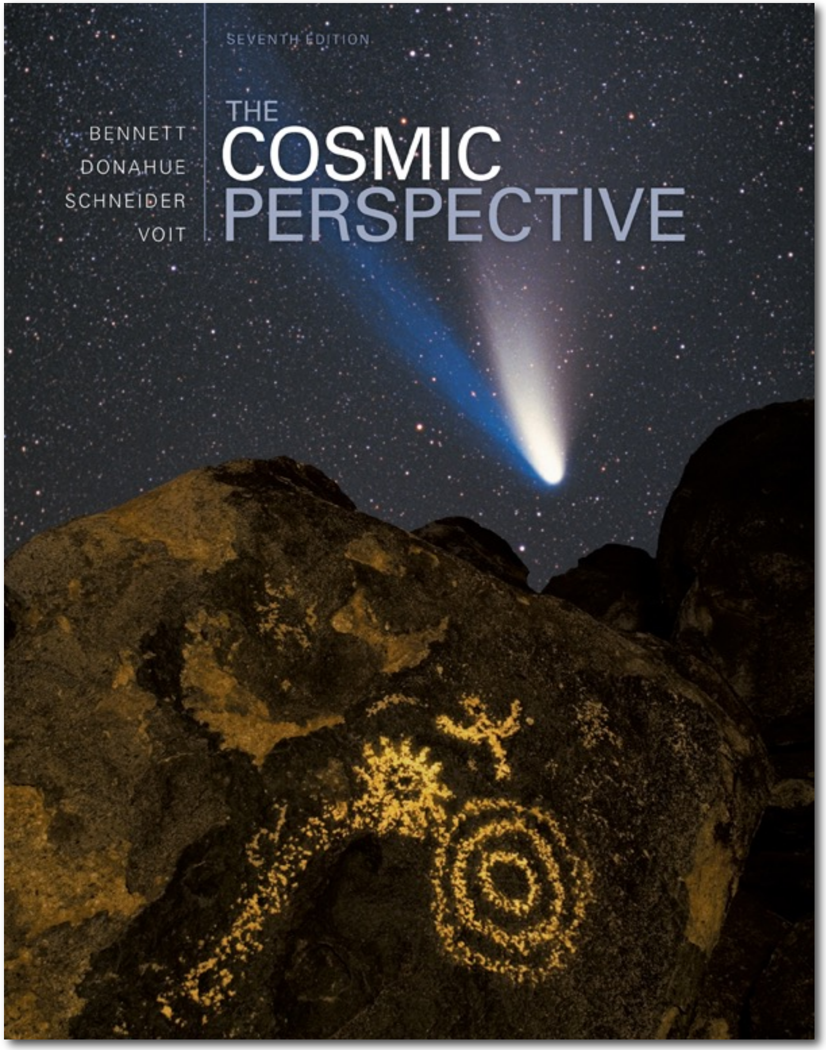
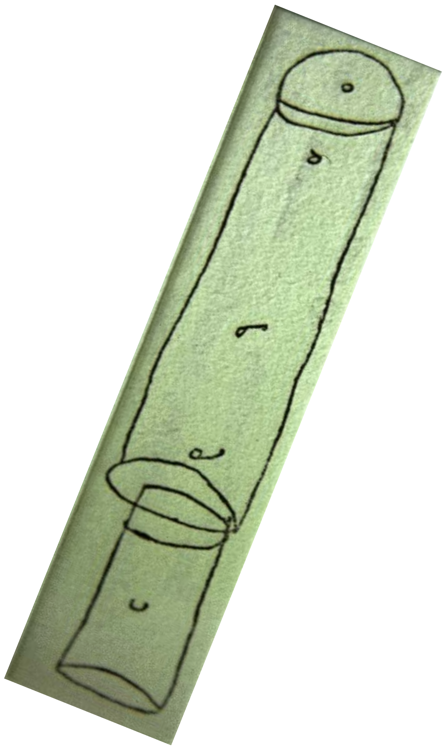
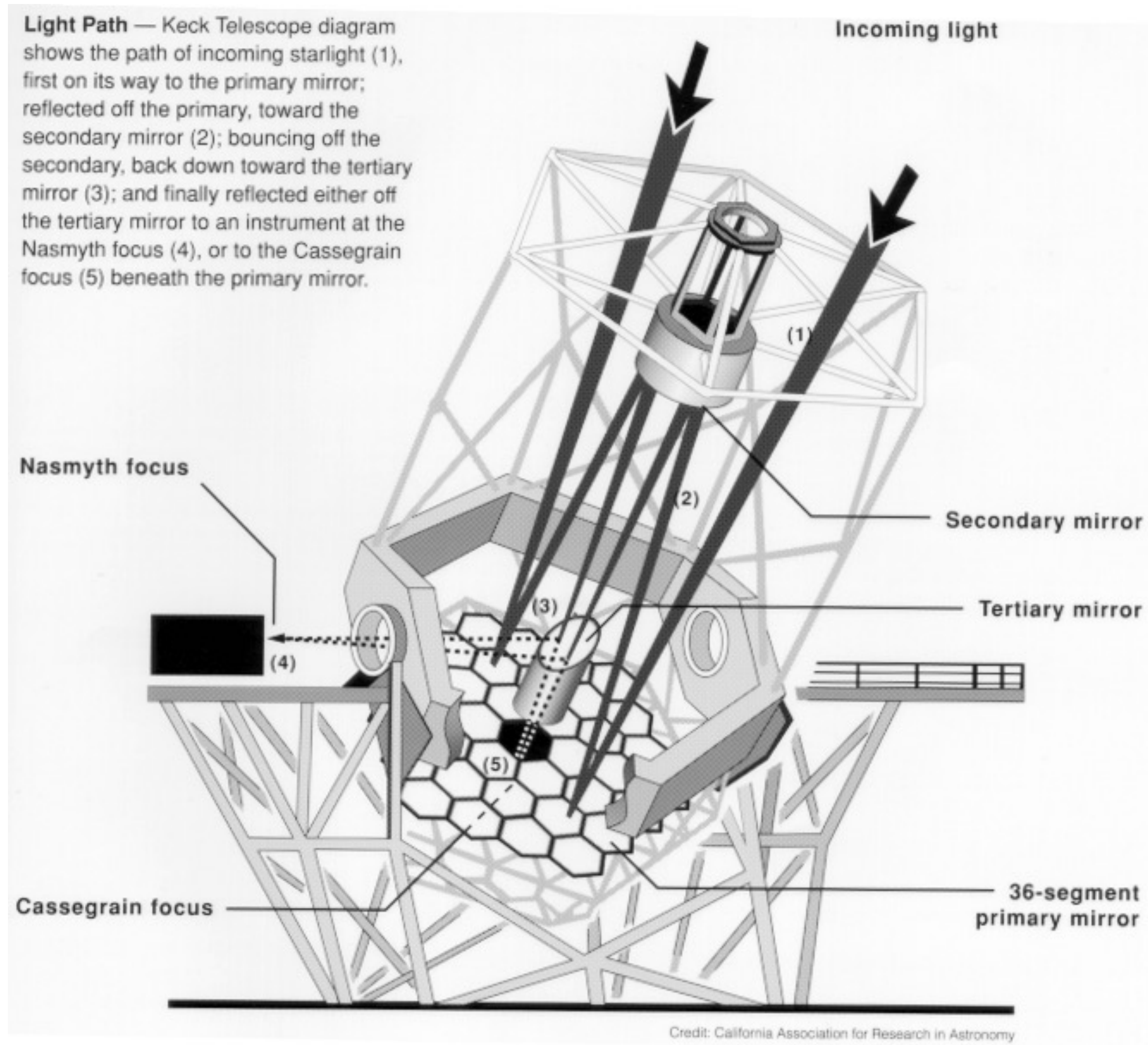
The Cosmic Perspective



Telescopes
Portals of Discovery

Telescopes Portals of Discovery



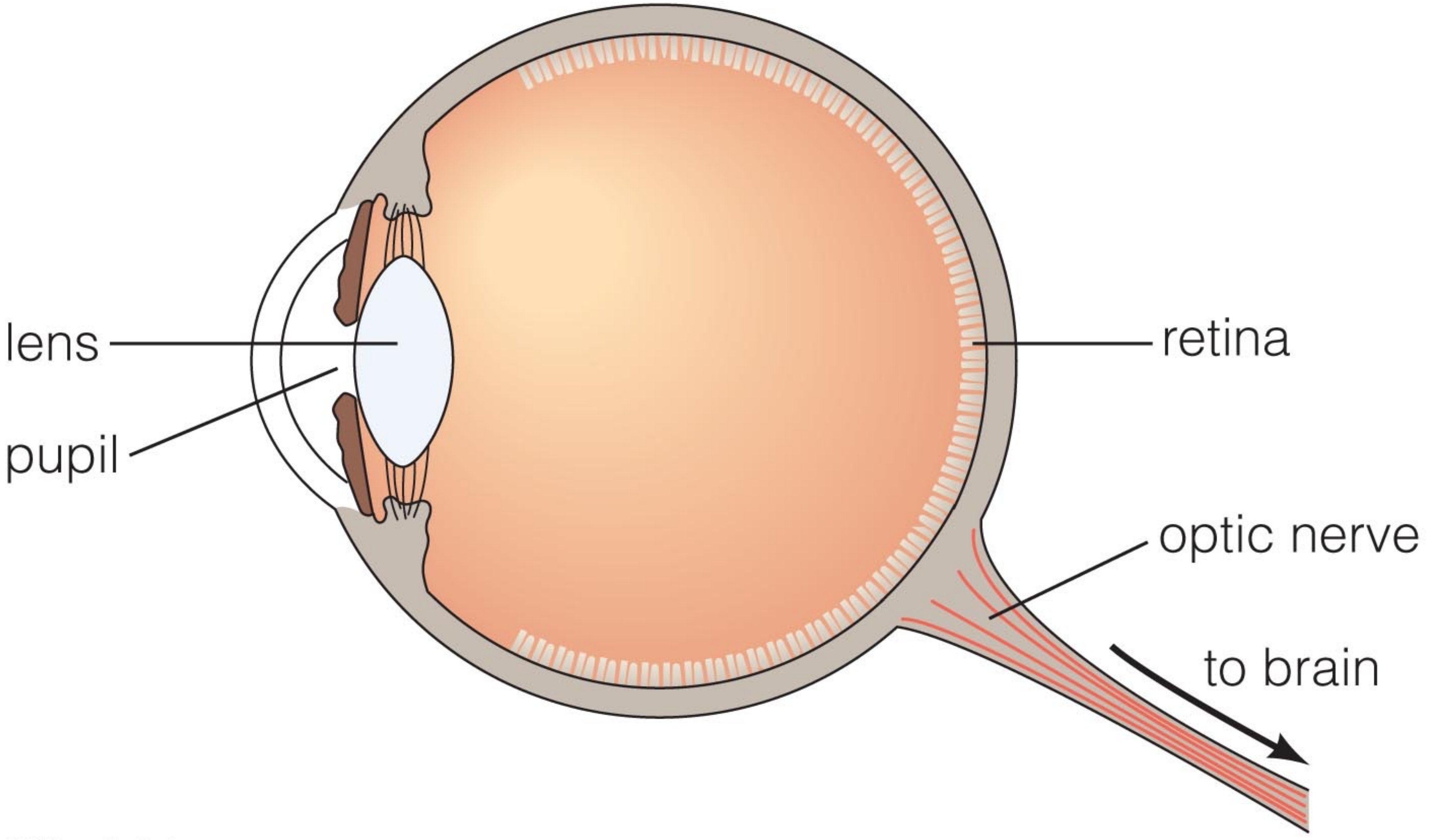


CofC Observatory

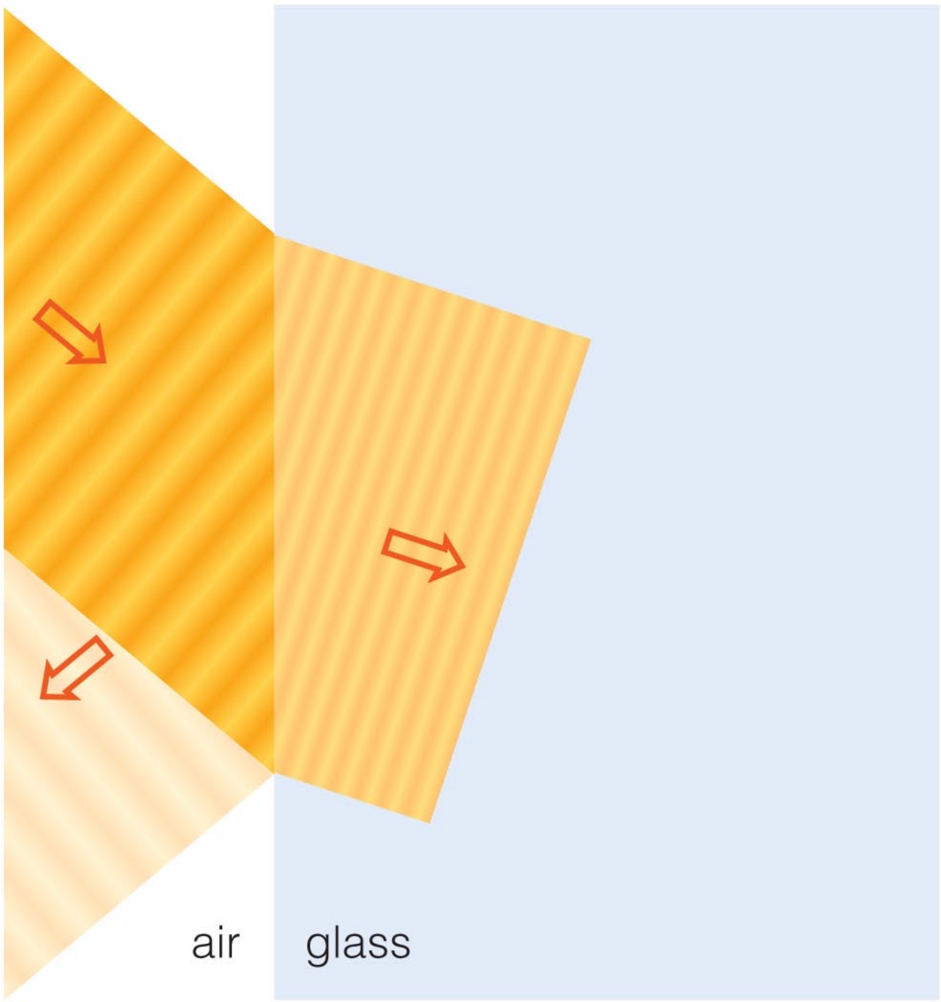
6.1 Eyes and Cameras: Everyday Light Sensors

- Our goals for learning:
  - **How do eyes and cameras work?**

The Eye

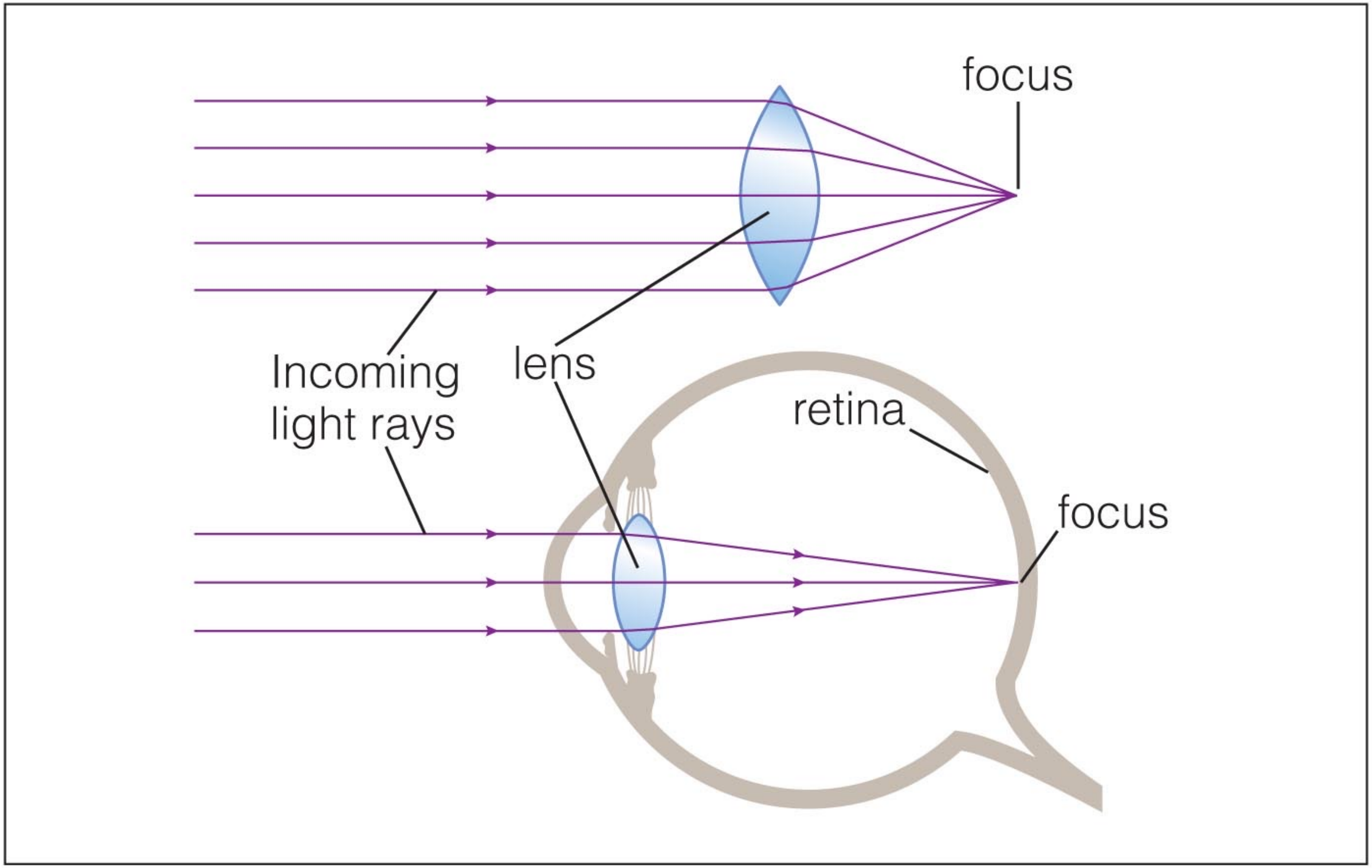


Refraction



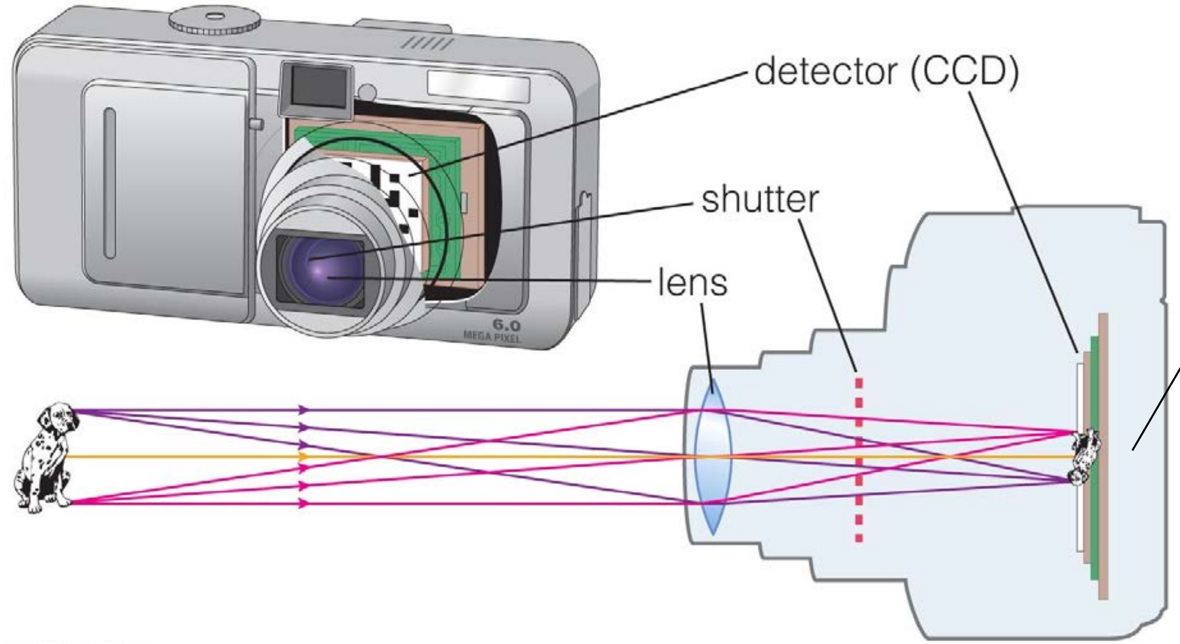
- Refraction is the bending of light when it passes from one substance into another.
- Your eye uses refraction to focus light.

Focusing Light



- Refraction can cause parallel light rays to converge to a focus.

Recording Images



Digital cameras detect light with charge-coupled devices (CCDs).

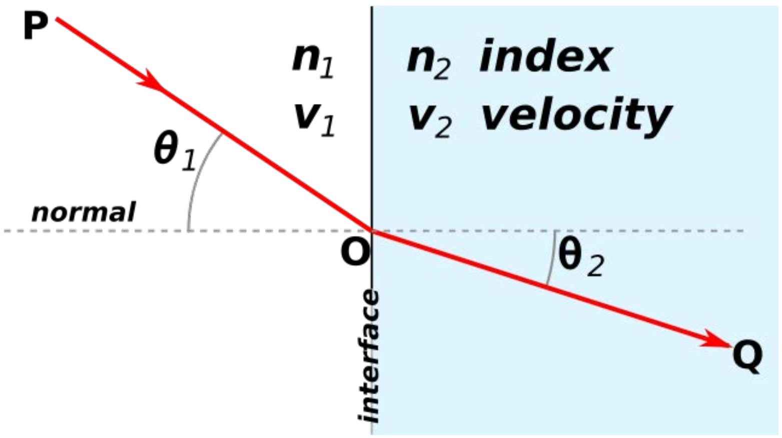
- A camera focuses light like an eye and captures the image with a detector.
- The CCD detectors in digital cameras are similar to those used in modern telescopes.

Refraction

Refraction is the change in direction of light due to a change in its speed. This usually happens when light goes from one type of medium to another.

Refraction is described by **Snell's law**, which states that the angle of incidence θ_1 is related to the angle of refraction θ_2 by:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

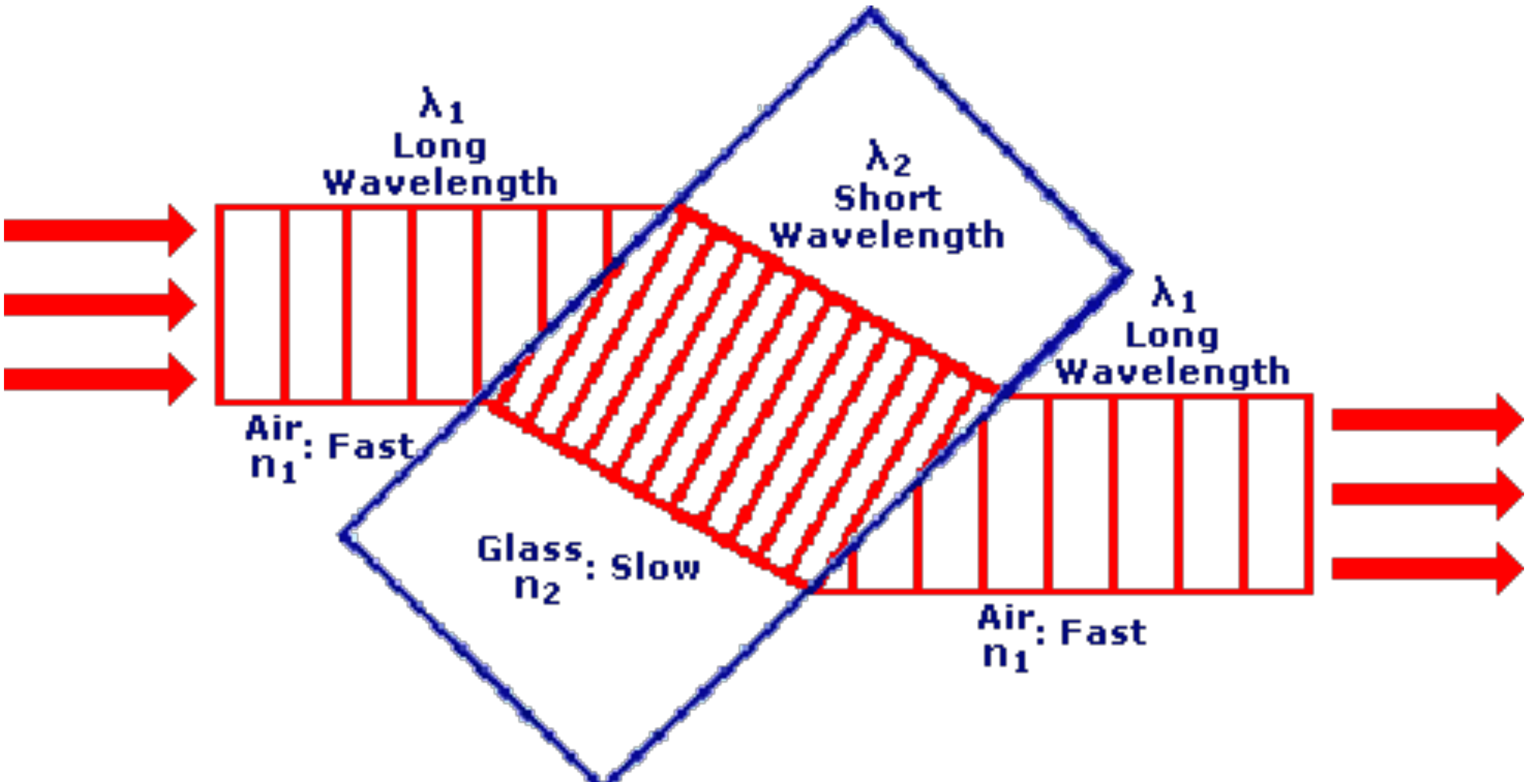


Where n_1 and n_2 are the indices of refraction and v_1 and v_2 are the velocities of light in media 1 and 2, respectively.
The index of refraction is defined as:

$$n = \frac{c_{vacuum}}{c_{medium}} \geq 1$$

Refraction

During refraction the velocity and the wavelength of light will change but the frequency of the wave will remain the same.



6.2 Telescopes: Giant Eyes

- Our goals for learning:
  - **What are the two most important properties of a telescope?**
  - **What are the two basic designs of telescopes?**
  - **What do astronomers do with telescopes?**

What are the two most important properties of a telescope?

1. **Light-collecting area:** Telescopes with a larger collecting area can gather a greater amount of light in a shorter time.

2. **Angular resolution:** Angular Resolution is the angular size of the smallest feature that can be distinguished. Telescopes that are larger are capable of taking images with greater detail.

Light-Collecting Area

The **light-collecting area** of a telescope is proportional to the area of the telescope's objective lens or mirror:

$$A = \pi R^2 = \frac{\pi D^2}{4}$$

where, D is the lens or mirror diameter.

Example: Each of the two Keck telescopes on Mauna Kea in Hawaii uses a concave mirror 10 m in diameter to bring starlight to a focus.

Question: How many times greater is the light-collecting area of either Keck telescope compared to that of the human eye? Assume a human eye has a pupil diameter of about 5 mm. (1 mm = 10^{-3} m)

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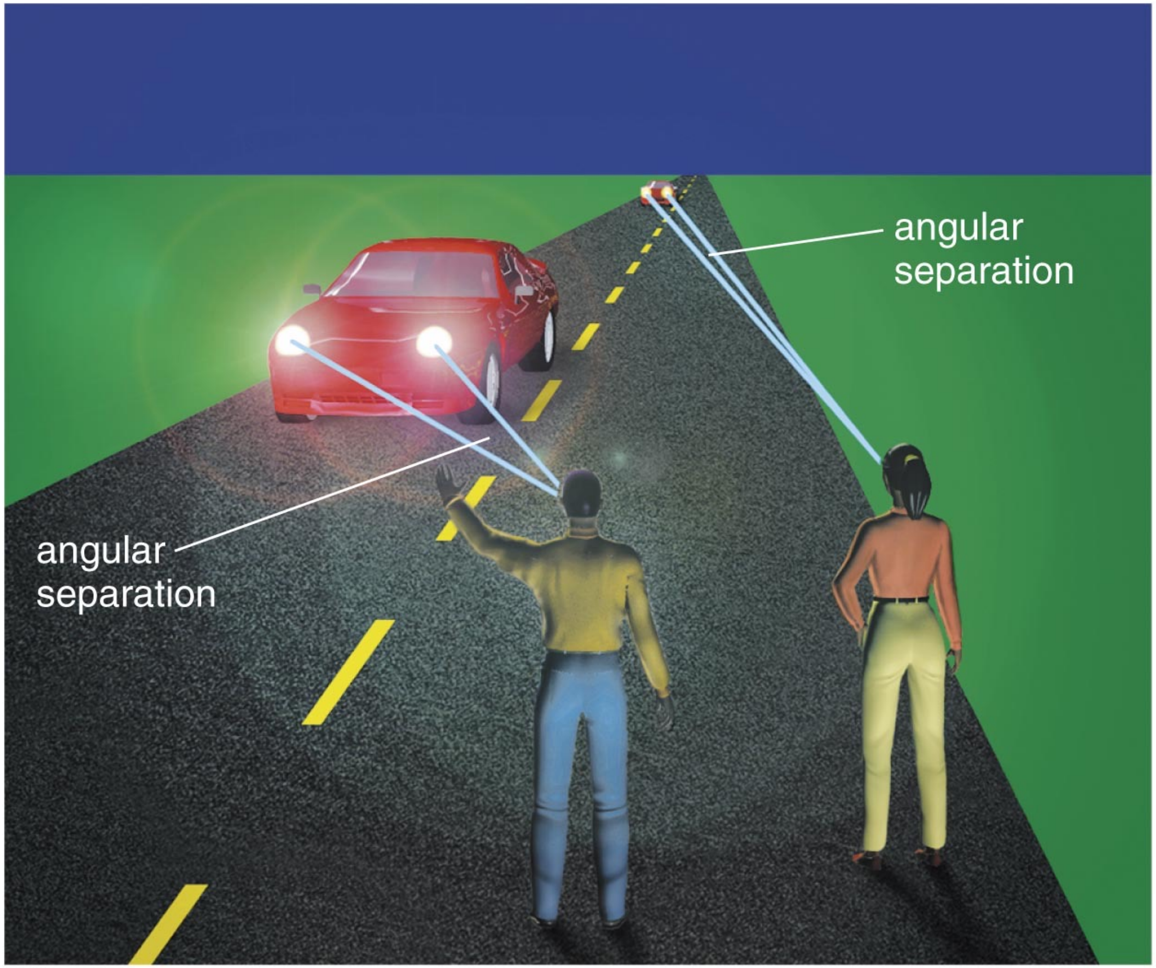
$$\frac{A_{Keck}}{A_{eye}} = \frac{\frac{\pi(10\ m)^2}{4}}{\frac{\pi(5\ mm)^2}{4}} = \frac{(10\ m)^2}{(5\times10^{-3}\ m)^2} = \left(\frac{10}{5\times10^{-3}}\right)^2 = 4\times10^6$$

Angular Resolution

- The *minimum* angular separation that the telescope can distinguish



Angular Resolution

An important property of a telescope is its **angular resolution**.

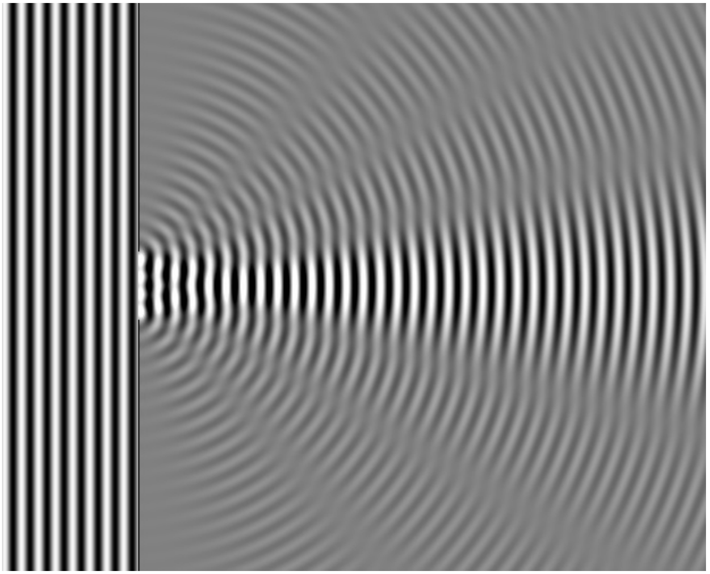
Angular resolution of a telescope is **the angular size of the smallest feature that can be distinguished**.

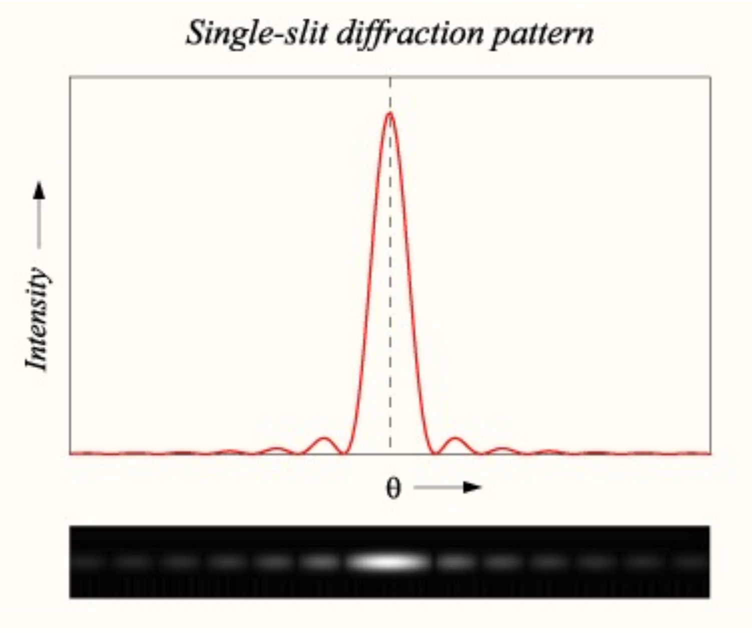
The angular resolution of your eye (for 20/20 vision) is about 1 arcmin. The planets have angular sizes of less than 1 arcmin and this is why they appear as points.

The angular resolution will depend on:
- **the quality of the mirrors, mirror design**
- **diffraction**
- **atmospheric turbulence (seeing)**

Diffraction

Diffraction is the apparent bending of waves around small obstacles and the spreading out of waves past small openings.





Diffraction

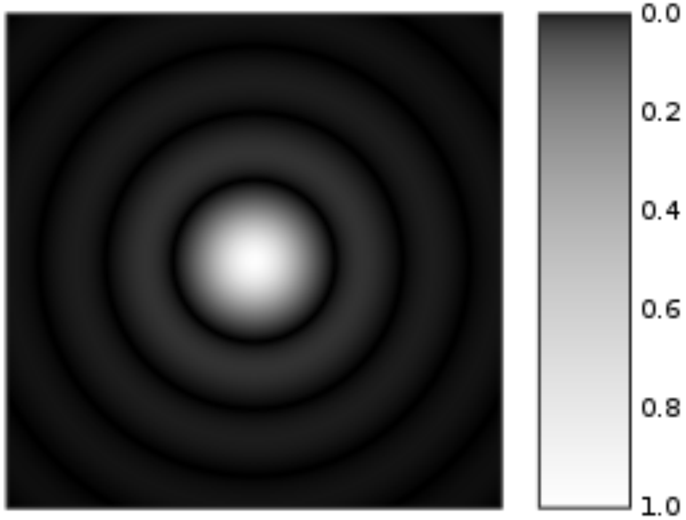
The light collected by a telescope at the focal point is not focused to a point but forms a **diffraction pattern** having a central peak with an angular size between the peak and the first null:

$$\theta(arc\sec) = 2.5 \times 10^5 \frac{\lambda}{D}$$

θ = diffraction - limited angular resolution of a telescope, in arcseconds

λ = wavelength of light, in meters

D = diameter of telescopes objective, in meters



Diffraction by a circular aperture. Notice the variation of intensity with angle.

Question: What is the diffraction limited angular resolution of
(a) the human eye (D = 5 mm)
(b) The Keck telescope (D = 10 m)
at 656 nm (H_α).

$1\text{mm} = 10^{-3}\text{m}$
$1\text{nm} = 10^{-9}\text{ m}$

Diffraction

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Question: What is the diffraction limited angular resolution of

(a) the human eye (D = 5 mm)

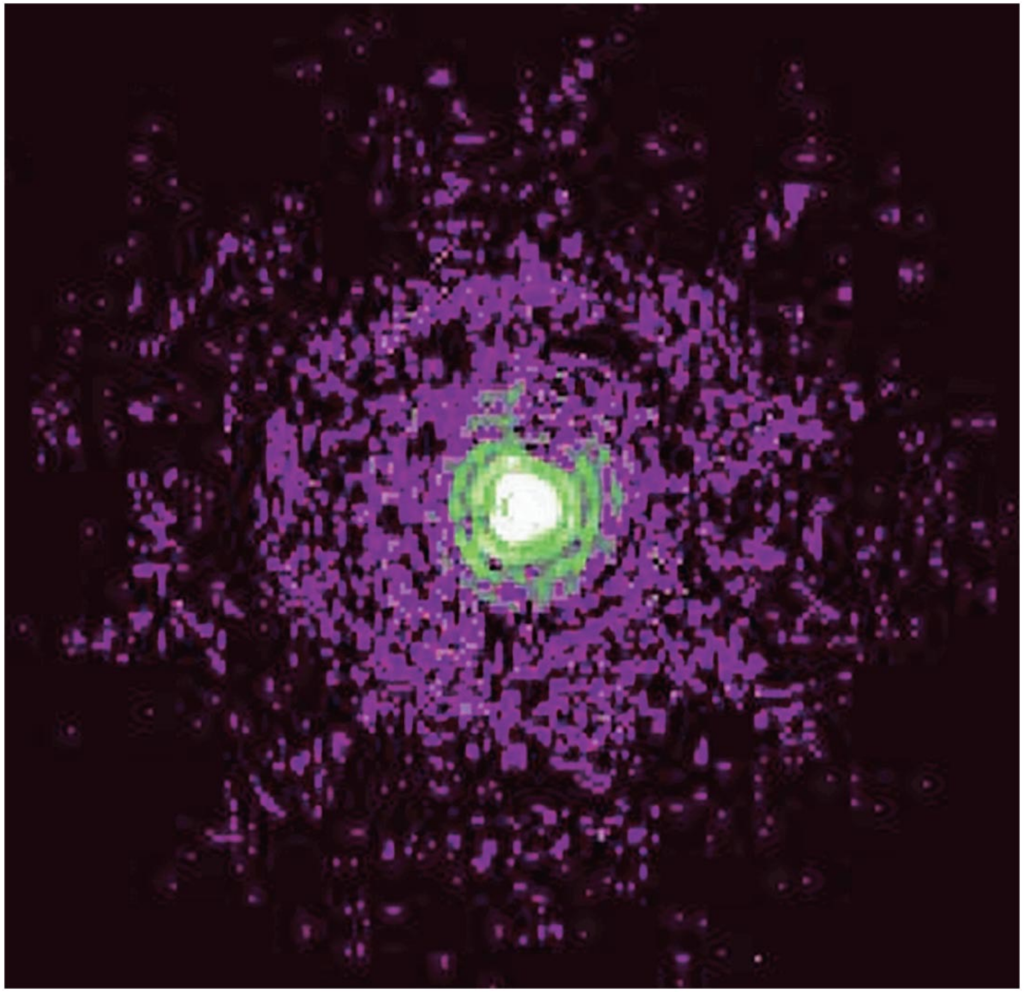
(b) The Keck telescope (D = 10 m)

at 656 nm (H_α).

$$\vartheta_{eye} = 2.5\times10^5\times\frac{656nm}{5mm} = 2.5\times10^5\times\frac{656\times10^{-9}m}{5\times10^{-3}m} = 32.8 \text{ arcsec}$$

$$\vartheta_{Keck} = 2.5\times10^5\times\frac{656nm}{10m} = 2.5\times10^5\times\frac{656\times10^{-9}m}{10\ m} = 0.0164 \text{ arcsec}$$

Angular Resolution



Close-up of a star from the Hubble Space Telescope

- The rings in this image of a star come from diffraction of light waves.
- This limit on angular resolution is known as the **diffraction limit**.

Seeing Disk

Turbulence in the atmosphere will blur an image. Even through the largest telescopes that are not limited by diffraction a point source looks like a blob. Turbulence will also make stars twinkle.

The angular size by which a star's size is broadened due to the atmosphere is called the **seeing disk**.

The size of the seeing disk depends on the location of the observations. For example, on **Kitt Peak** in Arizona and **Cerro Tololo** in Chile, the seeing disk is typically around 1 arcsec.

Correcting for Turbulence: Adaptive Optics

The goal of adaptive optics is to compensate for atmospheric turbulence.

In an adaptive optics system, sensors monitor the dancing motion of a star due to turbulence 10 to 100 times per second, and a powerful computer rapidly calculates the mirror shape needed to compensate.

If a bright star is not near the field of view a laser beam is used. The beam strikes sodium atoms in the sky, causing them to glow and **make an artificial "star."** Tracking the twinkling of this "star" makes it possible to undo the effects of atmospheric turbulence on telescope images.

Astronomers can make use of an artificial star by shining a powerful laser to correct for the blurring caused by the atmosphere.

European Southern Observatory's Very Large Telescope in Chile

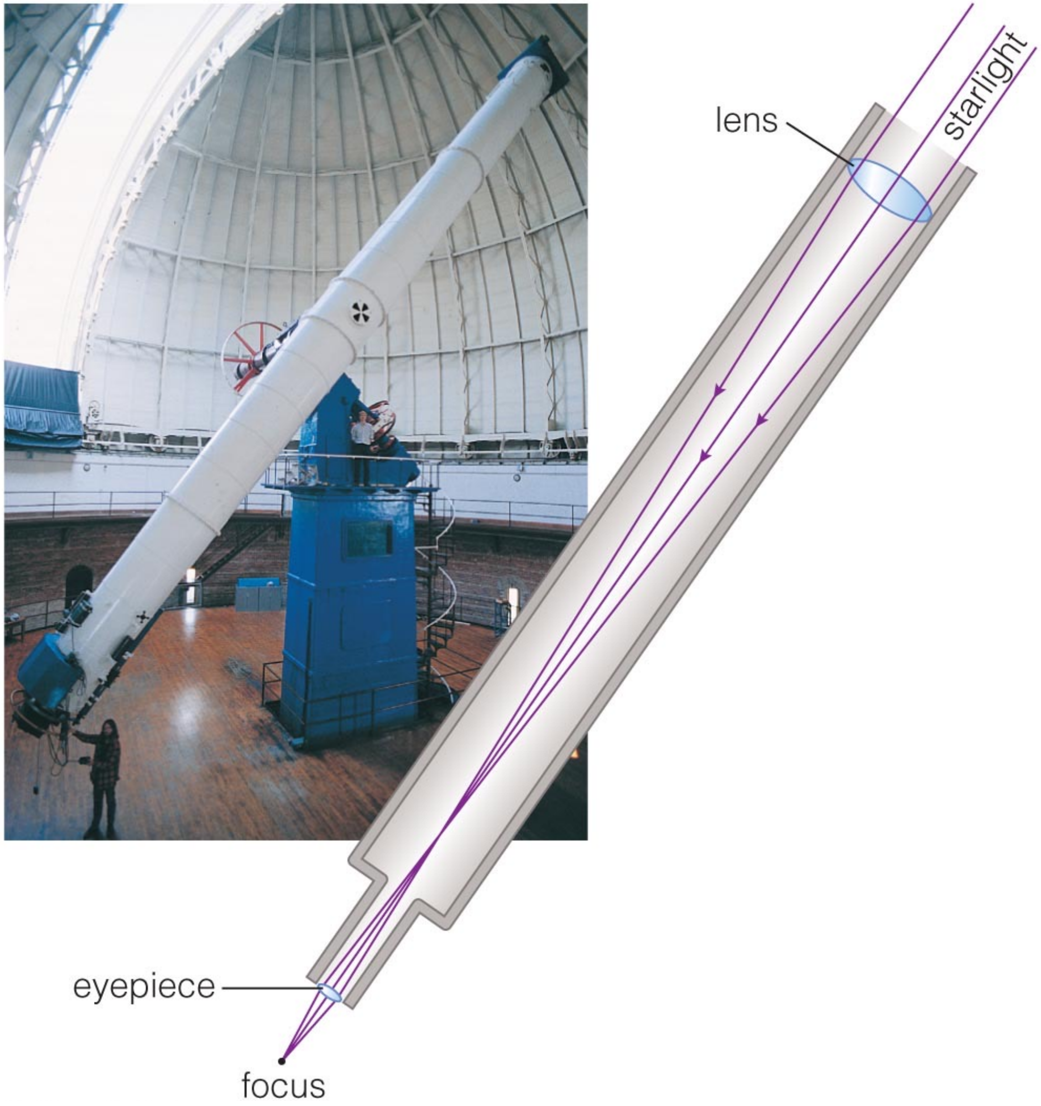
What are the two basic designs of telescopes?

- **Refracting telescope:** focuses light with lenses
- **Reflecting telescope:** focuses light with mirrors

The 68 cm refractor at the Vienna University Observatory.

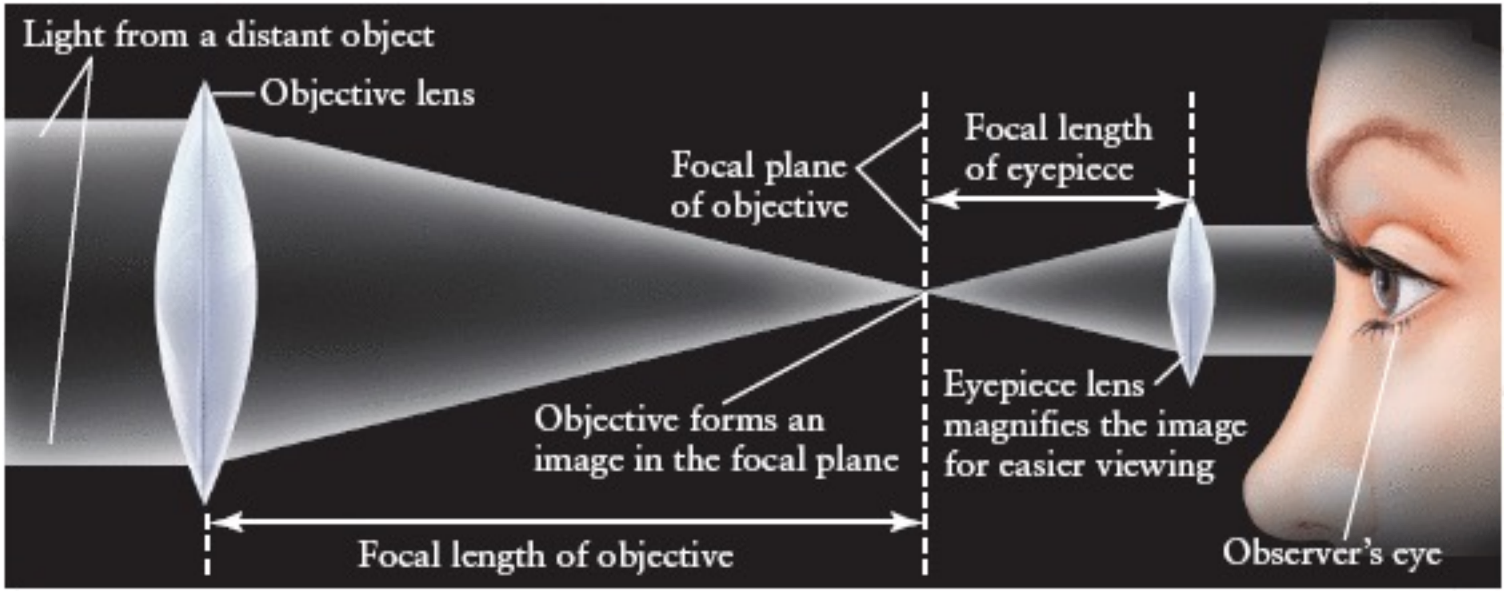
The 8 in reflecting telescope MEADE LX 200.

Refracting Telescope



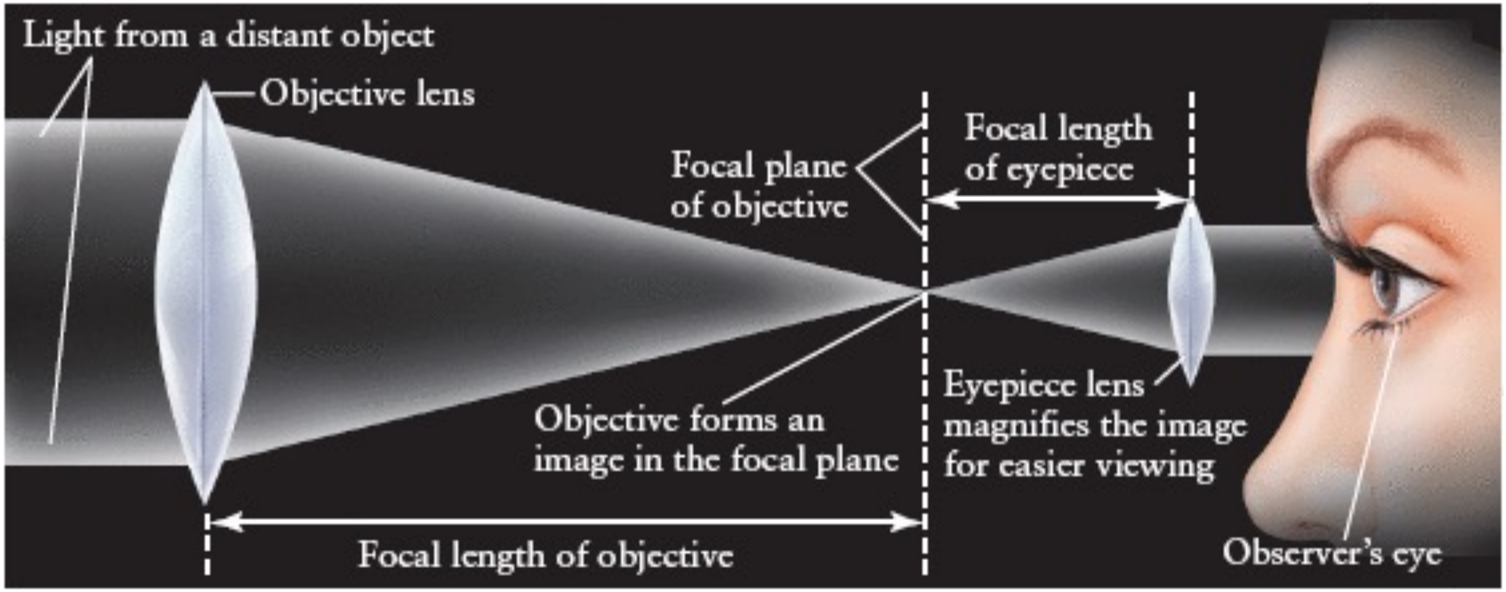
- Refracting telescopes need to be very long, with large, heavy lenses.

Refracting Telescope



A **refracting telescope** consists of a large-diameter **objective lens** (convex lens) with a **long focal length** and a small eyepiece lens of short focal length. The **eyepiece lens magnifies** the image formed by the objective lens in its focal plane (shown as a dashed line).

Refracting Telescope



The **magnification (M)** provided by a refracting telescope is the ratio of the focal length of the objective (f_1) to the focal length of the eyepiece (f_2). $M = f_1/f_2$

Assume a crater on the moon has an angular size of about 0.01° . A telescope with a magnification of 20× will make it appear to have an angular size of $20 \times 0.01° = 0.2°$

Refracting Telescope

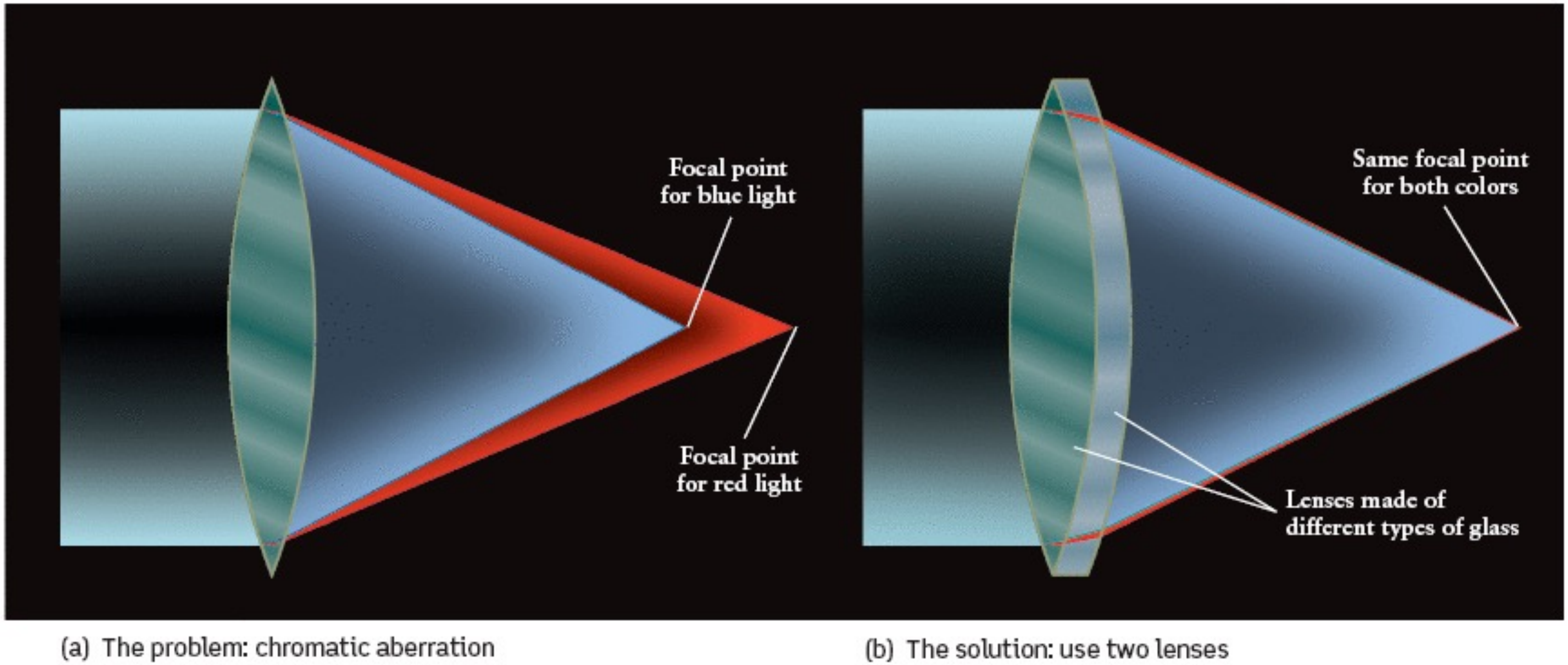
Example: A small refracting telescope has an objective of focal length 1 m. If the eyepiece has a focal length of 4.0 cm, what is the magnification of the telescope? (1 cm = 10^{-2} m)

Refracting Telescope

Example: A small refracting telescope has an objective of focal length 1 m. If the eyepiece has a focal length of 4.0 cm, what is the magnification of the telescope? (1 cm = 10^{-2}m)

$$M = \frac{f_1}{f_2} = \frac{1m}{4cm} = \frac{1m}{4 \times 10^{-2} m} = 25$$

Chromatic Aberration of Refractors



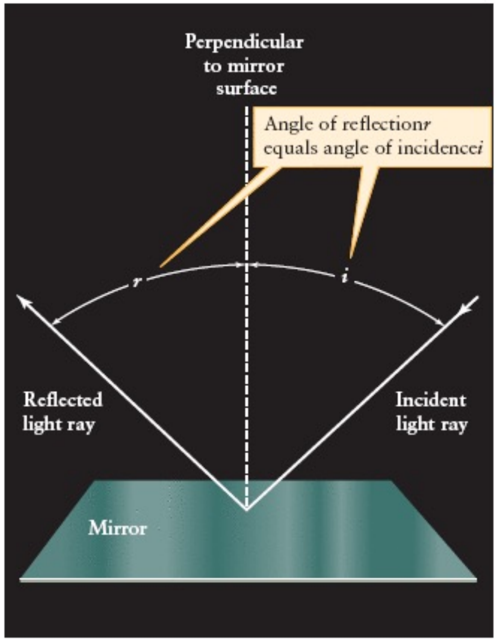
(a) A single lens suffers from a defect called **chromatic aberration**, in which different colors of light are brought to a focus at different distances from the lens. (b) This problem can be corrected by adding a second lens made from a different kind of glass.

Reflecting Telescope

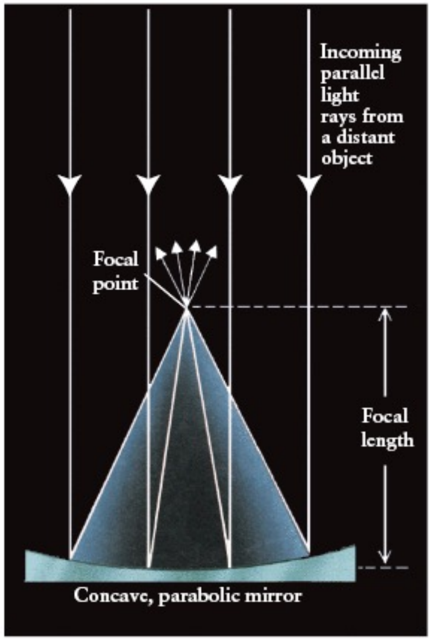
Almost all modern-day telescopes are reflecting telescopes. Some properties of reflection:

(a) The **angle of incidence** (i), is always equal to the **angle the angle of reflection** (r).

(b) A **parabolic mirror** causes parallel light rays to converge to a focus at the **focal point**. The distance between the mirror and the focal point is the **focal length** of the mirror.

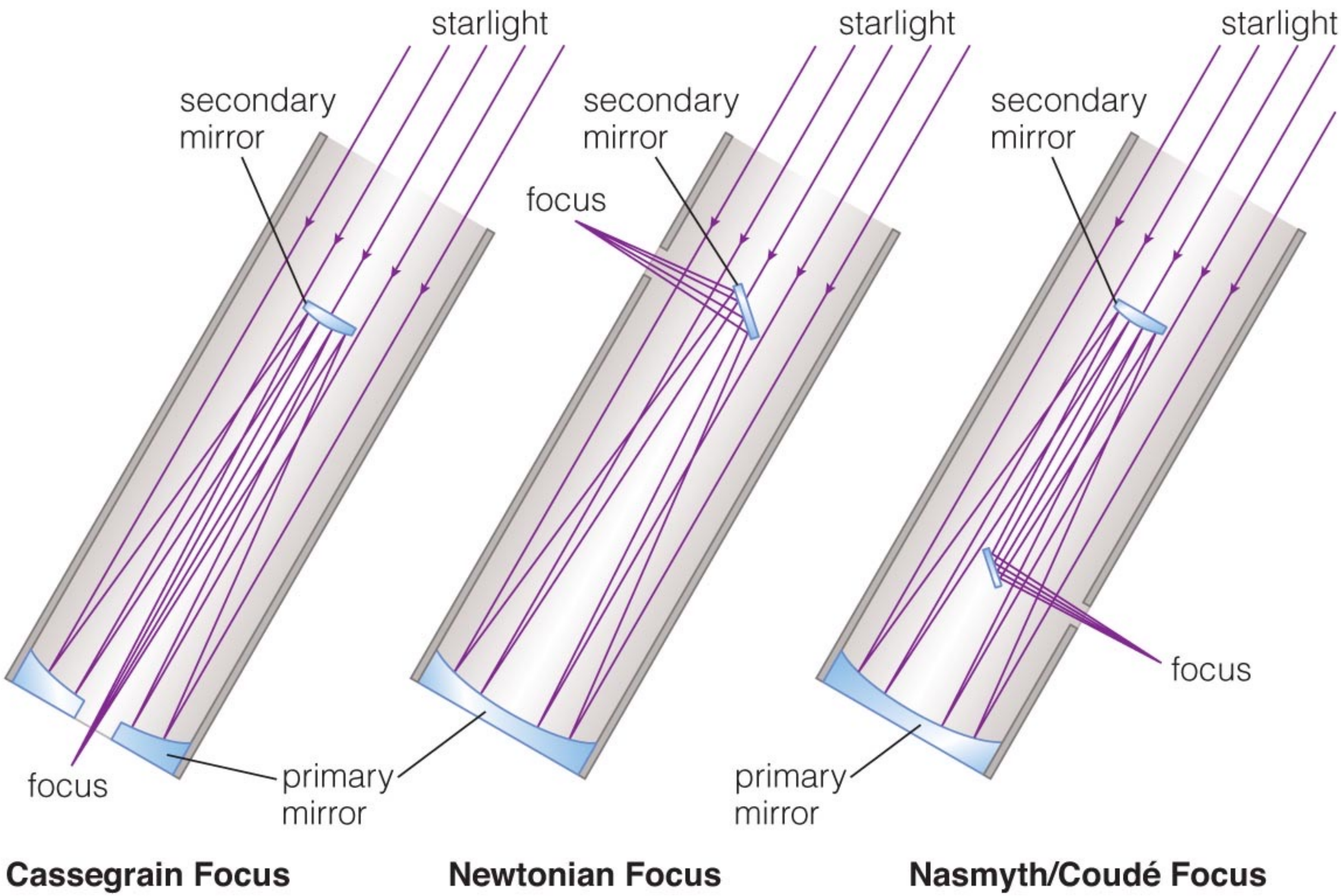


(a)



(b)

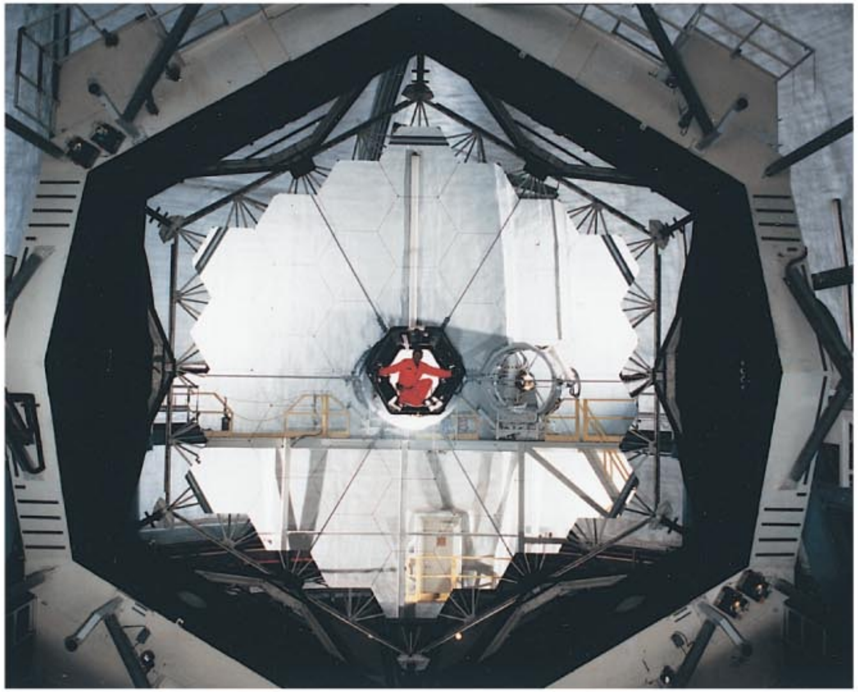
Designs for Reflecting Telescopes



The magnification of Newtonian and Cassegrain telescopes is the ratio of the focal length of the objective to the focal length of the eyepiece: M = f1/f2

Mirrors in Reflecting Telescopes

Twin Keck telescopes on Mauna Kea in Hawaii



Segmented 10-meter mirror of a Keck telescope

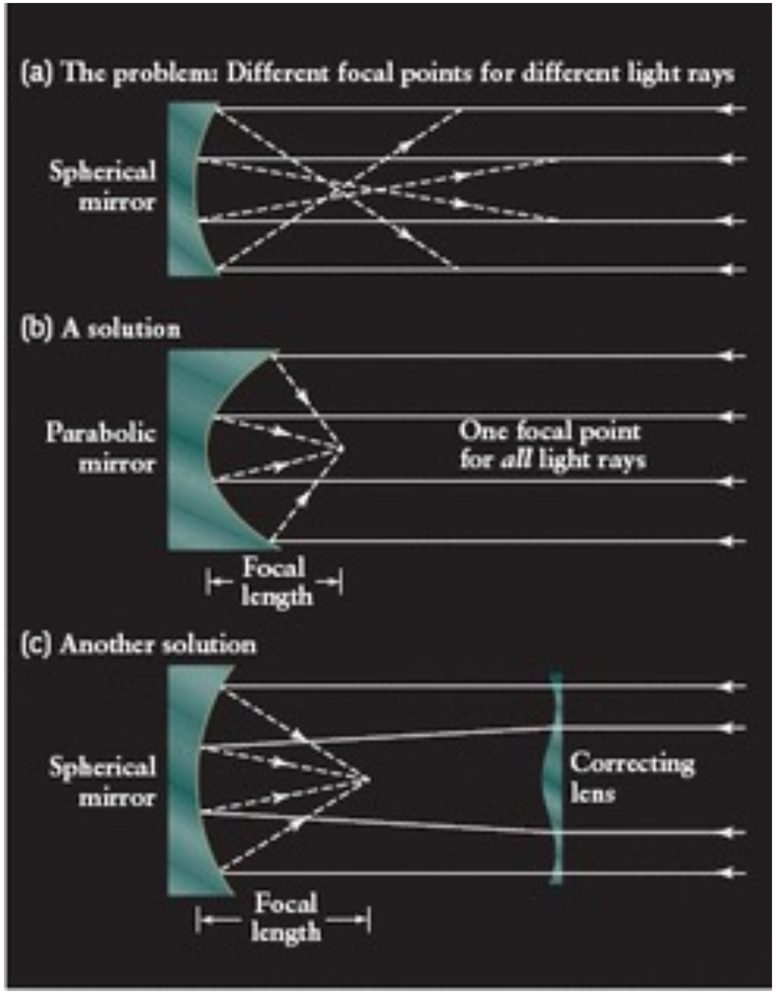
Spherical Aberration of Reflectors

Different parts of a spherically concave mirror reflect light to slightly different focal points. This effect, called **spherical aberration, causes image blurring.**

Spherical aberration can be corrected by using :

- a parabolic objective mirror

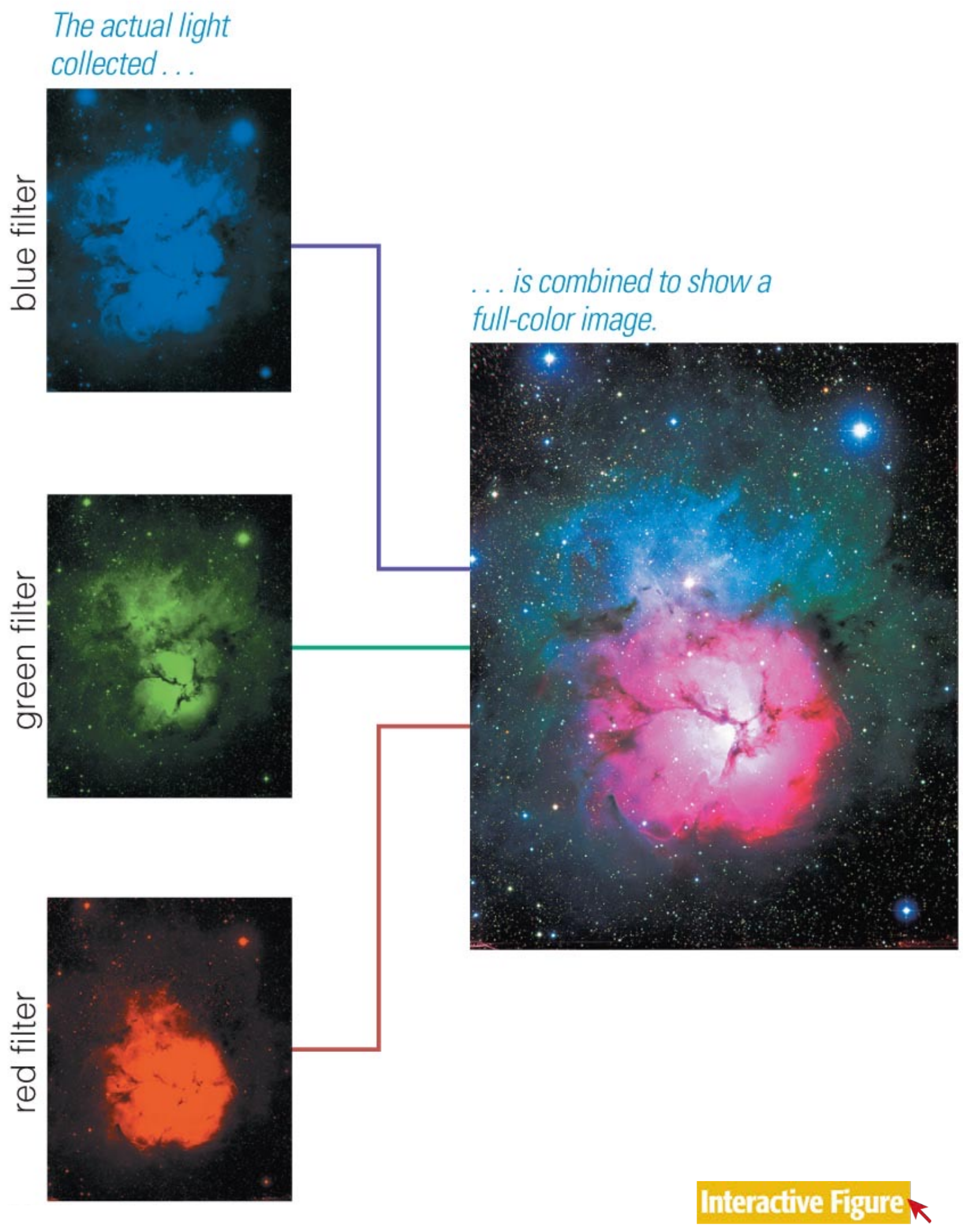
- or using a correcting lens



What do astronomers do with telescopes?

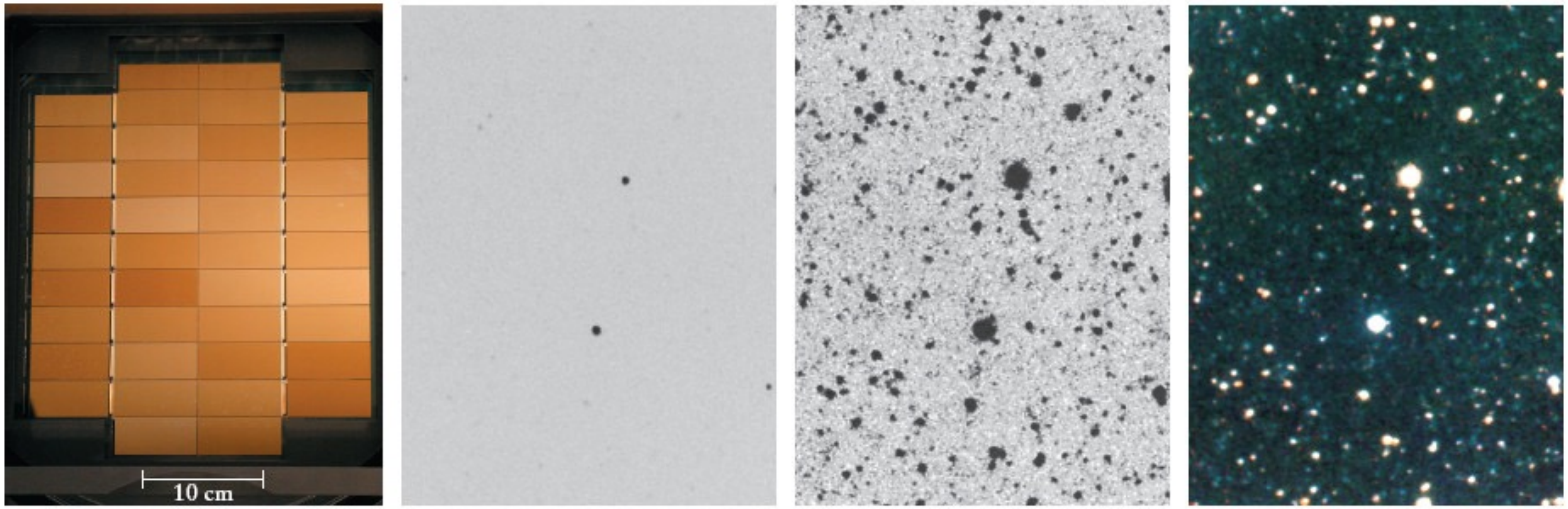
- **Imaging:** taking pictures of the sky
- **Spectroscopy:** breaking light into spectra
- **Time Monitoring:** measuring how light output varies with time

Imaging



- Astronomical detectors generally record only one color of light at a time.
- Several images must be combined to make full-color pictures.

Imaging instruments used in astronomy



(a) A mosaic of 40 charge-coupled devices (CCDs)

(b) An image made with photographic film

(c) An image of the same region of the sky made with a CCD

(d) Combining several CCD images made with different color filters

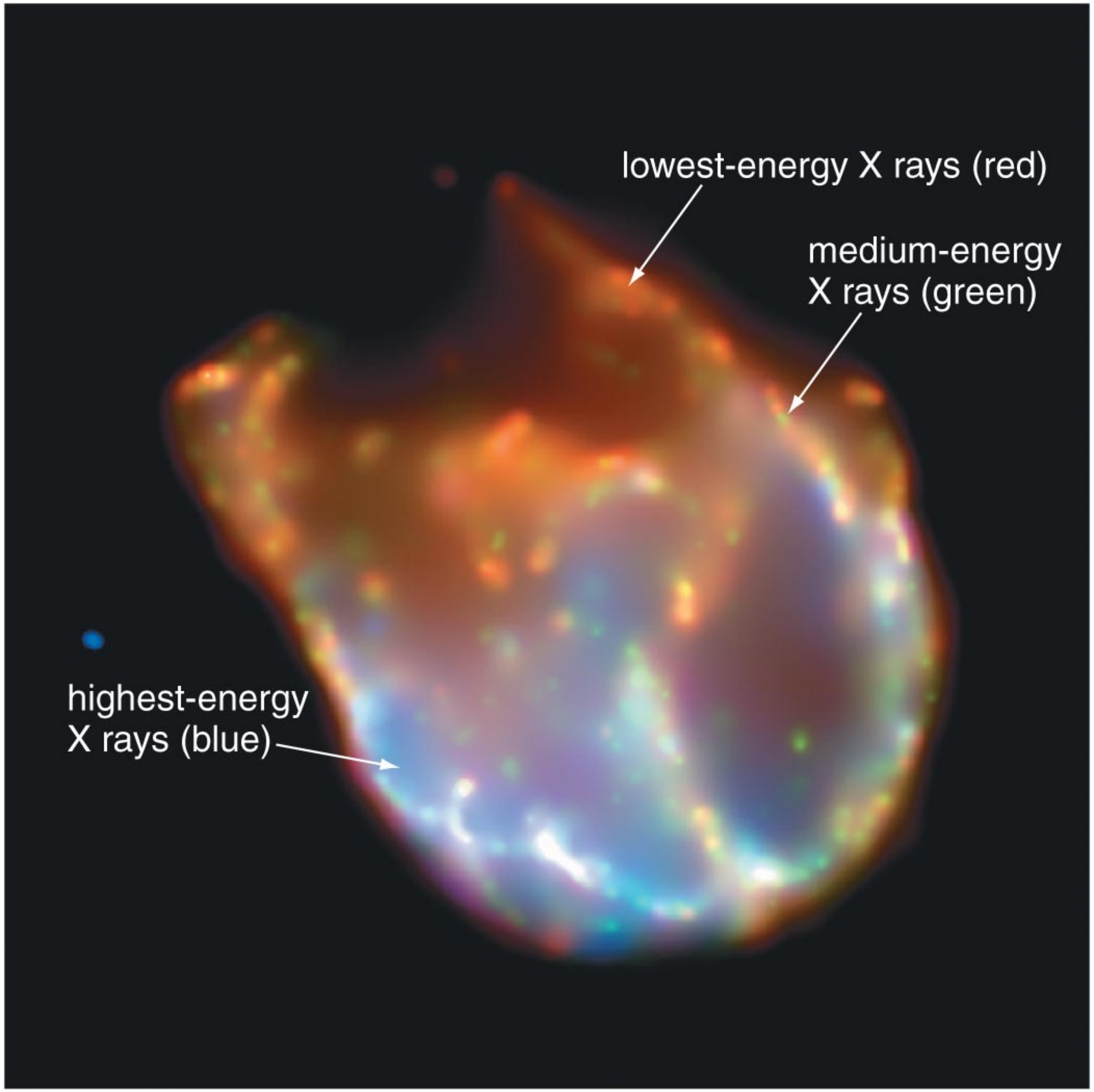
Telescopes can provide detailed pictures of distant objects. These images are usually recorded on **charge-coupled devices** (CCDs). Each one of the 40 CCDs used on the Canada-France-Hawaii Telescope (panel a) has 9.4 million pixels arranged in 2048 rows by 4608 columns.

This observation of the **Whirlpool Galaxy (M51)** was made with the CofC 24-inch telescope and an Apogee Aspen CCD. The image of M51 is a composite of 3 filters in the visible range: **B (blue), G (green)** and **R (red).**

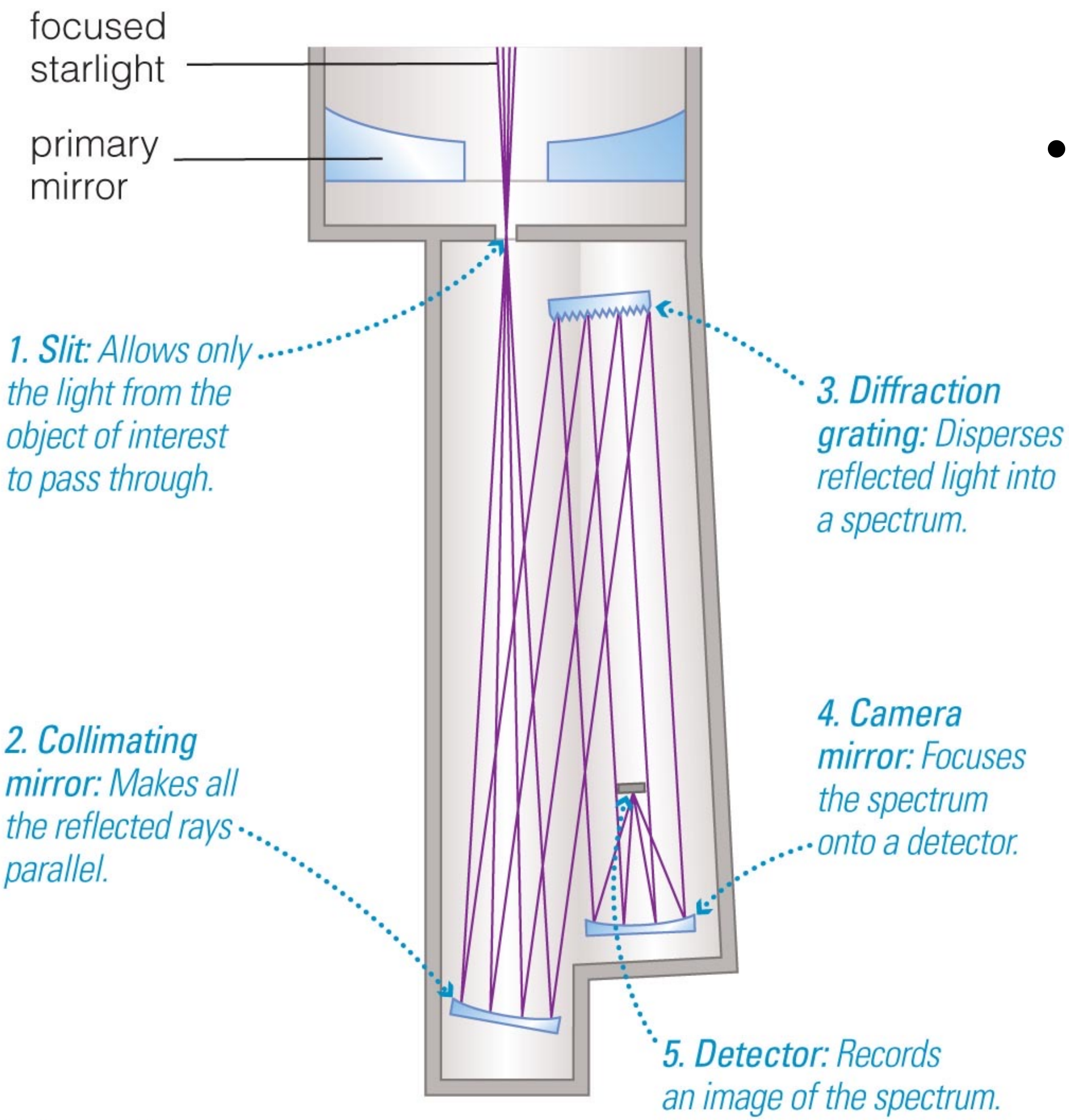
Imaging

- Astronomical detectors can record forms of light our eyes can't see.

- Color is sometimes used to represent different energies of non-visible light.

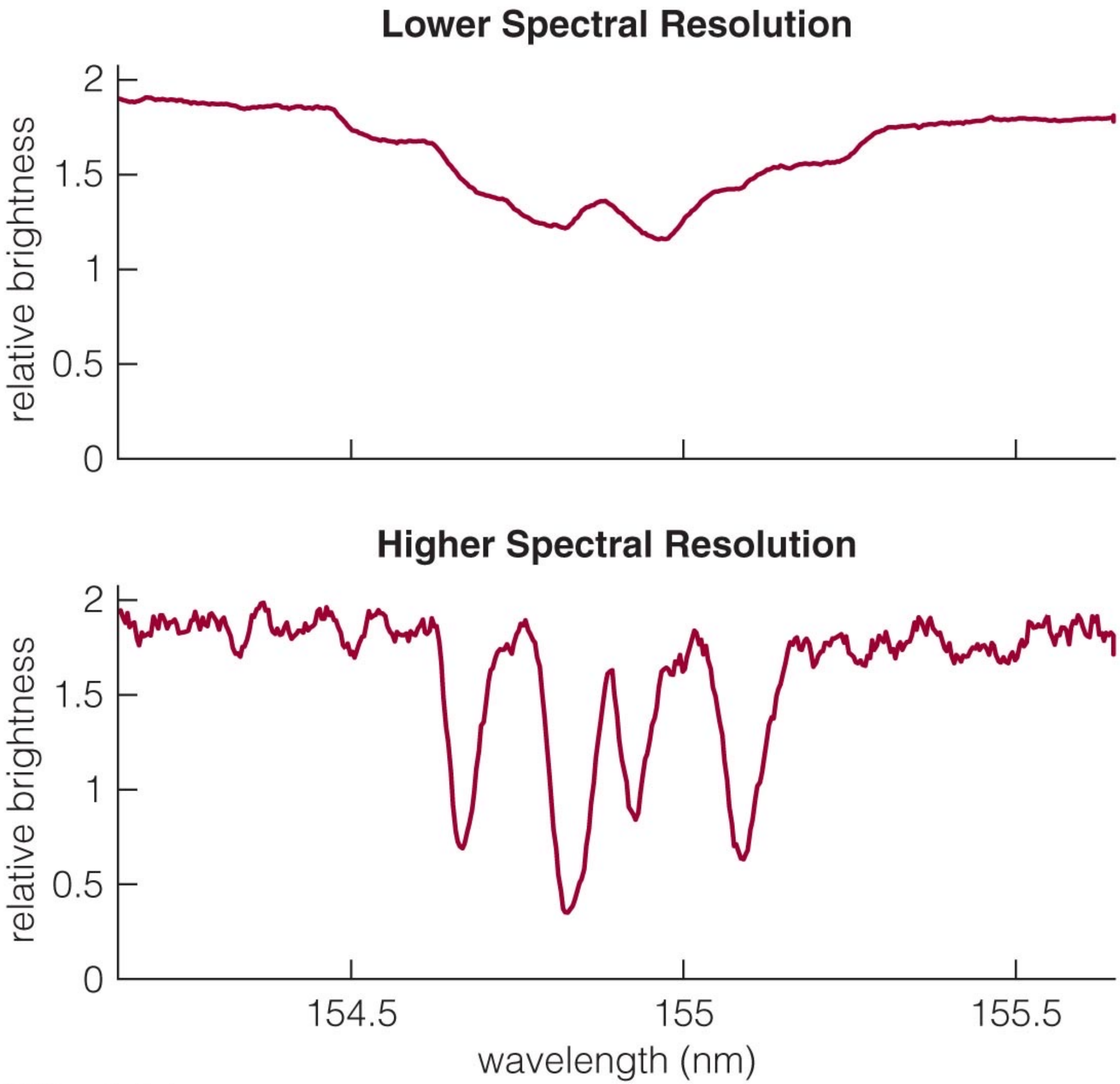


Spectroscopy



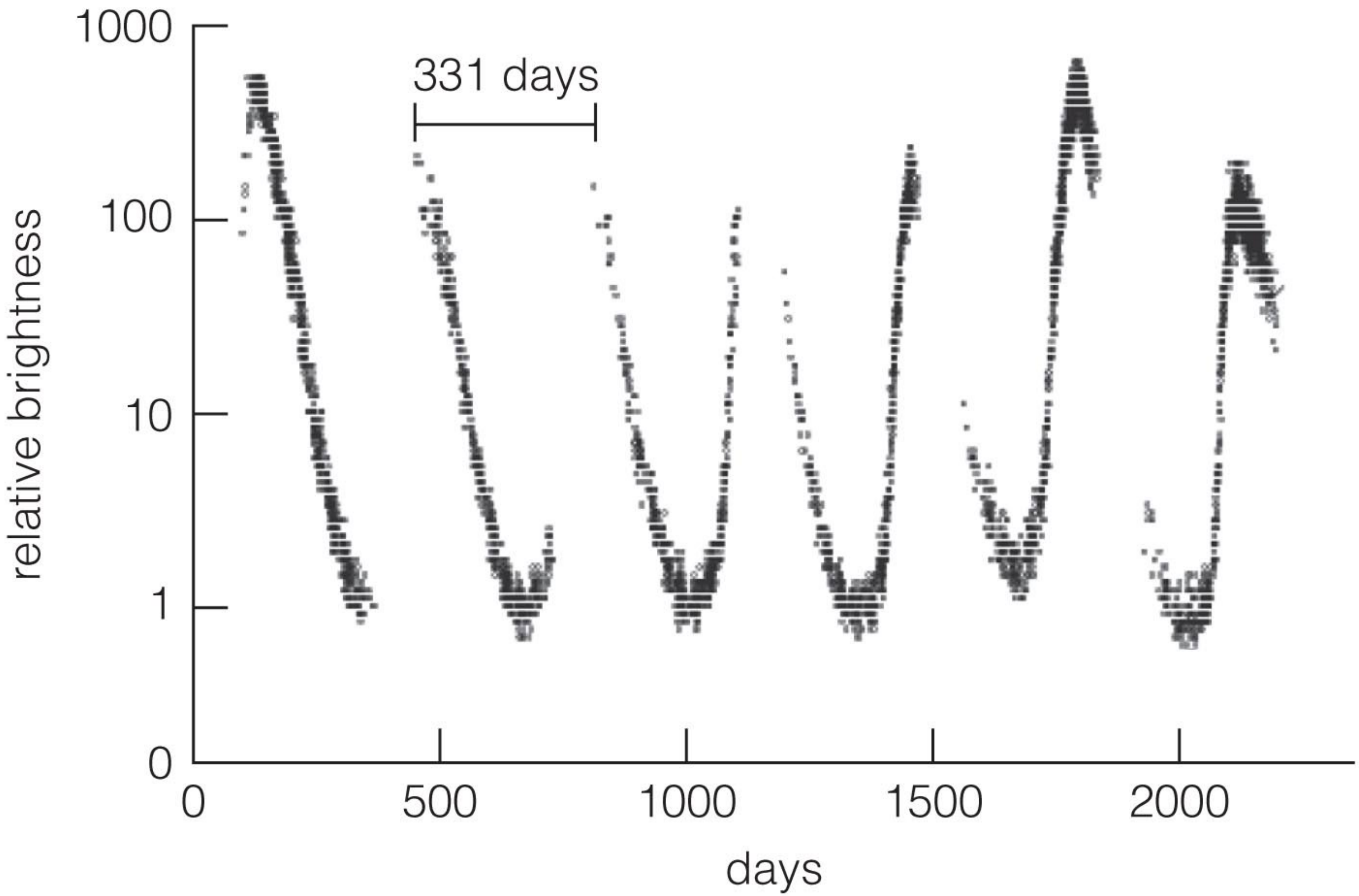
- A spectrograph separates the different wavelengths of light before they hit the detector.

Spectroscopy



- Graphing relative brightness of light at each wavelength shows the details in a spectrum.

Time Monitoring



- A light curve represents a series of brightness measurements made over a period of time.

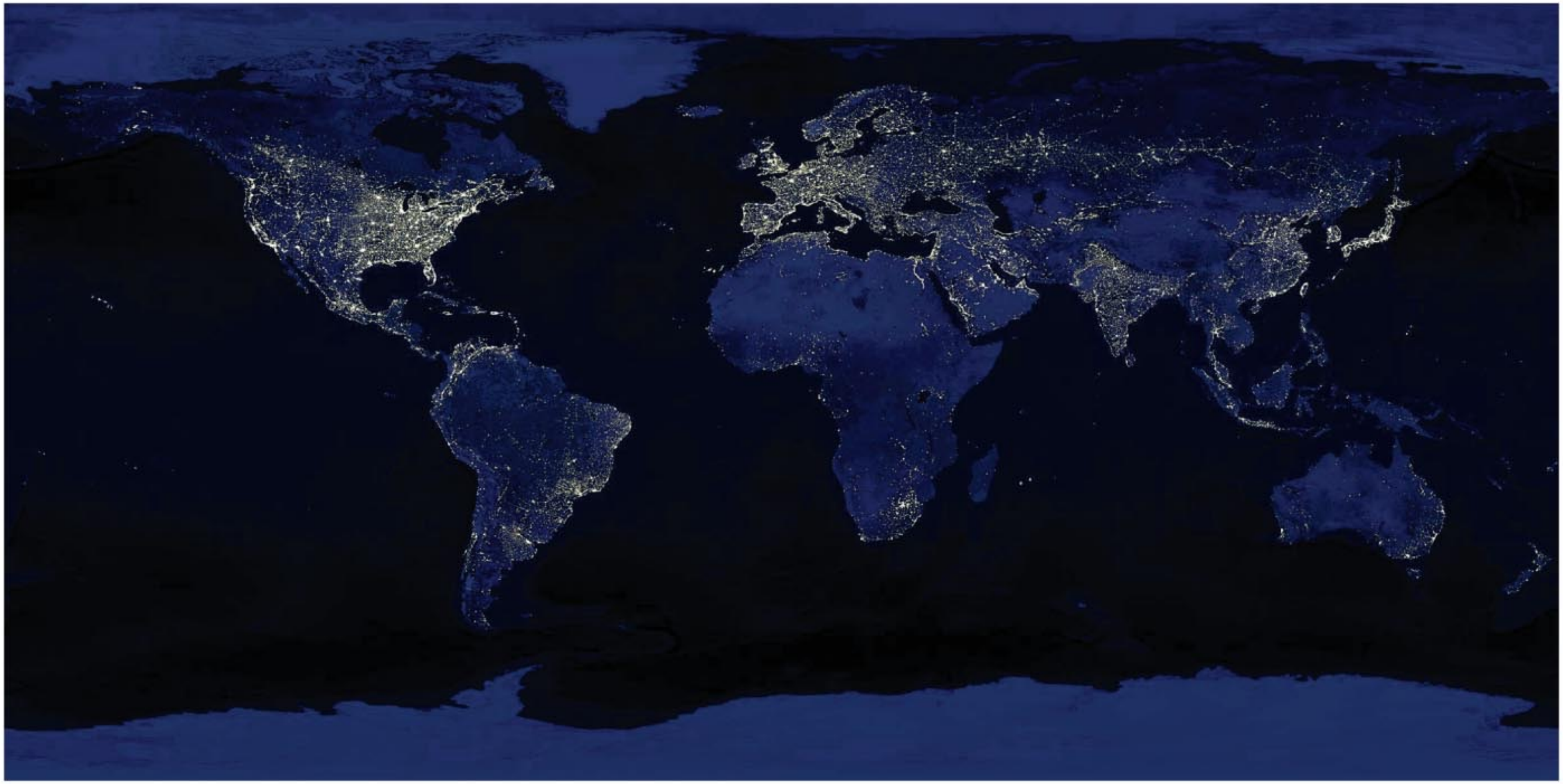
6.3 Telescopes and the Atmosphere

- Our goals for learning:
  - **How does Earth's atmosphere affect ground-based observations?**
  - **Why do we put telescopes into space?**

How does Earth's atmosphere affect ground-based observations?

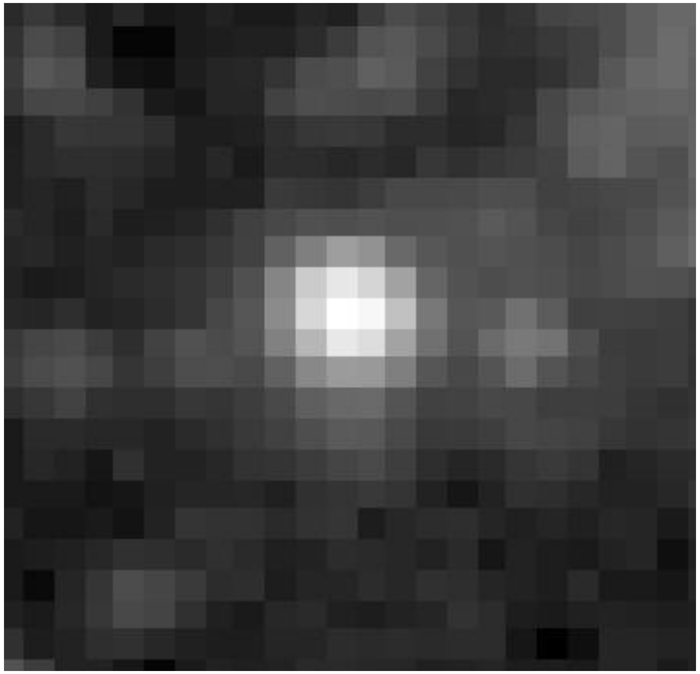
- The best ground-based sites for astronomical observing are:
  - calm (not too windy)
  - high (less atmosphere to see through)
  - dark (far from city lights)
  - dry (few cloudy nights)

Light Pollution

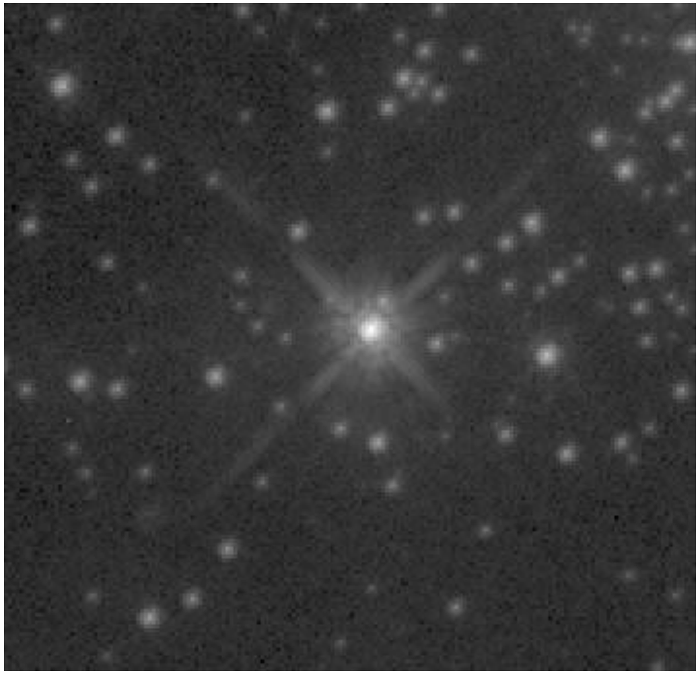


- Scattering of human-made light in the atmosphere is a growing problem for astronomy.

Twinkling and Turbulence



Bright star viewed with ground-based telescope



Same star viewed with Hubble Space Telescope

- Turbulent air flow in Earth's atmosphere distorts our view, causing stars to appear to twinkle.

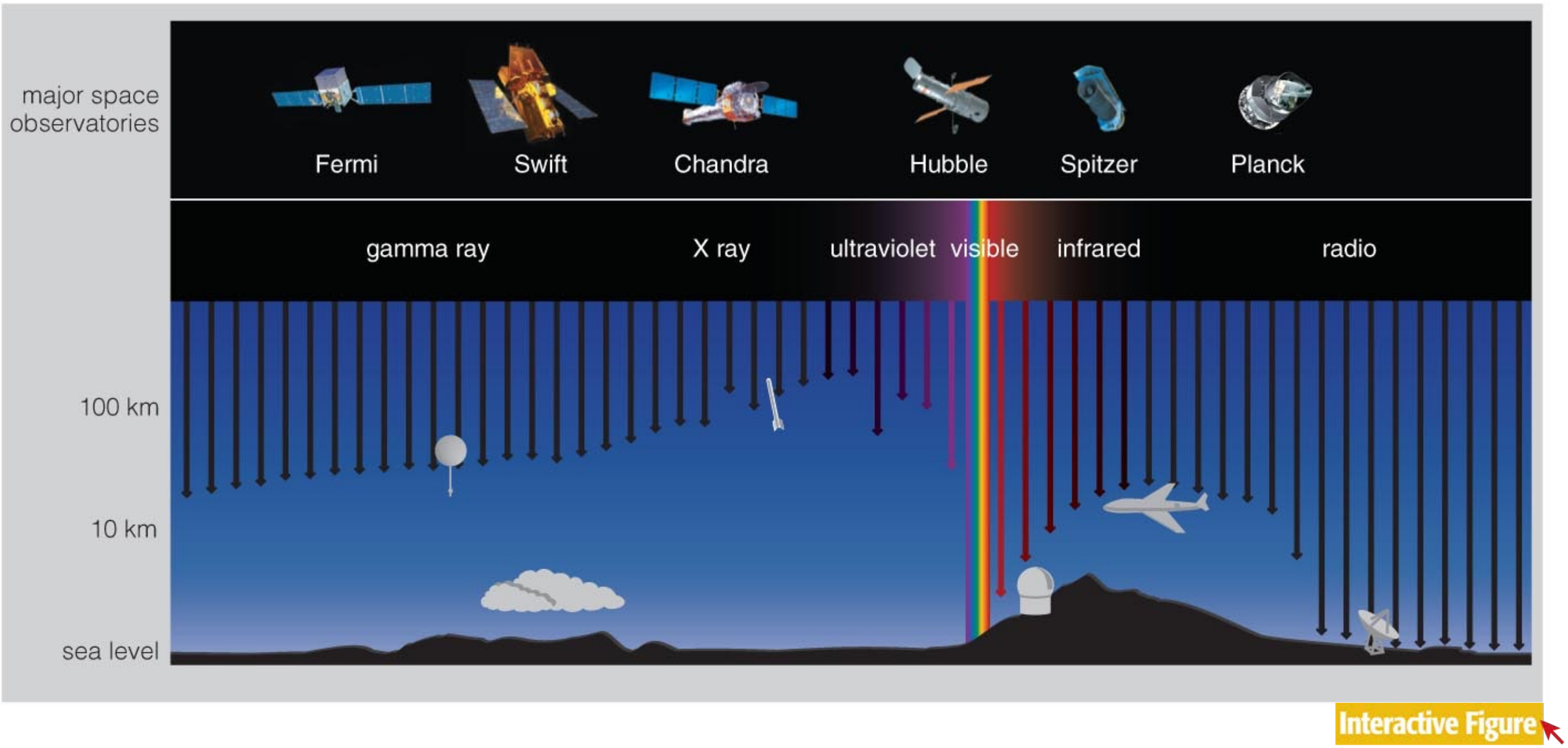
Calm, High, Dark, Dry

Summit of Mauna Kea, Hawaii

- The best observing sites are atop remote mountains.

Why do we put telescopes into space?

Transmission in Atmosphere



- Only radio and visible light pass easily through Earth's atmosphere.
- We need telescopes in space to observe other forms.

6.4 Telescopes and Technology

- Our goals for learning:
  - **How can we observe invisible light?**
  - **How can multiple telescopes work together?**

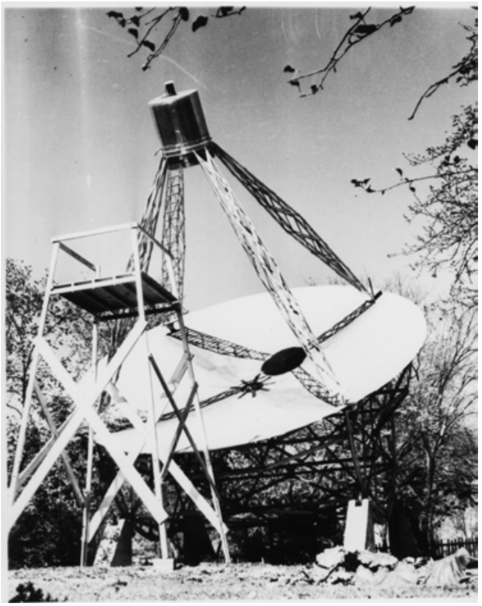
Radio Astronomy

The first radio waves of an astronomical origin were **discovered by Karl Jansky** in the early 1930s.

Jansky was trying to figure out what was causing interference at 20 MHz with a trans-atlantic radio link. He built a steerable radio antenna to search for the source of the noise.

He concluded that **an astronomical object in the direction of the constellation Sagittarius** must be causing the radio interference.

In 1936 **Grote Reber** built the first **parabolic "dish"** radio telescope and conducted the first sky survey in the radio frequencies.



Reber's radio telescope

VLA in New Mexico

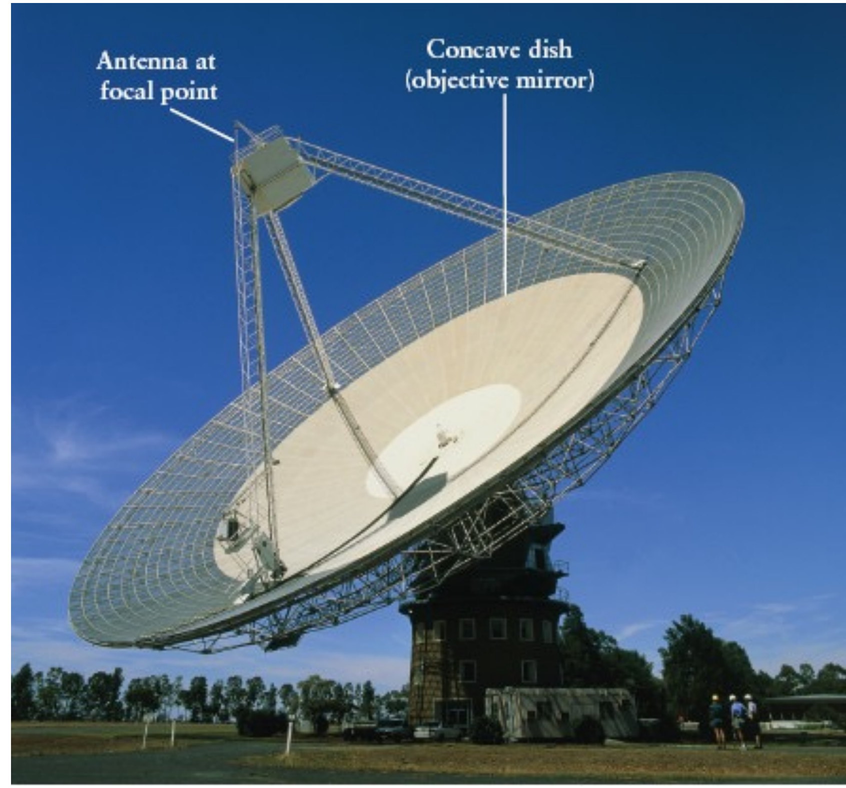
Radio Telescopes

A modern ratio telescope consists of :

- a parabolic dish

- an antenna tuned to the desired frequency located at the focus.

The signal picked up by the antenna is relayed to an amplifier and recording instruments usually located at the base of the telescope pier.



PARKES, NSW, Australia
(64 m diameter)

Questions:

1) What frequency does 64 m correspond to?

2) Why can't microwaves at ν = 2.45 GHz leak through a microwave door?

Radio Telescopes

Questions:

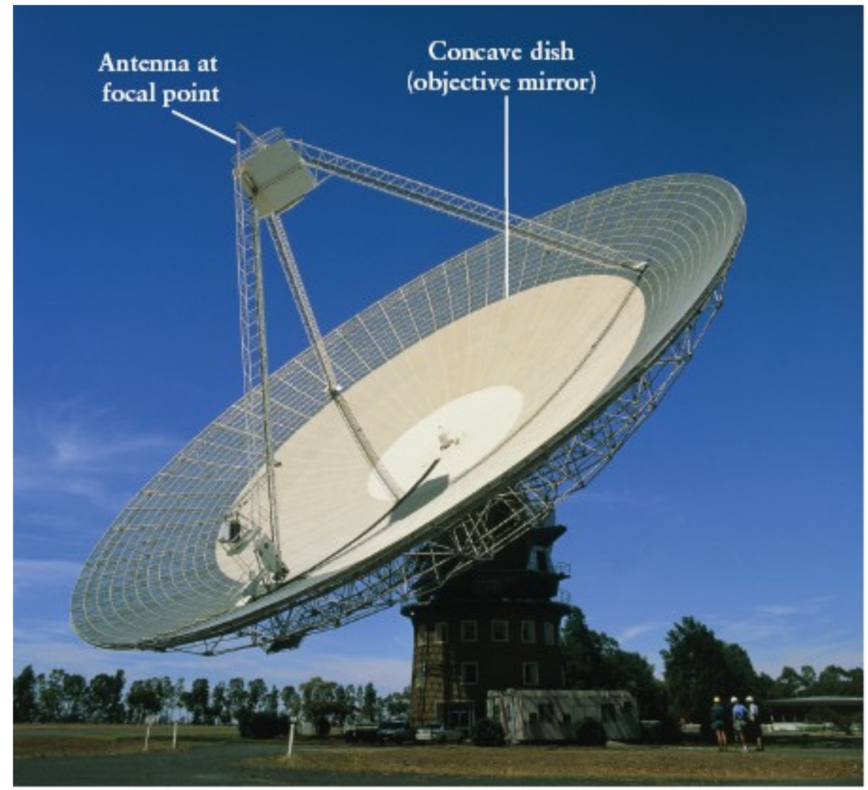
1) What frequency does 64 m correspond to?

$$c = \lambda\nu \rightarrow \nu = \frac{c}{\lambda} = \frac{3\times10^8 m/s}{64m} \rightarrow$$
$$\nu = 4688\ kHz$$

2) Why can't microwaves at ν = 2.45 GHz leak through a microwave door?

$$\lambda = \frac{c}{\nu} = \frac{3\times10^8 m/s}{2.45\times10^9 Hz} = 0.122m \rightarrow$$
$$\lambda = 12.2cm$$

The mesh in the glass window of a microwave has holes that are smaller than 12.2 cm. Microwaves reflect off the mesh and do not leak through.



PARKES, NSW, Australia (64 m diameter)

Radio Telescopes: Dealing with Diffraction

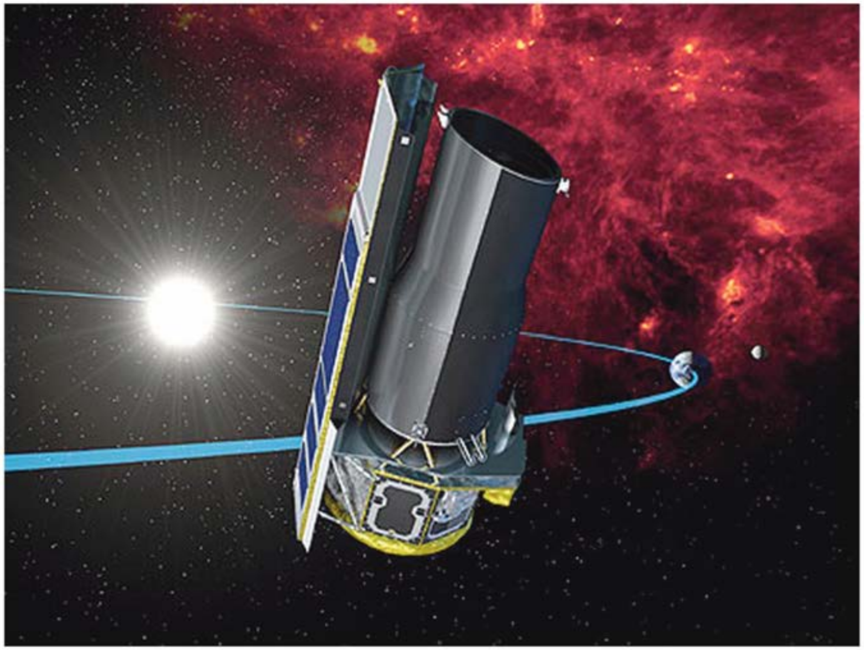
The diffraction limited angular resolution of a 25 m radio dish at $\lambda = 21\text{cm}$ is $\theta \sim 2.5 \times 10^5 \times (21 \text{ cm} / 25 \text{ m}) = 2100$ arcsec

To improve the angular resolution of radio telescopes, astronomers use the **interferometry technique** which relies on combining the signals of many radio telescopes.

The Very Large Array (VLA) consists of 27 parabolic dishes, each 25 m in diameter. By pointing all 27 telescopes at the same object and combining the 27 radio signals, the VLA can produce radio views of the sky with an angular resolution as small as 0.05 arcsec.

Infrared Telescopes

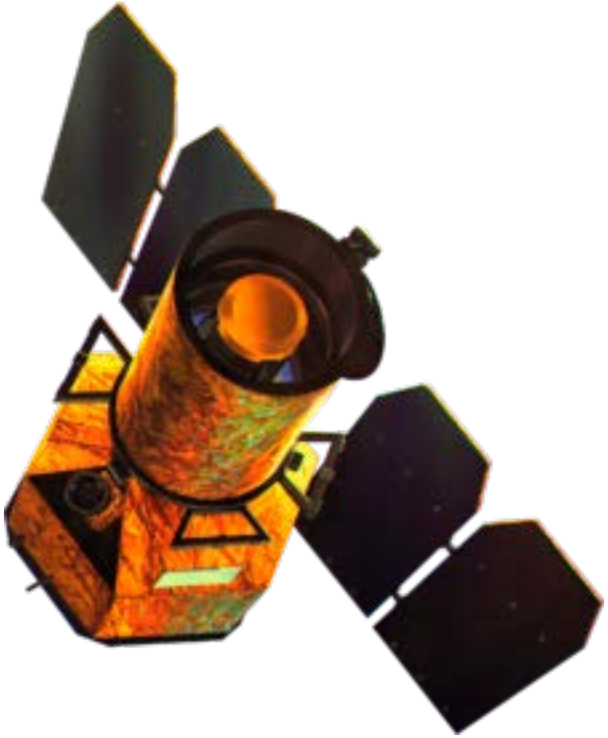
SOFIA



Spitzer

- Infrared light telescopes operate like visible-light telescopes but need to be above atmosphere to see all wavelengths.

Ultraviolet Telescopes



GALEX

GALEX image of spiral galaxy M81

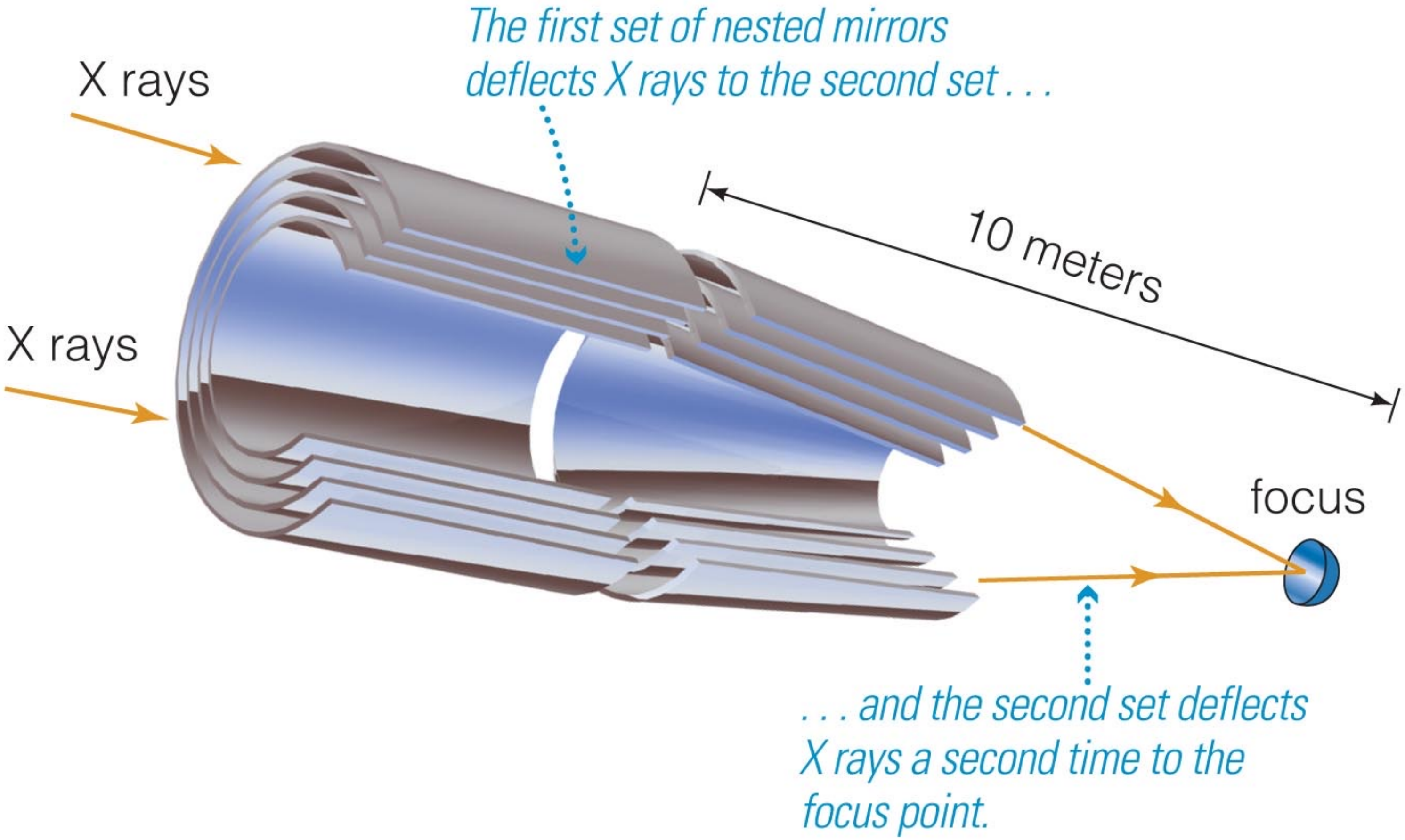
- Ultraviolet light telescopes operate like visible-light telescopes but need to be above atmosphere to see all wavelengths.

X-Ray Telescopes

Chandra X-Ray Observatory

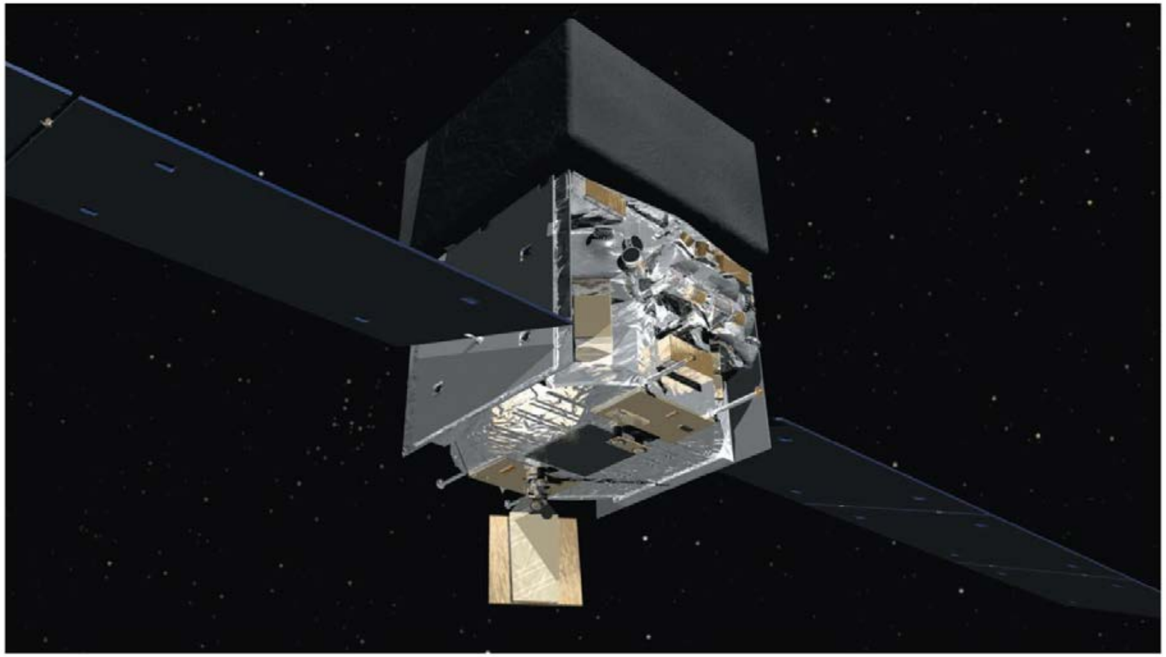
- X-ray telescopes also need to be above the atmosphere.

X-Ray Telescopes



- Focusing of X-rays requires special mirrors.
- Mirrors are arranged to focus X-ray photons through grazing bounces off the surface.

Gamma-Ray Telescopes

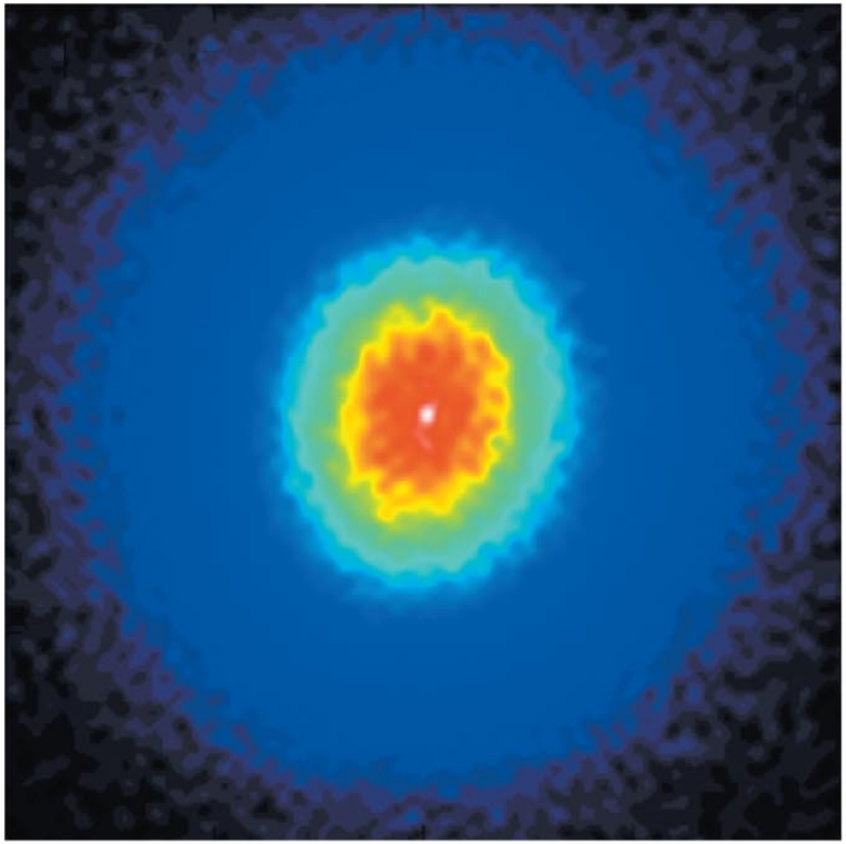


Fermi Gamma-Ray Observatory

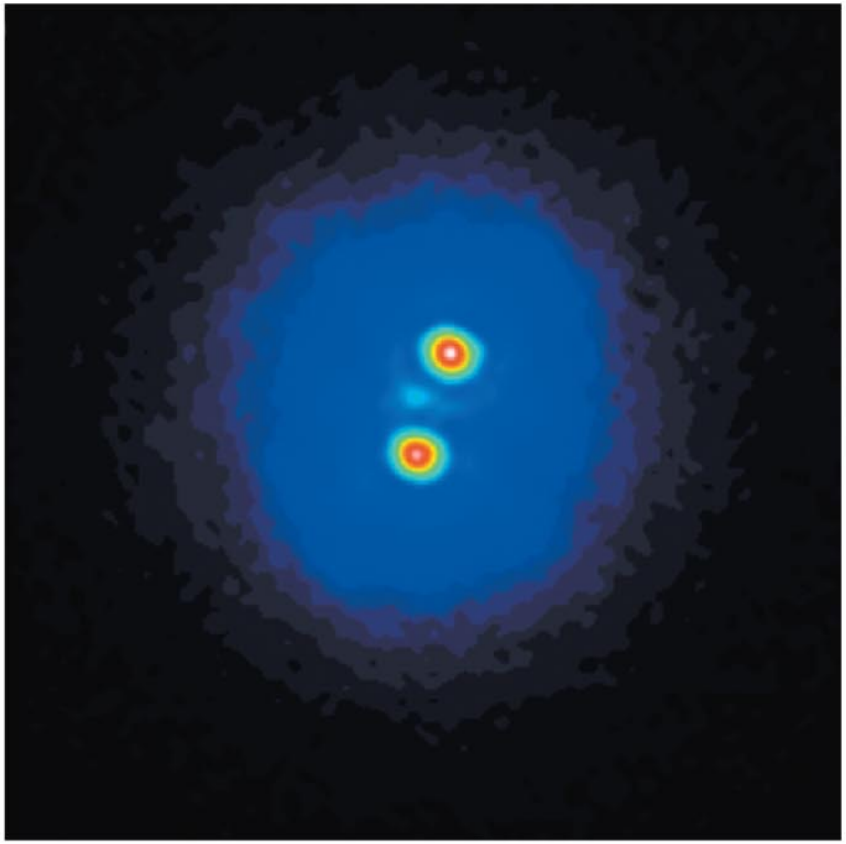
- Gamma-ray telescopes also need to be in space.
- Focusing gamma rays is extremely difficult.

EXTRA SLIDES

Adaptive Optics



Without adaptive optics

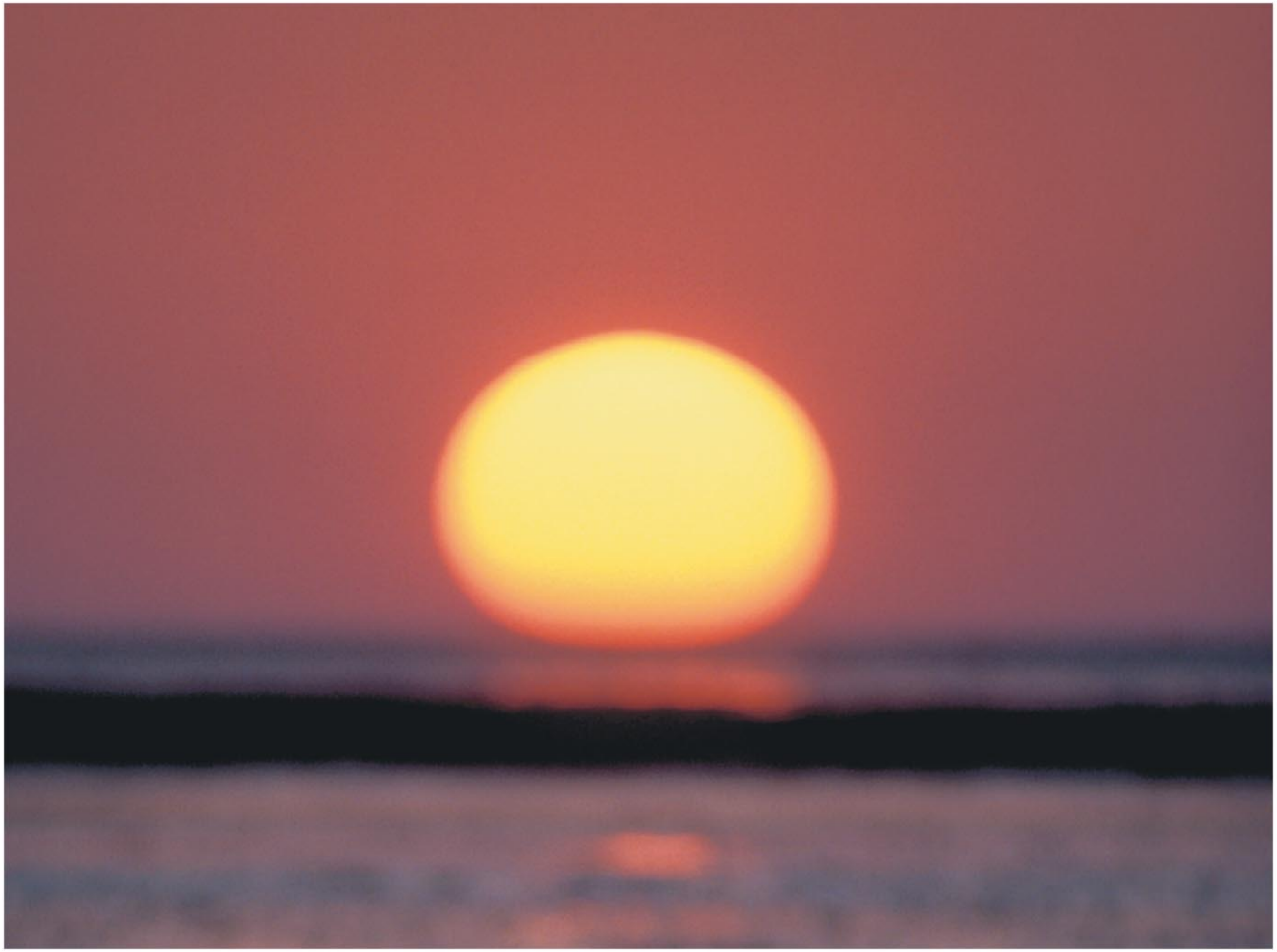


With adaptive optics

- Rapidly changing the shape of a telescope's mirror compensates for some of the effects of turbulence.

[redacted]

Example: Refraction at Sunset



- Sun appears distorted at sunset because of how light bends in Earth's atmosphere.

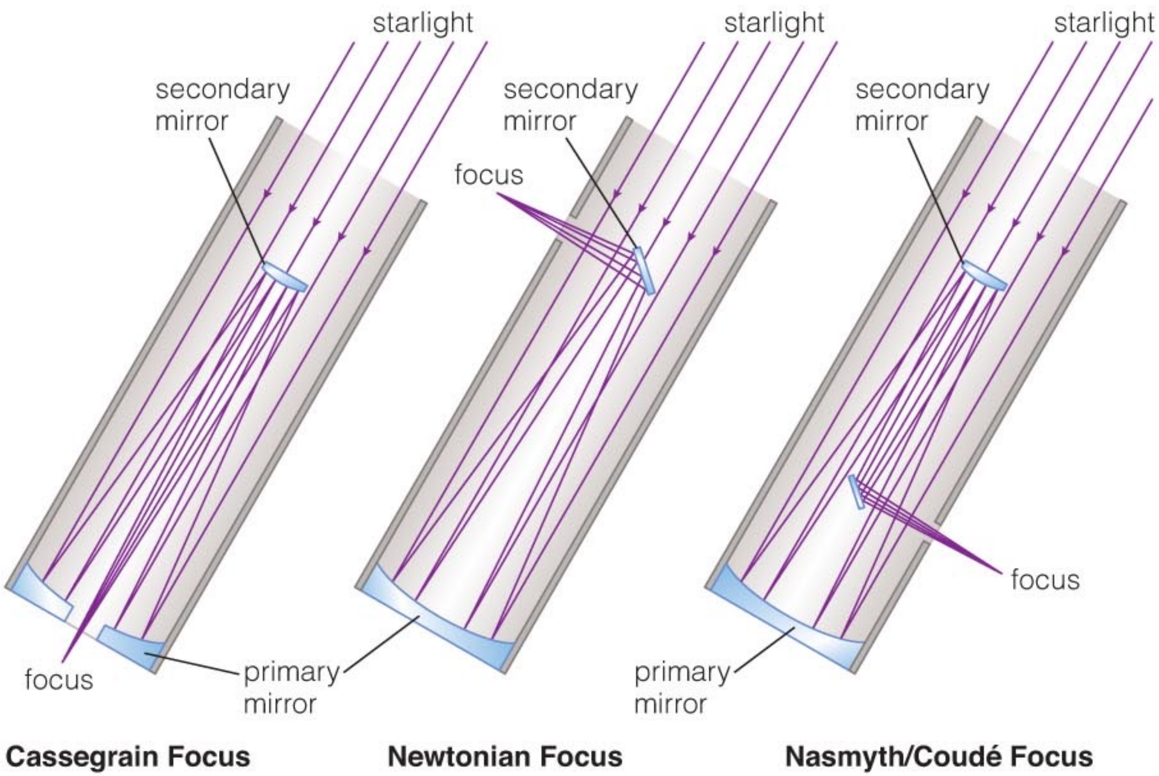
Total Lunar Eclipse of January 2019

The observation was made with the CofC 24 inch CDK PlaneWave telescope and an Apogee Aspen CG16M CCD.

The image of the eclipsed moon is a composite of 3 filters in the visible range:
B (blue), G (green) and R (red).

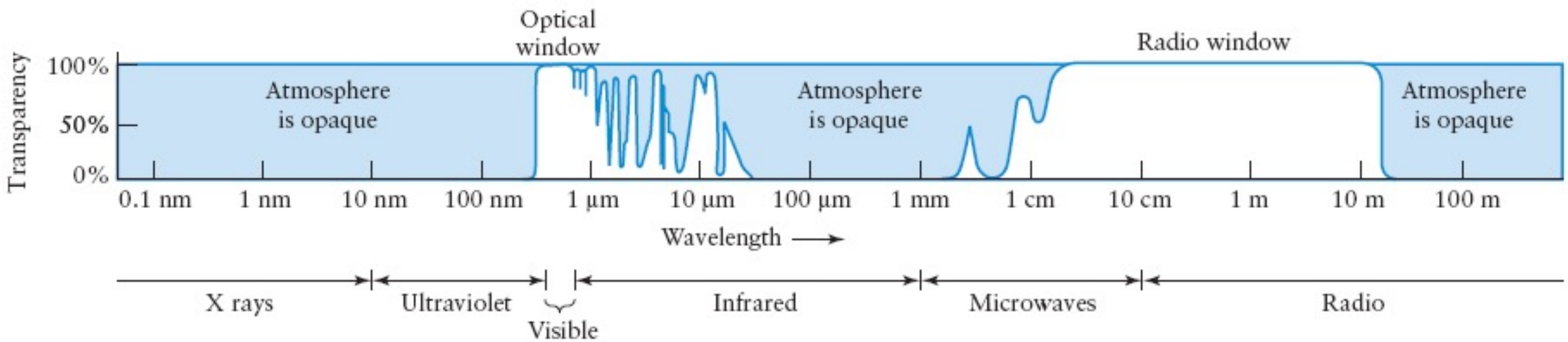
The exposure times were
3x1sec B / 3x1sec G / 3x1sec R

Reflecting Telescope



- Reflecting telescopes can have much greater diameters than refracting telescopes.
- Most modern telescopes are reflectors.

Transmission in Atmosphere



This graph shows the percentage of radiation that can penetrate the Earth's atmosphere at different wavelengths.

At wavelengths less than about 290 nm photons are absorbed by **atmospheric oxygen and nitrogen.**

Between the optical and radio windows photons are absorbed **by water vapor and carbon dioxide.**

At wavelengths longer than about 20 m, photons are reflected back into space by **ionized gases in the upper atmosphere**.