(Optical) Telescopes

Reference Reading: Observational Astronomy Ch6,7
(Optical) Telescopes

- What does a telescope do?
- What are the components of a telescope?
- How do we characterize telescopes?
Optical Telescopes

Describe the light path of the Palomar 5-m Hale telescope.
Optical Telescopes

Describe the light path of the Keck 10-m telescope.
Telescope Optics: Basic Principles

Two kinds of Telescopes:
- Refraction Telescopes & Reflection Telescopes

**Refraction:** light passing through a transparent material (e.g., lens)

**Reflection:** light bouncing off a surface (e.g., mirror)
Telescope Optics: Basic Principles

**Refraction: Snell’s Law**

When light passes through one material and into another material, the path of the light is bent at the boundary, since the speed of light is different in the two media.

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

\( n \): index of refraction (medium dependent)

\( n = \frac{c}{v} \)

index of refraction = speed of light in the vacuum / speed of light in the medium
Telescope Optics: Basic Principles

**Refraction: Snell’s Law**

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**Example**
**Telescope Optics: Basic Principles**

**Reflection**

Law of Reflection: the angle of incidence equals the angle of reflection, for all wavelengths of light

\[ \theta_i = \theta_r \]
Telescope Optics: Basic Principles

Refraction Telescopes

Refraction telescopes use lenses to focus the incoming light. Refraction telescopes are good for small telescopes (<1 meter) because it's very difficult to manufacture large lenses.

Yerkes 40 inch Refractor Telescope
Reflection telescopes use (multiple) mirrors to focus the incoming light. All the big telescopes in the world are reflection telescopes (e.g., the Keck 10 m telescopes).

We will focus on (Cassegrain) reflection telescopes in this course.
Telescope Optics: Basic Principles

Reflection Telescopes

Palomar 5 m.

Keck 10 m.
Telescope Optics:  
**Telescope Focus**

A telescope gathers the light, but it also focuses the light.

What is a focus? All the curved mirrors/lenses have their own focus (or foci).

The larger the curvature is, the smaller the focal length (or the larger the optical power) is. (Focal length is the distance between the center of a mirror [or lens] to the focus.)

Where is the focus of a flat mirror?
Telescope Optics:

**Telescope Focus**

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**Where is the focus of a flat mirror?** (The curvature of a flat mirror is zero, so its focus is at infinite.)
Telescope Optics:
Focus of Reflection Telescope

The telescope focus of a multi-mirror reflection telescope is the focus of the final mirror.

For the case of a “Cassegrain” telescope, the telescope focus is the focus of the secondary mirror.

What’s the size of a Cassegrain telescope?
Telescope Optics:
Focus of Reflection Telescope

The telescope focus of a multi-mirror reflection telescope is the focus of the final mirror.

For the case of a “Cassegrain” telescope, the telescope focus is the focus of the secondary mirror.

What’s the size of a Cassegrain telescope?
(It’s the size of the primary mirror which determines the light gathering power.)
What are the shapes of primary and secondary mirrors of a Cassegrain telescope?

e.g., sphere, ellipse, parabola, hyperbola, polynomial, Gaussian …

(The answer will come later in this section, but can you guess?)
Detectors are usually located at the telescope focus.

If the telescope focal plane is reimaged (or relayed) by reimaging optics (such as mirrors and/or lenses), then detectors need to be located at the focal plane of the reimaging optics.
Telescope Optics:
Focus of Reflection Telescope

- Detectors are usually located at the telescope focus.
- If the telescope focal plane is reimaged (or relayed) by reimaging optics (such as mirrors and/or lenses), then detectors need to be located at the focal plane of the reimaging optics.
Generally, the focal ratio (f/#, f/, f_{eff}) is the focal length divided by the size of a lens (or mirror):

\[ f/# = F_o / D_o \]
Telescope Optics: **Focal Ratio in General**

**Focal Ratio**

- The focal ratio ($f/\#$) characterizes the rate of convergence of a bundle of rays as they form an image.
- A lens (or system of lenses) will have a fixed focal length, but its focal ratio will depend on the aperture of its **stop**.
- Focal ratio is simply the inverse of the beam's divergence per unit length.
  - A beam that broadens 1 cm for every 10 cm of propagation is an $f/10$ beam.
High focal ratios (e.g. f/20) imply a narrow pencil of converging rays – a “slow” (from photographic exposure time) optical system.

Low focal ratios (e.g. f/2) indicate convergence over a wide angle and thus a “fast” system.
Telescope Optics: **Focal Ratio in General**

**Focal Ratio and Depth of Field**

- Fast systems are
  - prone to optical aberration (due to the large range of ray angles incident on the optics).
  - difficult to focus. A small shift in focal plane position produces significant blurring of the image.
  - Essential for wide-field imaging or broadband spectroscopy (where a wide range of angles much to be focused onto a surface)
Telescope usually has two mirrors. What is the focal ratio in this case?

Telescope diameter is determined by the size of the 1st (= primary) mirror. When it has multiple (usually 2) mirrors with power, each mirror has its own focus (e.g., primary focus, secondary focus). For the case of a Cassegrain telescope, usually the focus means the secondary focus (= Cassegrain focus) which is the focus of the secondary mirror.
Effective telescope focal ratio ($f/#, f/, f_{\text{eff}}$):

$$f/# = F_o/D_o$$

where $D_o$ corresponds to the diameter of the primary mirror and $F_o$ is determined by the secondary mirror.
For the 30-m TMT telescope, $D_o = 30$ meters and it has $f/15$ system. This means that its focal plane is 450 meters away from the primary mirror. Does this make any sense? What’s the catch?
Telescope Optics: **Telescope Focal Ratio**

Small f/# → fast system ⇒ bright images on the detector
Large f/# → slow system ⇒ fine image scale
Telescope Optics:

Plate Scale (= Image Scale) of Telescope

Plate Scale: the relation between an angular distance on the sky and a physical distance in the telescope’s focal plane

- D: diameter of the primary
- f: focal length of telescope
- f/# (focal ratio) = f/D
- u: angular distance on the sky in arcsec
- s: linear distance at the focal plane

\[(f) \times (u) = s, \text{ where } f = (f/#) \times (D) \text{ and } u \text{ is in radian} \]

- \[2 \pi \text{ radian} = 360 \text{ degree} = 360 \times 60 \times 60 \text{ arcsec} \]
- \[1 \text{ radian} = 206265 \text{ arcsec}, \text{ or } 1 \text{ arcsec} = 1/206265 \text{ radian} \]
- \[s = (f/#) \times (D) \times u / 206265 \text{ where } u \text{ in arcsec} \]

E.g. Palomar 5 meter telescope has a f/# = 16 (⇔ f/16) system

⇒ 1 arcsec on the sky corresponds to 0.388 mm

Plate Scale: 2.56 arcsec/mm
Telescope Optics:

**Plate Scale (=Image Scale) of Telescope**

Plate Scale: the relation between an angular distance on the sky and a physical distance in the telescope's focal plane.

\[ s = \frac{(f/\#) \times (D) \times u}{206265} \text{ where } u \text{ in arcsec} \]

Small \( f/\# \rightarrow \text{fast system} \Rightarrow \text{bright images on the detector} \)

Large \( f/\# \rightarrow \text{slow system} \Rightarrow \text{fine image scale} \)

\( \rightarrow \text{Fast systems produce small images, so light is concentrated and objects are bright on the detector. In slow systems, objects are more extended.} \)
Let’s have some feelings on angular distances and sexagesimal units.

How big is one arcsecond?
Let’s have some feelings on angular distances and sexagesimal units.

How big is one arcsecond?

Bowl of ‘Big Dipper’ ~ 5 degree in angular size.
How big is one arcsecond?

Human eye can resolve angles as small as 1-2 arcmin in daytime.

Second "star" from end of "Big Dipper" handle is two stars (Arabic "Alcor and Mizar" -- i.e. "horse and rider"), separated by 11'.

Known to Native American and other cultures as a test of visual acuity.
Telescope Optics: Collecting Light

**Telescope is a light bucket.**

Why is it better to have a larger telescope?

Light gathering power (LGP) of a telescope is proportional to the size of the telescope \((D)\) and exposure time \((t_{exp})\):

\[
LGP \propto D^2 t_{exp}
\]

The 10 m Keck telescope at Hawaii can collect in a day almost as much as light the 16 inch telescope in the UofT campus in 2 years from a star.

This is main reason why we want to build a big telescope!
Telescope Optics: Surface Brightness

The size and surface brightness of an extended object (e.g., Galaxy) at the telescope focal plane (where detector is located) depend on the telescope size and f-ratio.

• $h$ (image size on the detector) = $\theta \times f = \theta \times (f/#) \times D$
  ($\theta =$ angular size of an object, $f = (f/#) \times D =$ telescope focal length)

• surface brightness on the detector $\propto \frac{LGP}{h^2} \propto \frac{1}{(f/#)^2}$

if $f/#$ is small (fast), $h$ is small, surface brightness is large
if $f/#$ is large (slow), $h$ is large, surface brightness is small
(These apply for an extended object.)
Telescope Optics: Diffraction and Angular Resolution

Diffraction: bending of light around the edge of an object

Single Slit Diffraction

“A telescope not only gathers lights but it also diffracts them.”

Diffraction Examples
Telescope Optics:
Diffraction and Angular Resolution

Let's think of slit diffraction first!

double slit diffraction pattern:
interference of two single slit diffraction
complicated, narrower!

Diffraction Examples
Telescope Optics: 
Diffraction and Angular Resolution

Let's think of slit diffraction first!

slit number ↑ ⇒ complicated interference
Use the interference to distinguish the wavelength!
(basis of the diffraction grating)

Diffraction Examples
Telescope Optics: Diffraction and Angular Resolution

Single slit of aperture $D$

![Diagram](image)

$\text{Path difference} = (D/2) \sin \theta$

**FIGURE 6.7** For a minimum to occur, the path difference between paired rays must be a half-wavelength.

If the path difference is half of the wavelength, destructive interference will occur at $y$.

$$\frac{D}{2} \sin \theta = \frac{1}{2} \lambda, \quad \text{or} \quad \sin \theta = \frac{\lambda}{D}.$$  

$$\sin \theta = m \frac{\lambda}{D},$$

**General condition for destructive interference, $m = \text{integer number}$**.
Telescope Optics:
Diffraction and Angular Resolution

Interference of diffractions from multi-slits

Note that the pattern of two different wavelengths are shown!

$m$: order of the principal maxima

Different wavelengths have their maxima at different locations for the same orders!

Diffraction is wavelength dependent!

Diffraction Examples
Telescope Optics: Diffraction and Angular Resolution

Multi-slit Interference

\[ I = |\psi|^2 = 4a^2 C^2 \left[ \frac{\sin(qa)}{qa} \right]^2 \left[ \frac{\sin(Nqd)}{\sin(qd)} \right]^2. \]

N: number of slits

a: half slit size

d: slit distance
Telescope Optics:
Diffraction and Angular Resolution

As the slit diffraction, telescopes have two-dimensional diffraction patterns which are dependent on the size of the primary and the wavelength!
Telescope Optics: Angular Resolution

When a star’s light passes through a lens or reflects off a mirror, it is diffracted into an image that has a bright core surrounded by concentric rings of light.

⇒ a telescope develops a diffraction pattern!

Central core (Airy Disk) + cocentric rings (diffraction rings)

light distribution (after telescopes mirrors)

Airy Disk has ≤ 84% of the total light!
Telescope Optics: Angular Resolution

The distribution can be described by Bessel Function.

The minima at
\[
\sin \theta = 1.22 \frac{\lambda}{D}, 2.23 \frac{\lambda}{D}, 3.24 \frac{\lambda}{D}, \ldots
\]

Figure 16.7. Intensity scan through a diffraction pattern.

Figure 16.8. The diffraction pattern in the focal plane of the objective.
Telescope Optics: Angular Resolution

Angular Resolution: the smallest angular distance that can resolve two nearby stars

If two stars are too close, one cannot resolve them.

If two stars are far away, it's trivial to resolve them.

Then, what's the smallest angular distance to resolve them?

Superposition of diffraction patterns of two nearby stars

↑ two dimensional distribution

Figure 1.1.29. Image of two distant point sources through a circular aperture (negative image).

→ one dimensional distribution

Resolved

Rayleigh Criterion

Unresolved
Telescope Optics: Angular Resolution

Angular Resolution: the smallest angular distance that can resolve two adjacent stars.

Better resolution means sharper images.

Rayleigh Criterion:
Angular Resolution (radian) = \( 1.22 \frac{\lambda}{D} \)
where \( D \) is the diameter of the telescope (primary) and \( \lambda \) is the wavelength of the light.

e.g., What's the angular resolutions of the campus 18 inch telescope and 10-m Keck telescope with the visual light?
Telescope Optics

Large telescopes can gather more lights and can also resolve better!

but ……

Why do we want to have telescopes in space than ground?

It’s difficult to build telescopes in space.
Telescope Optics: Seeing

Earth's atmosphere is turbulent which perturbs the phase of light. (Note that the light is wave!) This is because the turbulent atmosphere has index of refraction that varies from a small cell to cell.
Telescope Optics: Seeing

The same point source viewed in perfect, and actual conditions.

unscattered flat wave seen through perfect optics

flat wave scattered by Earth's atmosphere

atmosphere refracts starlight in random directions very quickly—stars "twinkle".

multiple images created
Telescope Optics: Seeing

The effects of the Earth’s atmosphere on the visible images of astronomical objects are called ‘seeing.’

One of the seeing effects is the blurring of images at the focal plane of a telescope.
Telescope Optics: Seeing

One of the most important effects of seeing is degrading of the telescope resolution. This is because the size of the blurred image is usually greater than the size of a telescope diffraction pattern. It is in fact that the seeing size that determines the telescope resolution in most of ground-based observations.

1" seeing → if two stars are separated within 1", their blurred images will overlap at the telescope’s focal plane.

Typical seeing of visual light: Toronto ~ 5", Mauna Kea ~ 1", there is no seeing at the space, seeing is also wavelength dependent.
Telescope Optics: Types of Telescopes

Different types of telescopes have different types of primary and secondary mirrors, and usually mirrors are conic sections.

Cassegrain, Gregorian, Ritchey-Chretian, Schmidt, ……

- **Cassegrain**: parabolic mirror + (convex) hyperbolic mirror
- **Gregorian**: parabolic mirror + ellipsoidal mirror
- **Richey-Cretian**: hyperbolic mirror + hyperbolic mirror
- **Schmidt**: spherical mirror + corrector lens
Telescope Optics: Types of Telescopes

Why are parabolic and hyperbolic mirrors used often?

Parabola: Hyperbola:

directrix

equal distances

$PF_1 - PF_2 = \text{a constant}$
Telescope Optics: Types of Telescopes

Why are parabolic and hyperbolic mirrors used often?

**Parabola:** The set of all points in the plane whose distances from a fixed point, called the focus, and a fixed line, called the directrix, are always equal.

**Hyperbola:** The set of all points in the plane, the difference of whose distances from two fixed points, called the foci, remains constant. Note that foci of a hyperbola are located at the different sides.
Telescope Optics: Types of Telescopes

Why are parabolic primaries used widely?

The Parabolic Mirror

- Consider light from a very distant spot on the optical axis.

- A parallel wavefront passes A in phase. We want it to arrive at the focus still in phase. Therefore, all paths from A to the focus must be the same length.

- A parabola is the locus of points equidistant from a point and a line. Therefore, c = d and the distance from A to the focus is a constant.
Why a parabolic primary and a hyperbolic secondary for a Cassegrain telescope?

- **Parabolic primary** produces a perfect image at #1.
- **Hyperbolic secondary** relays the virtual image at #1 to a real image at #2.
- Greater compactness than Gregorian telescope.
- But - hyperbolic secondary is hard to make and off-axis performance is not terribly good.
Telescope Optics: Types of Telescopes

Gregorian telescope has a parabolic primary like Cassegrain. How about its secondary?

Gregorian Telescope

- Conic sections produce perfect (geometric) images and can be strung together to form complex systems.

  ![Diagram of a Gregorian Telescope]

  two foci at the same side

- **Parabolic primary** produces a perfect image at #1.
- ? **Secondary** transfers a perfect image to #2.
- An erect image is produced.
Telescope Optics: Types of Telescopes

Gregorian telescope has a parabolic primary like Cassegrain. How about its secondary?

Gregorian Telescope

- Conic sections produce perfect (geometric) images and can be strung together to form complex systems.
- Parabolic primary produces a perfect image at #1.
- Ellipsoidal secondary transfers a perfect image to #2.
- An erect image is produced.

two foci at the same side
Telescope Optics: Types of Telescopes

Schmidt Telescope: spherical primary + lens corrector

Parabolic mirrors do not form a sharp image at the focus for the off-axis rays. (Think of the path difference.)

Schmidt Camera: By placing a corrector lens before a spherical mirror, one can form a sharp image of a wide field for a small (~1 meter) telescope.
Telescope Optics: Types of Telescopes

Different types of telescopes have different types of primary and secondary mirrors, and usually mirrors are conic sections.

Cassegrain, Gregorian, Ritchey-Chretian, Schmidt, …..
Telescope Optics: Mounting System
Equatorial vs. Altitude-Azimuth

**Equatorial Mount**
- two axes parallel to polar and declination axis
- aligned to the Earth’s rotation axis
- Palomar 5-m telescope
- easy to track
- difficult to build large ones

Equatorial Mount

Palomar 5 m Telescope
Telescope Optics: Mounting System
Equatorial vs. Altitude-Azimuth

Altitude-Azimuth Mount
- two axes parallel to the alt. and az. axes
- aligned to the local zenith
- big telescopes (e.g., Keck)
- compact design

Alt-Azimuth Mount

Thirty Meter Telescope
Telescope Optics: Mounting System
Equatorial vs. Altitude-Azimuth

In which mounting system does the field rotate at the focal plane during (long) exposure?
Example) An observer is using a telescope to resolve a binary star system where two stars are a separated by 0.4 arcsec. Ignoring the seeing effect of the atmosphere, what is the minimum size of the telescope needed to resolve the binary? Use $0.5 \, \mu m$ for the wavelength.

Example) If the seeing is 2 arcsec, what is the smallest size of the telescope with which observers can overcome the seeing to have better resolution? Do not worry about the brightness of the objects. Let's assume they are all very bright.
Telescope Optics: Examples

Example) **Calculate the image scale of a telescope with a diameter of 500 mm and a focal ratio of 5; give the answer in arcsec per mm.**

Example) **Compare the intrinsic resolution of the Palomar 5-m optical/infrared telescope (wavelength = 1 μm) and the 300-m Arecibo radio telescope (wavelength = 21 cm).**

Example) **Suppose two stars have an angular separation of 3 arcsec on the sky. How far apart are these images at the focal plane of a telescope with the final focal ratio of f/16? The diameter of the telescope is 1 meter.**