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.
    - $c = 3x10^8$ m s^{-1} (vacuum)
    - $c = 2x10^8$ 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 α.**
    - **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.**
    - **<u>Focal length</u> of a lens is the distance from the lens to the point where the light from a parallel beam is brought to a focus.**
    - **<u>Focal plane</u> 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.

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

- **Refracting Telescope**
  - **Magnification and light gathering**
    - **Most important aspect of a telescope is the amount of light it can collect.**

$$\text{Light gathering power} \propto \text{area of lens}$$
$$\propto \text{diameter}^2$$

    - **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**

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

    - **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 <u>incident</u> to a flat reflecting surface at an angle α to the perpendicular is <u>reflected</u> at an angle α.**

  – **A Reflecting Curved Surface**
    - **A concave reflecting surface will bring light to a common focus.**
    - **<u>Focal length</u> 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 from 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^o 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 <u>does not</u> 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.**

$$\theta = 2.5\text{x}10^5 \frac{\lambda}{D}$$

θ : **diffraction limit (arcseconds)**

λ : **wavelength (m)**

D : primary mirror diameter (m)

- **Longer wavelength $\rightarrow$ worse images.**
- **Bigger telescopes $\rightarrow$ better images.**

– Example: (1m telescope at 500nm)

$$\theta = 2.5x10^5 \frac{\lambda}{D}$$

$$= 2.5x10^5 \frac{600x10^{-9}}{1}$$

$$= 0.15\,\text{arcsec}$$

- 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≢ 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^{o}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.**

$$\theta = 2.5\text{x}10^5 \frac{\lambda}{D} = 2.5\text{x}10^5 \frac{0.20}{10}$$

$$= 1.4 \text{ degrees}$$

    - **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.