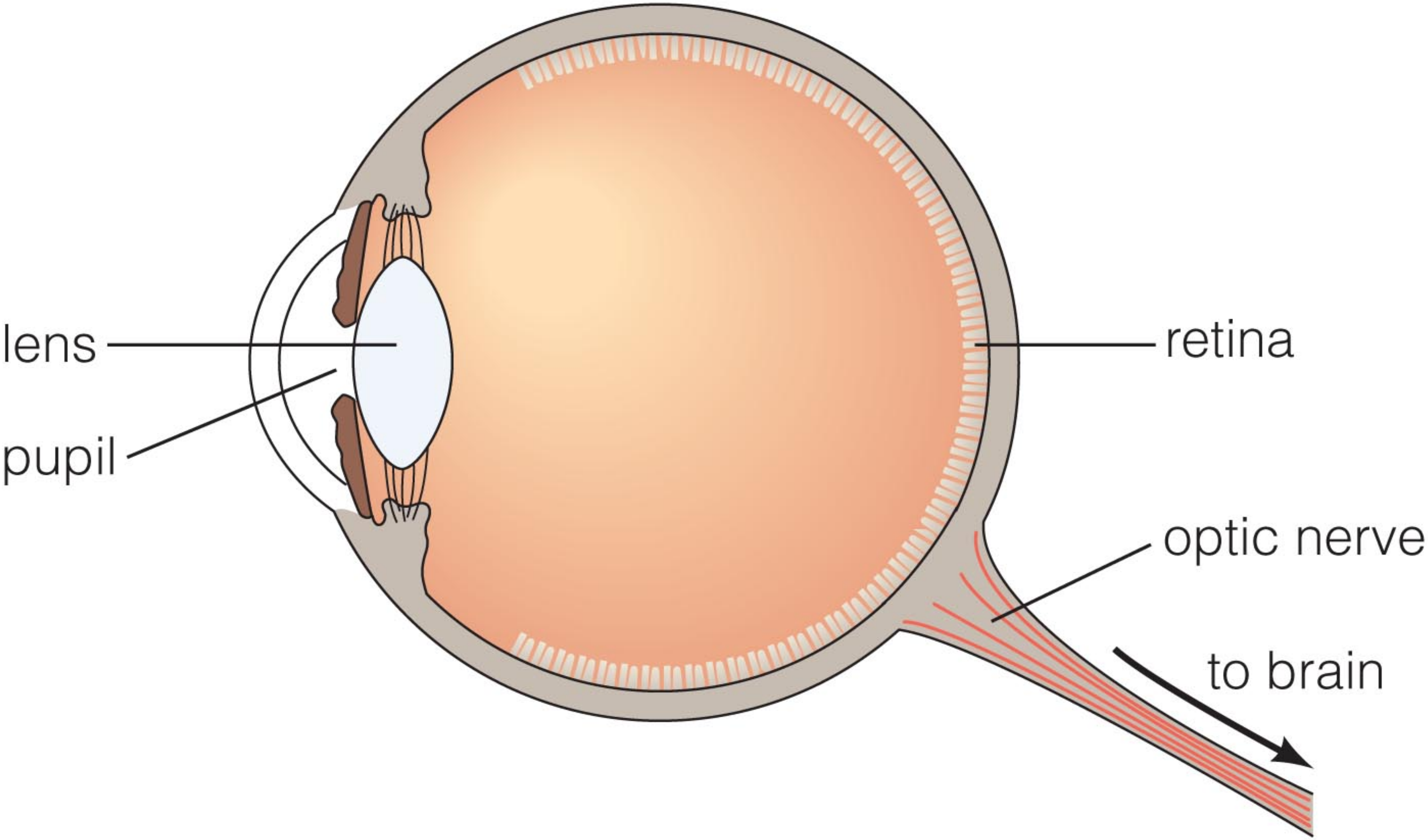
Chapter 6: Telescopes Portals of Discovery

Telescopes: Portals of Discovery

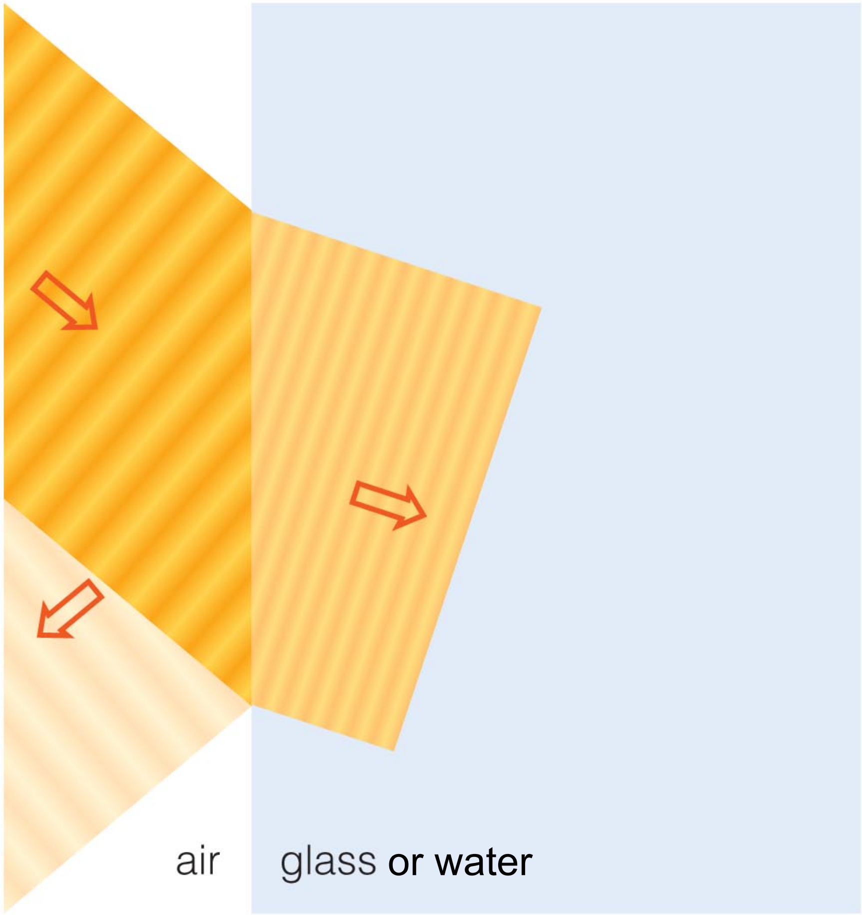
6.1 Eyes and Cameras: Everyday Light Sensors – Visible wavelengths

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

The Eye



Refraction



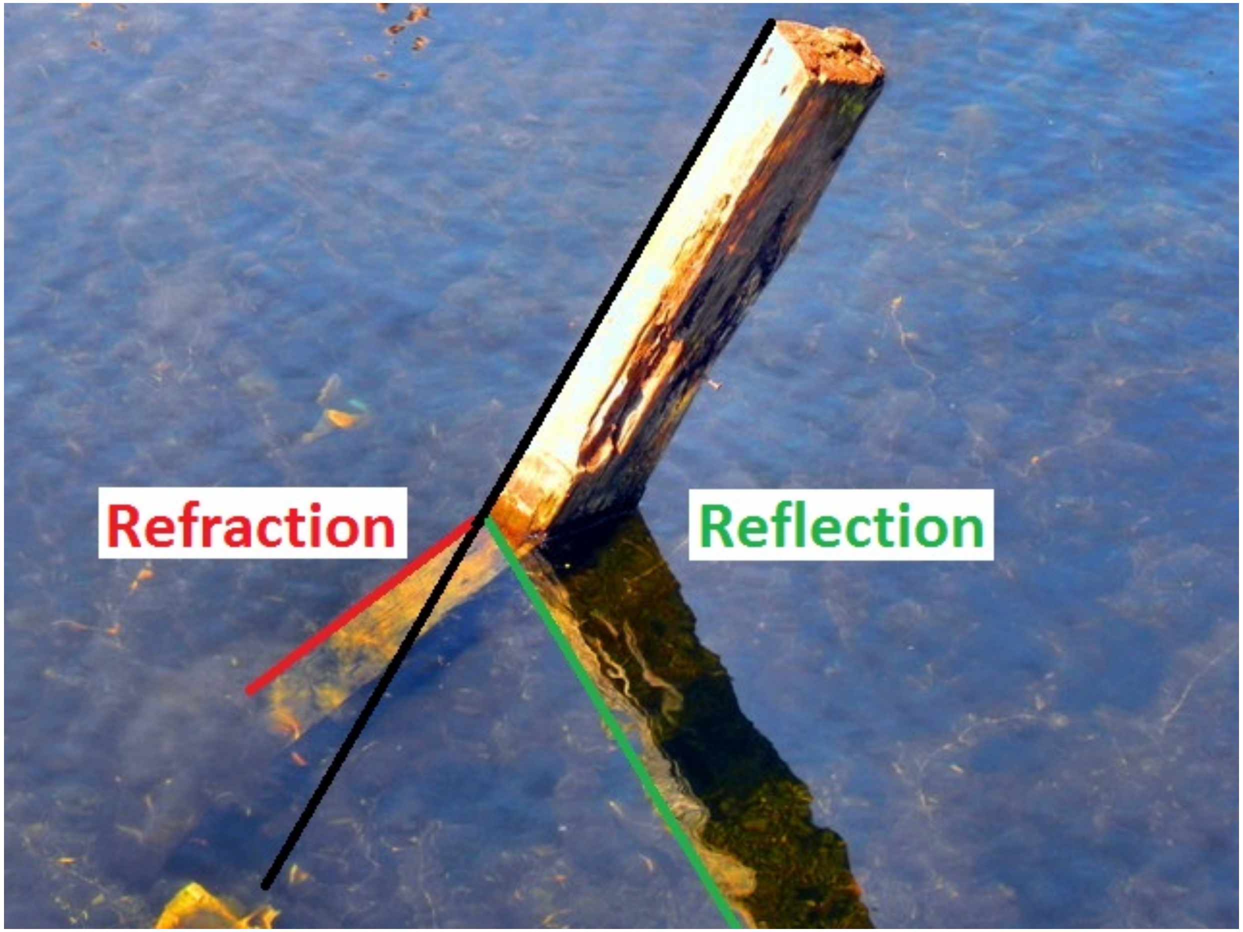
- Refraction is the bending of light when it passes from one medium into another.
- Your eye uses refraction to focus light.

Example: Refraction in a glass of water

- The pencil appears bended in the water, due to refraction

Source: Lykeio Neapolis

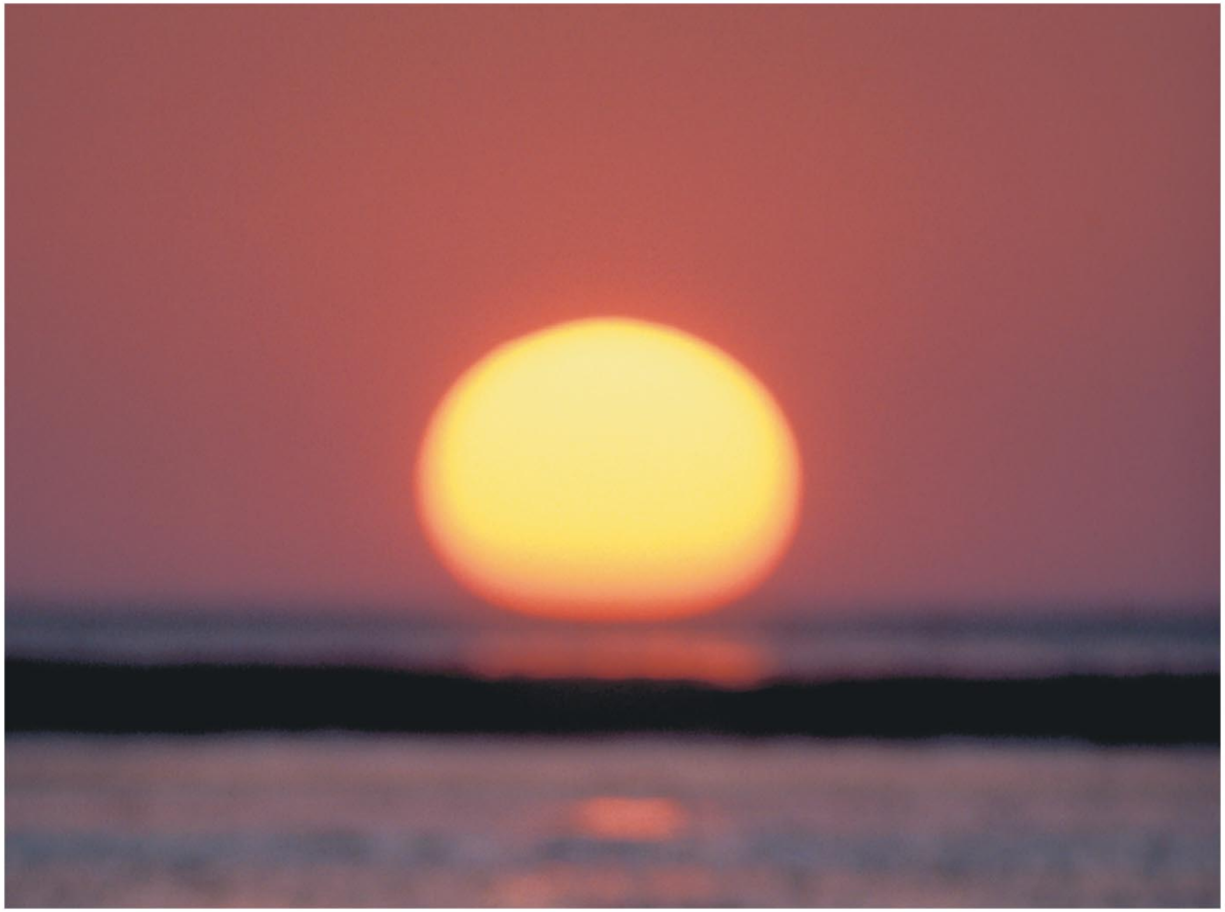
Example: Refraction vs. Reflection



- Refraction and reflection may end up in a situation like this

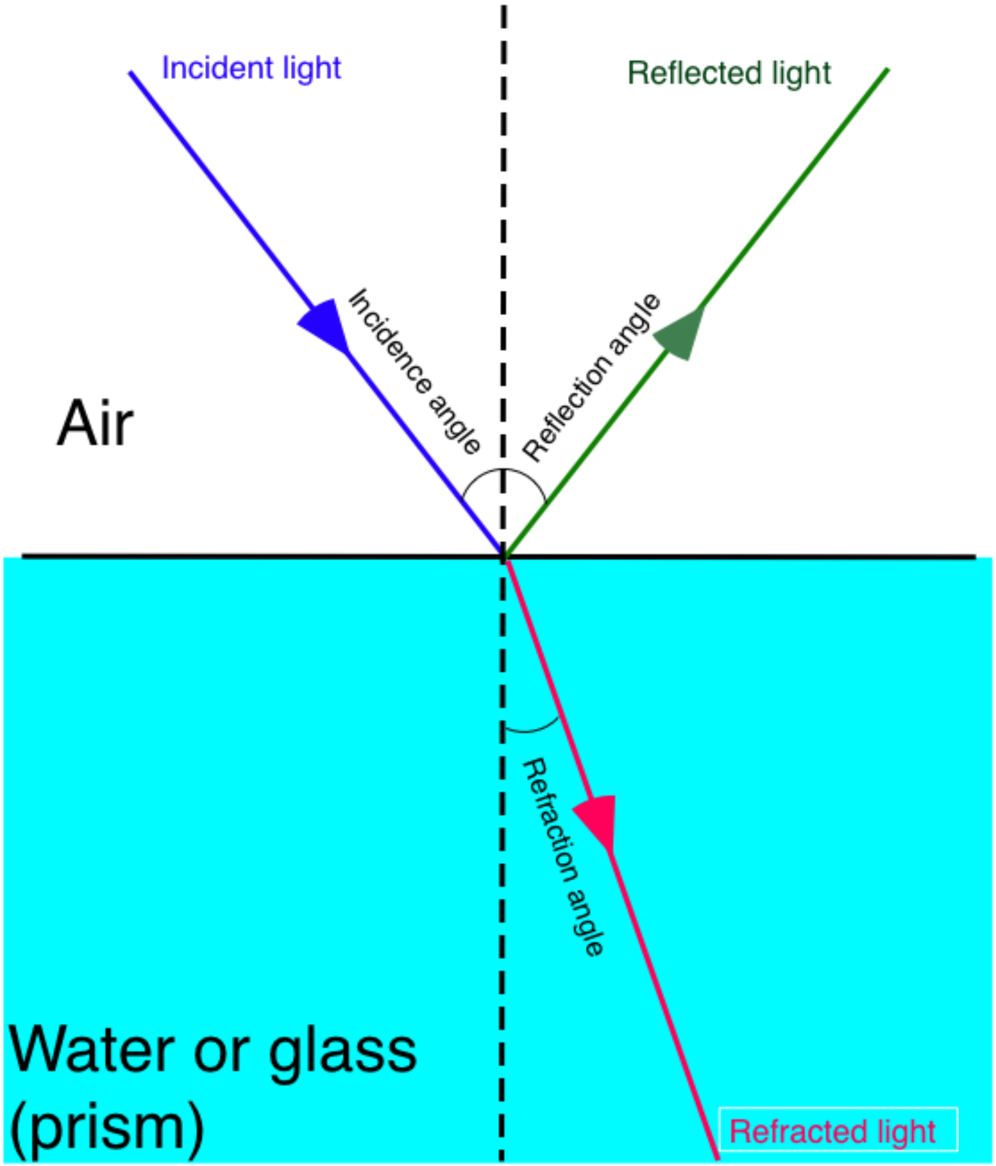
Source: Unreal Engine Forums

Example: Refraction at Sunset



- Sun appears distorted at sunset because light bends in Earth's atmosphere from higher to lower layers

A geometrical explanation

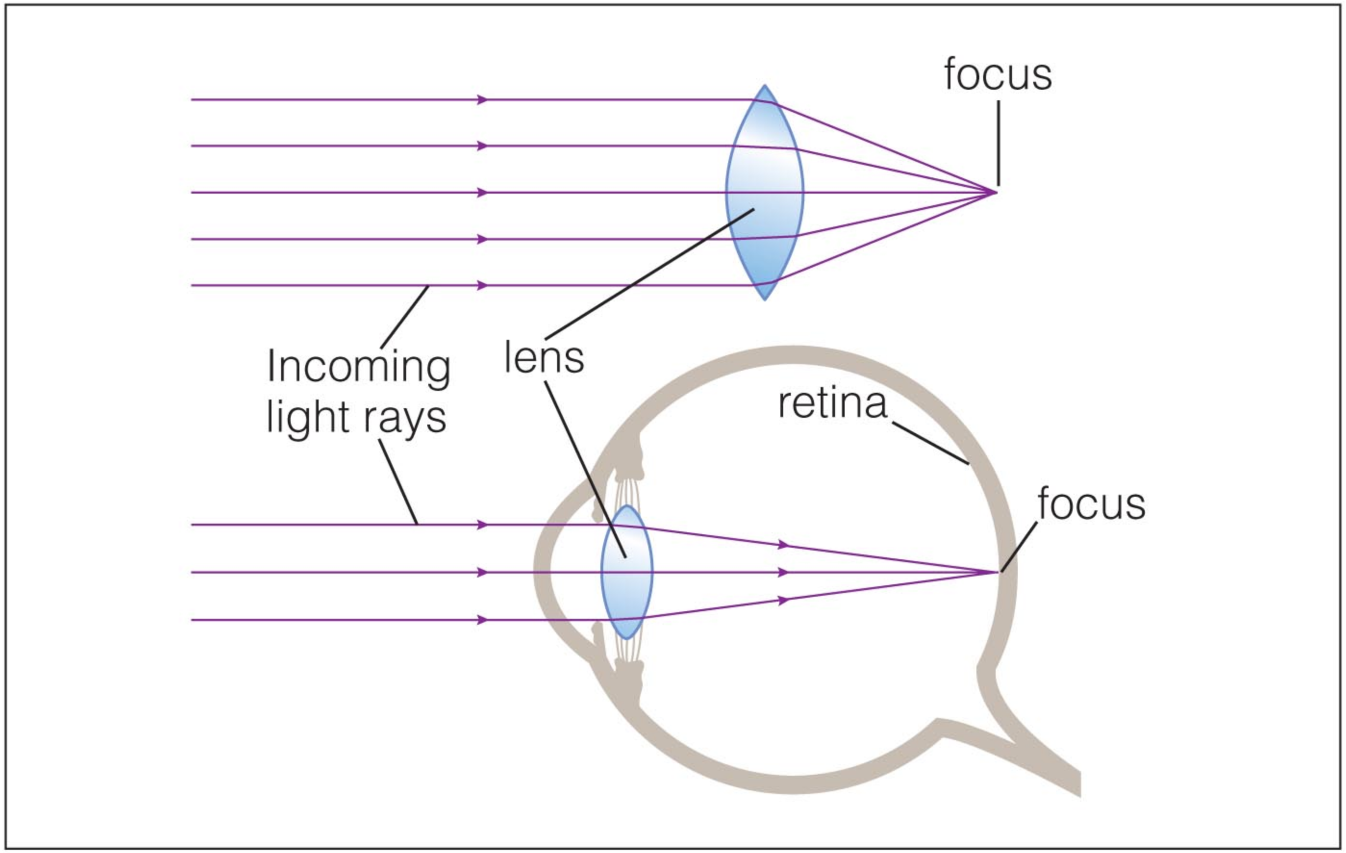


Incidence angle = Reflection angle

Incidence angle ≠ Refraction angle

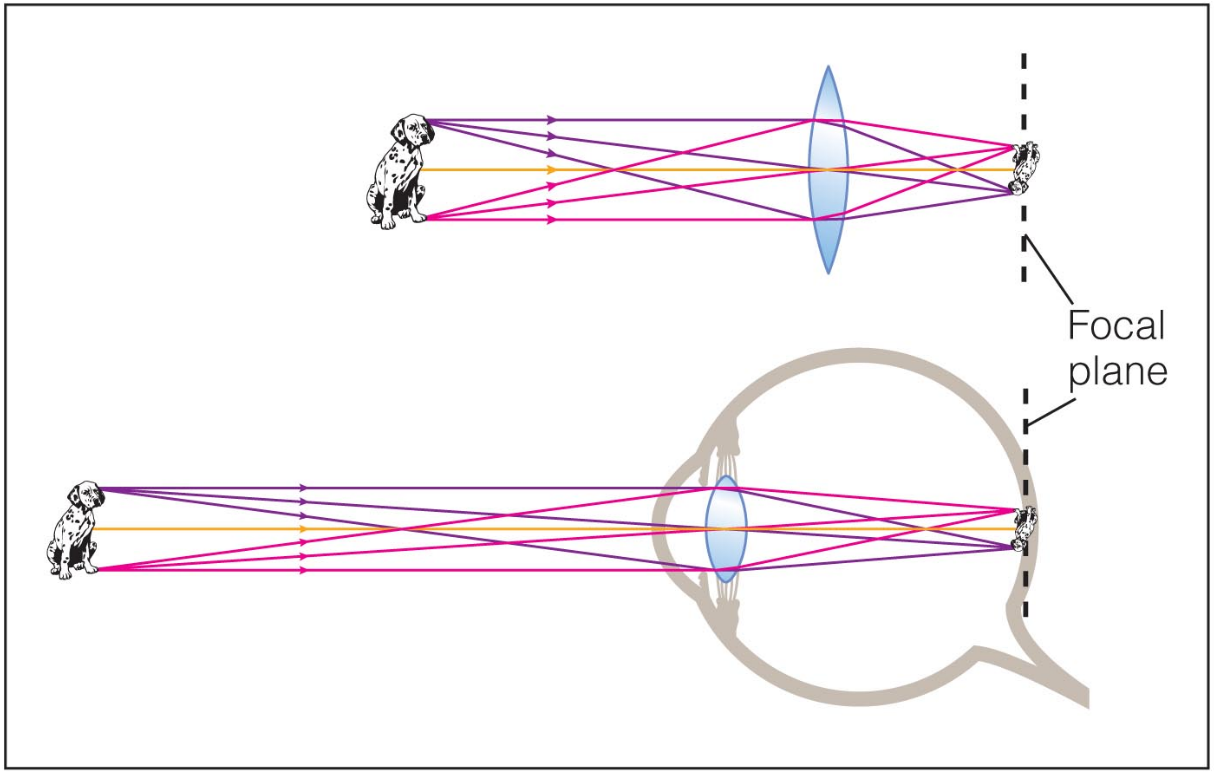
- While the incidence angle is equal to the reflection angle, the refraction angle is different
- How different is the refraction angle depends on the properties of the medium (water, glass, other fluid)

Focusing Light



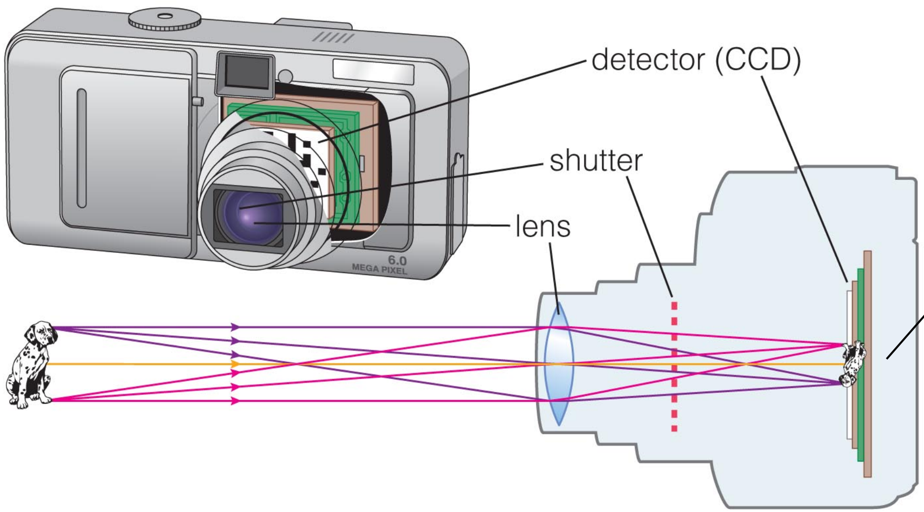
- Refraction can cause parallel light rays to converge to a focus.

Image Formation



- The focal plane is where light from different directions comes into focus.
- The image behind a single (convex) lens is actually upside-down!

Recording Images

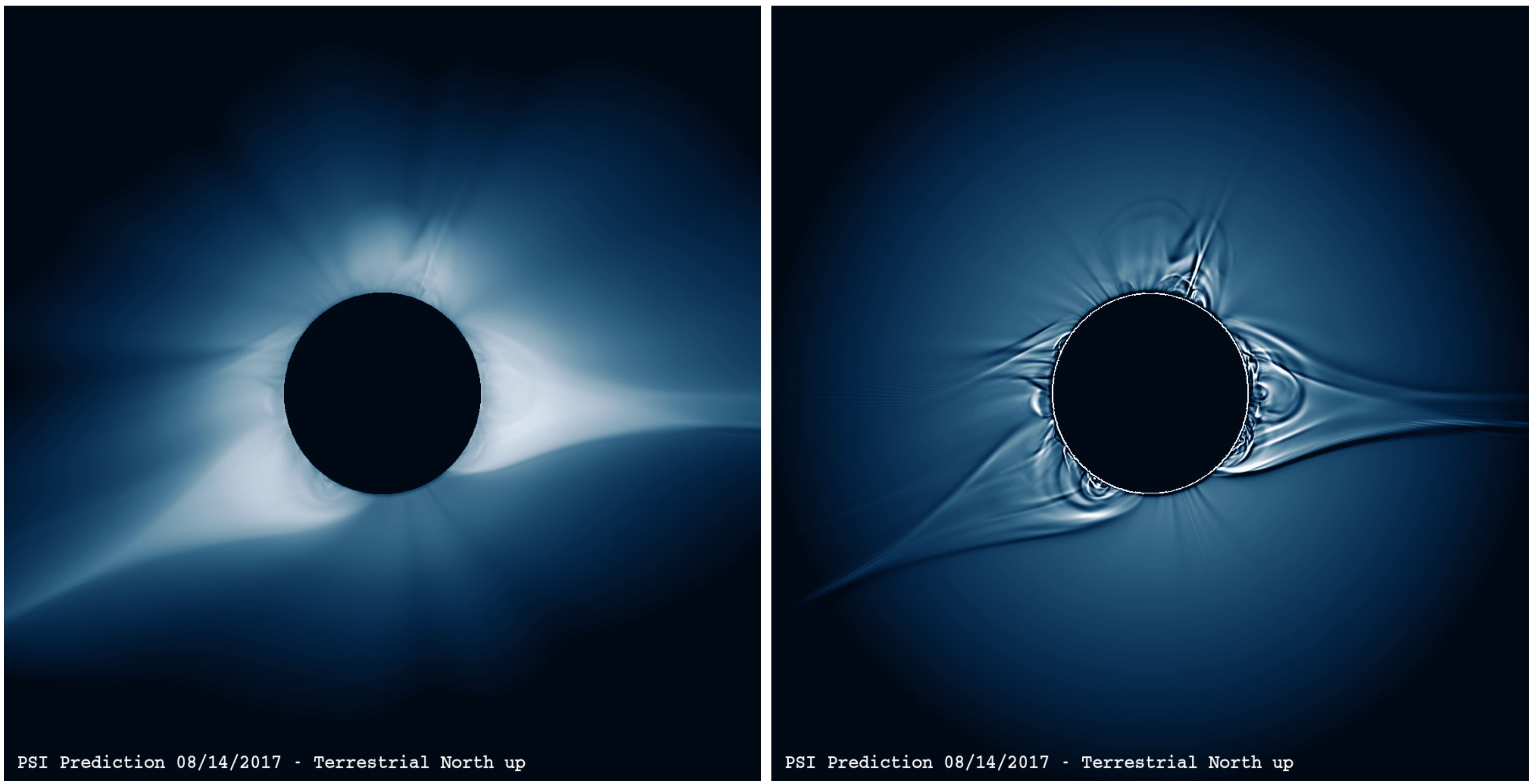


Digital cameras detect light with charge-coupled devices (CCDs).

- 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.

Image Processing

- Astronomers often use computer software to combine, sharpen, or refine images.



A predicted solar eclipse, unsharpened (left) and sharpened (right)

What have we learned?

- **How do eyes and cameras work?**
  - Eyes use refraction to bend parallel light rays so that they form an image.
  - The image is in focus if the focal plane is at the retina.
  - Cameras focus light like your eye and record the image with a detector.

6.2 Telescopes: Giant Eyes

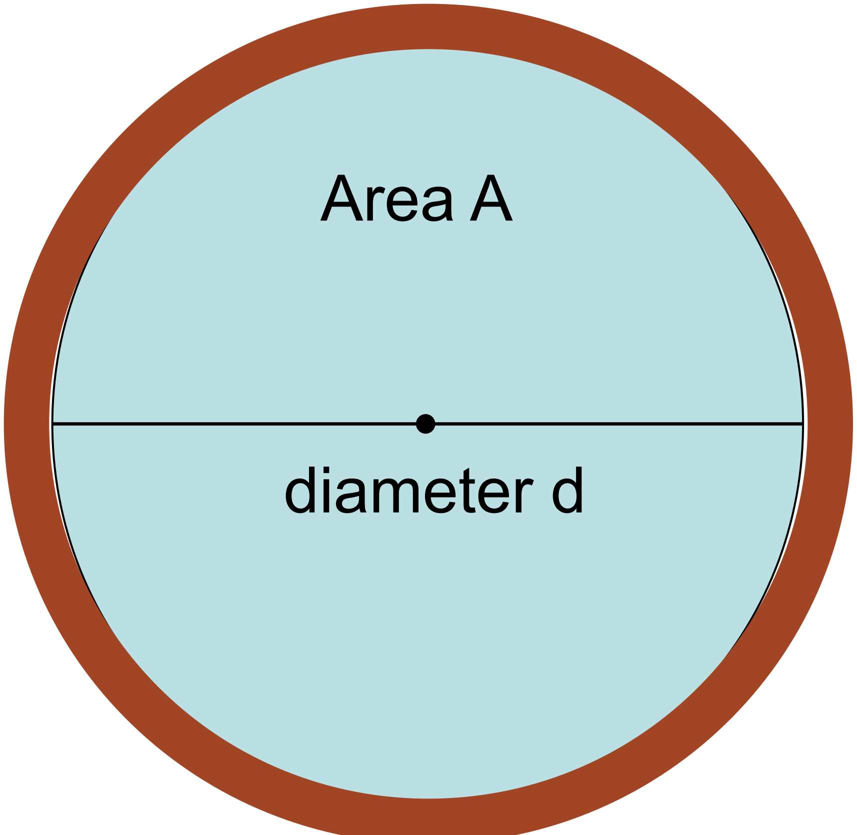
- Our goals for learning:
  - **What are the two most important properties of a telescope?**
  - **What are the two basic designs of telescopes?**
  - **What do astronomers do with telescopes?**

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:** Telescopes that are larger are capable of taking images with greater detail.

Light-Collecting Area

- A telescope's diameter tells us its light-collecting area: $A = \pi(d/2)^2$
- The largest optical telescopes currently in use have a diameter of about 10 meters.



$A = \pi\ (d\ /\ 2)^2$

$\pi = 3.14159\ldots$

Thought Question

How does the collecting area of a 10-meter telescope compare with that of a 2-meter telescope?

a) It's 5 times greater.
b) It's 10 times greater.
c) It's 25 times greater.

Thought Question

How does the collecting area of a 10-meter diameter telescope compare with that of a 2-meter diameter telescope?

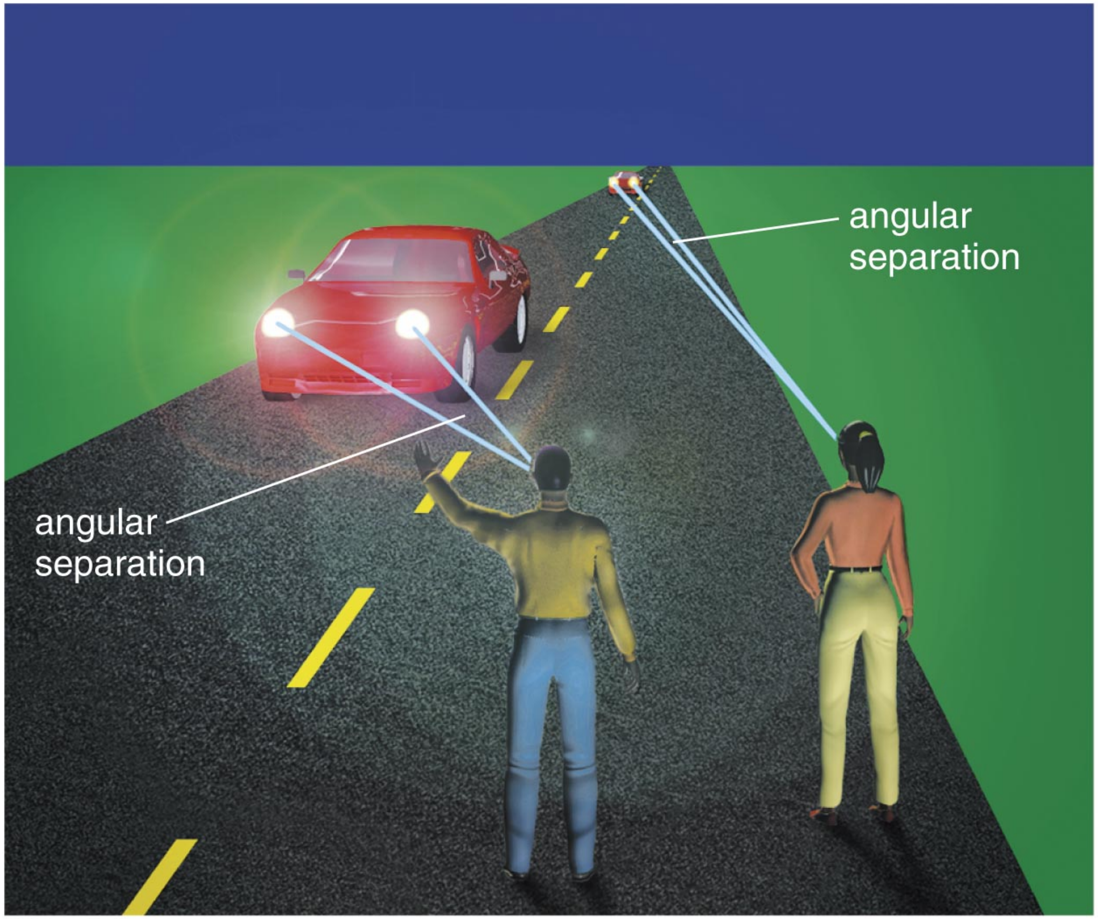
a) It's 5 times greater.
b) It's 10 times greater.
c) **It's 25 times greater.**

$$A_1 = \pi(5d/2)^2$$
$$A_2 = \pi(d/2)^2$$

$$\frac{A_1}{A_2} = \frac{\cancel{\pi}}{\cancel{\pi}} \frac{(5\cancel{d}/\cancel{2})^2}{(\cancel{d}/\cancel{2})^2} = 5^2 = 25$$

Angular Resolution

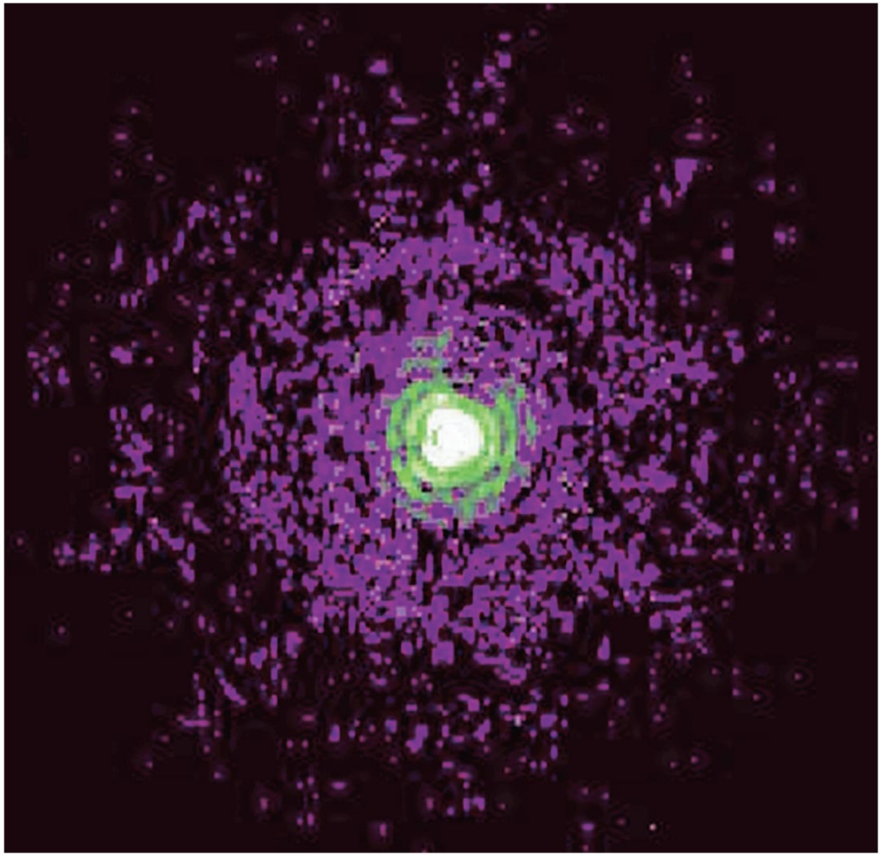
- The *minimum* angular separation that the telescope can distinguish



Angular Resolution

- Ultimate limit to resolution comes from interference of light waves within a telescope.
- Larger telescopes are capable of greater resolution because there's less interference.

Angular Resolution



- Close-up of a star from the Hubble Space Telescope

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

What are the two basic designs of telescopes?

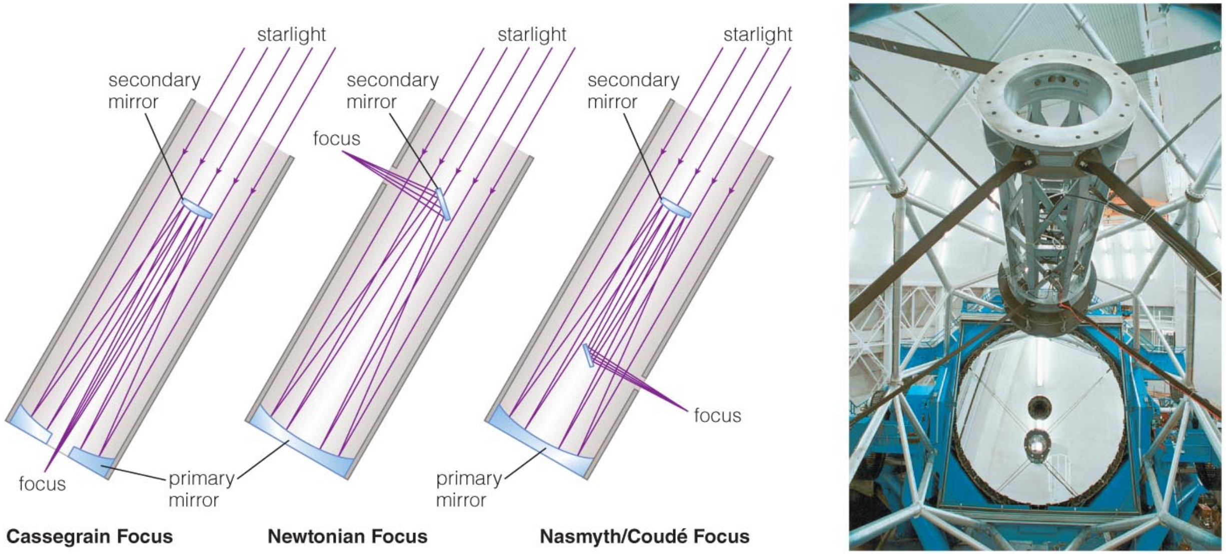
- **Refracting telescope:** focuses light with lenses
- **Reflecting telescope:** focuses light with mirrors

Refracting Telescope

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

So, refracting telescopes are long!

Reflecting Telescope



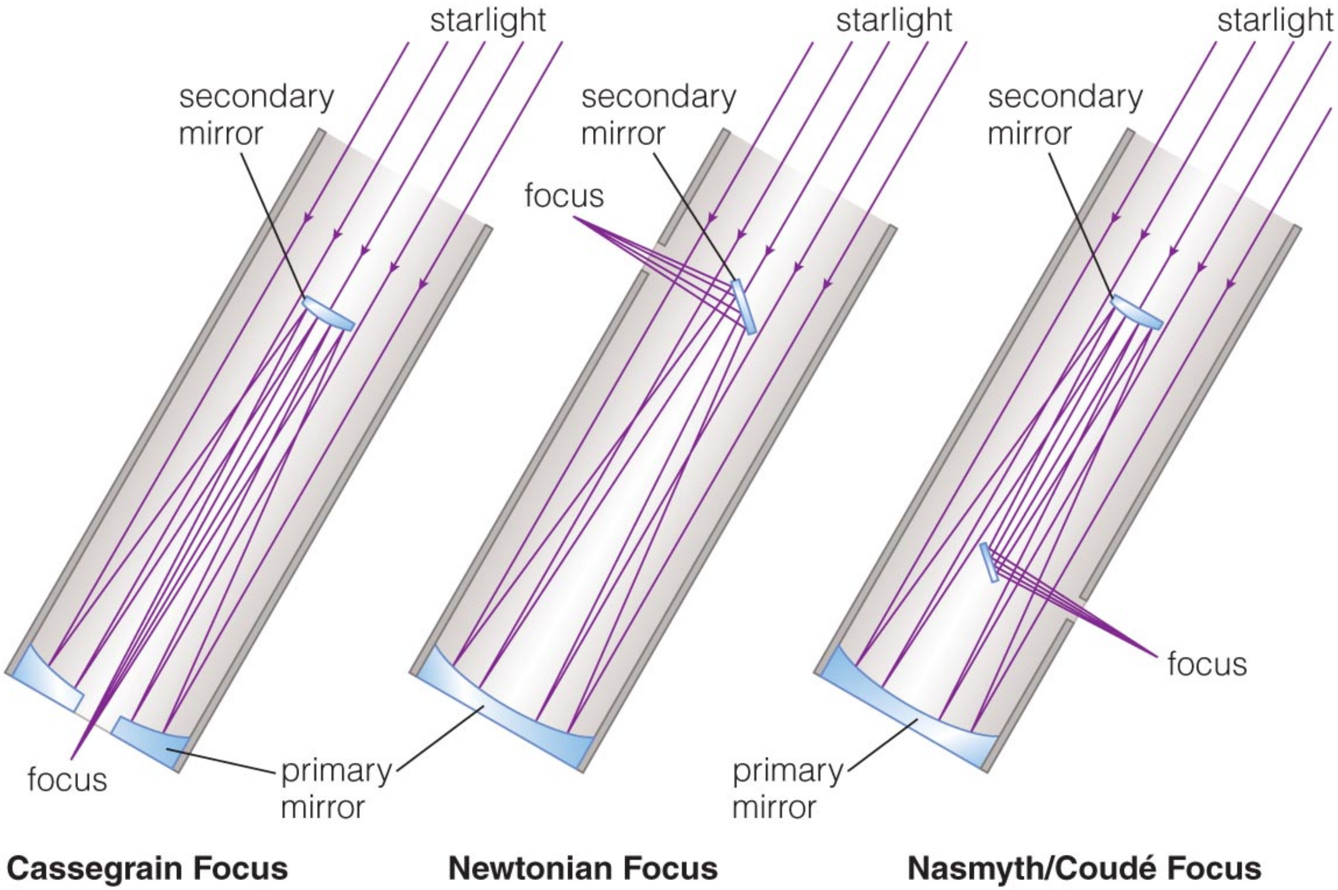
a Three variations on the basic design of a reflecting telescope. In all cases, a reflecting telescope collects light with a precisely curved primary mirror that reflects light back upward to the secondary mirror. In the *Cassegrain* design, the secondary mirror reflects the light through a hole in the primary mirror, so that the light can be observed with cameras or instruments beneath the telescope. In the *Newtonian* design, the secondary mirror reflects the light out to the side of the telescope. In the *Nasmyth* and *Coudé* designs, a third mirror is used to reflect light out the side but lower down than in the Newtonian design.

b The Gemini North telescope, located on the summit of Mauna Kea, Hawaii, is a reflecting telescope with the Cassegrain design. The primary mirror, visible at the bottom of the large lattice tube, is 8 meters in diameter. The secondary mirror, located in the smaller central lattice, reflects light back down through the hole visible in the center of the primary mirror.

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

So, reflecting telescopes are wide!

Designs for Reflecting Telescopes



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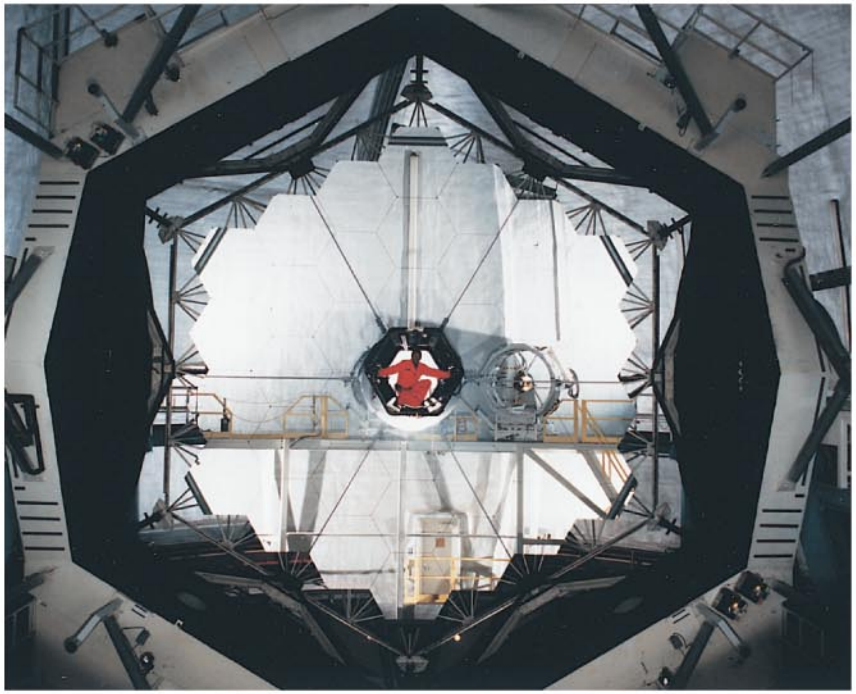
Mirrors in Reflecting Telescopes

Twin Keck telescopes on Mauna Kea in Hawaii

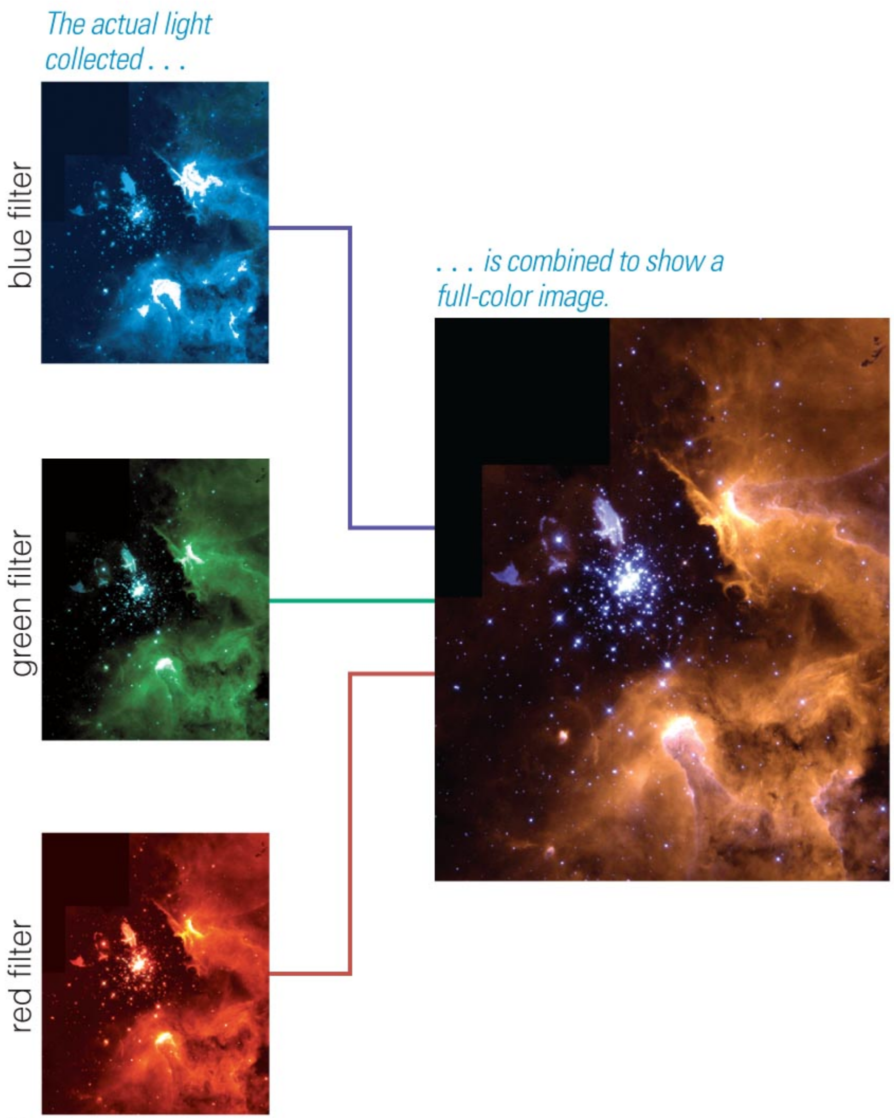


Segmented 10-meter mirror of a Keck telescope

What do astronomers do with telescopes?

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

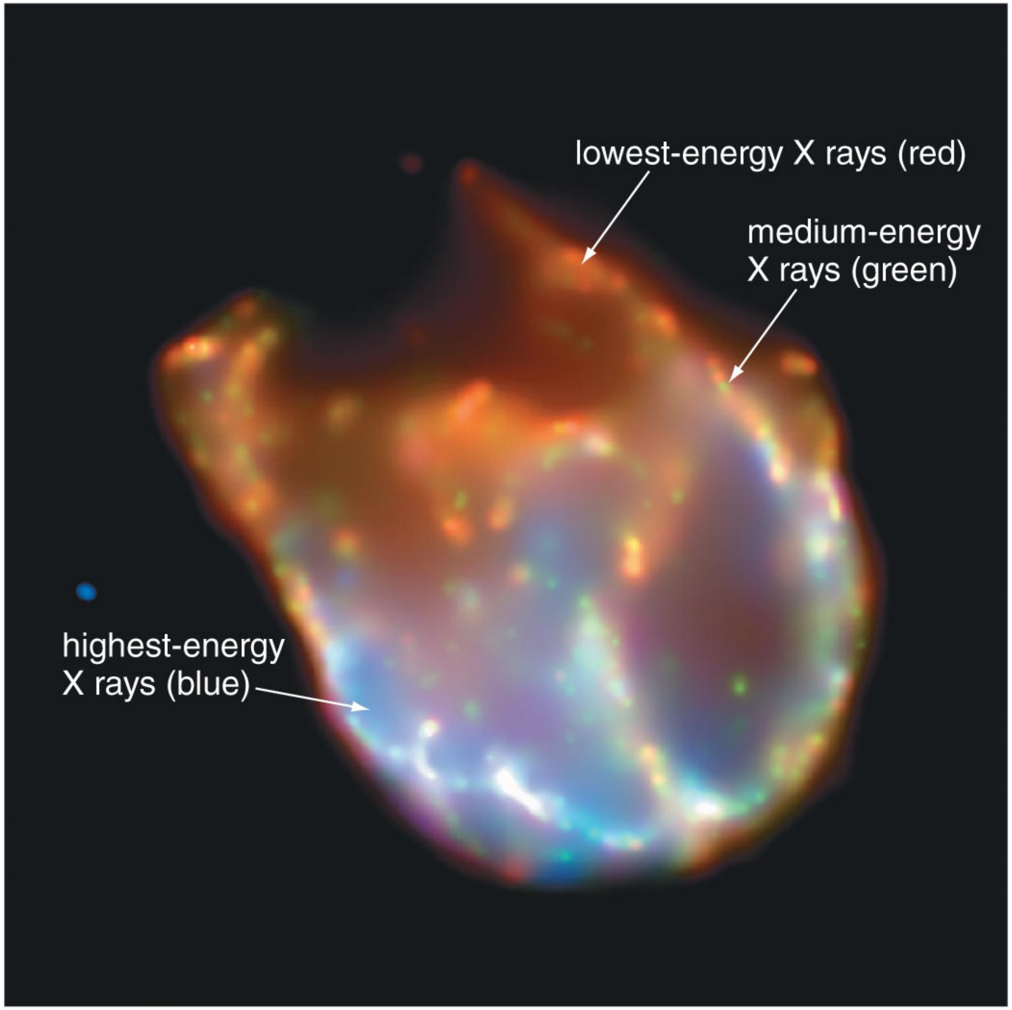
Imaging



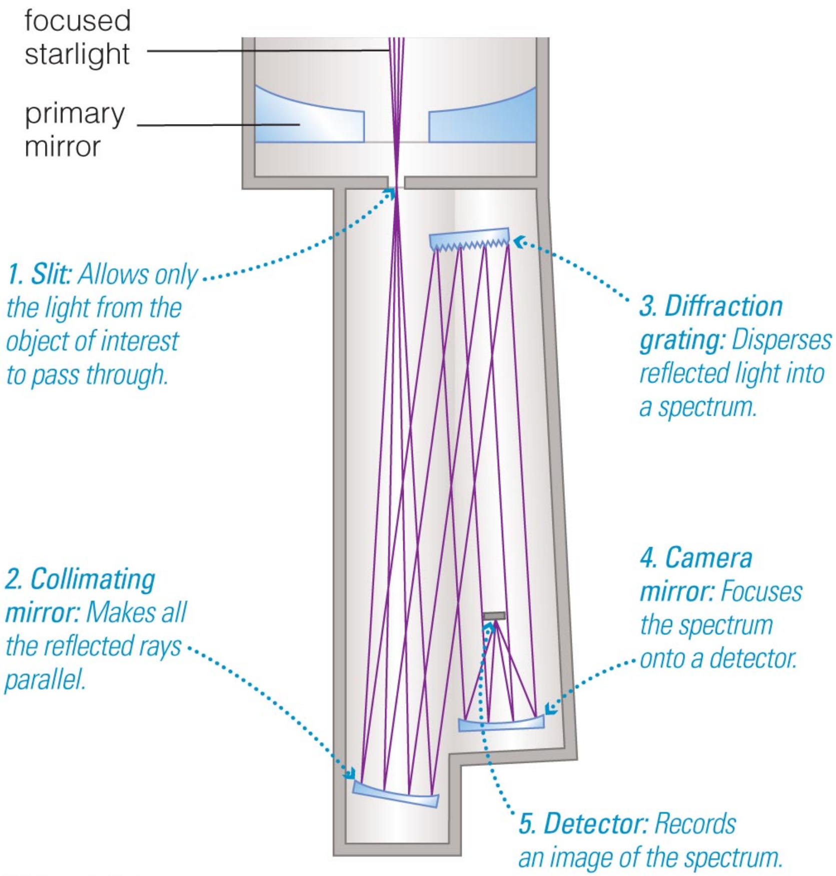
- Astronomical detectors generally record only one color of light at a time.
- Several images must be combined to make full-color pictures.

Imaging

- Astronomical detectors can record forms of light our eyes can't see.
- Color is sometimes used to represent different energies of non-visible light: this is artificial, however, as colors do not exist beyond visible light

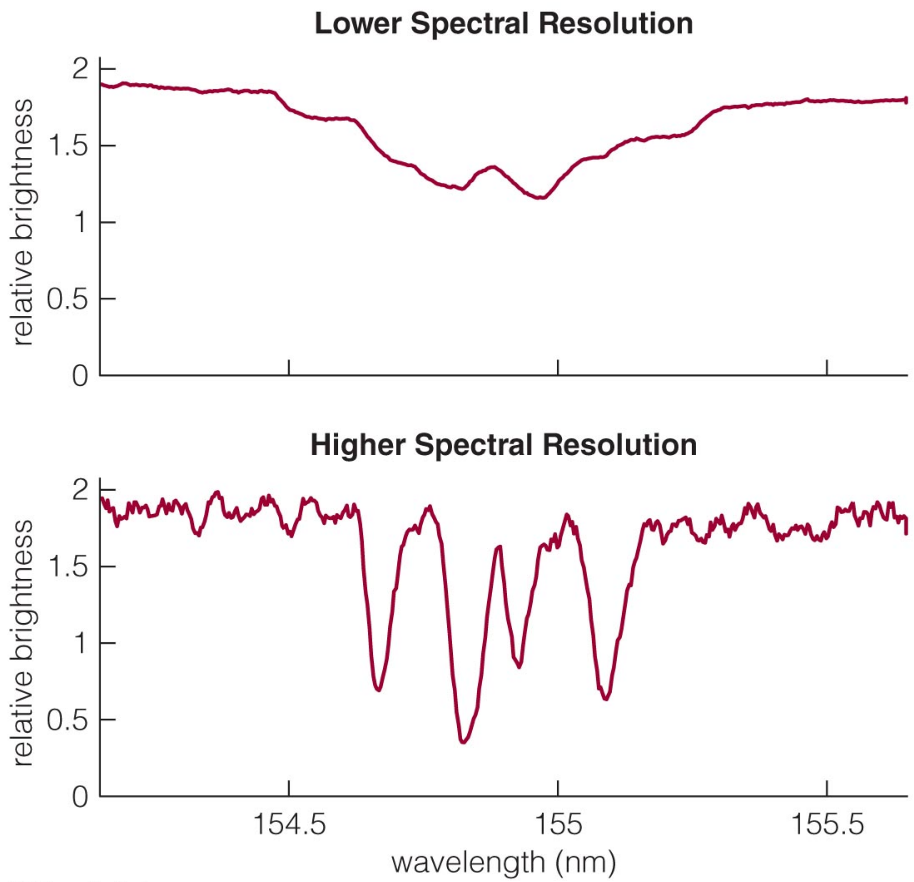


Spectroscopy



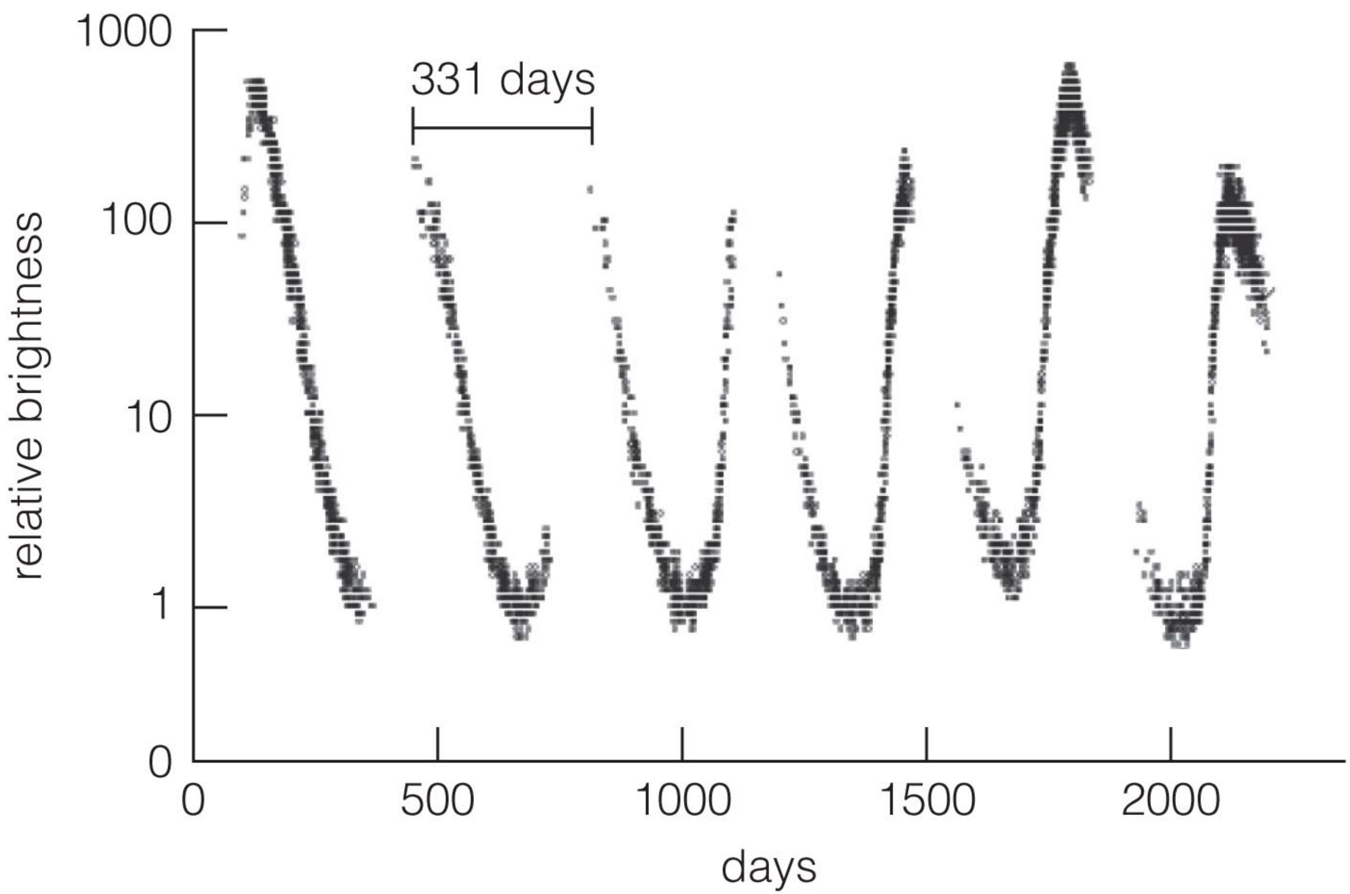
- A spectrograph separates the different wavelengths of light before they hit the detector.

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.

What have we learned?

- **What are the two most important properties of a telescope?**
  - Collecting area determines how much light a telescope can gather.
  - Angular resolution is the smallest angular separation a telescope can distinguish.
  - Angular resolution is restricted by the diffraction limit of a telescope
- **What are the two basic designs of telescopes?**
  - <u>Refracting</u> telescopes focus light with lenses.
  - <u>Reflecting</u> telescopes focus light with mirrors.
  - The vast majority of professional telescopes are reflectors.

What have we learned?

- **What do astronomers do with telescopes?**
  - Imaging
  - Spectroscopy
  - Time Monitoring

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?**

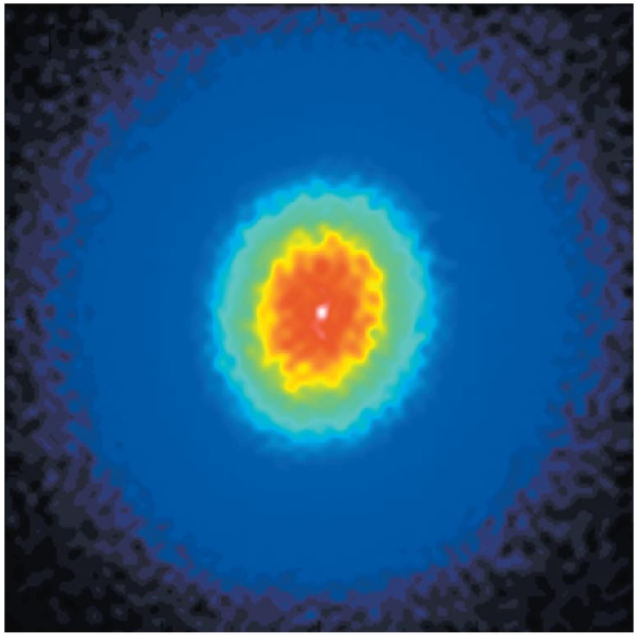
How does Earth's atmosphere affect ground-based observations?

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

Light Pollution

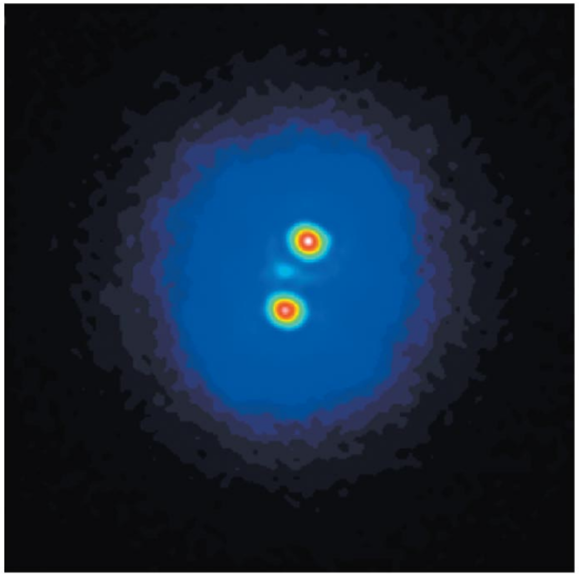
- Scattering of human-made light in the atmosphere is a growing problem for astronomy.

Adaptive Optics



a Atmospheric blurring makes this ground-based image of a double star look like that of a single star.

Without adaptive optics



b When the same telescope is used with adaptive optics, the two stars can be clearly distinguished. The angular separation between the two stars is 0.28 arcsecond.

With adaptive optics

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

Calm, High, Dark, Dry

- The best observing sites are atop remote mountains.

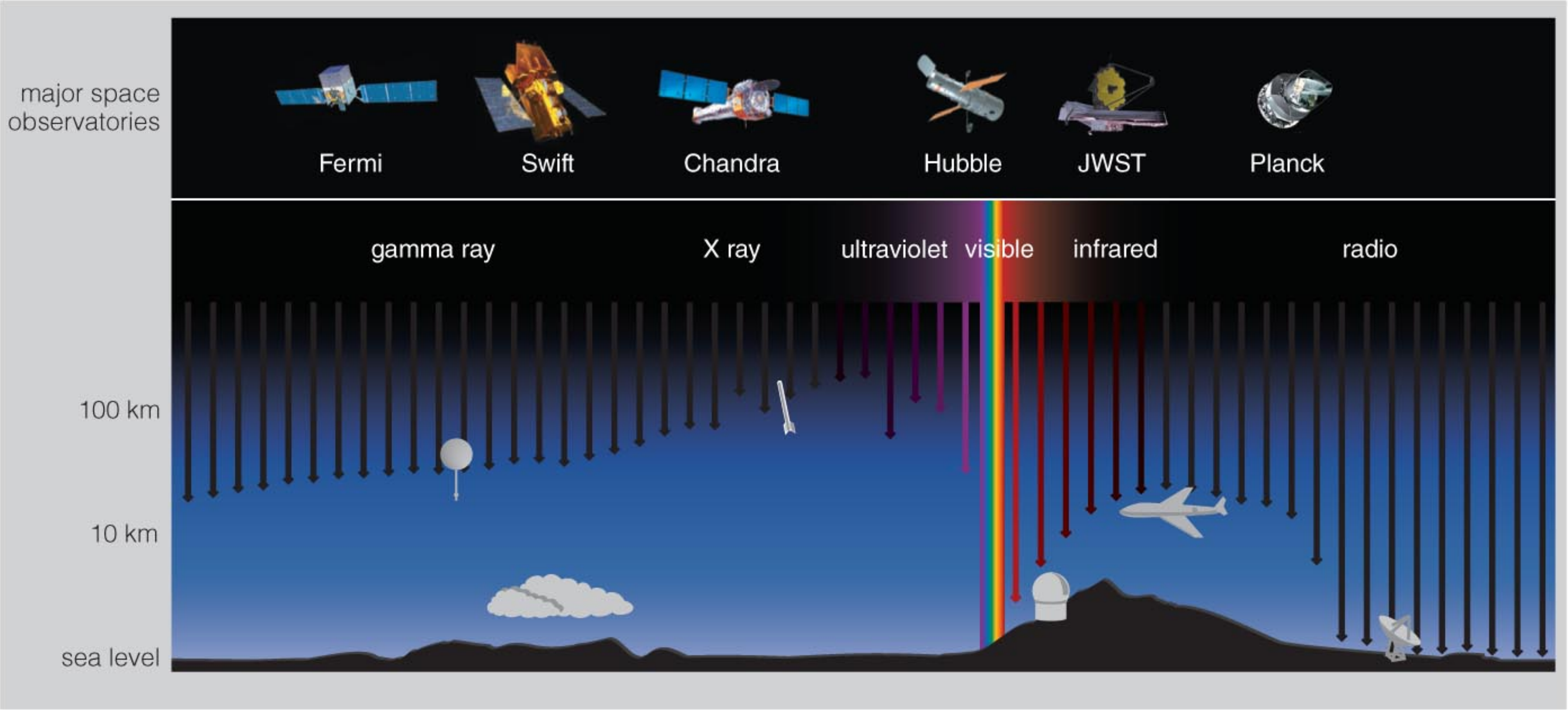
Summit of Mauna Kea, Hawaii

Why do we put telescopes into space?

Why do we put telescopes into space?

A model of Hubble's successor, the James Webb Space Telescope

Transmission through Earth's Atmosphere



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

What have learned?

- **How does Earth's atmosphere affect ground-based observations?**
  - Telescope sites are chosen to minimize the problems of light pollution, atmospheric turbulence, and humid or stormy weather.
- **Why do we put telescopes into space?**
  - Forms of light other than radio and visible do not pass through Earth's atmosphere.
  - Also, much sharper images are possible because there is no turbulence.

6.4 Telescopes Across the Spectrum

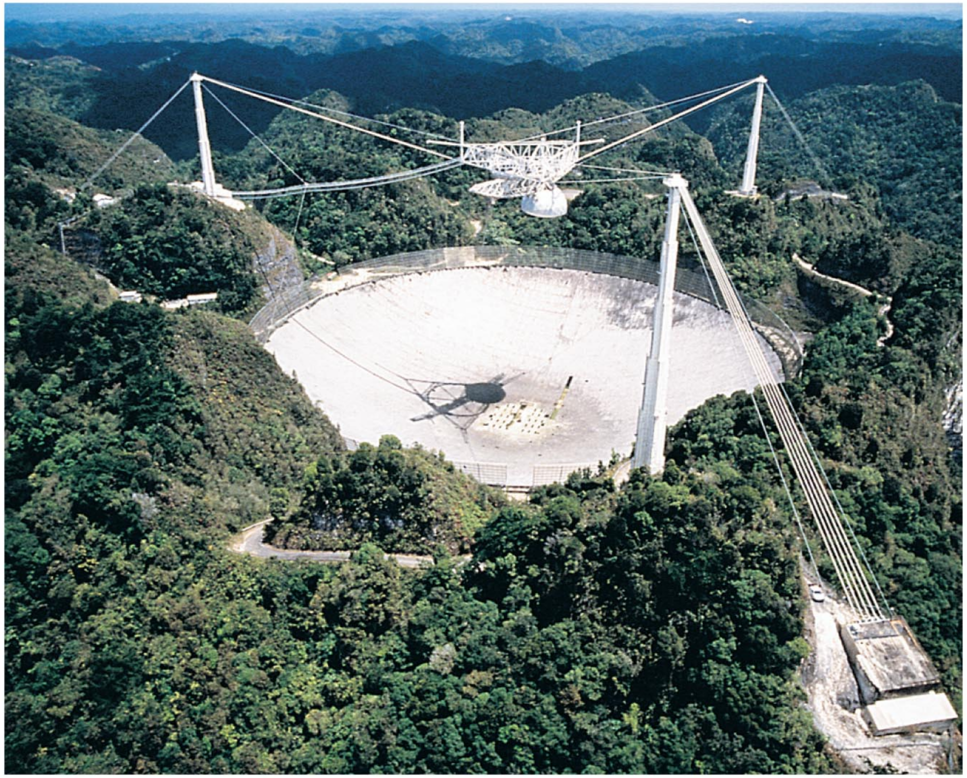
- Our goals for learning:
  - **How do we observe invisible light?**
  - **How can multiple telescopes work together?**

How do we observe invisible light?

- A standard satellite dish is essentially a telescope for observing radio waves.

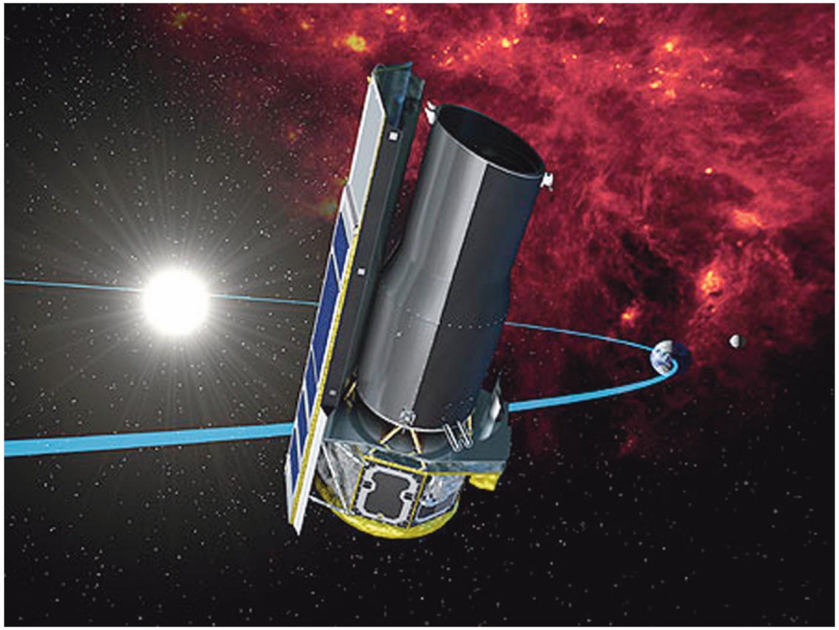
Radio Telescopes

- A radio telescope is like a giant mirror that reflects radio waves to a focus.



Infrared and Ultraviolet Telescopes

SOFIA



Spitzer

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

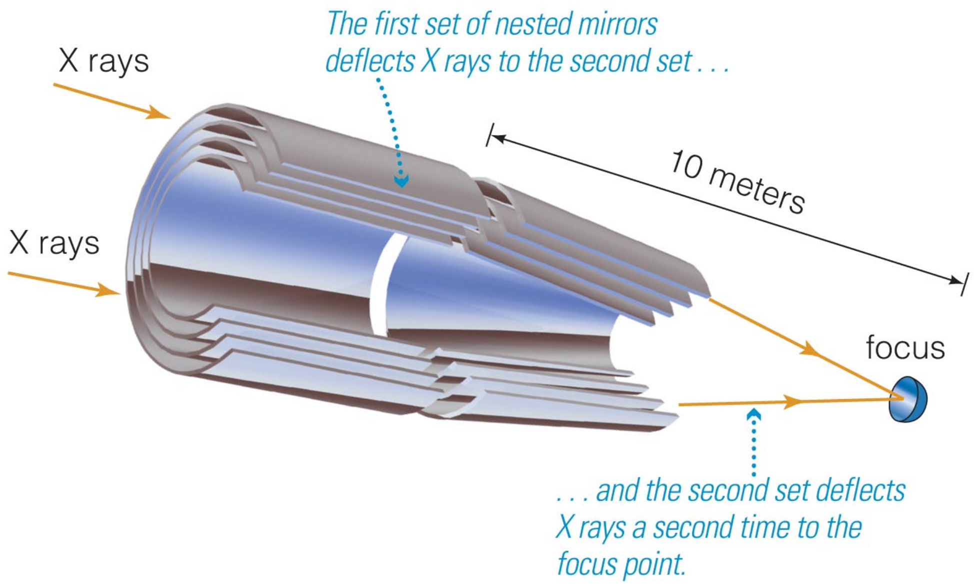
X-Ray Telescopes

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

a Artist's illustration of the Chandra X-Ray Observatory, which orbits Earth.

Chandra X-Ray Observatory

X-Ray Telescopes

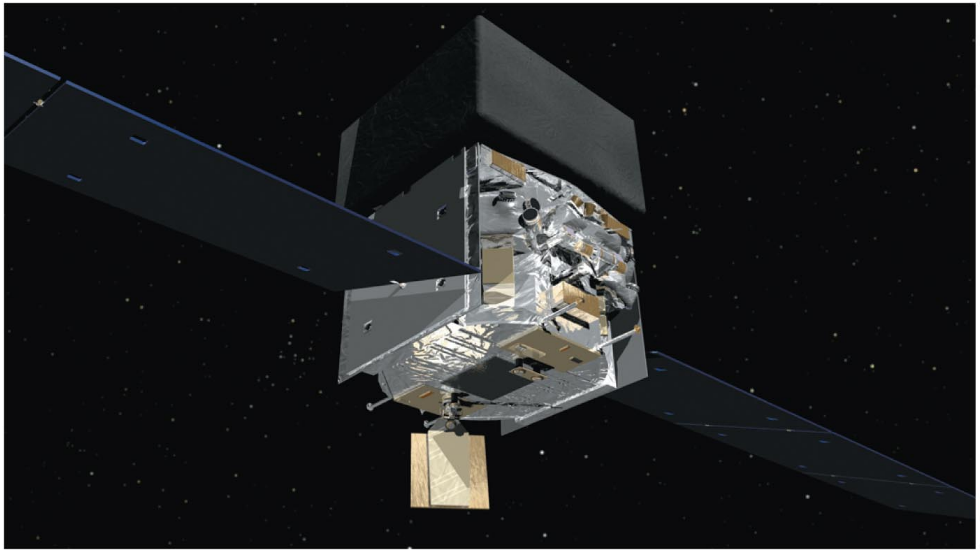


b This diagram shows the arrangement of Chandra's nested, cylindrical X-ray mirrors. Each mirror is 0.8 meter long and between 0.6 and 1.2 meters in diameter.

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

Gamma-Ray Telescopes

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



Fermi Gamma-Ray Observatory

Looking Beyond Light

- We can also gain knowledge by collecting other signals using different sorts of "telescopes"
  - neutrinos
  - cosmic rays
  - gravitational waves

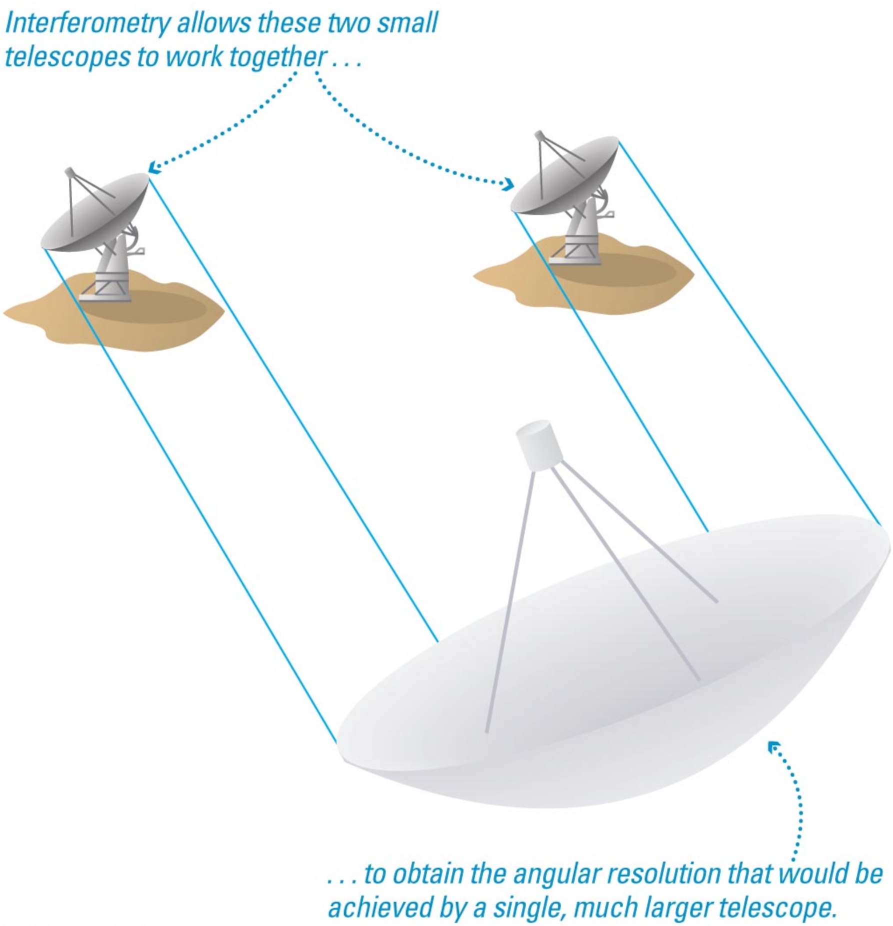
Arial view of part of LIGO

How can multiple telescopes work together?

How can multiple telescopes work together?

NRAO : VLA

Interferometry



- Interferometery is a technique for linking two or more telescopes so that they have the angular resolution of a single large one.

Interferometry

- Easiest to do with radio telescopes
- Now possible with infrared and visible-light telescopes

Very Large Array (VLA)

Interferometry in the visible light

Aerial photo of Mount Wilson (Eric Simison, Sea West Enterprises).

GSU's Center for High Angular Astronomy (CHARA): an optical interferometric array of six telescopes

Interferometry in the visible light


Aerial photo of Mount Wilson (Eric Simison, Sea West Enterprises).

GSU’s Center for High Angular Astronomy (CHARA): an optical interferometric array of six telescopes

What have learned?

- **How do we observe invisible light?**
  - Telescopes for invisible light are usually modified versions of reflecting telescopes.
  - Many of the telescopes used for observing invisible light are in space.
- **How can multiple telescopes work together?**
  - Linking multiple telescopes using interferometry enables them to produce the angular resolution of a much larger telescope.