1 Telescopes

1.1 Lenses

A lens works by **changing the direction of light** at each of its two surface.

- The **principal axis** is the straight line through the centre of the lens perpendicular to the lens.
- **Converging lens** make parallel rays converge to a focus.

  The **principal focus** is the point where rays parallel to the principal axis are focused to.
- **Diverging lens** makes parallel rays diverge.

  The point where rays appear to come from is the **principal focus**.
- The **focal length** is the distance from the centre of the lens to the principal focus.

Ray Diagrams

- The lens is assumed to be **thin** so it can be 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** marked on the principal axis at the same distance from the lens on each side of the lens.
- The **object** represented by an upright arrow.

Converging Lens

- **Beyond the principal focus** of the lens, a **real image** is formed on the screen where the light rays meet.
- If the object is moved **nearer the principal focus**, the screen must be moved further away from the lens to see a clear image.
- When the object is **nearer to the lens** than the principal focus, a magnified, **virtual image** is formed where the light rays appear to come from.

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**. The viewer would therefore see a **virtual image at infinity**.

1.2 The Refracting Telescope

Two converging lens with different focal lengths.

- **The objective** is the lens with the longer focal length.
- **The eyepiece** is the one the viewer looks through.

The distance between the two lenses is altered until the image of the distance object is seen in focus. The image would be **enlarged, virtual and inverted**.

1. The objective lens focuses the light rays to form a **real image** of the object in the **same plane as the principal focus** of the objective lens.
2. The eyepiece gives the viewer looking through the telescope a **magnified view of this real image**. The magnified view is a virtual image because it is formed where the rays emerging from the eyepiece appear to have come from.

Because the real image formed by the objective is inverted, the virtual image is therefore inverted.

A telescope in **normal adjustment** means the telescope is adjusted so the virtual image seen by viewer is at infinity, and the distance between the two lenses is the sum of their focal length.

- The real image of the distance object is **formed in the focal plane** of the objective.
- The eyepiece is adjusted to its focal plane coincides with the focal plane of the objective.

As a result, the light ray that form each point of the real image leaves the eyepiece parallel to one another. To the viewer, these rays appear to come from a **virtual image at infinity**.

1. Light ray from each point of the object are effectively parallel to each other, and leave telescope as a parallel beam.
2. The **real image formed** by the objective lens is inverted and diminished in size.

   The eyepiece acts as a magnifying glass to magnify this real image.

Angular Magnification

$$\text{Angular magnification } M = \frac{\beta}{\alpha}$$

- β = angle subtended by the final image at infinity to the viewer.
- α = angle subtended by the distance image to the unaided eye.

For small α and $\beta < 10°$

$$M = \frac{\beta}{\alpha} = \frac{f_0}{f_e}$$

Collecting Power

The **amount of light** a telescope collect is called its collecting power, proportional to the square of the objective diameter.

1.3 Reflecting Telescopes

A **concave mirror** instead of a **converging lens** is used as the objective of a reflecting telescope. The concave mirror is referred to as the **primary mirror**.

- Parallel rays directed at it are reflected and focused to a point by the mirror.
- The distance from the principal focus to the centre of the mirror is the **focal length**.
- So the concave mirror will form a **real image** of a distant object in the focal plane.

The Cassegrain Reflecting Telescope

- The **secondary mirror** is a convex mirror between the focal point and the concave mirror.
- This mirror **focus light** onto a small hole in the concave mirror, then **passes through the eyepiece** behind the concave mirror centre.

So the viewer sees a virtual image at infinity.

Using a concave mirror instead of a plane mirror increases the **effective focal length** of the objective.

$$M = \frac{f_o}{f_e}$$

where f_o increases the angular magnification.

The primary mirror is **parabolic** in shape rather than spherical to minimise **spherical aberration** due to the primary mirror. Spherical aberration occurs because the outer rays of a beam parallel to the principal axis are brought to focus at a point nearer to the mirror than the focal point.

Reflectors vs Refractors

- Reflecting telescope can be **much wider**, because high-quality concave mirrors can be manufactured wider than concave lens. More light can be collected, allowing dimmer stars to be seen.
- **Image distortion** due to **spherical aberration** is reduced if the mirror surface is parabolic.

- **Chromatic aberration** creates unwanted colours in the image by splitting white light into colours. So the object formed by the lens is tinged with colour.
- Wide lenses are much heavier than wide mirrors.

Reflecting telescope

- Uses lens only, and contains **no secondary mirror** which would block out some light.
- Has a **wider field of view**, so astronomical objects are easier to locate than a reflector of the same length.

Reflecting telescope

- Are **shorter** than reflectors with the same angular magnification.

1.4 Angular Resolution

The **angular separation** of the two stars is the angle between the straight lines from the Earth to each star.

If two stars are can just be seen as separate images, if the telescope is replaced by a narrower objective, we will not be able to see the two stars as separate stars.

1. The lens is in an aperture where the **diffraction** of light always occurs.
2. The diffraction of light through the objective causes the image to spread out slightly.
3. The narrower the objective, the greater the amount of diffraction that occurs when light passes through the narrow objective, the greater the spread of the image.

$$\text{Angle of the first dark ring} = \frac{\lambda}{D}$$

Two stars near each other can be resolved if the central diffraction spots of their image **do not overlap significantly**.

The **Reyleigh criterion** 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.

$$\text{Minimum angular resolution } \theta \approx \frac{\lambda}{D}$$

The **minimum angular resolution** is used to describe the quality of a telescope is used to describe the quality of a telescope in terms of the **minimum angular separation** it can achieve.

1.5 Telescopes and Technology

A CCD is an array of **light-sensitive pixels** which becomes charged when exposed to light.

1. The CCD is **exposed to light** for a pre-set time.
2. 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.
3. The **voltage of each output electrode** is read out electronically.
4. The **capacitor is discharged** before the next pulse of charge is received.

The **quantum efficiency** of a pixel is the **percentage incident photons** that liberate an electron.

- The quantum efficiency of a pixel is about 70%.
- Much more efficient than the human eye at about 1-2%.

So a CCD will detect much fainter astronomical images than either the eye or film.

Advantages of a CCD

- It can be used to **record changes** of an image, or record a **sequence of fast-changing astronomical images**.
- The **wavelength sensitivity** is much wider than that of the human eye.
- The **quantum efficiency** is the same across wavelength from 400nm to 800nm.

However, CCDs used in astronomy need to have a **large number of pixels** in a small area and therefore expensive. They also need to be cooled to very low temperatures, otherwise **random emission of electrons** causes dark current which does not depend on the intensity of light.

Radio Telescopes

Single dish radio telescopes consists 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 dish is turned by motors to compensate for the Earth's rotation.

- The dish surface consists of a **wire mesh**, lighter than metal sheets but just as reflective in terms of reflection, providing the **mesh spacing** is less than $\dfrac{\lambda}{20}$.
- Collecting area $= \frac{1}{4}\pi D^2$

- Minimum angular resolution = $\frac{\lambda}{D}$.

Infrared Telescopes

Infrared telescopes have a **large concave reflector** which focuses infrared radiation onto an infrared detector at the focal point of the reflector. Dust clouds in space emit infrared radiation, so infrared telescopes can provide image that cannot be seen using optical telescopes.

Ground-based infrared telescopes

- They need to be **cooled** to stop infrared radiation from its own surface swamping with infrared radiation from space.
- **Water vapour** in 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.

Infrared telescopes on a satellite needs to be cooled to a few degrees above absolute zero.

Ultraviolet Telescopes

- Ultraviolet telescopes must be carried on satellites because UV radiation is absorbed by the Earth's atmosphere.
- They must also use mirrors because UV radiation is absorbed by glass.
- UV radiation is emitted by atoms at high temperatures, and gives information about hot spots in the object.

X-ray and Gamma-ray Telescopes

X-ray and gamma-ray telescopes must also be carried out on satellites because they are absorbed by the Earth's atmosphere.

- X-ray telescopes reflect X-ray onto a suitable detector.
- Gamma-ray telescopes detect gamma photons as they pass through a detector containing **:**layers of pixels, triggering a signal in each pixel as it passes through.

  The direction of each incident gamma photon can be determined from the signals.