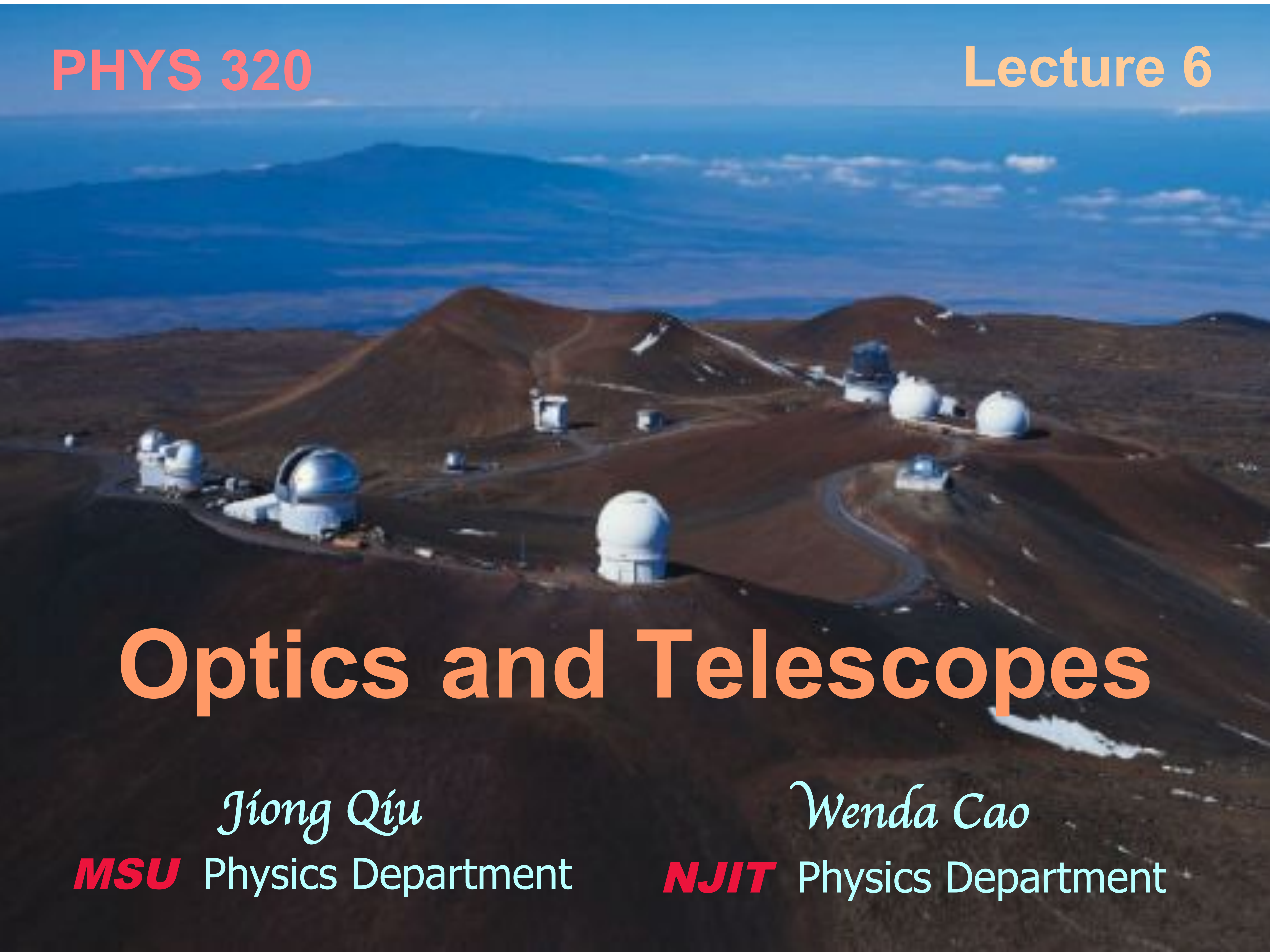

PHYS 320 Lecture 6

Optics and Telescopes

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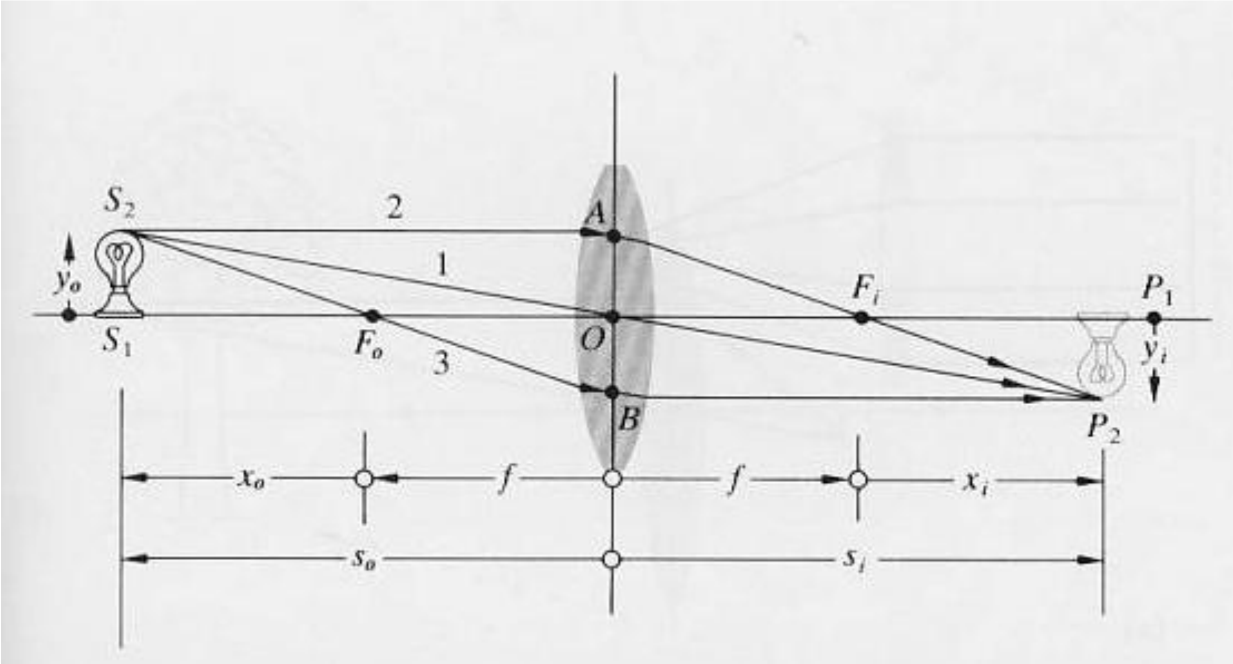
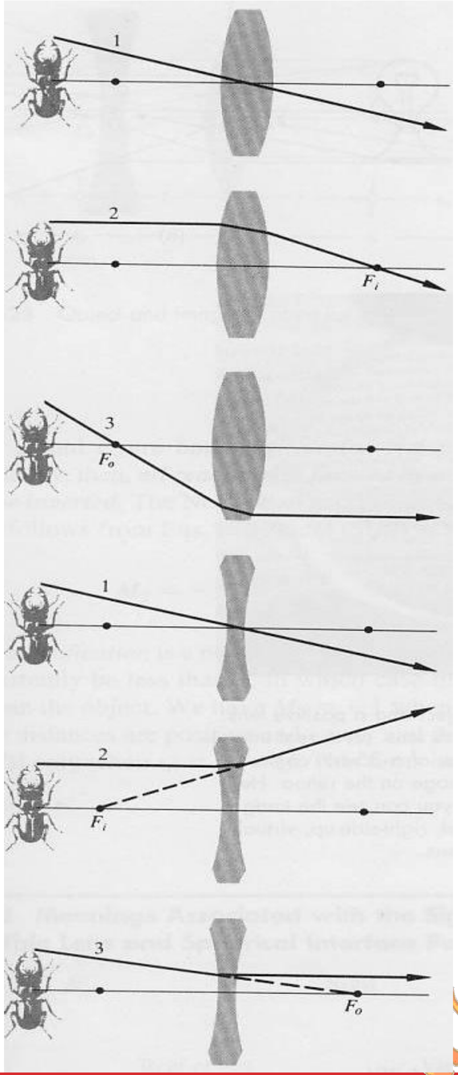
Guiding Questions

1. Why is it important that telescopes be large?
2. Why do most modern telescopes use large mirrors rather than large lens?
3. Why are observatories in such remote locations?
4. How do astronomers use telescope to measure the parameters of distance objects?
5. Why do astronomers need telescopes that detect radio waves and other non-visible forms of light?
6. Why is it useful to put telescopes in orbit?

6.1 Optics - Thin Lens Formula

- ***Tracing a few key rays***





$$\frac{1}{s_0}+\frac{1}{s_i}=\frac{1}{f}$$

$$x_0 x_i = f^2$$

$$M_T \equiv \frac{y_i}{y_0} = -\frac{s_i}{s_0} = -\frac{x_i}{f} = -\frac{f}{x_0}$$

Optics - Mirror Formula

- ***Under paraxial approximation,***

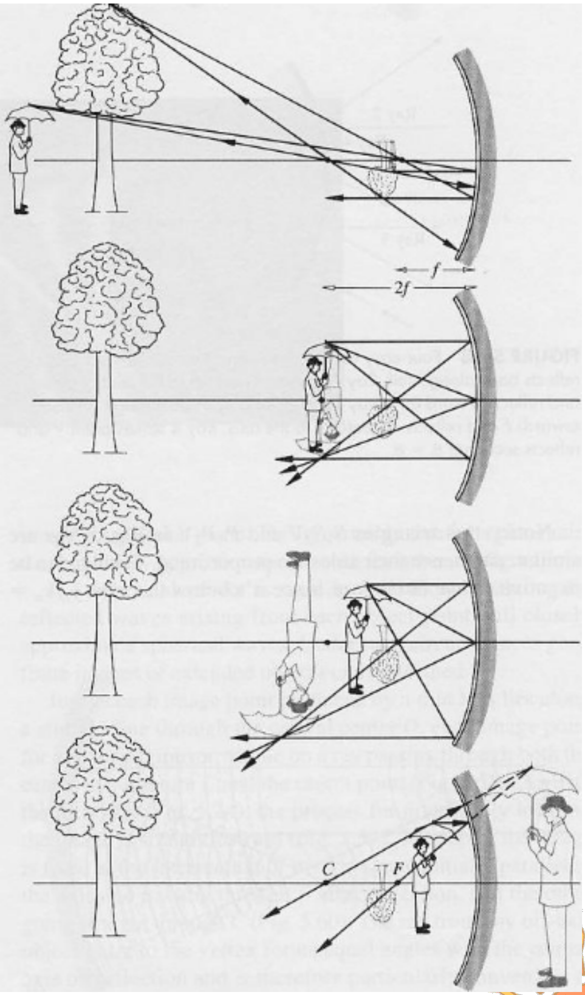
$$f_0 = f_i = -\frac{R}{2}$$

Concave

Object	Image			
Location	Type	Location	Orientation	Relative Size
$\infty > s_o > 2f$	Real	$f < s_i < 2f$	Inverted	Minified
$s_o = 2f$	Real	$s_i = 2f$	Inverted	Same size
$f < s_o < 2f$	Real	$\infty > s_i > 2f$	Inverted	Magnified
$s_o = f$		$\pm\infty$		
$s_o < f$	Virtual	$\lvert s_i \rvert > s_o$	Erect	Magnified

Convex

Object	Image			
Location	Type	Location	Orientation	Relative Size
Anywhere	Virtual	$\lvert s_i \rvert < \lvert f \rvert$, $s_o > \lvert s_i \rvert$	Erect	Minified



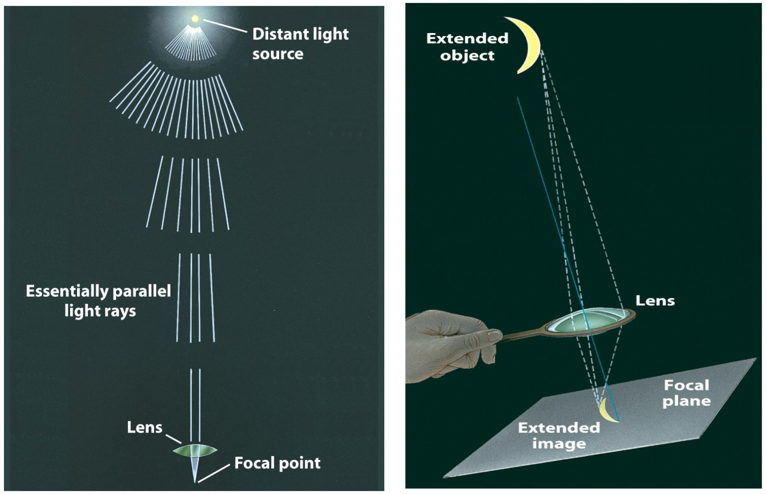
$$\frac{1}{s_0} + \frac{1}{s_i} = \frac{1}{f}$$

$$x_0 x_i = f^2$$

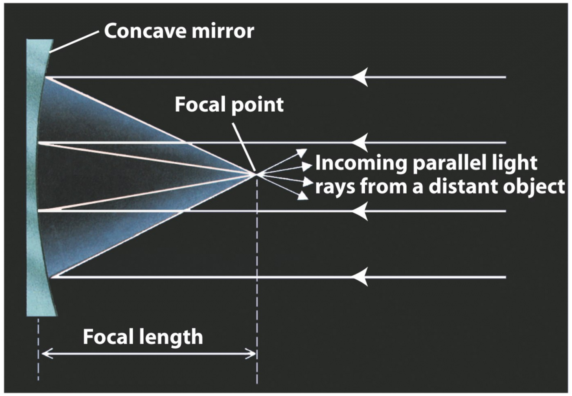
$$M_T \equiv \frac{y_i}{y_0} = -\frac{s_i}{s_0} = -\frac{x_i}{f} = -\frac{f}{x_0}$$

6.2 Refracting and Reflecting Telescopes

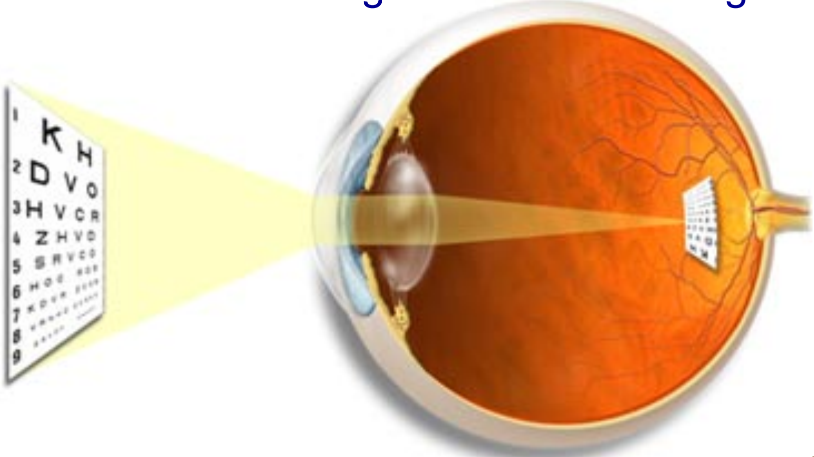
- A lens or mirror changes the direction of light to concentrate incoming light at a **focus** and form an image of the light source at the **focal plane.**
- Telescopes using lens are **refractors**, and those using mirrors are **reflectors**.



A lens refracts light to make an image.



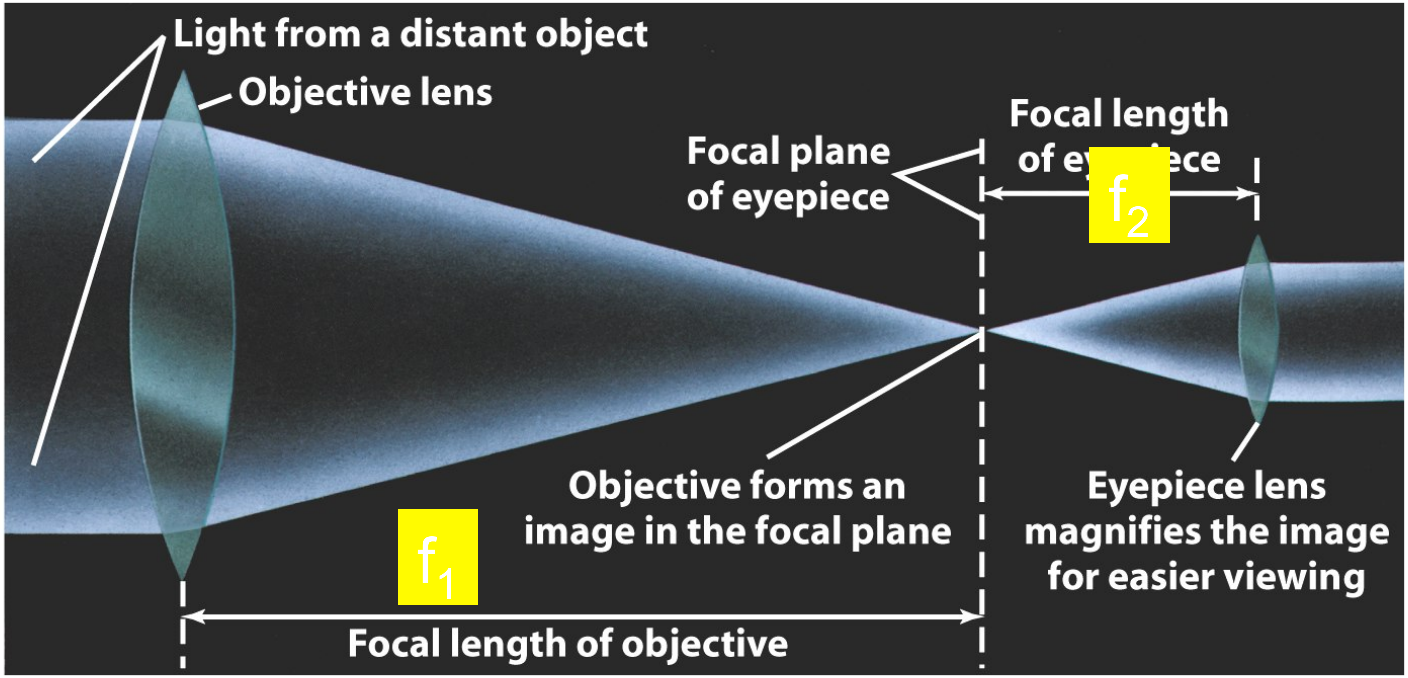
A mirror reflects light to form an image.



A human eye is a lens.

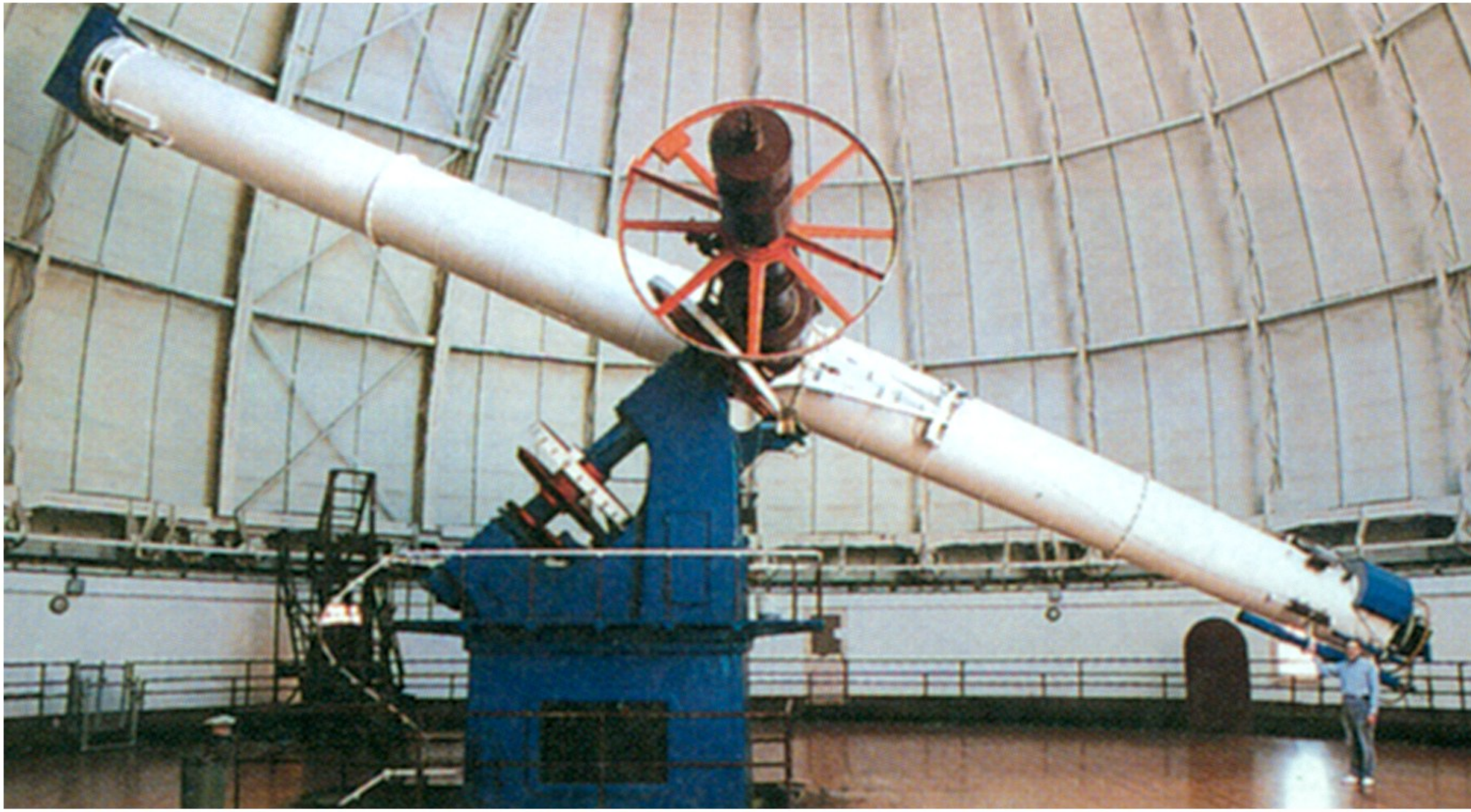
Refracting Telescope

A refracting telescope uses a large diameter **objective lens** with a long **focal length** to form an image and a small **eyepiece lens** with a short focal length to magnify the image.



In modern astronomy, a CCD (charge-coupled device) camera replaces the eyepiece and is placed at the focal plane to record image in digital format.

The largest refractor ever built since 1897, 102 cm (=1.02 m) diameter, 19.5 m focal length. Housed in Yerkes Observatory near Chicago.



Angular size of the Sun is about 32′ (arc-minute), could you find the physical size at the focus when we use a thin lens with a focal length of 3.85-m ?

Most Modern Telescopes Are Reflectors

Problems with refractors:

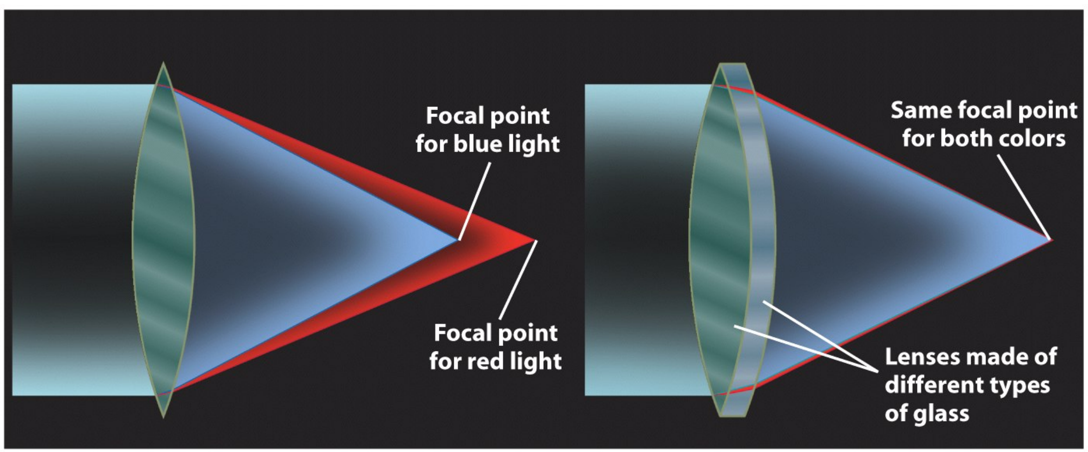
- **Chromatic aberration**: focal length varies with wavelength
- Costly to make a large lens free of defects, such as bubbles
- Light is absorbed and scattered in the glass
- Heavy to support, distortion under weight

Advantages of reflectors:

- The mirror is made to be highly reflective.
- Fewer problems with chromatic aberration, glass defects, support and distortion.
- Spherical aberrations can be corrected.

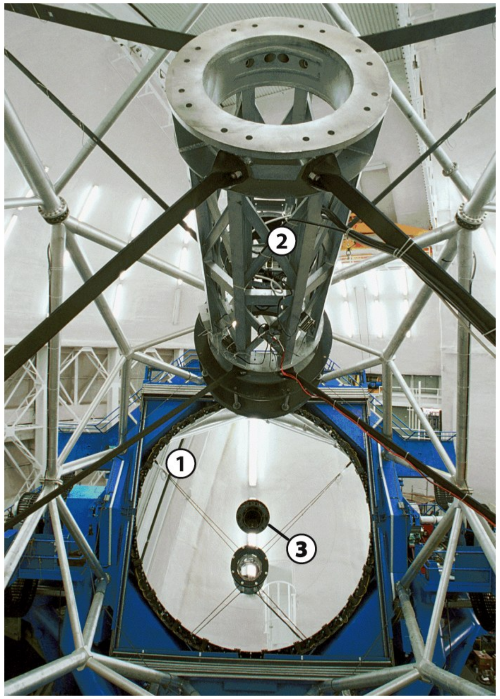
$$\frac{1}{f_\lambda} = (n_\lambda - 1)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

- $n\lambda$ is the index of refraction at wavelength λ, Note that the index of refraction depends on wavelength (see http://refractiveindex.info/)
- R1 and R2 are the radii of curvature of the lens (negative radius for a diverging lens)

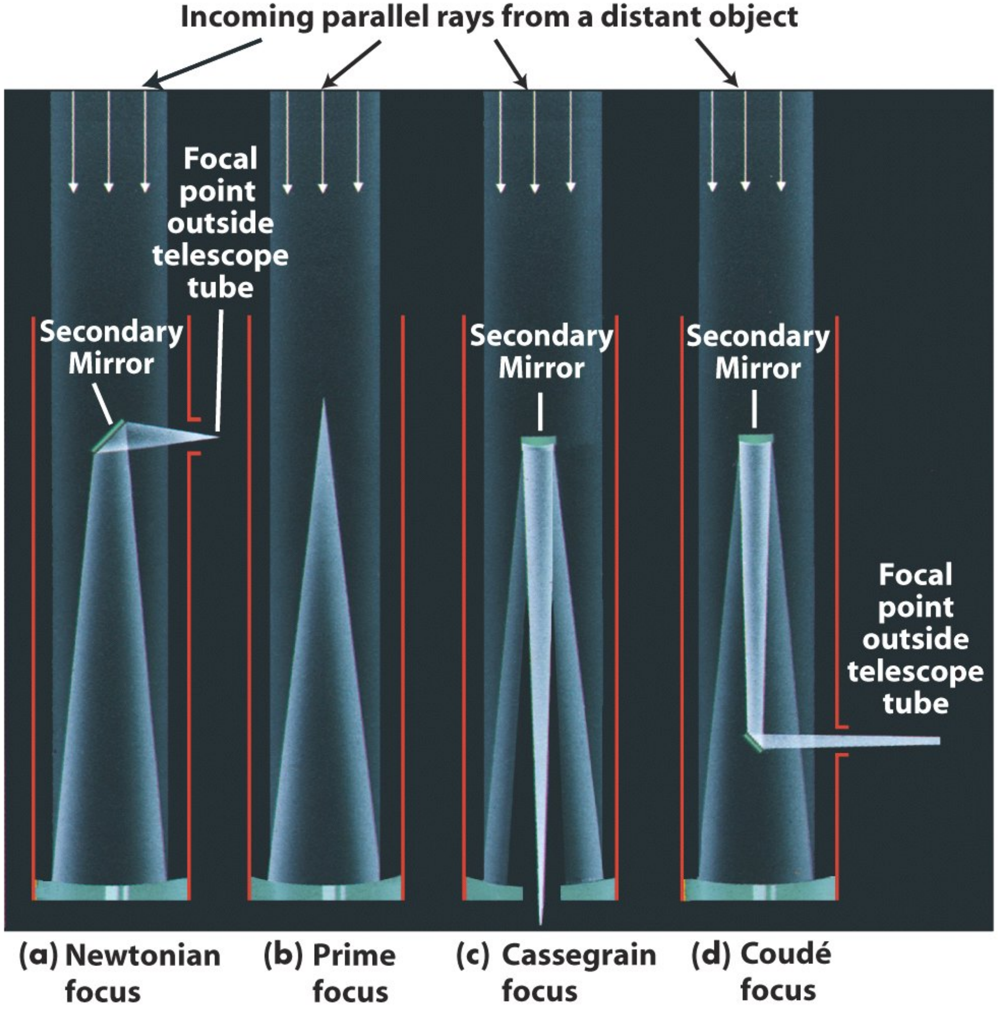


(a) The problem: chromatic aberration (b) The solution: use two lenses

- There are many designs of reflecting telescopes, mostly with a **primary mirror** and a **secondary mirror**.
  - Newtonian focus
  - Prime focus
  - Cassegrain focus
  - Coude focus

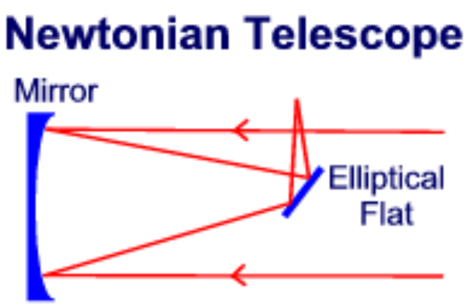


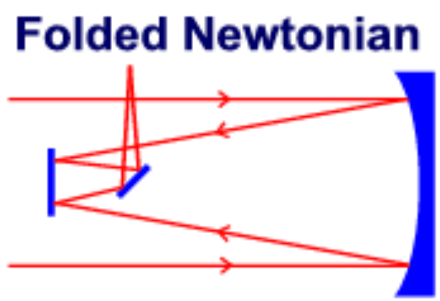
Gemini North Telescope on Mauna Kea



Newtonian Telescope Optics

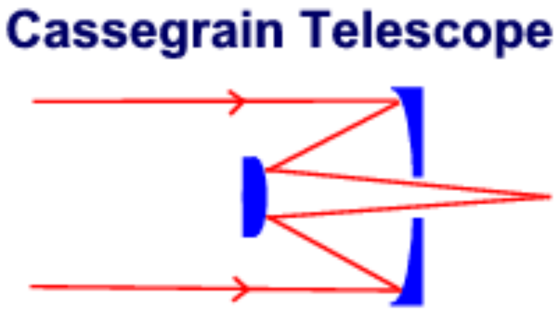
- Most commonly used of the amateur telescopes
- Ease of construction, portability, insensitivity to alignment and cheap
- Primary mirror placed at the bottom of telescope tube
- Secondary mirror: small elliptically shaped flat mirror
- An alternative: "Folded Newtonian" provides high magnification with a long focal length
- Main drawback: coma aberration at the edge of the field of view
- A disadvantage is the extra obscuration caused by the circular flat

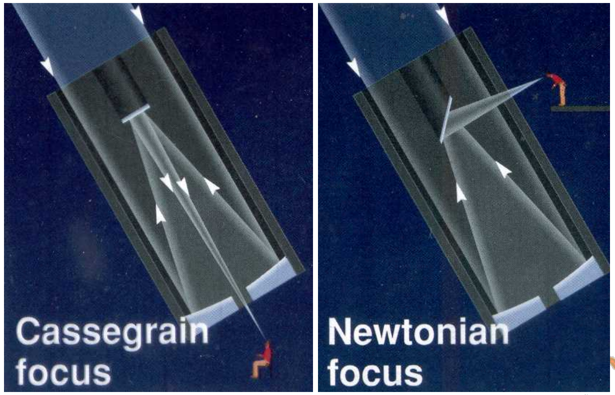




Cassegrain Telescope Optics

- Most commonly used of the astronomical night-time telescopes
- Longer effective focal length and higher magnification
- Concave PM with a hole at its center: placed at the bottom of tube
- Convex SM with a small aperture: placed near the top of telescope
- **Classical Cassegrain:** a parabolic PM with a hyperbolic SM
- **Dall-Kirkham system:** an under-corrected parabolic PM with a spherical SM for direct viewing with small field of view
- **Ritchey-Chretien (RC) system:** overcorrected hyperbolic PM and SM for a wide field with a coma free

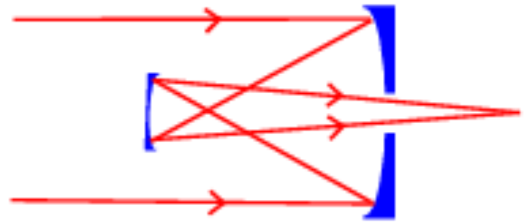




Gregorian Telescope Optics

- Most commonly used of the solar telescopes
- Prime focus for installation of solar heat stop
- Concave PM and SM: placed at the bottom and near the top of the telescope structure
- Concave SM with a small aperture: placed near the top of telescope
- Optics: a parabolic PM with a elliptical SM
- A disadvantage for on-axis Gregorian telescope is the extra obscuration caused by the SM and support structure

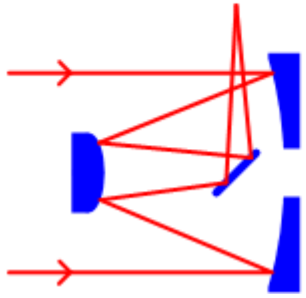
Gregorian Telescope



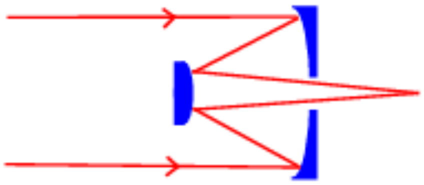
Nasmyth Telescope Optics

- A derivative of the Cassegrain and Gregorian telescopes
- Small flat mirror in front of PM deliver the focus to the side of telescope
- Nasmyth foci of very large astronomical telescopes provide access to professional, bulky and heavy instrumentations

Nasmyth Telescope



Cassegrain Telescope



8 m Subaru Telescope

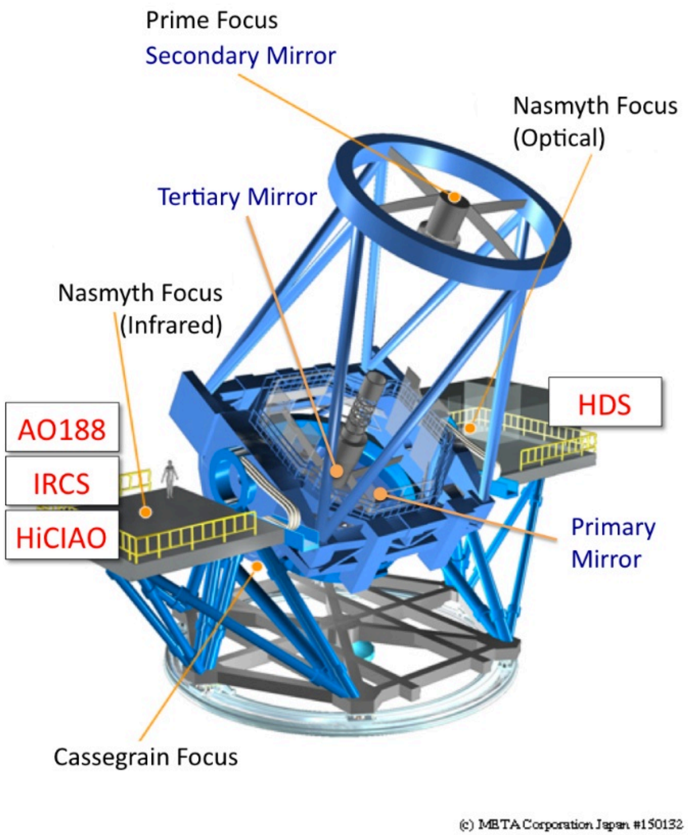
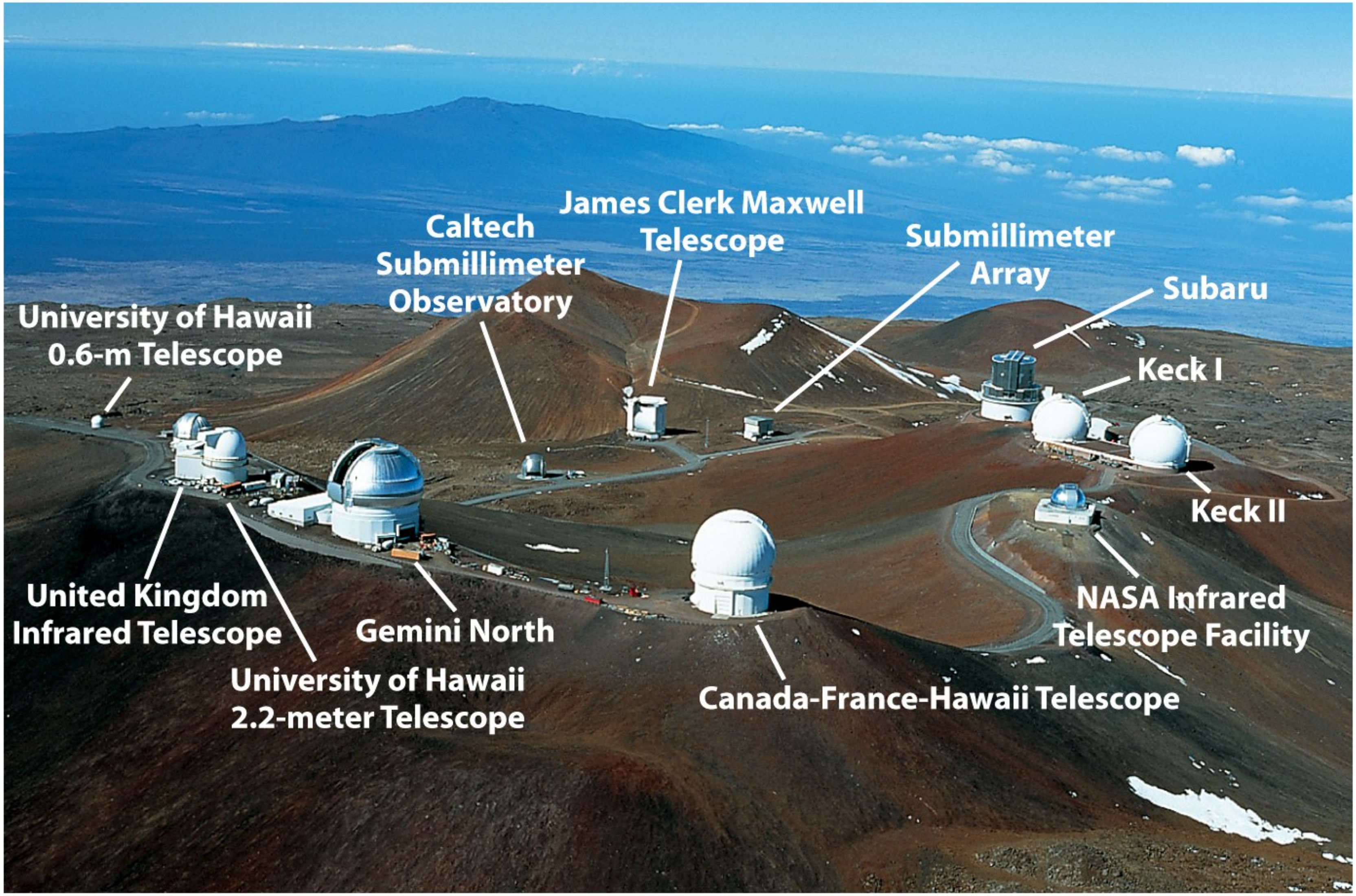


table 6-1 **The World's Largest Optical Telescopes**

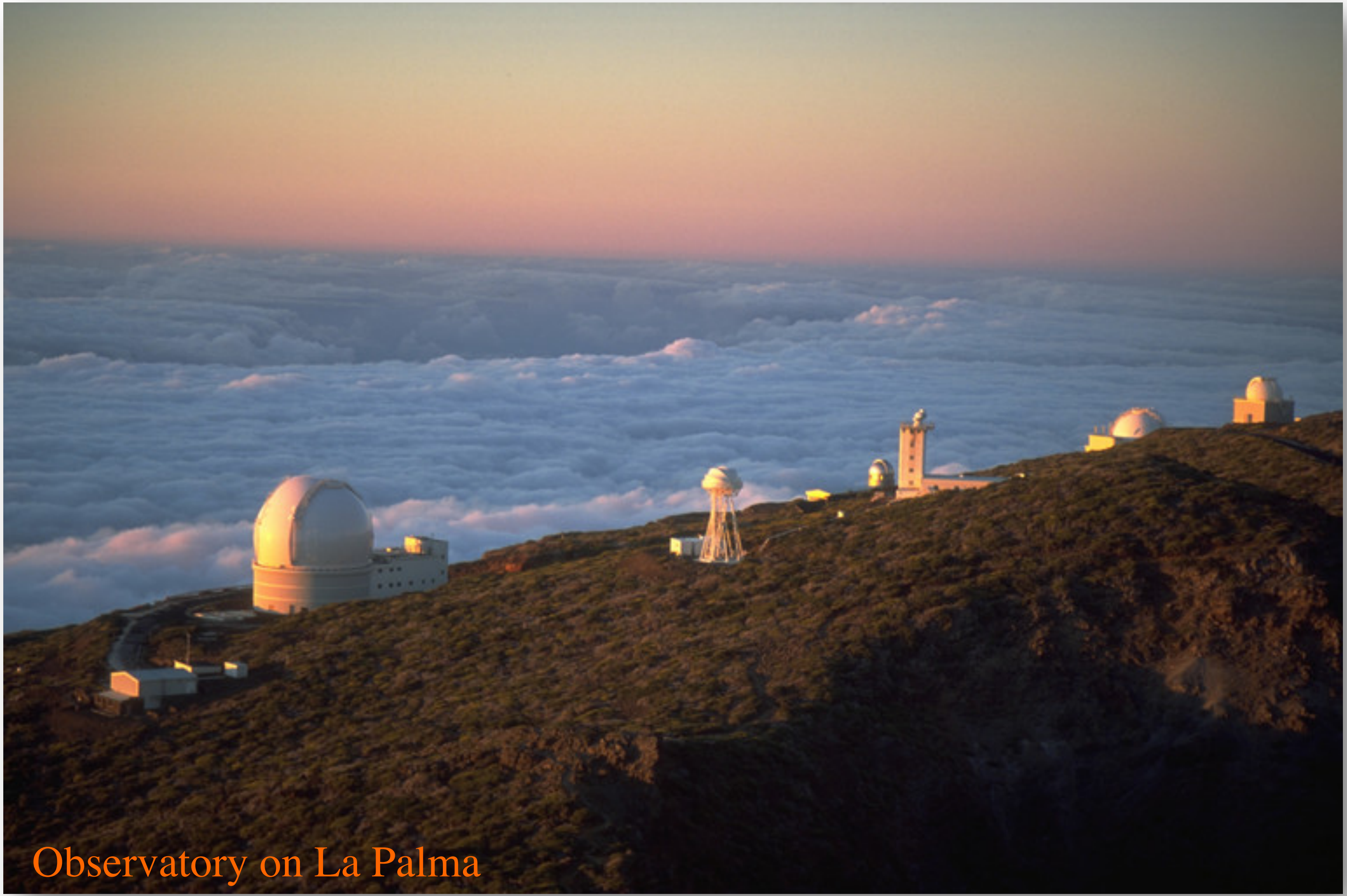
Telescope	Location	Year of completion	Mirror diameter (m)
Gran Telescopio Canarias	La Palma, Canary Islands, Spain	2004	10.4
Keck II	Mauna Kea, Hawaii	1996	10.0
Keck I	Mauna Kea, Hawaii	1993	10.0
Hobby-Eberly Telescope	McDonald Observatory, Texas	1998	11.0*
South African Large Telescope	Sutherland, South Africa	2004	9.2
Large Binocular Telescope	Mount Graham, Arizona	2004–05	Two 8.4
Subaru	Mauna Kea, Hawaii	1999	8.3
VLT UT 1–Antu	Cerro Paranal, Chile	1998	8.2
VLT UT 2–Kueyen	Cerro Paranal, Chile	1999	8.2
VLT UT 3–Melipal	Cerro Paranal, Chile	2000	8.2
VLT UT 4–Yepun	Cerro Paranal, Chile	2000	8.2
Gemini North (Gillett)	Mauna Kea, Hawaii	1999	8.1
Gemini South	Cerro Pachón, Chile	2000	8.1

**The objective mirror of the Hobby-Eberly Telescope is 11.0 m in diameter, but in operation only an area of 9.2 m in diameter is used to collect light.*

The world's largest telescopes are reflectors.



The telescopes of Mauna Kea



Observatory on La Palma

From left to right, the William Herschel Telescope, Dutch Open Telescope, the Carlsberg Meridian Telescope, the Swedish Solar Telescope, the Isaac Newton Telescope (second from right) and the Jacobus Kapteyn Telescope (far right) at Roque de los Muchachos. (Photo by Bob Tubbs)

European Southern Observatory (ESO) in Chile. (Copyright: R. Rekola)

6.2 Telescope Terms

- ***Clear Aperture***
- ***Effective focal length***
- ***Focal ratio or f-number***

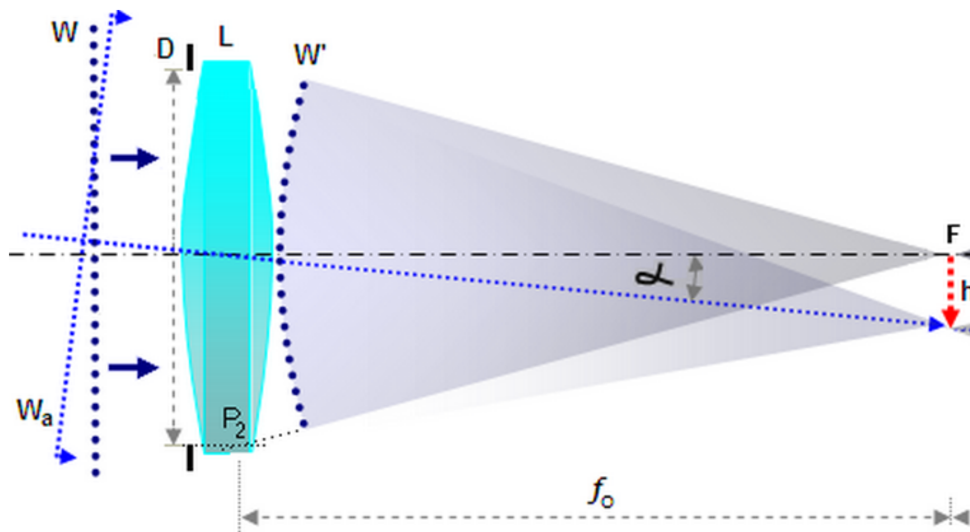
$$f-number = f/\# = N = \frac{f}{D}$$

  - ***Fast beam:*** *small f-number, short exposure time*
  - ***Slow beam:*** *large f-number, long exposure time*
  - *The 1.6 m NST has an effective focal length of 83.2 m, what is the f-ratio at the Gregorian focus?*
- ***Image scale:***

$$s = \frac{\alpha}{h} = \frac{1}{f}\,(\mathrm{rad/mm})$$

$$s'' = \frac{206265}{f}\,(''/\mathrm{mm})$$

$$s' = \frac{3438}{f}\,('/\mathrm{mm})$$



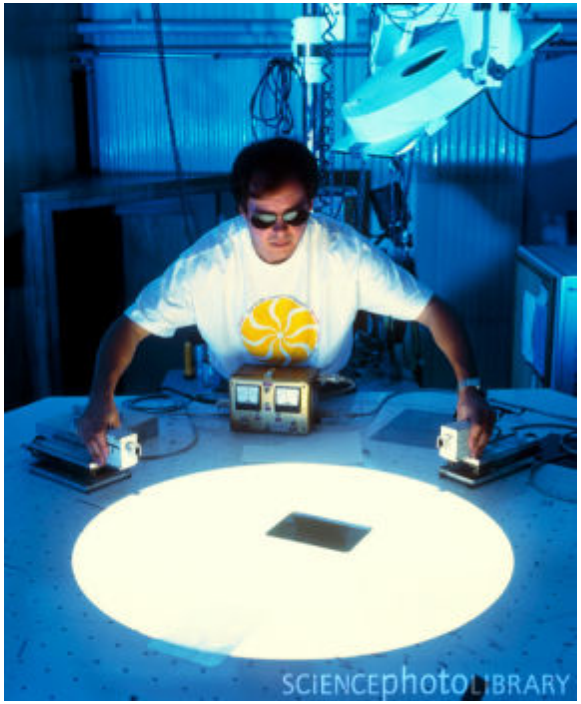
- McMath-Piece Telescope has 1.52 m aperture, and f ratio of 56.58. Angular size of the Sun is about 32′ (arc-minute), could you find the physical size of the Sun on its focal plane?

$$s = \frac{\alpha}{h} = \frac{1}{f} \text{(rad/mm)}$$

$$s'' = \frac{206265}{f} \text{("/mm)}$$

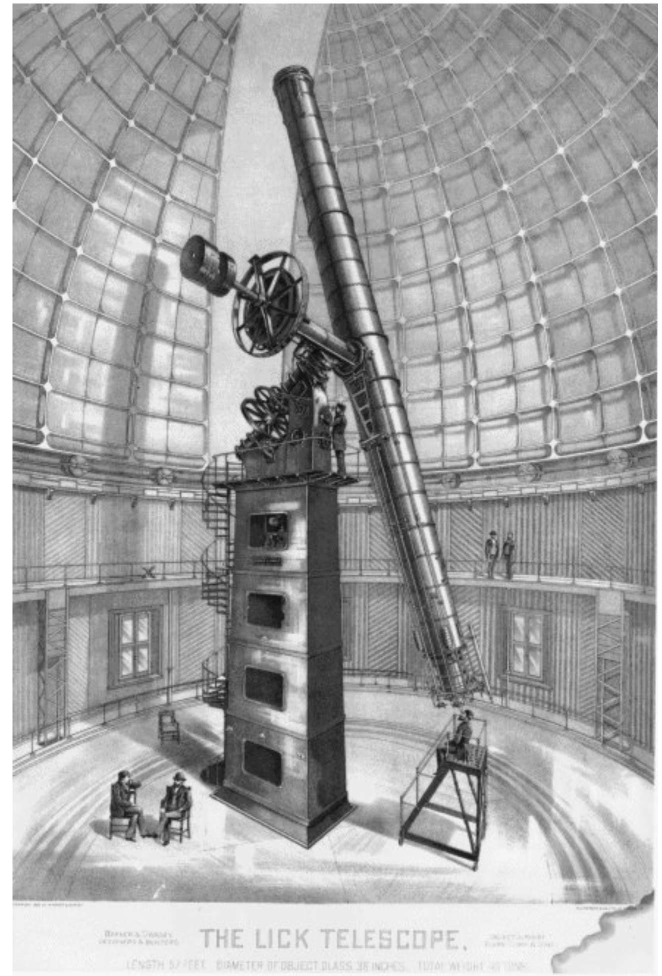
$$s' = \frac{3438}{f} \text{('/mm)}$$

$$h = f_{eff}\alpha$$



6.3 Capabilities of Telescopes

- Magnification Power
- Light Gathering Power
- Resolving Power

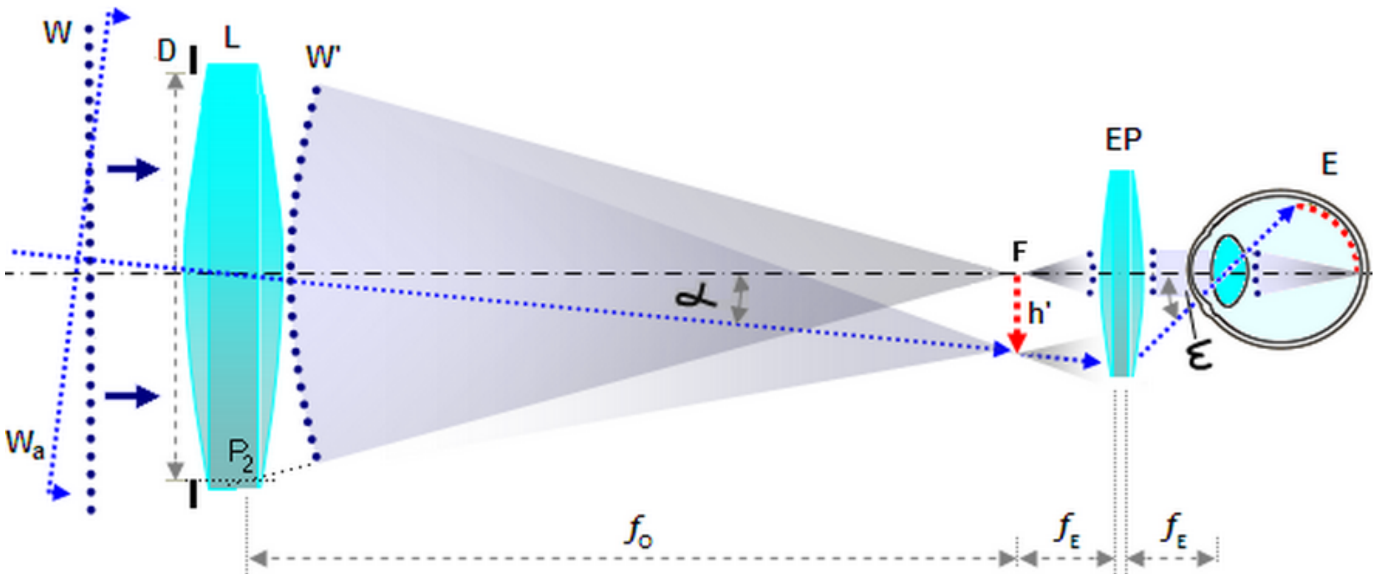


Telescope Magnification

- Magnification is given by a ratio of the image size produced on the retina when looking through a telescope, versus retinal image size with the naked eye.
- Common eyepieces for telescopes are 26 mm and 12.5 mm. An f/10 telescope of 8" aperture (203 mm) would provide corresponding magnifications of 78X and 162X for these two eyepieces.

$$M_T = \frac{\varepsilon}{\alpha} = \frac{\tan\varepsilon}{\tan\alpha} = \frac{h'/f_e}{h'/f_o} = \frac{f_o}{f_e}$$

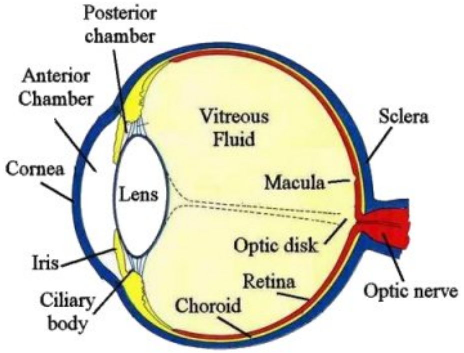
$$M_T = \frac{f_o}{f_e} = \frac{D}{d} = \frac{D}{d_{eye}}$$



Light Gathering Power

- Aperture diameter D: effective diameter of the telescope primary mirror.

eye	SDO/HMI	Hinode	NST	ATST	KECK
6mm	14cm	50cm	1.6m	4m	10m
1	5.4×10^2	6.9×10^3	7.1×10^4	4.4×10^5	2.7×10^6



$$\frac{\pi(\frac{D}{2})^2}{\pi(\frac{d}{2})^2} = \left(\frac{D}{6\text{ mm}}\right)^2$$

- The **light gathering power** of a telescope is proportional to the area of the objective lens/mirror, which is proportional to the square of the lens/mirror diameter - bigger telescopes produce brighter images.

$$P = F_{obs}A = \frac{L}{4\pi d^2}\pi\frac{D^2}{4} = \frac{R^2\sigma T^4}{4d^2}\pi D^2 \text{ (J s}^{-1}\text{)} \propto D^2$$

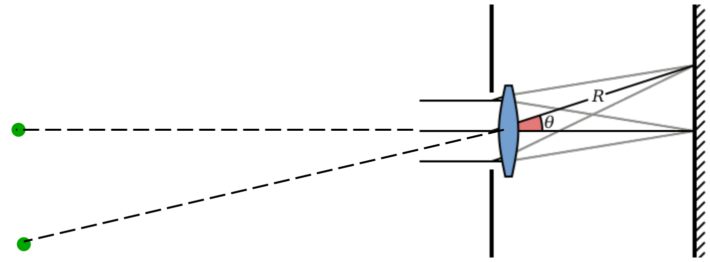
Ex.1: The pupil size of the human eye is about 5mm, and its focal length is 17mm. The largest refractor ever built has a diameter of 102 cm and focal length of 19.5 m. (a) How many times greater is the light gathering power of this telescope compared to that of human eyes? (b) What's the magnification of the telescope if the focal length of its eyepiece is the same as that of the human eye?

$$\text{(a)} \quad \left(\frac{102 \text{ cm}}{5 \text{ mm}}\right)^2 = \left(\frac{1020 \text{ mm}}{5 \text{ mm}}\right)^2 = 204^2 = 4.2\times 10^4$$

$$\text{(b)} \quad \frac{19.5 \text{ m}}{17 \text{ mm}} = \frac{195000 \text{ mm}}{17 \text{ mm}} = 1.1\times 10^3$$

Telescope Resolution

- **Rayleigh criterion:** angle defined as that for which the central peak of one PSF falls upon the first minimum of the other



$$\theta\ (rad) = 1.22\,\frac{\lambda}{D}$$

$$\theta\ ('') = 0.25\,\frac{\lambda\,(\mu m)}{D\,(m)}$$

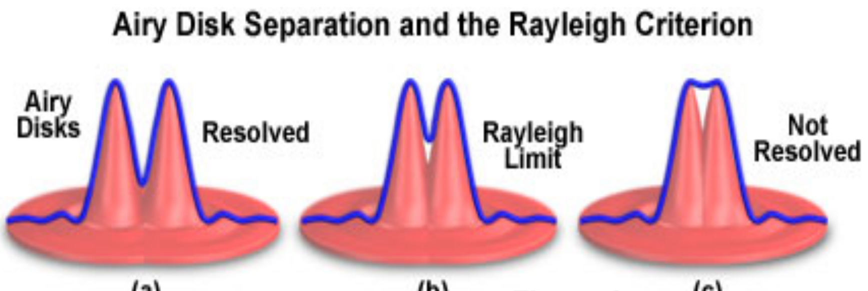
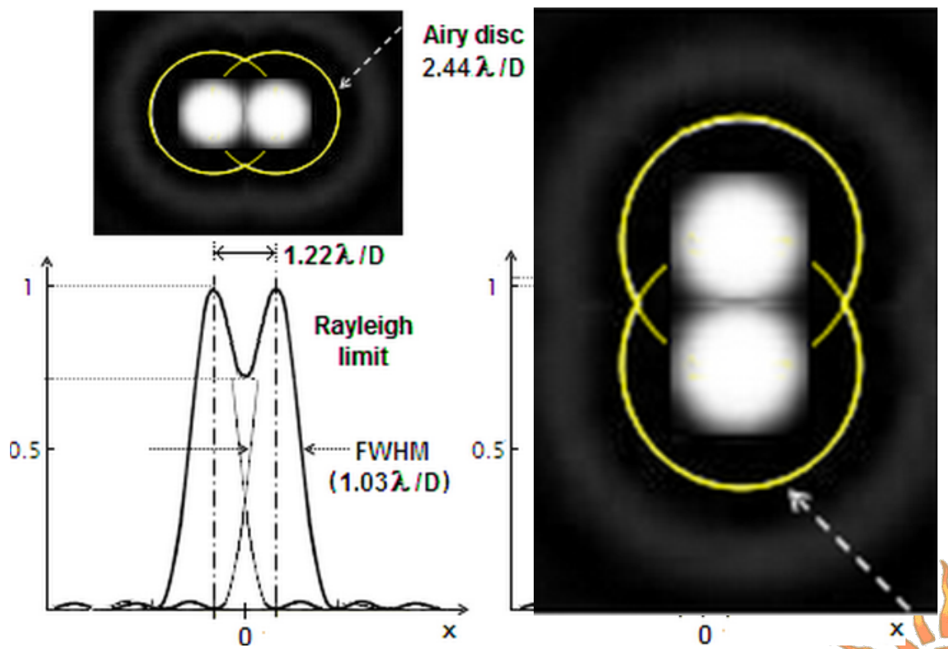


Figure 1



- The angular resolution of a telescope is limited by **diffraction**: bigger telescope, more details.
- **Diffraction limited angular resolution:**

$$\theta = 2.5\times10^{5}\,\frac{\lambda}{D}$$

θ = diffraction limited angular resolution, in arcsec
λ = wavelength of light, in meters
D = diameter of telescope objective, in meters

The **angular resolution** of a telescope determines how much detail we may see in an image -- the angular resolution of human eyes is 1 arcmin, and all planets have angular size of or less than 1 arcmin.

Ex.2: Diffraction limited angular resolution of Keck Telescopes

(D = 10m): $\theta = 2.5\text{x}10^{5}$ (550nm/10m) = 0.01 arcsec.

Ex.3: To have 1 arcsec angular resolution by observing at microwave wavelength (3 cm), how big a mirror is needed?

D = $2.5 \text{ x } 10^{5}\,(\lambda/\theta) = 2.5\text{x}10^{5}$ (0.03 m/1) = 7500 m (!)

Telescope Resolution

- **Angular resolution:** can be quantified as the smallest angle between two point sources for which separate recognizable images are produced

$$\theta \ (rad) = 1.22 \frac{\lambda}{D}$$

$1\, rad = 206265''$ $\qquad$ $1'' = 725$ km on the Sun

eye	SDO/HMI	Hinode	NST	ATST	KECK
6mm	14cm	50cm	1.6m	4m	10m
1	5.4×10^2	6.9×10^3	7.1×10^4	4.4×10^5	2.7×10^6
> 60”	0.74”	0.21”	0.06”	0.03”	0.01”
43500 km	534 km	150 km	47 km	19 km	< 8 km

Aiming at large telescopes:

the larger the aperture, the brighter is the image.

the larger the aperture, the more details we can see…

Q: shall we build telescopes of larger objective focal length to better resolve an image?

Key Words

- adaptive optics
- angular resolution
- baseline
- chromatic aberration
- chemical composition
- diffraction
- focal length
- focal plane
- interferometry
- magnification
- objective lens
- objective mirror
- optical telescope
- radio telescope
- reflecting telescope (reflector)
- refracting telescope (refractor)
- seeing
- spectrograph
- spherical aberration

Summary

- Refracting telescopes (refractors) form images by bending light rays to a focus point through glass lens. They have shortcomings like chromatic aberration, glass defects, and distortion by weight.
- Reflecting telescopes (reflectors) form images by reflecting light rays to the focus from curves mirrors, most used in modern astronomy.
- Theoretically, a telescope's diffraction limited angular resolution depends on the diameter of the objective and observing wavelength.

Star trails above Mauna Kea
(Peter Michaud, Gemini Observatory)