

# Telescopes and Optics

- **Goals**
  - **How do telescopes work?**
  - **How do astronomers utilize telescopes?**
  - **Why do we move into space?**
- **Principals of Optics**
  - **Refraction**

## Figure 6-1

- **Light travels slower in dense materials.**
- **$c = 3 \times 10^8 \text{ m s}^{-1}$  (vacuum)**
- **$c = 2 \times 10^8 \text{ m s}^{-1}$  (glass)**
- **Light passing from one medium to the next (e.g. air to glass) can change the direction of the light.**
- **This is caused by the change in the velocity of light.**

- **Refraction and Lenses**

- **Figure 6-2, 6-4**

- **Refraction enables a lens to focus light**

- Light incident on lens is refracted by an angle  $\alpha$ .
    - Light leaving the lens is refracted by an angle  $-\alpha$ .
    - Curved lenses can focus or disperse light.

- **Lenses**

- Convex lenses focus parallel rays of light to a common focal point.
    - Concave lenses disperse parallel rays of light.
    - Focal length of a lens is the distance from the lens to the point where the light from a parallel beam is brought to a focus.
    - Focal plane is the plane onto which an extended image will be brought to a common focus.

- **Light from Galaxies and Stars is Parallel.**

- **Refracting Telescope**

- **A Single Lens**

- As with a camera or your eye a single lens will bring an image in to focus at the focal plane (film or your retina).
    - To view the image (not a picture of the image) you require a second lens (or project onto a screen).

- **Double Lens System**

- Figure 6-5**

- Second lens magnifies the image.
        - Objective lens: larger lens, larger focal length, forms the image.
        - Eyepiece lens: smaller lens, smaller focal length, magnifies the image.

$$\begin{aligned} \text{Magnification} &= \frac{\text{angular diameter through eyepiece}}{\text{angular diameter by eye}} \\ &= \frac{\text{focal length of the objective lens}}{\text{focal length of the eyepiece lens}} \end{aligned}$$

- **Refracting Telescope**

- **Magnification and light gathering**

- Most important aspect of a telescope is the amount of light it can collect.

**Light gathering power  $\propto$  area of lens**  
 **$\propto$  diameter<sup>2</sup>**

- More light: fainter object (e.g. eye's pupil)
      - Limit on magnification is the atmosphere.

- **Example: Refracting Telescope**

- Objective focal length = 120 cm
    - Eyepiece focal length = 4 cm

$$\text{Magnification} = \frac{120 \text{ cm}}{4 \text{ cm}} = 30 \text{ (30x)}$$

- Magnification power is written as 30x
      - If an eyepiece of 2cm focal length is used the magnification is 60x.
      - Shorter the focal length of the eye piece (or longer the focal length of the objective lens) the more magnification.

- **Aberrations**

- **Chromatic aberration**

- Figure 6-7**

- The refraction of light by a lens depends on its wavelength.
      - Different wavelengths are brought to focus at different focal points.
      - Only one wavelength will be in focus and a colored halo will result.
      - Combining layers of glass can resolve this.

- **Spherical Aberration**

- Figure 6-13**

- A spherical mirror does not bring light to a common focus at the same point (a curved focal plane). This results in a fuzzy image.
      - Parabolic mirrors solve this problem but at the cost of field of view.
      - If the mirror does not have a common focal length at all points the light is not brought to focus at a common focal plane (e.g. Hubble Space Telescope).

- **Refracting vs Reflecting Telescopes**

- **Early telescopes (<1900s)**

- Refracting telescopes using 2 lenses (e.g. Galileo).
    - Larger the lens the fainter the objects we can view.
    - Large lenses require large focal lengths (short focal lengths are hard to make).
    - Large defect free lenses are hard to manufacture - largest lens made (Yerkes) is 102cm (19.5m focal length).
    - Lens are not very efficient.

- **Newer Telescopes (>1900s)**

- Use mirrors in place of lenses.
    - Largest mirrors are 8m in size.
    - “Easy” to construct short focal lengths.
    - Mirrors are very efficient (99%).
    - Easy to support.

- **Reflecting Telescopes**

- **Figures 6-9, 6-10**

- **Reflecting Surface**

- **Light incident to a flat reflecting surface at an angle  $\alpha$  to the perpendicular is reflected at an angle  $\alpha$ .**

- **A Reflecting Curved Surface**

- **A concave reflecting surface will bring light to a common focus.**
    - **Focal length of a mirror is the distance from the mirror to the point where the light from a parallel beam is brought to a focus.**
    - **The objective mirror is called a primary mirror.**
    - **No chromatic aberration.**
    - **Light is focused in front of the mirror - need to “pick off” the image.**
    - **Pick off mirror is called the secondary.**

- **Types of Reflecting Telescopes**

**Figure 6-11**

- **Newtonian**

- Beam is picked off by a 45° flat mirror.
- Earliest reflecting telescope design.

- **Prime Focus**

- Detector is placed within the barrel of the telescope.
- Limits the number of reflections.

- **Cassegrain**

- Light is reflected back down by a concave secondary mirror.
- Light passes through the primary.
- Most common design - short tube.

- **Coude**

- Light Reflects off the secondary.
- Light is picked off by a tertiary mirror. and reflected to the pivot point (Nasmyth) of the telescope.

- **Reflecting Telescope**

- **Image Scale**

- A telescope's focal length determines the scale of an image formed.

- **Image brightness**

- The telescope's f-value or focal ratio (i.e., focal length divided by diameter) determines image brightness.

- **Obscuration due to secondary**

- Secondary mirror blocks some of the light from reaching the mirror.
    - Secondary does not block part of the image (light from a source comes from all angles).

- **How well can we see?**
  - **Image quality is limited by the atmosphere (e.g. twinkling stars)**
    - The atmosphere is turbulent.
    - Light passing through the atmosphere gets refracted and the paths of photons are not the same.
    - The size of a point source due to the blurring of the atmosphere is called the seeing disk (0.5 - 1 arcsec).
  - **Telescope size limits resolution**
    - How well we can separate two close sources (angular resolution) depends on telescope size.
$$\theta = 2.5 \times 10^5 \frac{\lambda}{D}$$

$\theta$  : diffraction limit (arcseconds)  
 $\lambda$  : wavelength (m)  
 $D$  : primary mirror diameter (m)
    - Longer wavelength → worse images.
    - Bigger telescopes → better images.

– **Example: (1m telescope at 500nm)**

$$\begin{aligned}\theta &= 2.5 \times 10^5 \frac{\lambda}{D} \\ &= 2.5 \times 10^5 \frac{600 \times 10^{-9}}{1} \\ &= 0.15 \text{ arcsec}\end{aligned}$$

- Even with a 1meter the atmosphere limits how well we can resolve objects.

**10m telescope**

$$\theta = 0.015 \text{ arcsec}$$

– **Adaptive optics**

- We can correct for the turbulence by deforming the primary/secondary mirrors.
- Equivalent to correcting the wavefront of the light.

- **Detectors**

- **Photographic plates**

- Used for imaging from 1900s to 1980s.
    - Low sensitivity (2% efficiency).
    - Non-linear reaction (exposure  $\propto$  intensity).
    - Wide field (5 degrees).

- **Charge Coupled Devices (CCDs)**

- Used in imaging from 1980s.
    - High sensitivity (70-90%).
    - Linear relation between photons and signal.
    - Similar to digital cameras (run at  $-90^{\circ}\text{C}$ ).
    - Large fields (1 degree mosaics).

- **New Wavelengths**

- **Radio Telescopes**

- Stars, galaxies and gas emit at radio frequencies - synchrotron radiation.
    - Easier to build - surface of telescope does not need to be as accurate (1/10th of a wavelength).
    - Dishes made of wire and metal.
    - Resolution poorer.

$$\theta = 2.5 \times 10^5 \frac{\lambda}{D} = 2.5 \times 10^5 \frac{0.20}{10}$$
$$= 1.4 \text{ degrees}$$

- Use interferometry to improve resolution.
      - Resolution determined by the largest distance between telescopes (i.e. their separation).
      - Observe through cloud, day time, rain.

## – Space-based Observatories

### Figure 6-27

- Transparency of the atmosphere is not a problem (ultraviolet and far-infrared).
- Atmospheric turbulence is not a problem (diffraction limited images).
- Sky background is lower.
- NASA's Great Observatories Program

**Hubble Space Telescope (UV, optical, and IR) 1990.**

**Gamma Ray Observatory [Compton] 1991.**

**Advanced X-Ray Astronomical Facility [Chandra] 1999.**

**Space Infrared Telescope Facility [SIRTF] 2003.**