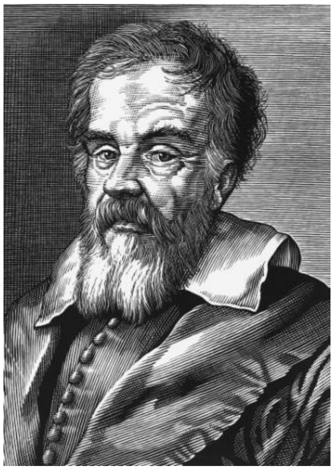


Figure 6 *Galileo*

Summary questions

1 Draw a ray diagram of a telescope consisting of two converging lenses to show how an image is formed of a distant object. Show clearly on your ray diagram the principal focus of the lenses, the position of the viewer's eye and label the two lenses.

2 A telescope consists of two converging lenses of focal lengths 60 mm and 450 mm. It is used in *normal adjustment* to view a distant object that subtends an angle of 0.15° to the telescope.

- **a** Explain what is meant by the term 'normal adjustment'.
- **b** Calculate:
  - **i** the angular magnification of the telescope
  - **ii** the angle subtended by the virtual image seen by the viewer.

3 Explain the following observations made using a telescope.

- **a** A star too faint to see with the unaided eye is visible using the telescope.
- **b** The Galilean moons of Jupiter can be observed using a telescope but not by the unaided eye.

4 A telescope consisting of two converging lenses has an eyepiece of focal length 40 mm. When used in normal adjustment, the angular magnification of the telescope is 16.

- **a** Calculate:
  - **i** the focal length of the objective lens
  - **ii** the separation of the two lenses.
- **b** The image of a tower of height 75 m viewed through the telescope subtends an angle of 4.8° to the viewer. Calculate:
  - **i** the angle subtended by the tower to the viewer's unaided eye
  - **ii** the distance from the tower to the viewer.

1.3 Reflecting telescopes

Learning objectives:

- What is a Cassegrain reflecting telescope?
- What is meant by spherical aberration and chromatic aberration?
- What are the relative merits of a reflecting telescope and a refracting telescope?

The Cassegrain reflecting telescope

A **concave mirror** instead of a converging lens is used as the objective of a reflecting telescope. The concave reflecting mirror is referred to as the **primary** mirror because a secondary smaller mirror reflects light from the concave reflector into the eyepiece.

The shape of a concave mirror is such that parallel rays directed at it are reflected and focused to a point by the mirror. The principal axis of the mirror is the line normal to its reflecting surface through its centre. If rays are parallel to the principal axis of the concave mirror then the point where the reflected rays converge is called the **principal focus** F (i.e. the focal point) of the mirror. Figure 1 shows the idea. The distance from the principal focus to the centre of the mirror is the **focal length**, *f*, of the mirror.

The light rays from a distant point object are effectively parallel when they reach the mirror. So a concave mirror will form a real image of a distant point object in the focal plane, the plane containing the principal focus.

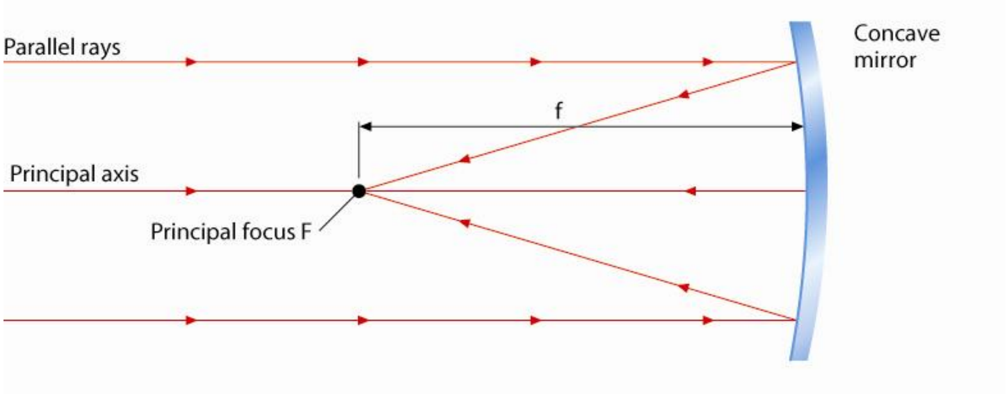


Figure 1 *The focal length of a concave mirror*

In a **Cassegrain reflecting telescope**, the secondary mirror is a convex mirror positioned near the focal point of the primary mirror between this point and the primary mirror itself. The purpose of the convex mirror is to focus the light onto or just behind a small hole at the centre of the concave reflector. The light passing through this small hole then passes through the eyepiece which is behind the concave mirror centre, as shown in Figure 2. The distance from the concave mirror to the point where it focuses parallel rays is increased by using a convex mirror instead of a plane mirror as the secondary mirror. This distance is the effective focal length of the objective.

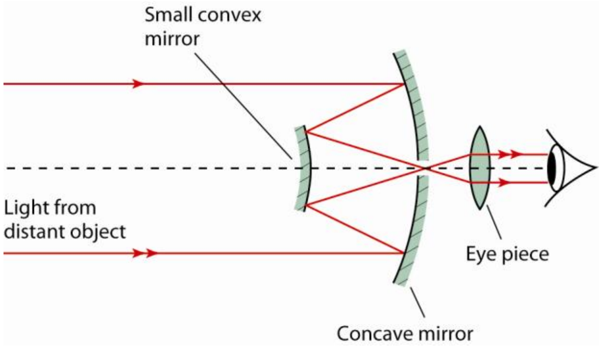


Figure 2 *Ray diagram for a Cassegrain reflector*

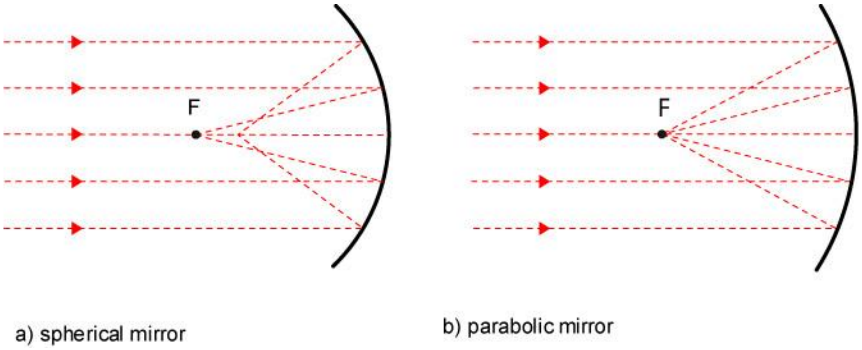
When the telescope is directed at a distant object, a viewer looking into the eyepiece sees a virtual image of the distant object. The light from the distant object is:

1 reflected by the concave mirror, then
2 reflected by the convex mirror onto the small hole at the centre of the concave mirror into the eyepiece, then
3 refracted by the eyepiece into a parallel beam which enters the viewer's eye.

Consequently, the viewer sees the virtual image at infinity.

Notes on the Cassegrain telescope

1 The effective focal length of the objective is increased by using a secondary convex mirror. Therefore, the angular magnification (= focal length of objective ÷ focal length of eyepiece) is also increased.
2 In a typical Cassegrain reflector, the image of a distant object is usually brought into focus by adjusting the position of the secondary convex mirror along the principal axis.
3 The primary mirror should be **parabolic** in shape rather than spherical to minimise **spherical aberration** due to the primary mirror. This effect happens with a spherical reflecting surface because the outer rays of a beam parallel to the principal axis are brought to a focus nearer the mirror than the focal point, F, as shown in Figure 3(a). In comparison, the parabolic mirror in Figure 3(b) focuses all the light rays to F.



a) spherical mirror

b) parabolic mirror

Figure 3 *Spherical aberration*

Comparison of refractors and reflectors

Reflecting telescopes in general have a key advantage over refracting telescopes because they can be much wider. This is because high-quality concave mirrors can be manufactured much wider than a convex lens can. The wider the objective is, the greater the amount of light they can collect from a star, enabling stars to be seen that would be too faint to see even with a refractor. As explained in Topic 1.2, the light collected by a telescope is proportional to the area of the objective. As the area is proportional to the square of its diameter, a reflector with an objective of diameter 200 mm can collect 25 times as much light as a refractor with an objective of diameter 40 mm.

Telescopes with wide objectives usually have a concave mirror as the objective rather than a convex lens. The high quality of a wide concave mirror compared with a wide convex lens is because:

- image distortion due to spherical aberration is reduced if the mirror surface is parabolic
- unwanted colours in the image are reduced. Such unwanted colours are due to splitting of white light into colours when it is refracted. The result is that the image formed by a lens of an object is tinged with colour, particularly noticeable near the edge of the lens. The effect is known as **chromatic aberration**. Figure 4 illustrates the effect. Notice the blue image is formed nearer the lens than the red image; this is because blue light is refracted more than red light.

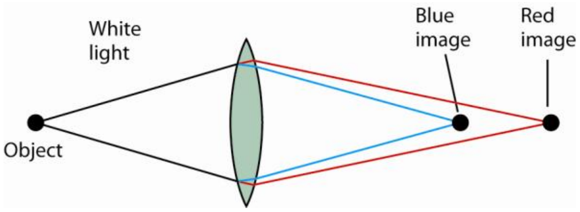


Figure 4 *Chromatic aberration*

Also, a wide lens would be much heavier than a wide mirror and would make the telescope top-heavy.

Further comparisons between refractors and reflectors are summarised below.

Refracting telescopes:

- use lenses only and do not contain secondary mirrors and supporting frames which would otherwise block out some of the light from the object
- have a wider field of view than reflectors of the same length because their angular magnification is less. Astronomical objects are therefore easier to locate using a refractor instead of a reflector of the same length.

Reflecting telescopes:

- are shorter and therefore easier to handle than refractors with the same angular magnification
- have greater angular magnification than refractors of the same length and therefore produce greater magnification of distant objects such as the Moon and the planets.

Summary questions

1 Draw a ray diagram to show the passage of light from a distant point object through a Cassegrain reflecting telescope. Show the position of the eye of the observer on your diagram and label the parts that make up the telescope and the effective focal point of the objective.

2 **a** State what is meant by chromatic aberration.

b Explain why the objective of a refracting telescope produces chromatic aberration whereas that of a Cassegrain reflector does not.

3 State and explain one disadvantage and one advantage, other than reduced chromatic aberration, a Cassegrain telescope has in comparison with a simple refractor telescope.

4 A Cassegrain telescope has a primary mirror of diameter 80 mm.

a Calculate the ratio of the light energy per second it collects to the light energy per second collected by the eye when the eye pupil is 8 mm in diameter.

b The telescope objective has an effective focal length of 2.8 m and its eyepiece has a focal length of 0.07 m. Calculate its angular magnification.

1.4 Resolving power

Learning objectives:

- What do we mean by angular separation?
- Why does a wide telescope resolve two stars that cannot be resolved by a narrower telescope?
- What is the Rayleigh criterion for resolving two point objects?

Diffraction

The extent of the detail that can be seen in a telescope image depends on the width of the objective. Imagine viewing two stars near each other in the night sky. The **angular separation** of the two stars is the angle between the straight lines from the Earth to each star, as shown in Figure 1.

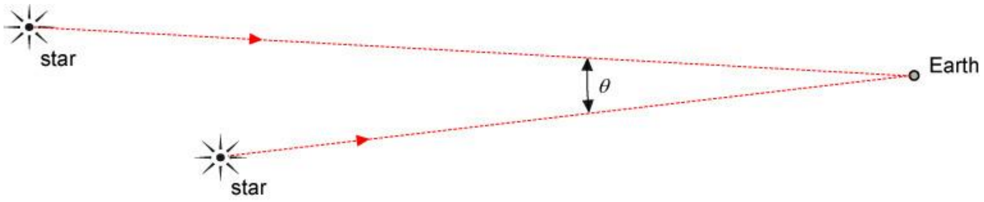


Figure 1 *Angular separation*

Suppose the two stars are viewed through a telescope and their images can just be seen as separate images. In other words, the telescope just resolves the two stars. If the telescope is replaced by one with a narrower objective, the images of the two stars would overlap too much and the observer would not be able to see them as separate stars. This is because:

- the objective lens or mirror is in an aperture (i.e. a gap) which light from the object must pass through and diffraction of light always occurs whenever light passes through an aperture
- instead of focusing light from a star (or other point object) to a point image, diffraction of light passing through the objective causes the image to spread out slightly.
- the narrower the objective, the greater the amount of diffraction that occurs when light passes through the narrower objective. So the greater the spread of the image.

Diffraction at a circular aperture

Diffraction at a **circular aperture** can be observed on a screen when a narrow beam of light passes through a small circular aperture before reaching the screen. Figure 2 shows the diffraction pattern on the screen. The pattern consists of a central bright spot surrounded by alternate concentric dark and bright rings. The bright rings are much fainter than the central spot and their intensity decreases with distance from the centre.

The objective of a telescope is a circular aperture containing a convex lens or a concave mirror. Diffraction occurs when light from a star passes through the aperture. As the light is focused by the objective, the star image showing the same type of pattern as in Figure 2 is observed in the focal plane of the objective. An observer looking through the eyepiece would see a magnified view (i.e. a magnified virtual image) of the star image formed by the objective.

For light of wavelength λ passing through a circular aperture of diameter D, it can be shown that an approximate value of the angle of diffraction, in radians, of the first dark ring is given by $\frac{\lambda}{D}$.

Link

Topic 13.6 of *AS Physics A* looks at single slit diffraction.

Prove for yourself that, for an objective of diameter 80 mm , the angle of diffraction θ for the first dark ring is approximately 6.3×10^{-6} radians (= 0.00036 degrees) for light of wavelength 500 nm. In comparison, the corresponding angle for an objective of diameter 20 mm would be four times larger (i.e. 0.0014(4) degrees).

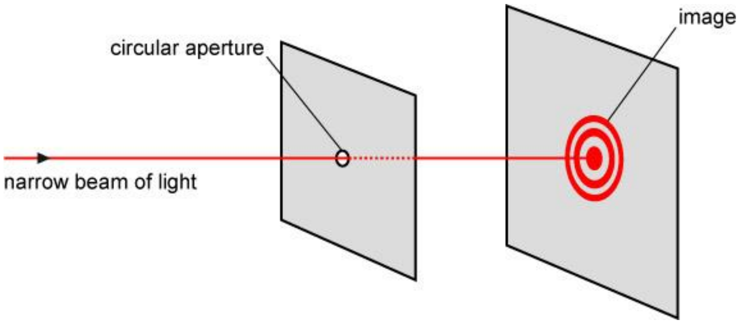


Figure 2 *Diffraction of a small circular aperture*

Resolving two stars

Two stars near each other in the night sky can be resolved (i.e. seen as separate stars) if the central diffraction spots of their images do not overlap significantly. This condition can be expressed numerically using the **Rayleigh criterion** which states that resolution of the images of two point objects is **not** possible if any part of the central spot of either image lies inside the first dark ring of the other image. As shown in Figure 3, this means that the angular separation of the two stars must be at least equal to the angle of diffraction of the first dark ring.

In other words, using the above approximation for the angle of diffraction of the first dark ring, the least angular separation θ for the resolution of two stars is given approximately by the condition:

$$\theta \approx \frac{\lambda}{D}$$

where λ = the wavelength of light, and D = the diameter of the circular aperture.

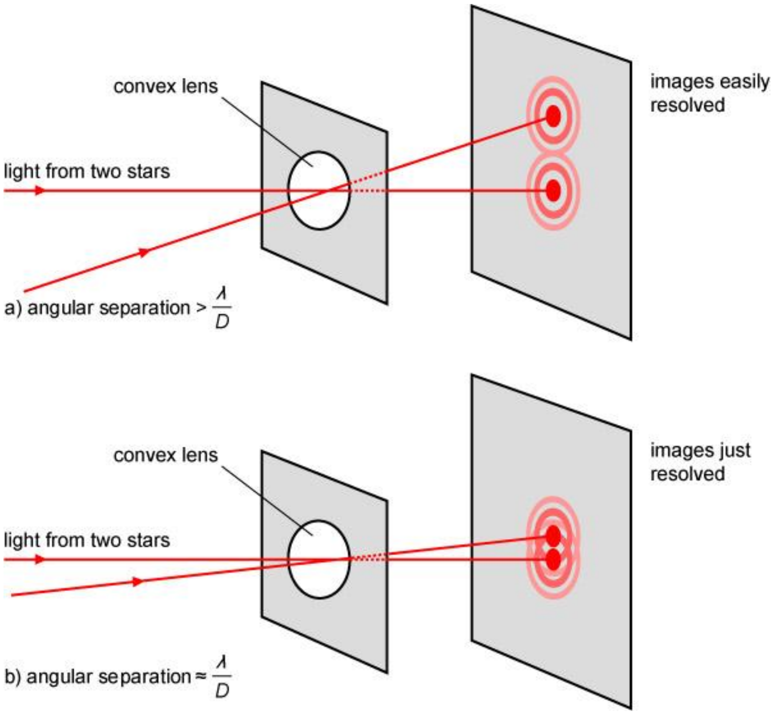


Figure 3 *Resolving two stars*

For example, a telescope with an 80 mm diameter objective will just be able to resolve two stars with an angular separation of 0.000 36 degrees, assuming an average value of 500 nm for the wavelength of light. Without the telescope, the human eye would **not** be able to resolve them as the typical eye pupil diameter is about 8 mm which is a tenth of the width of an 80 mm wide telescope. The unaided eye can resolve two stars only if their angular separation is at least 0.0036 degrees (i.e. ten times greater than that with an 80 mm wide telescope).

AQA Examiner's tip

When you use the formula, make sure your calculator is in radian mode and don't forget to convert angles to radians if their values are wanted in radians or given in degrees.

Remember: 2π radians = 360 degrees.

Notes

1. **Resolution** or **resolving power** are both used sometimes to describe the quality of a telescope in terms of the minimum angular separation it can achieve. For example, a telescope described as having a resolution or resolving power of 0.004 degrees can resolve two stars which have an angular separation of at least 0.004 degrees.
2. The Rayleigh criterion applies to the detail visible in extended images as well as to stars. For example, a telescope with a resolving power of 5×10^{-5} radians (= 0.003 degrees) is capable of seeing craters on the lunar surface which have an angular diameter of 0.003 degrees. As the Moon is about 380 000 km from Earth, such craters are about 20 km in diameter.
3. Refraction due to movement of air in the atmosphere causes the image of any star seen through a telescope to be 'smudged' slightly. As a result, ground-based telescopes with objectives of diameter greater than about 100 mm do not achieve their theoretical resolution.

The stunning clarity of images from the Hubble Space Telescope is because the telescope has an objective mirror of diameter 2.4 m and is above the atmosphere and therefore does not suffer from atmospheric refraction. Hence it achieves its theoretical resolution which is about 240 times greater than that of a 100 mm wide telescope.

How science works and application

The Hubble Space Telescope

Figure 4 *A HST image of a cluster of galaxies*

After it was first launched in 1990, HST images were found to be poor because of spherical aberration in its primary mirror due to a manufacturing fault. This was corrected in 1993 when a space shuttle mission was launched to enable astronauts to fit small secondary mirrors to compensate exactly for the fault and give amazing images that have dramatically increased our knowledge of space.

The Hubble Space Telescope detects images at wavelengths from 115 nm to about 1000 nm, thus giving infrared, visible and ultraviolet images.

Summary questions

1 **a** What is the name for the physical phenomenon that causes the image formed by a lens or mirror of a point object to be spread out?

b **i** Sketch the pattern of the image of a distant point object formed by a lens.

ii Describe how the pattern would differ if a wider lens of the same focal length had been used?

2 State and explain what is meant by the Rayleigh criterion for resolving two point objects using a telescope.

3 Two stars have an angular separation of 8.0×10^{-6} rad.

a Assuming light from them has an average wavelength of 500 nm, calculate an approximate value for the diameter of the objective of a telescope that can just resolve the two stars.

b Discuss how the image of the two stars would differ if they were viewed with a telescope with an objective of twice the diameter and the same angular magnification.

4 The Hubble Space Telescope has an objective of diameter 2.4 m.

a Show that the theoretical resolution of the HST is 1.2×10^{-5} degrees.

b Hence estimate the diameter of the smallest crater on the Moon that can be seen using the telescope. Assume the wavelength of light is 500 nm.

Earth–Moon distance = 3.8×10^{8} m

1.5 Telescopes and technology

Learning objectives:

- What is a charge-coupled device (CCD) and why is it important in astronomy?
- How does a CCD work?
- What are non-optical telescopes used for?
- How do non-optical telescopes compare with each other and with optical telescopes?

Charge-coupled devices

Astronomers have always used photographic film to capture images ever since photography was first invented in the 19th century. However, the charge-coupled device invented in the late 20th century fitted to a telescope has dramatically extended the range of astronomical objects that can be seen as well as providing images of stunning quality.

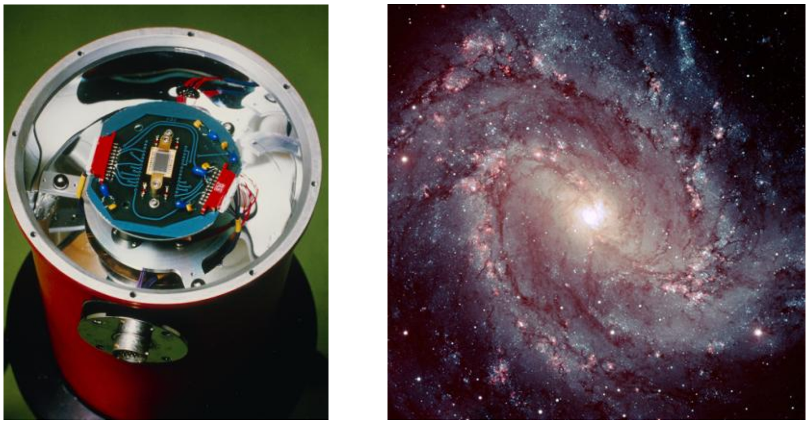


Figure 1 *Using a CCD* **(a)** *A CCD in a telescope* **(b)** *A CCD image of a spiral galaxy*

The CCD is an array of light-sensitive **pixels** which become charged when exposed to light. After being exposed to light for a pre-set time, the array is connected to an electronic circuit which transfers the charge collected by each pixel in sequence to an output electrode connected to a capacitor. The voltage of the output electrode is ‘read out’ electronically then the capacitor is discharged before the next pulse of charge is received. In this way, the output electrode produces a stream of voltage pulses, each one of amplitude in proportion to the light energy received by an individual pixel. Figure 2 shows part of an array of pixels.

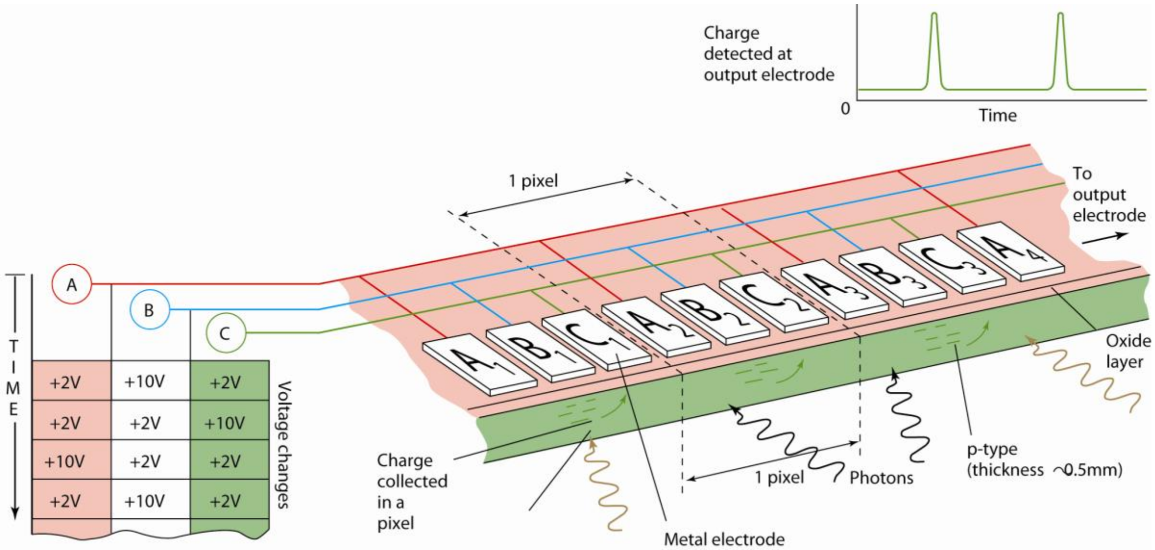


Figure 2 *Inside a CCD*

Each pixel has three small rectangular metal electrodes (labelled A, B and C in Figure 2) which are separated by a thin insulating layer of silicon dioxide from p-type silicon which is the light-sensitive material underneath. The electrodes are connected to three voltage supply ‘rails’.

- The rectangular electrodes and the insulating layer are thin enough to allow light photons to pass through and each liberate an individual electron in the light-sensitive material underneath.
- When collecting charge, the central electrode in each pixel (labelled B in Figure 2) is held at +10 V and the two outer electrodes at +2 V. This ensures the liberated electrons accumulate under the central electrode.
- After the pixels have collected charge for a certain time, the charge of each pixel is shifted towards the output electrode via the adjacent pixels. This is achieved by altering the voltage level of each electrode in a sequence of three-step cycles, as shown in Figure 2.

The quantum efficiency of a pixel is the percentage of incident photons that liberate an electron. About 70% of the photons incident on a pixel each liberates an electron. Therefore, the quantum efficiency of a pixel is about 70%. In comparison, the grains of a photographic film have a quantum efficiency of about 4% as only about 4 in every 100 incident photons contributes to the darkening of each grain. So a CCD is much more efficient than a photographic film and hence it will detect much fainter astronomical images than a film.

Further advantages of a CCD

- Its use in recording changes of an image. It can record a sequence of fast-changing astronomical images which can be seen by the eye but could not be recorded on a photographic film.
- Its wavelength sensitivity from less than 100 nm to 1100 nm is wider than that of the human eye which is from about 350 nm to 650 nm. Hence it can be used with suitable filters to obtain infrared images.
- The quantum efficiency of a CCD is the same at about 70% from about 400 nm to 800 nm, reducing to zero below 100 nm and at 1100 nm.

However, CCDs for use in astronomy need to have a larger number of pixels in a small area and are therefore expensive compared with CCDs in most electronic cameras. More significantly, CCDs used in astronomy are often cooled to very low temperatures using liquid nitrogen otherwise random emission of electrons causes a ‘dark’ current which does not depend on the intensity of light.

Radio telescopes

Single-dish radio telescopes each consist of a large parabolic dish with an aerial at the focal point of the dish. A steerable dish can be directed at any astronomical source of radio waves in the sky. The atmosphere transmits radio waves in the wavelength range from about 0.001 m to about 10 m. When the dish is directed at an astronomical source that emits radio waves in the above wavelength range, the waves reflect from the dish onto the aerial to produce a signal. The dish is turned by motors to enable it to scan sources and to compensate for the Earth’s rotation.

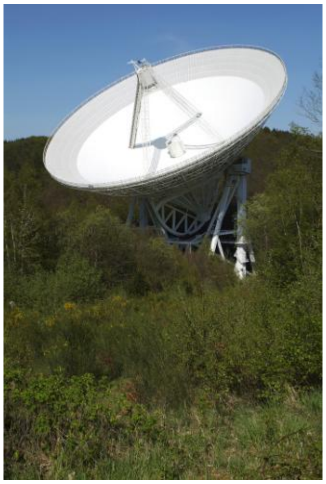


Figure 3 *A single-dish radio telescope*

The amplitude of the signal is a measure of the intensity of the radio waves received by the dish. The signal from the aerial is amplified and supplied to a computer for analysis and recording. As the dish scans across the source, the signal is used to map the intensity of the radio waves across the source to give a ‘radio’ image of the source.

The dish surface usually consists of a wire mesh which is lighter than metal sheets and just as effective in terms of reflection, provided the mesh spacing is less than about $\frac{\lambda}{20}$, where λ is the wavelength of the radio waves.

The dish diameter, D, determines

- the collecting area of the dish ($= \frac{1}{4}\pi D^2$)
- the resolving power of the telescope ($= \frac{\lambda}{D}$)

The Lovell radio telescope at Jodrell Bank in Cheshire has a 76 m steerable dish which gives a resolution of 0.2 degree for 21 cm wavelength radio waves. In comparison, the Arecibo radio telescope in Puerto Rica is a 300 m fixed concave dish set in a natural bowl. As it is four times wider than the Lovell telescope, it can therefore resolve radio images to about 0.05 degrees ($= \frac{1}{4}$ of 0.2°) and detect radio source 16 times fainter (as it collects 16 times as much radio energy per second than the Lovell telescope does). However, the Arecibo telescope can only detect radio sources when they are close to its principal axis.

Uses of radio telescopes

Locating and studying strong radio sources in the sky

The Sun, Jupiter and the Milky Way are all strong sources of radio waves. Some galaxies are also relatively strong emitters of radio waves. Such galaxies are usually elliptical or spherical without spiral arms. Many radio galaxies are found near the centre of clusters of galaxies and their optical images often show evidence of violent events such as two galaxies merging or colliding or a galaxy exploding or emitting immensely powerful jets of matter.

Mapping the Milky Way galaxy

Hydrogen atoms in dust clouds in space emit radio waves of wavelength 21 cm. These are emitted when the electron in a hydrogen atom flips over so its spin changes from being in the same direction as the proton’s spin to a lower energy level in the opposite direction. The Milky Way is a spiral galaxy with the Sun in an outer spiral arm. Dust clouds in the spiral arms prevent us from seeing stars and other radio sources, such as hot gas behind the dust clouds, as dust absorbs light. However, radio waves are not absorbed by dust so radio telescopes are used to map the Milky Way.

Link

Electromagnetic waves were looked at in Topic 1.3 of *AS Physics A*.

Infrared telescopes

Infrared telescopes have a large concave reflector which focuses infrared radiation onto an infrared detector at the focal point of the reflector. Objects in space such as planets that are not hot enough to emit light emit infrared radiation. In addition, dust clouds in space emit infrared radiation. Infrared telescopes can therefore provide images from objects in space that cannot be seen using optical telescopes.

Ground-based infrared telescopes

A ground-based infrared telescope needs to be cooled to stop infrared radiation from its own surface swamping infrared radiation from space. Water vapour in the atmosphere absorbs infrared radiation, so an infrared telescope needs to be sited where the atmosphere is as dry as possible and as high as possible. The 3 m diameter infrared telescope on a mountain in Hawaii is located there because the atmosphere is very dry and the water vapour that is present has less effect than if the telescope was at a lower level.

Infrared telescopes on satellites

An infrared telescope on a satellite in orbit above the Earth is not affected by water vapour. However, the telescope still needs to be cooled to a few degrees above absolute zero to be able to detect infrared radiation from weak infrared sources.

IRAS, the first infrared astronomical satellite, launched in 1978, discovered bands of dust in the solar system and dust around nearby stars. It carried a 60 cm wide infrared telescope fitted with a detector capable of detecting infrared wavelengths from 0.01 mm to about 1 mm.

The Hubble Space Telescope with its objective at 2.4 m wide is capable of detecting infrared wavelengths from 700 nm to about 1000 nm (= 0.001 mm). It can form images of 'warm' objects such as dying stars and planets in other solar systems that emit thermal radiation but not light.

Ultraviolet telescopes

Ultraviolet (UV) telescopes must be carried on satellites because UV radiation is absorbed by the Earth's atmosphere. As UV radiation is also absorbed by glass, a UV telescope uses mirrors to focus incoming UV radiation onto a UV detector. UV radiation is emitted by atoms at high temperatures, so UV telescopes are used to map hot gas clouds near stars and to study hot objects in space such as glowing comets, supernova and quasars. Comparing a UV image of an object with an optical or infrared image gives useful information about hot spots in the object.

- The International Ultraviolet Explorer (IEU) launched in 1978 carried a 0.45 m wide Cassegrain telescope with a UV detector instead of an eyepiece in its focal plane.
- The Hubble Space Telescope uses a CCD to detect images at wavelengths from 115 nm to about 1000 nm, giving ultraviolet images as well as visible and infrared images according to the filters used over the CCD.
- The XMM-Newton space observatory, launched in 1999 and still in operation, carries a 30 cm wide modified Cassegrain reflector fitted with a detector with a wavelength range from 170 nm to 650 nm. So, it can give ultraviolet as well as optical images.

Figure 4 *A combined UV and optical image of the galaxy M82 galaxy (UV in blue).*

X-ray and gamma-ray telescopes

They need to be carried on satellites as the Earth's atmosphere absorbs X-rays and gamma rays. Discoveries using such telescopes include:

- X-ray pulsars, stars that emit X-ray beams that sweep round the sky as they spin
- X-ray and gamma-ray 'bursters' billions of light years away which emit bursts of gamma rays.

X-ray telescopes work by reflecting X-rays off highly-polished metal plates at 'grazing' incidence onto a suitable detector. Gamma ray telescopes work by detecting gamma photons as they pass through a detector containing layers of 'pixels', triggering a signal in each pixel it passes through it. The direction of each incident gamma photon can be determined from the signals. The

International Gamma Ray Astrophysics Laboratory (INTEGRAL) launched in 2002 is being used to study supernova, gamma ray bursts and black holes. As gamma rays and X-rays are very short wavelength, diffraction is insignificant and image resolution is determined by the pixel separation.

Summary questions

The table below is an incomplete comparison of different types of astronomical telescopes.

Type	Location	Wavelength range	Resolution (degrees)	Key advantages	Major disadvantages
optical	ground or satellite	350–650 nm	10^{-5} for HST	gives very detailed images, can detect distant galaxies	ground telescopes suffer from atmospheric refraction
radio	ground	1 mm to 10 m	0.2 for Lovell	radio waves pass through dust in space and through the atmosphere	large, supporting structure needed for a steerable dish.
infrared				can detect warm objects that do not emit light, can detect dust clouds in space	mirror needs to be cooled
ultraviolet					must be above the Earth's atmosphere e.g. on a satellite
X and gamma			0.2 for INTEGRAL		must be above the Earth's atmosphere e.g. on a satellite

1 Copy this table and use the information in this topic to complete columns 2 and 3.

2 **a** Use the information in the previous pages to estimate the resolution in degrees of:

- **i** HST at a wavelength of 0.001 mm
- **ii** XMM-Newton at a wavelength of 170 nm

b Use your estimates to complete column 4 of your table.

3 Complete column 5 by giving two key advantages of:

a UV telescopes

b X-ray and gamma ray telescopes.

4 The collecting power of a telescope is a measure of how much energy per second it collects. This depends on the area of its objective as well as the power per unit area (intensity) of the incident radiation.

a For the same incident power per unit area, list the following telescopes in order of their collecting power:

Hubble Space Telescope (2.4 m in diameter)
INTEGRAL (0.60 m diameter)
IRAS (0.60 m diameter)
Lovell telescope (76 m diameter)
XMM-Newton (0.30 m diameter)

b The Lovell radio telescope is linked to other radio telescopes in England so they act together as an effective radio telescope of much greater width. Discuss without calculations how the resolving power and the collecting power of the linked system compare with that of the Lovell telescope on its own.