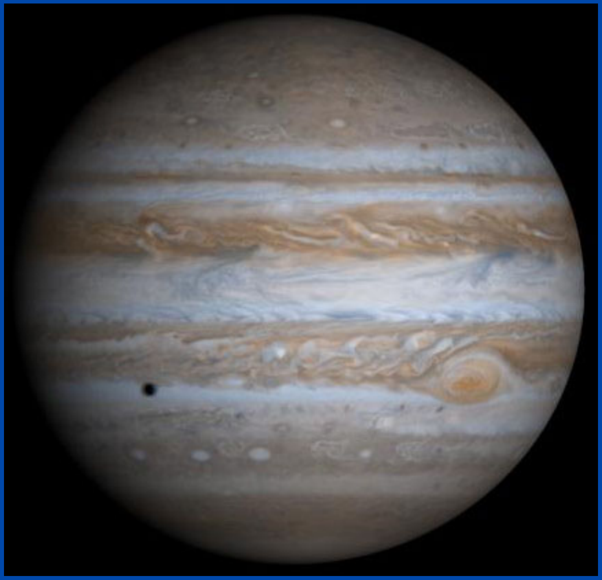
Lecture 6: Telescopes and Spacecraft



Jupiter as seen by Cassini spacecraft

Claire Max

April 22, 2014

Astro 18: Planets and Planetary Systems

UC Santa Cruz

Class logistics

- I fell behind on the reading assignments posted on the web. They are now all there. Sorry!
  - Supplementary reading for those of you who know calculus is posted on the eCommons site
- Homework due Thursday
  - Includes optional problems involving calculus

Exams

- **Mid-Term:**
  - **Thursday May 8th in class (noon to 1:45)**
- **Final:**
  - **Wednesday June 11th, 8am – 11am**

- People who added class late:
  - Please see me during break at 12:45
  - Thanks!

Topics for this lecture

- **Telescopes and spacecraft: how we learn about the planets**
  - **Lenses**
  - **Cameras and the eye**
  - **Telescope basics (optical, x-ray, radio telescopes)**
  - **Blurring due to atmospheric turbulence; adaptive optics**
  - **Airborne telescopes**
  - **Spacecraft**

Telescopes: Main Points

- Telescopes gather light and focus it
  - Larger telescopes gather more light
  - Telescopes can gather "light" at radio, infrared, visible, ultraviolet, x-ray, γ-ray wavelengths
- Telescopes can be on ground, on planes, in space
- If Earth's atmosphere weren't turbulent, larger ground-based telescopes would give higher spatial resolution
  - Adaptive optics can correct for blurring due to turbulence

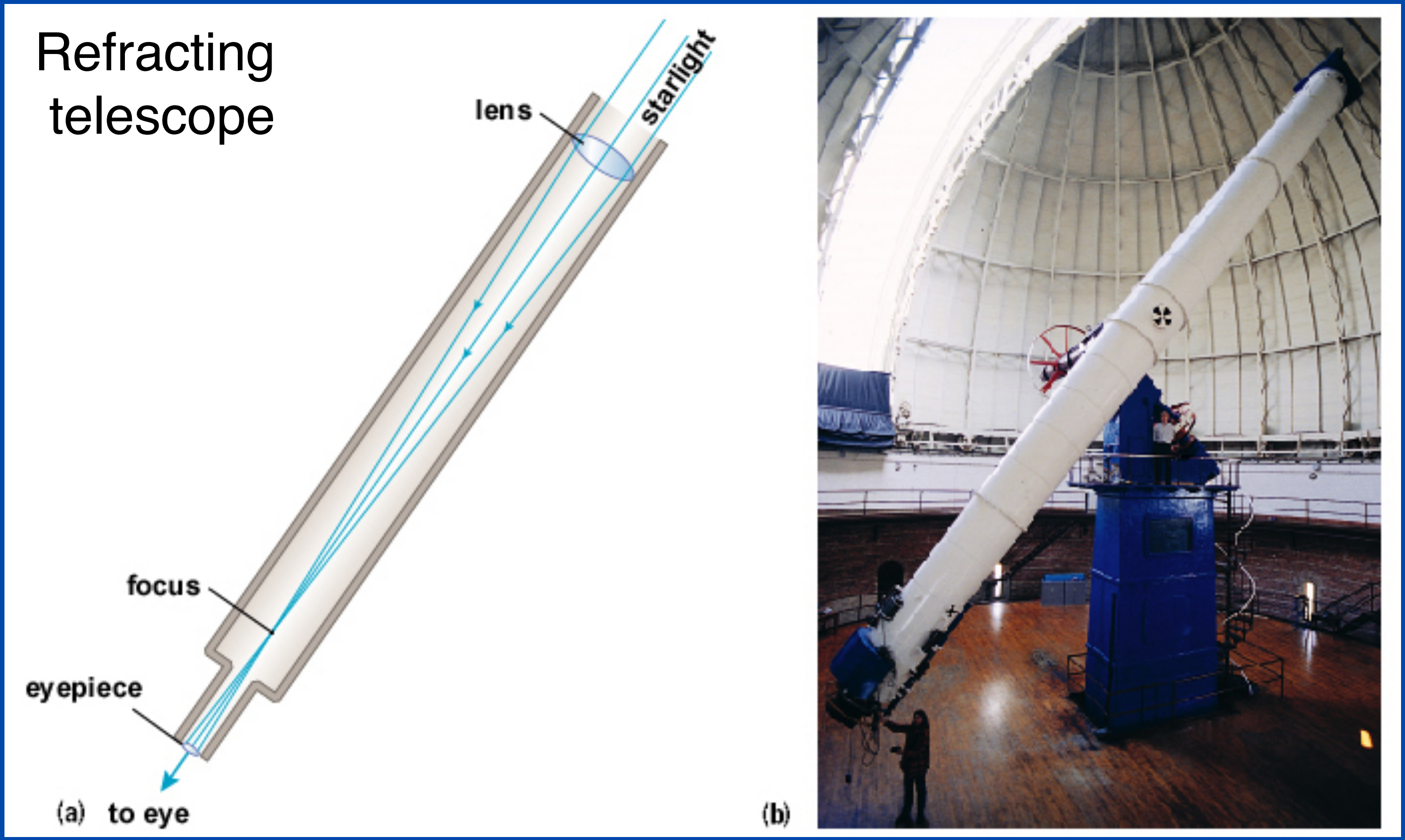
Every new telescope technology has resulted in major new discoveries and surprises

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.**

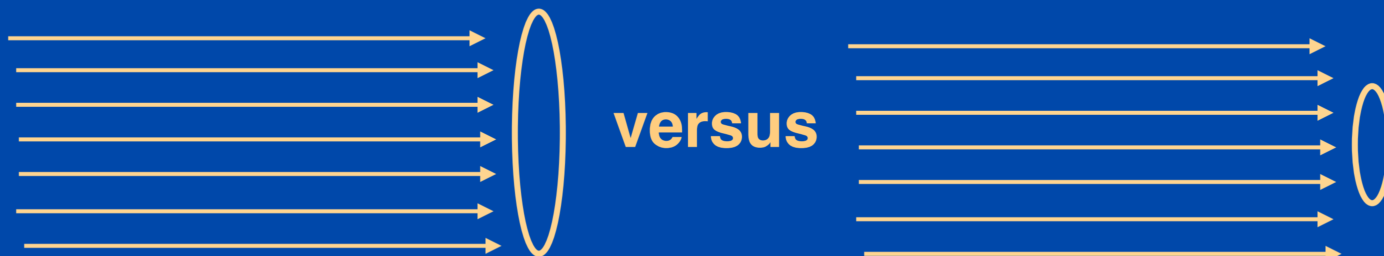
Telescopes gather light and focus it



- **Telescope as a "giant eye"**
  - **You can gather more light with a telescope, hence see fainter objects**

Amount of light gathered is proportional to area of lens

- Why area?



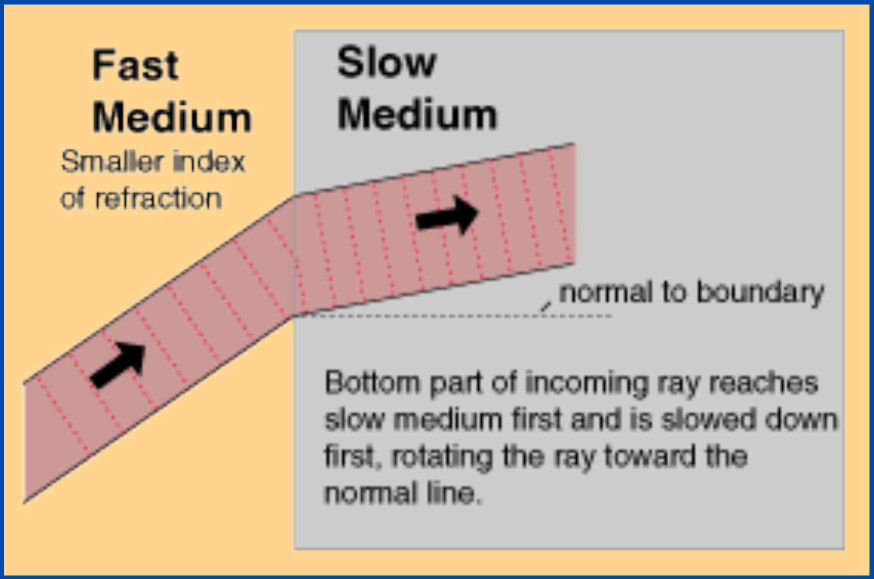
- "Size" of telescope is usually described by diameter d of its primary lens or mirror
- Collecting area of lens or mirror = $\pi r^2 = \pi (d/2)^2$

Light-gathering power

- **Light-gathering power $\propto$ area = $\pi\,(d/2)^2$**
- **Eye:**
  - **At night, pupil diameter ~ 7 mm, Area ~ 0.4 cm^2**
- **Keck Telescope:**
  - ***d* = 10 meters = 1000 cm, Area = 7.85 x 10^5 cm^2**
  - **Light gathering power is 1.96 million times that of the eye!**

Refracting telescopes focus light using “refraction”

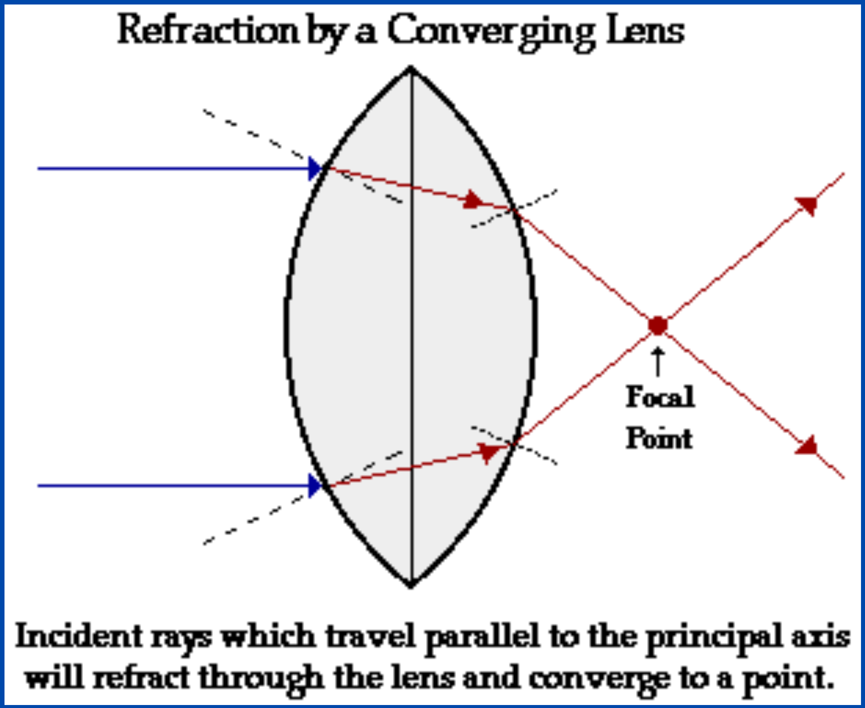
- Speed of light is constant in a vacuum
- But when light interacts with matter, it usually slows down a tiny bit
- This makes “rays” of light bend at interfaces



Refraction animation

- http://www.launc.tased.edu.au/online/sciences/physics/refrac.html

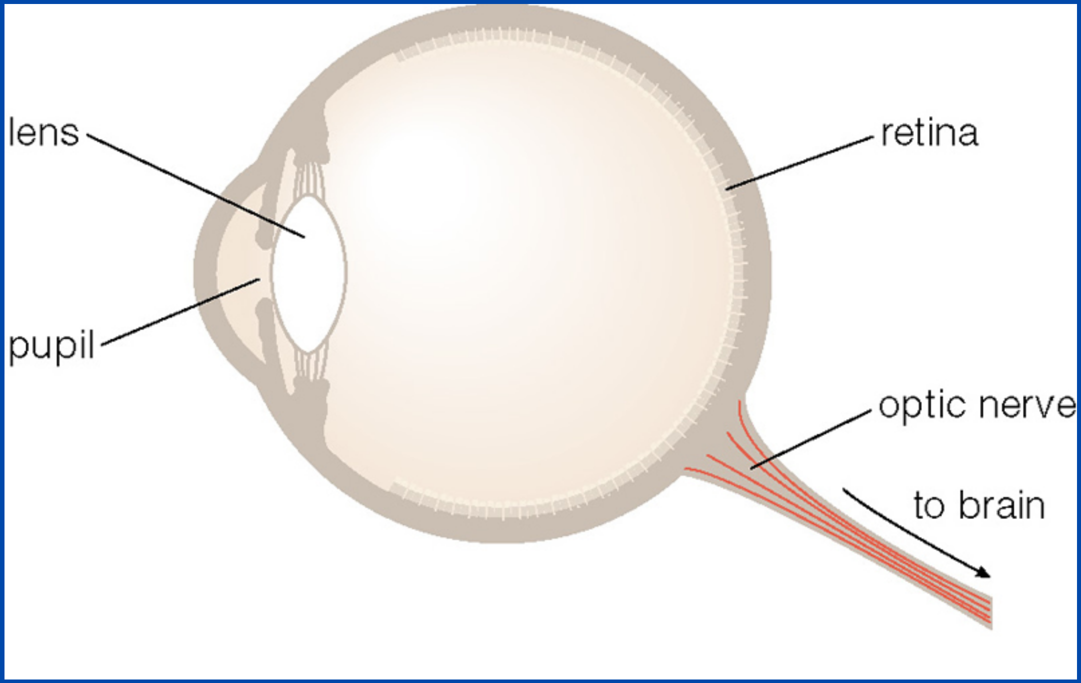
A lens takes advantage of the bending of light to focus rays



Focus – to bend all light waves coming from the same direction to a single point

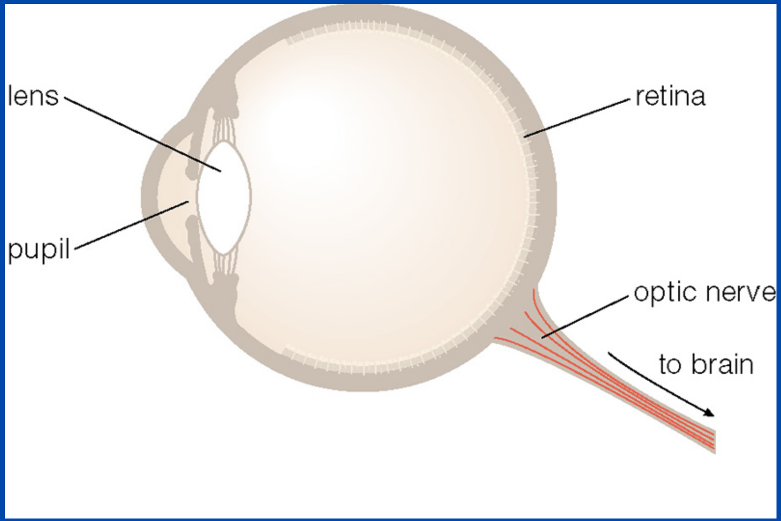
Parts of the Human Eye

- pupil – **allows light to enter the eye**
- lens – **focuses light to create an image**
- retina – **detects the light and generates signals which are sent to the brain**

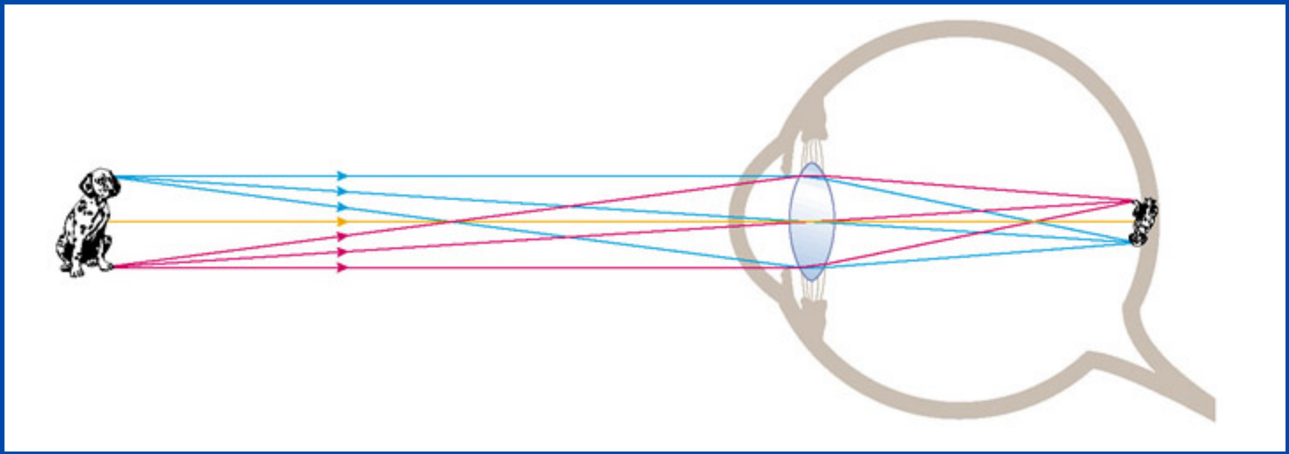


Camera works the same way: the *shutter* acts like the *pupil* and the *film* acts like the *retina*!

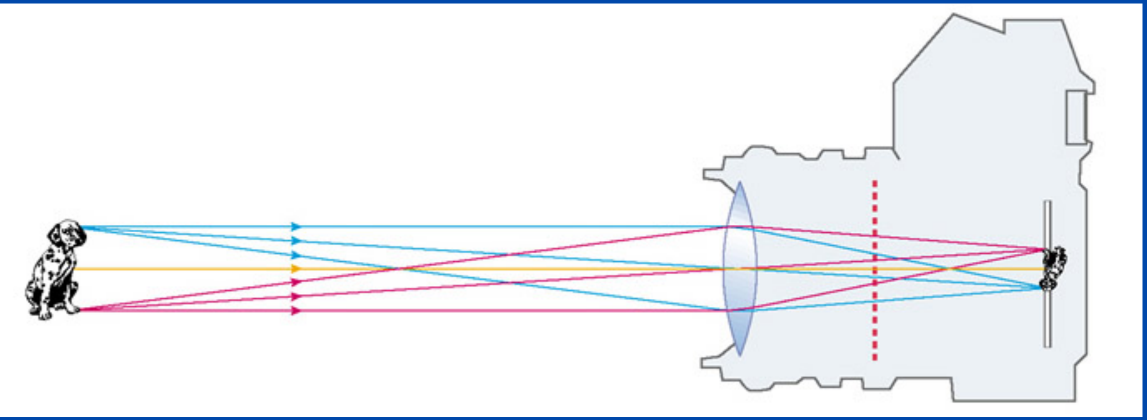
The lens in our eyes focuses light on the retina



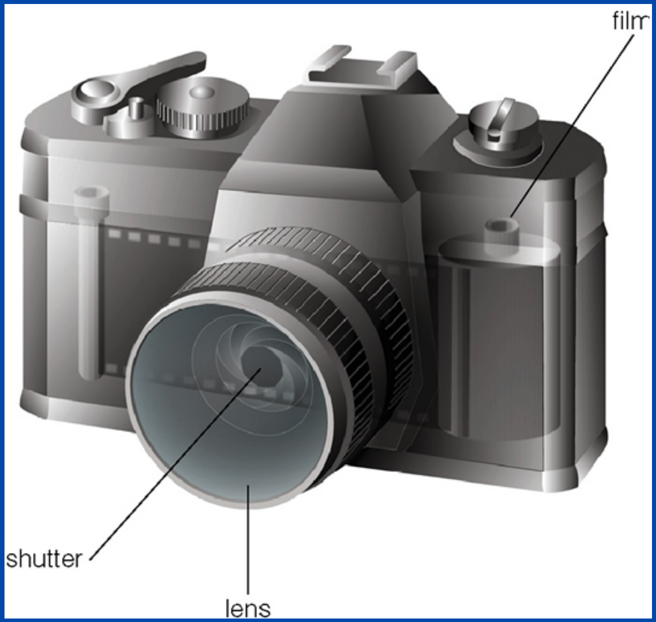
Note that images are upside down!
Our brains compensate!

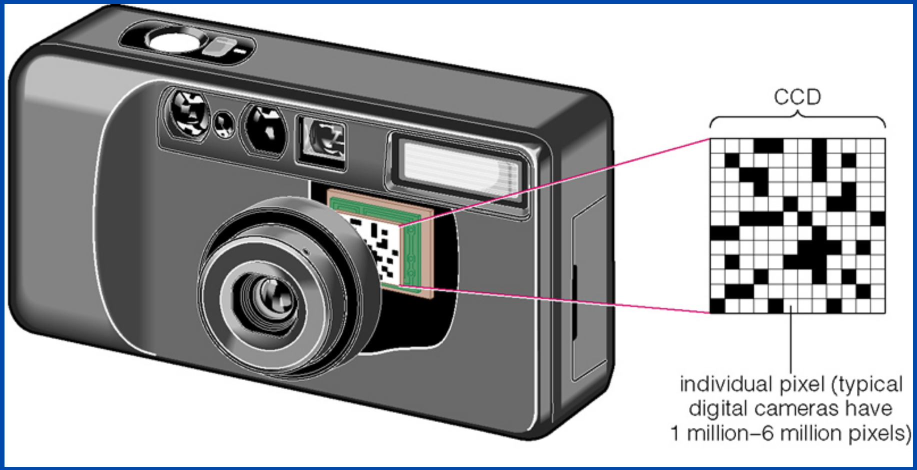


Camera lens focuses light on film or CCD detector



Upside down





What have we learned?

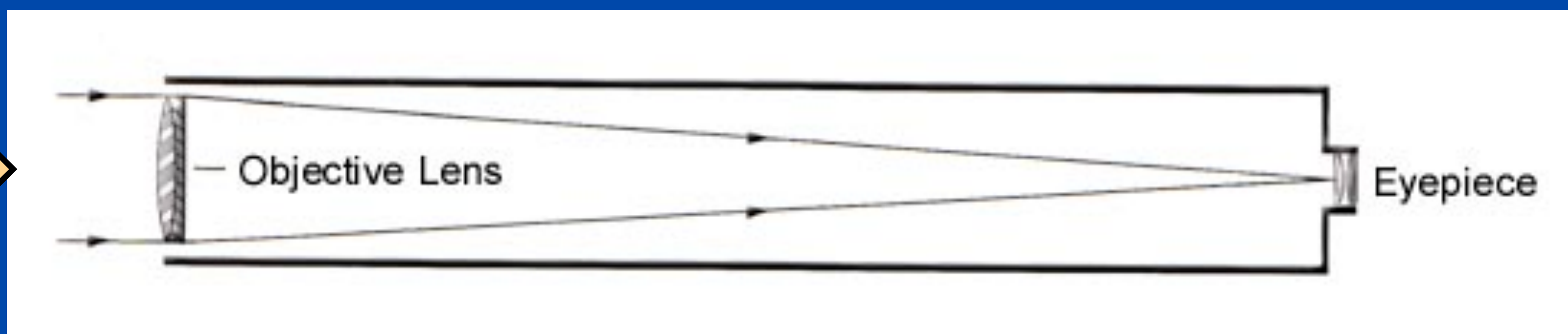
- **How does your eye form an image?**
  - **It uses refraction to bend parallel light rays so that they form an image.**
  - **The image is in focus if the focal plane is at the retina.**

- **How do we record images?**
  - **Cameras focus light like your eye and record the image with a detector.**
  - **The detectors (CCDs) in digital cameras are like those used on modern telescopes**

What are the two basic designs of telescopes?

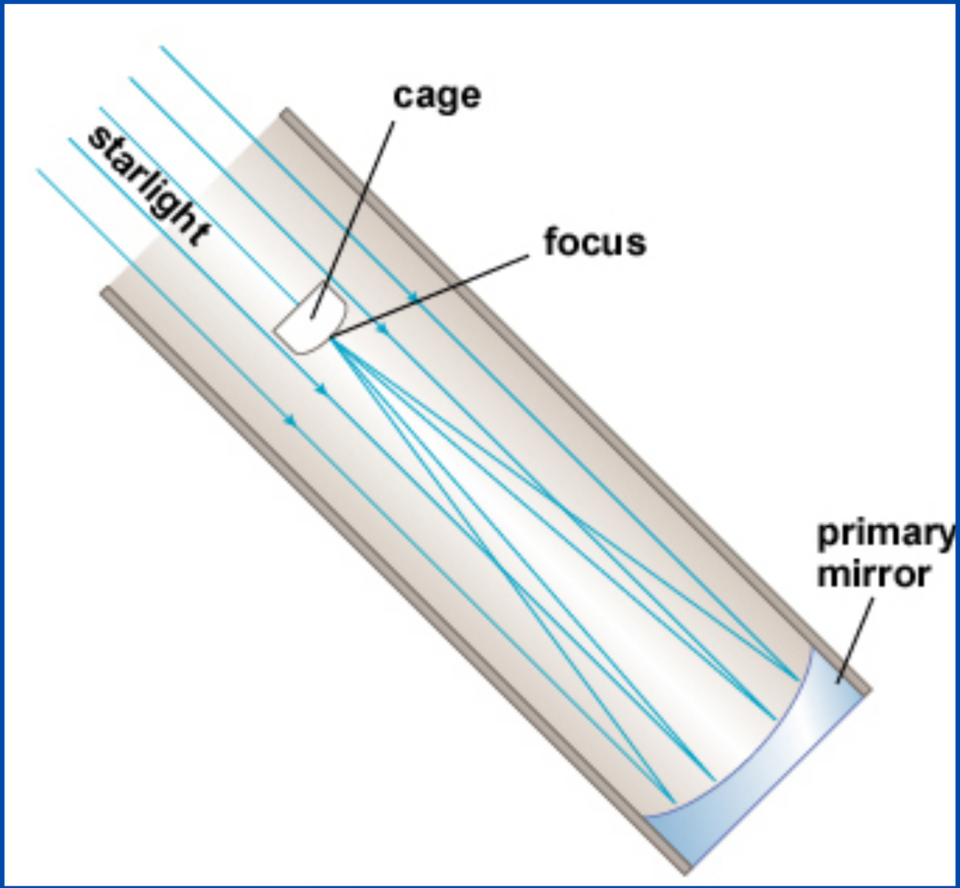
- Refracting telescope: **Focuses light with lenses**
- Reflecting telescope: **Focuses light with mirrors**

Cartoon of refracting telescope



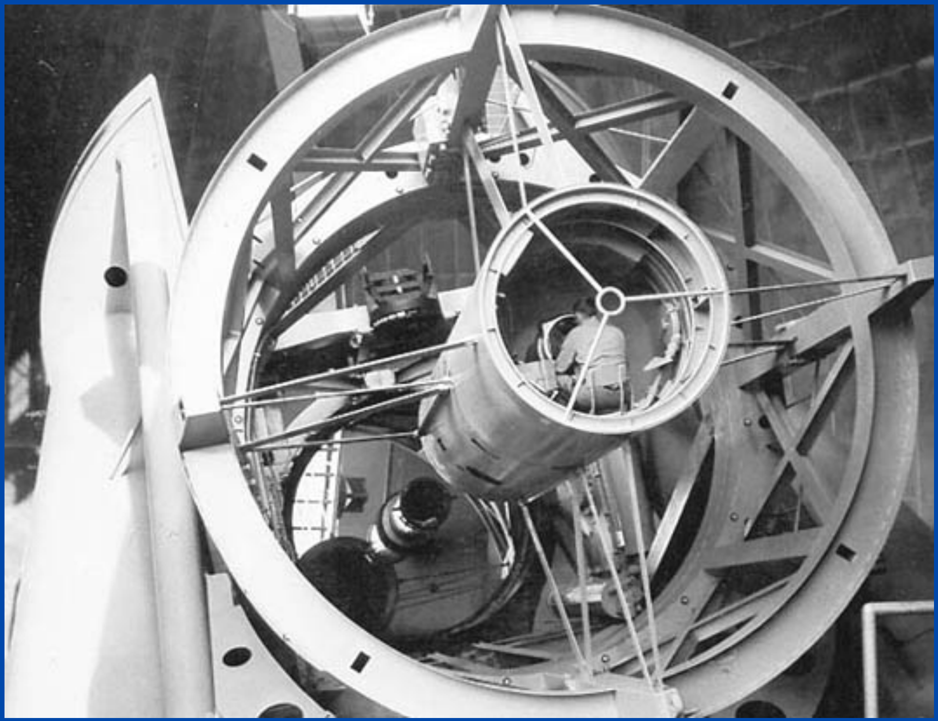
Telescopes can use mirrors instead of lenses to gather and focus light

- **For practical reasons, can't make lenses bigger than ~ 1 meter**
- **Can make mirrors much larger than this**
  - **Largest single telescope mirrors today are about 8.5 m**
- **Old-fashioned reflecting telescope:**
  - **Observer actually sat in "cage" and looked downward**



Mount Palomar (near San Diego): Prime focus cage and an inhabitant

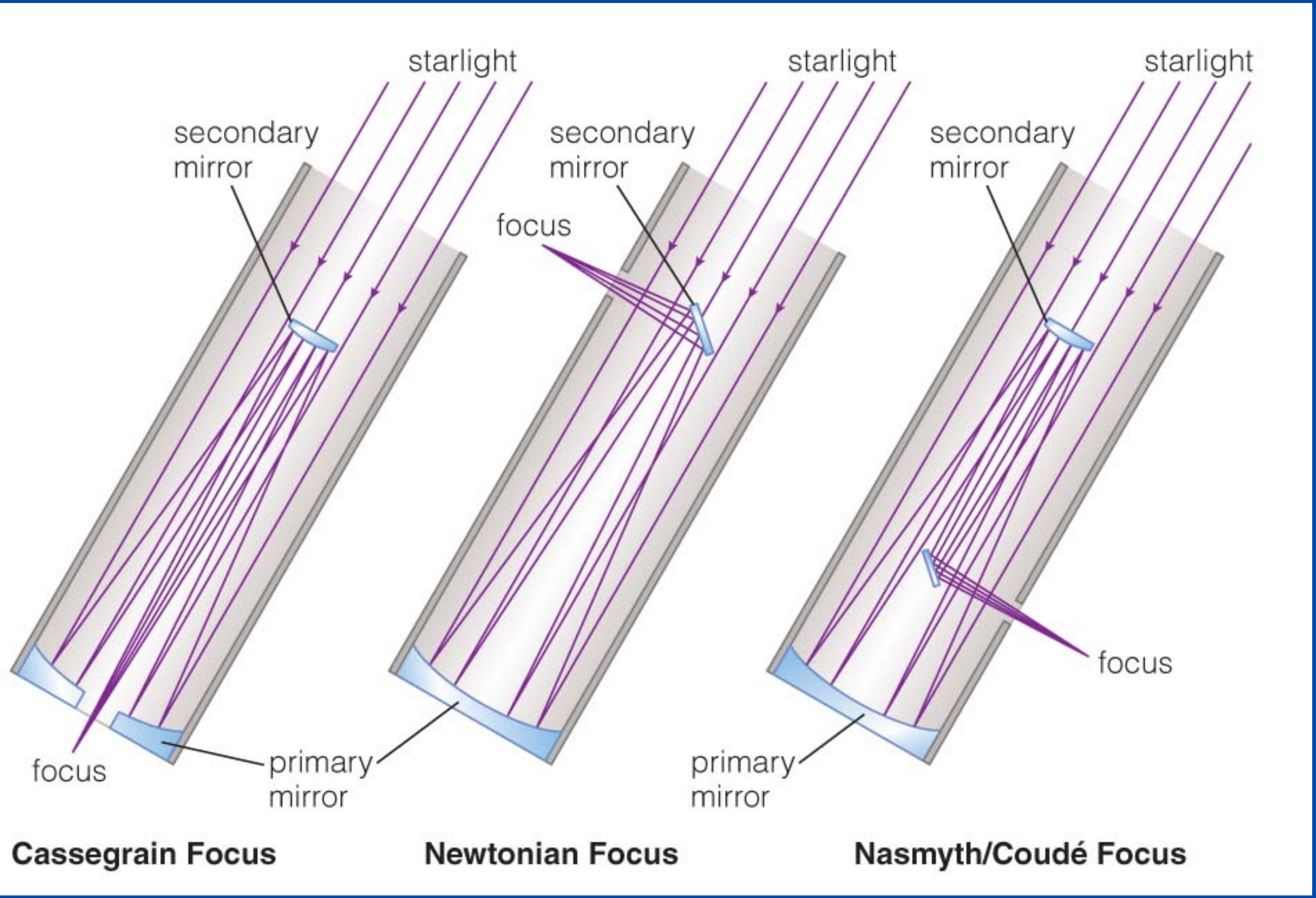
- "NOTE: Smoking and drinking are not permitted in the prime focus cage" (On web page of Anglo Australian Telescope)
- Until the 1970's, women weren't permitted either!



Looking down the telescope tube from the top. Mirror is at the bottom.

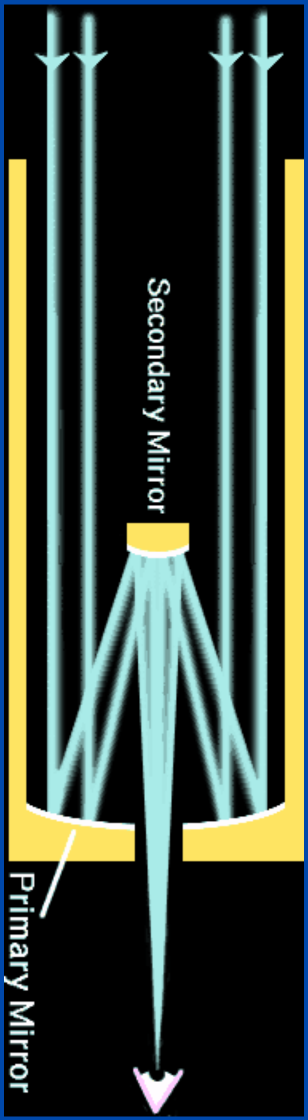
More photos of Prime Focus Cage: things really have gotten better!

Designs for Reflecting Telescopes



Most of today's reflecting telescopes use Cassegrain design

- Light enters from top
- Bounces off primary mirror
- Bounces off secondary mirror
- Goes through hole in primary mirror to focus



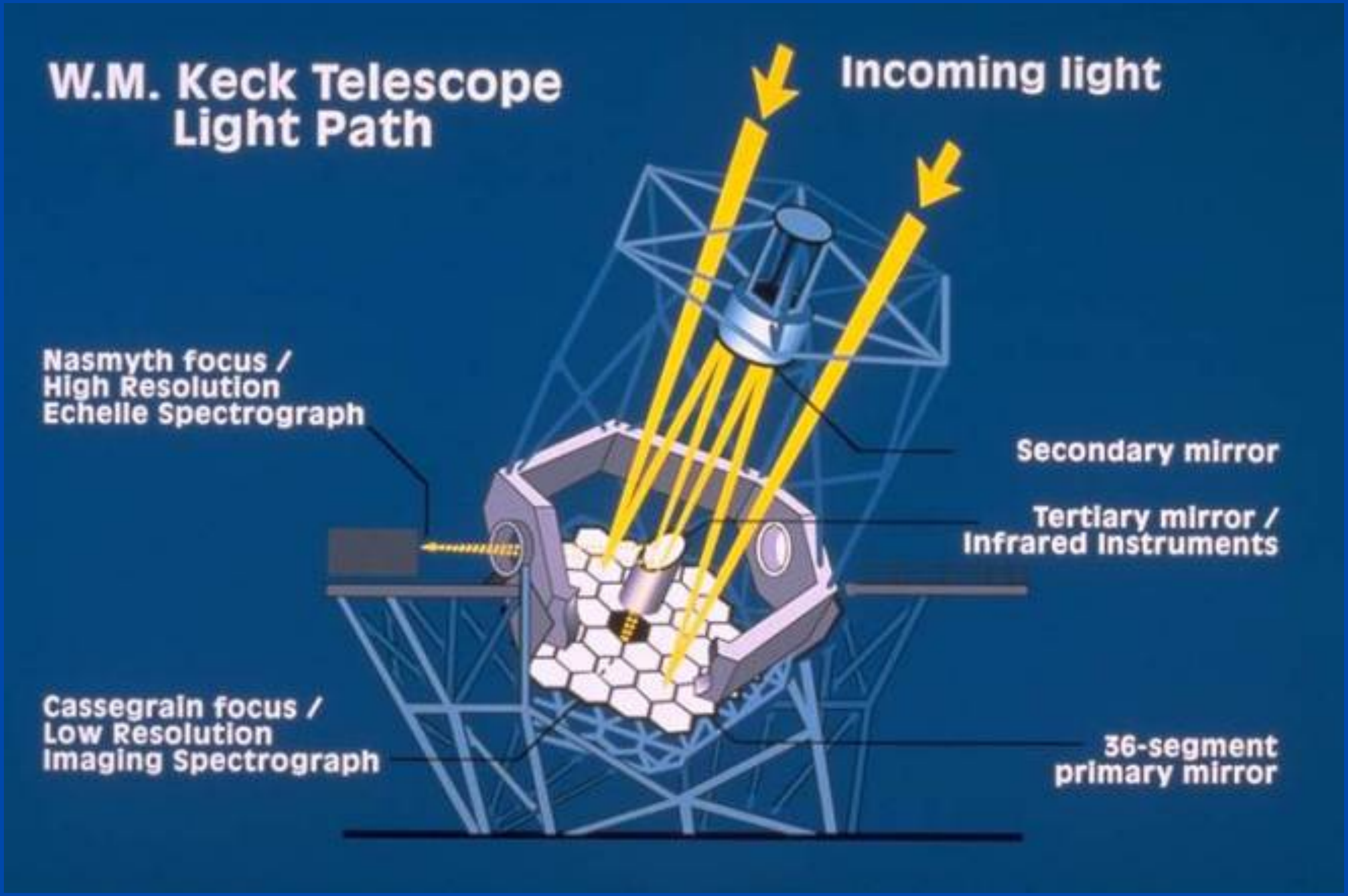
Examples of real telescopes

- **Backyard telescope:**
  - **3.8" diameter refracting lens**
  - **Costs ~ $300 at Amazon.com**
  - **Completely computerized: it will find the planets and galaxies for you**

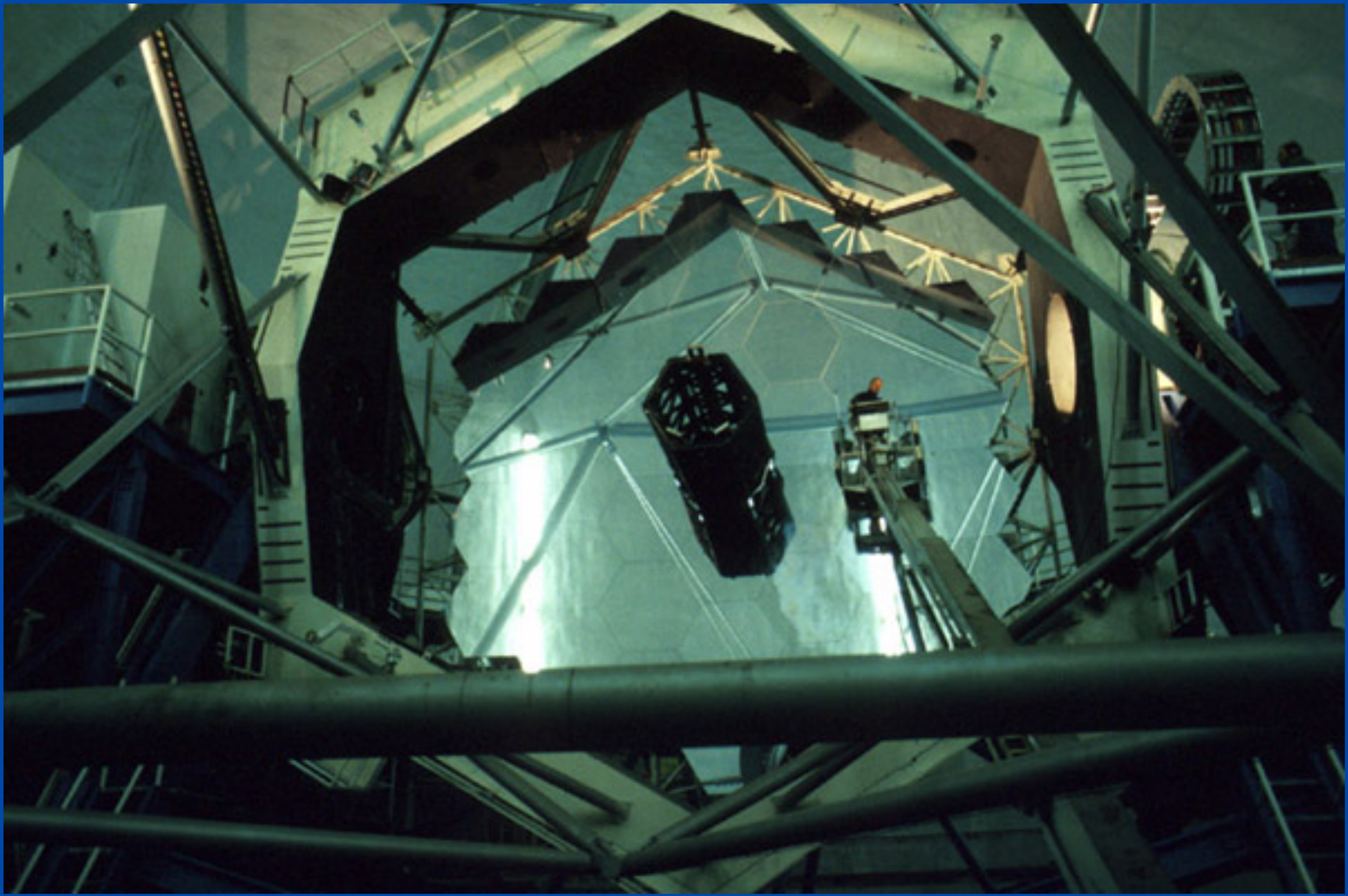
Largest optical telescopes in world

- **Twin Keck Telescopes on top of Mauna Kea volcano in Hawaii**

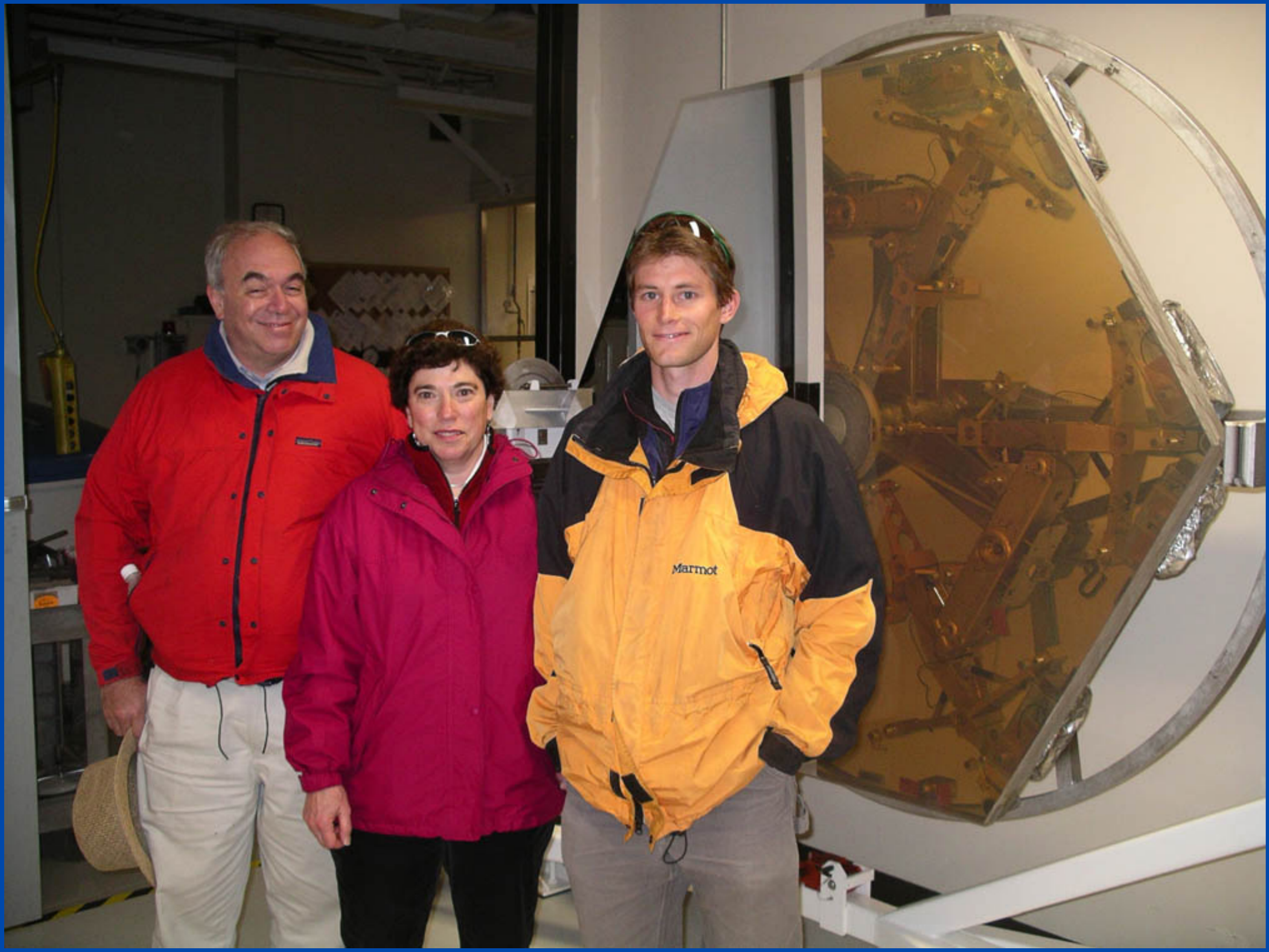
36 hexagonal segments make up the full Keck mirror



Cleaning the Keck's 36 segments

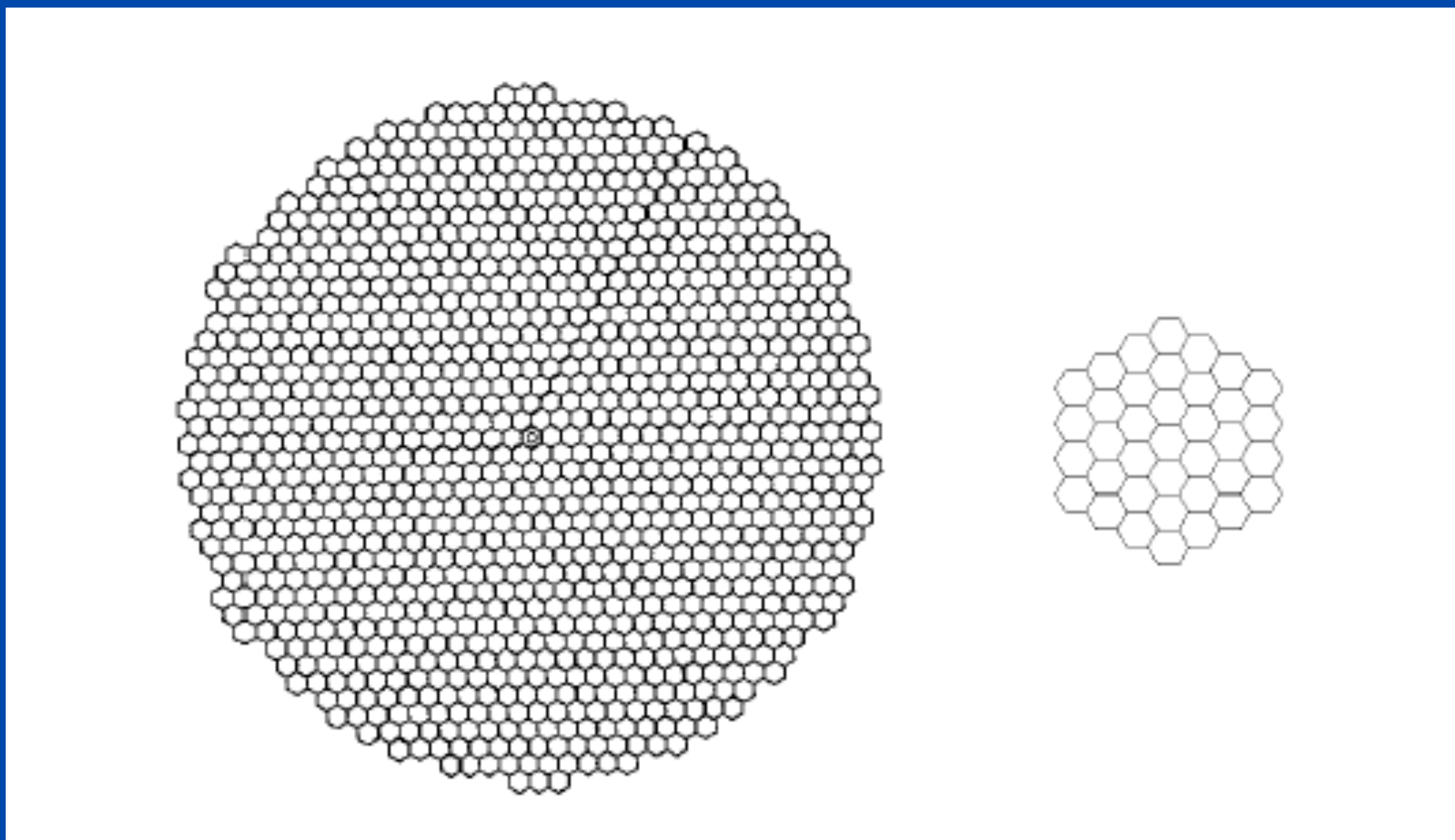


One Keck segment (in storage)

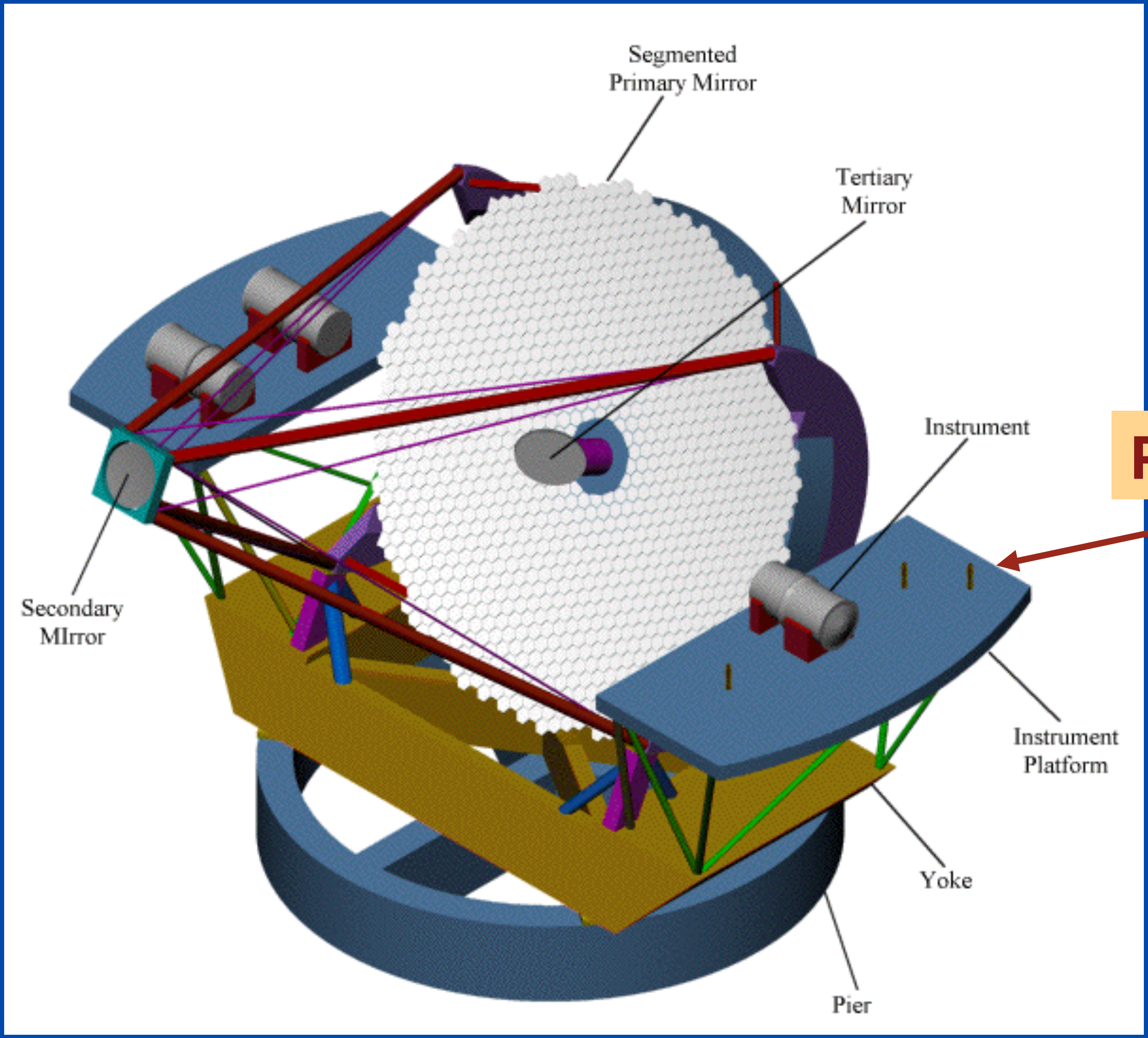


Future plans are even more ambitious

Thirty Meter Telescope **Keck Telescope**

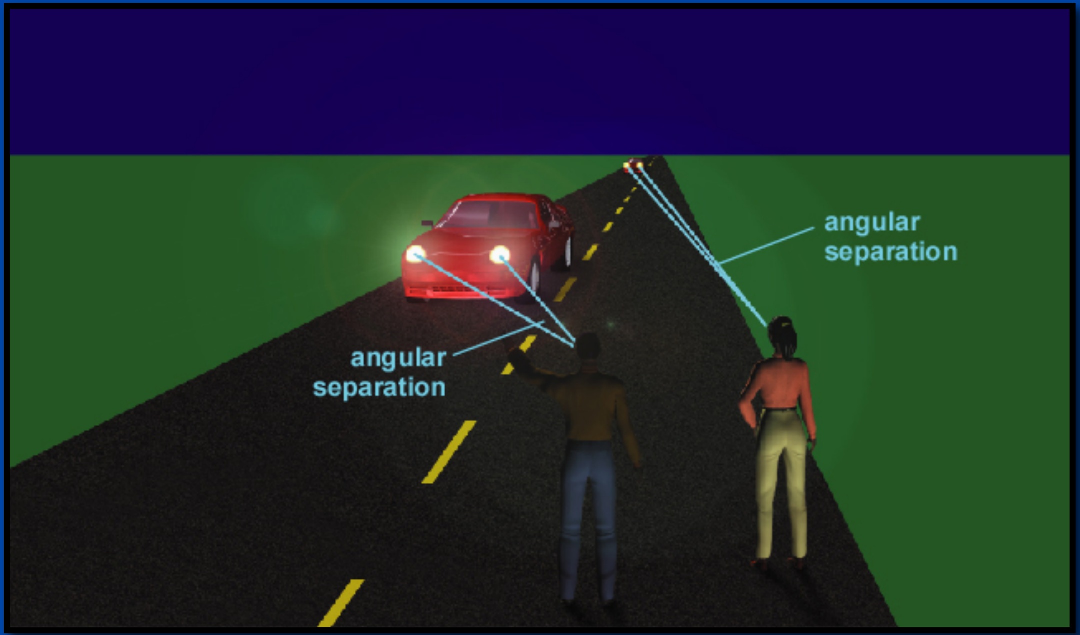


Future plans are even more ambitious



People!

Concept of angular resolution



Car Lights

Angular resolution

- The ability to separate two objects.
- The angle between two objects decreases as your distance to them increases.
- The smallest angle at which you can distinguish two objects is your *angular resolution*.

How big is one "arc second" of angular separation?

- A full circle (on the sky) contains 360 degrees or 2π radians
  - Each degree is 60 arc minutes
  - Each arc minute is 60 arc seconds

$$1 \text{ arc sec} \times \frac{1 \text{ arc min}}{60 \text{ arc sec}} \times \frac{1 \text{ degree}}{60 \text{ arc min}} \times \frac{2\pi \text{ radians}}{360 \text{ degrees}} =$$

$$= \frac{2\pi}{60 \times 60 \times 360} \text{radians} = 4.8 \times 10^{-6} \text{ radian} = 4.8\ \mu\text{rad} \approx 5\ \mu\text{rad}$$

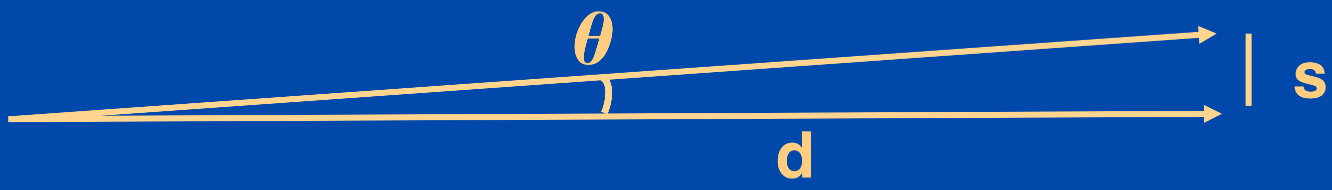
$$\text{or } 1\ \mu\text{rad} \approx 0.2 \text{ arc sec}$$

What does it mean for an object to "subtend an angle Θ" ?

Θ is the apparent angular size of the object

"Small angle formula"

- $\sin\Theta \sim \Theta$ if Θ is << 1 radian
- $s = d \sin\Theta \sim d\,\Theta$



- Example: how many arc sec does a dime subtend if it is located 2 km away?

A dime is about 1 cm across, so

$$\theta \approx \frac{s}{d} \approx \frac{1\ \text{cm}}{2\ \text{km}} \times \frac{1\ \text{km}}{1000\ \text{m}} \times \frac{1\ \text{m}}{100\ \text{cm}} = \frac{1}{2} \times 10^{-5}\,\text{radians} \times \frac{1\ \mu\text{rad}}{10^{-6}\ \text{rad}} = 5\ \mu\text{rad} = 1\ \text{arc sec}$$

Concept Question

From Earth, planet A subtends an angle of 5 arc sec, and planet B subtends an angle of 10 arc sec. If the radius of planet A equals the radius of planet B, then

a) planet A is twice as big as planet B.

b) planet A is twice as far as planet B.

c) planet A is half as far as planet B.

d) planet A and planet B are the same distance.

e) planet A is four times as far as planet B.

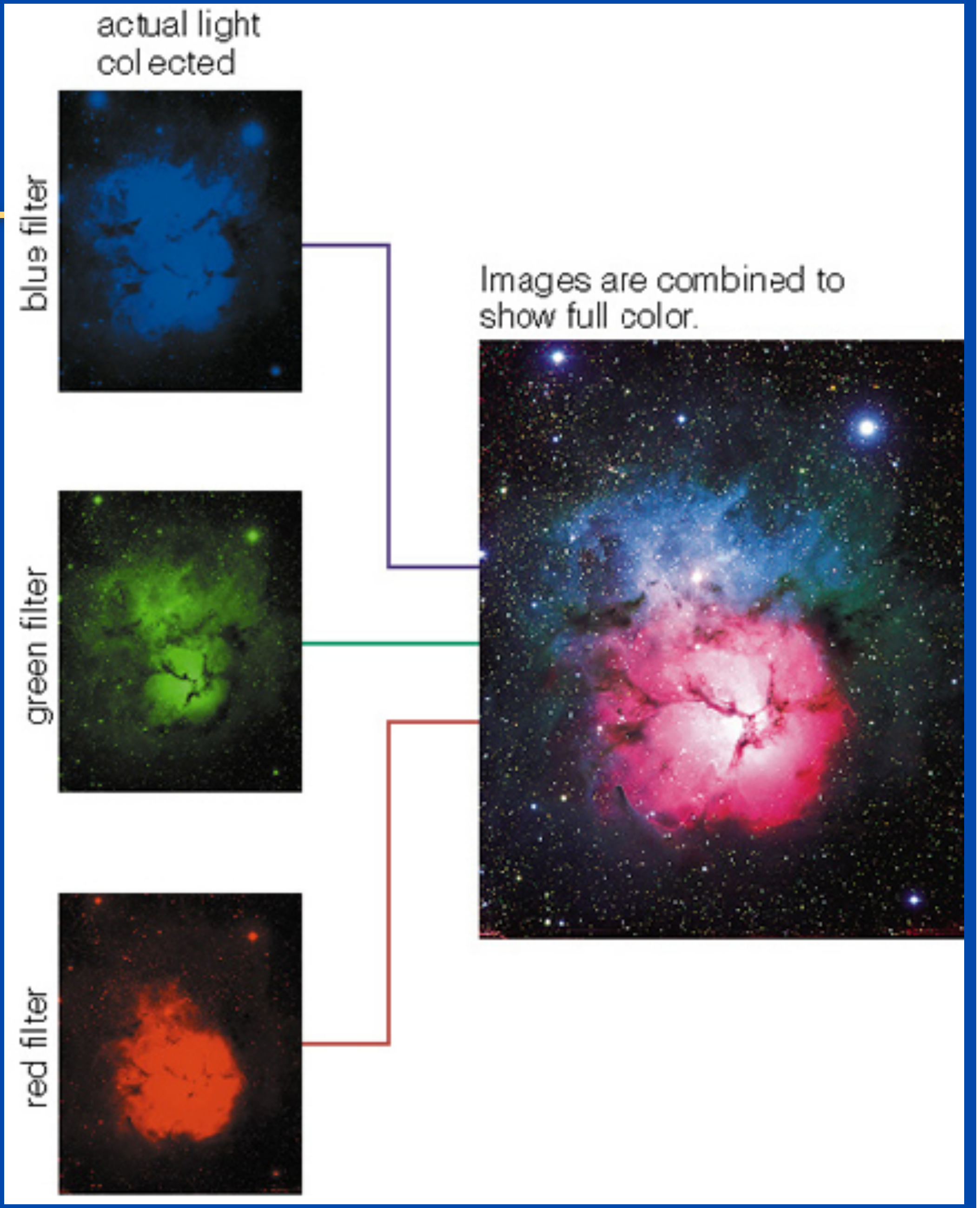
What do astronomers do with telescopes?

- Imaging: **Taking (digital) pictures of the sky**
- Spectroscopy: **Breaking light into spectra**
- Timing: **Measuring how light output varies with time**

Imaging

- *Filters* are placed in front of a camera to allow only certain colors through to the detector

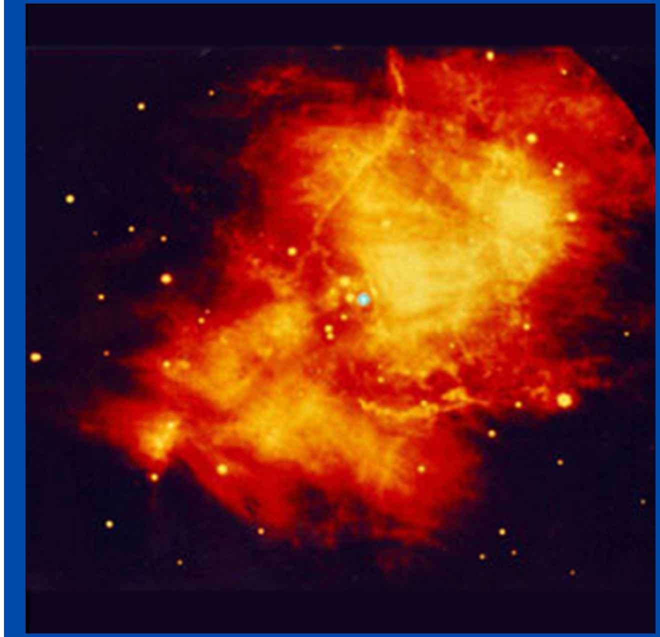
- Single color images are then superimposed to form true color images.



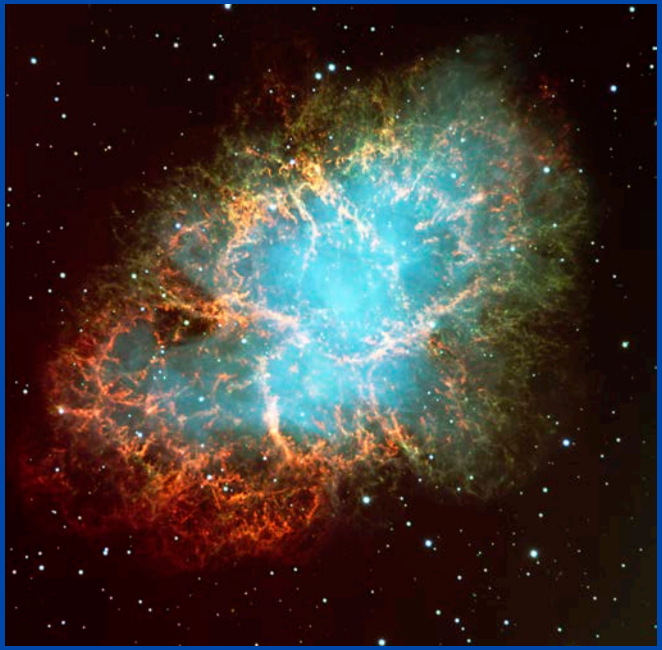
How can we record images of nonvisible light?

- Electronic detectors such as CCDs can record light our eyes can't see
  - Infrared light, ultraviolet light, even x-rays
- We can then represent the recorded light with some kind of color coding, to reveal details that would otherwise be invisible to our eyes

"Crab Nebula" - supernova remnant where a star blew up 1000 yrs ago

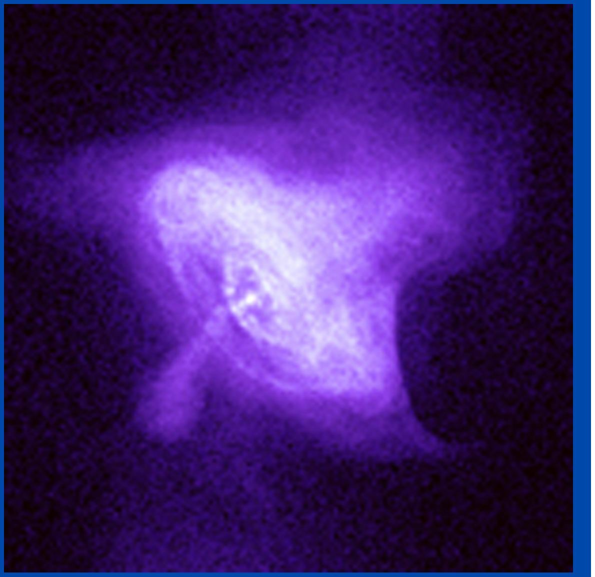


Infra-red light



Visible light

From above the atmosphere



X-rays

In principle, larger telescopes should give sharper images

- **Concept of "diffraction limit"**
  - **Smallest angle on sky that a telescope can resolve**

$$\theta_d = \left(\frac{\lambda}{D}\right) \text{radians}$$

where λ = wavelength of light, D = telescope diameter in the same units as λ

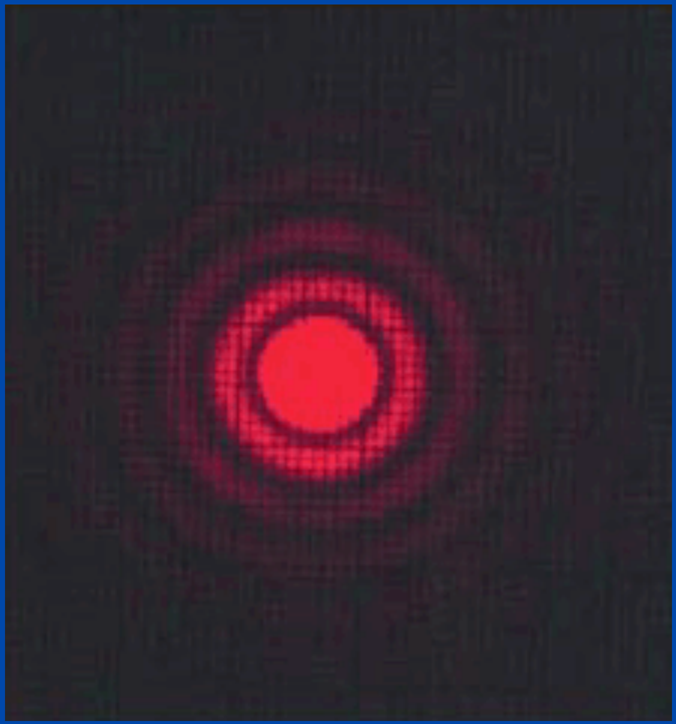
  - **Numerically:**

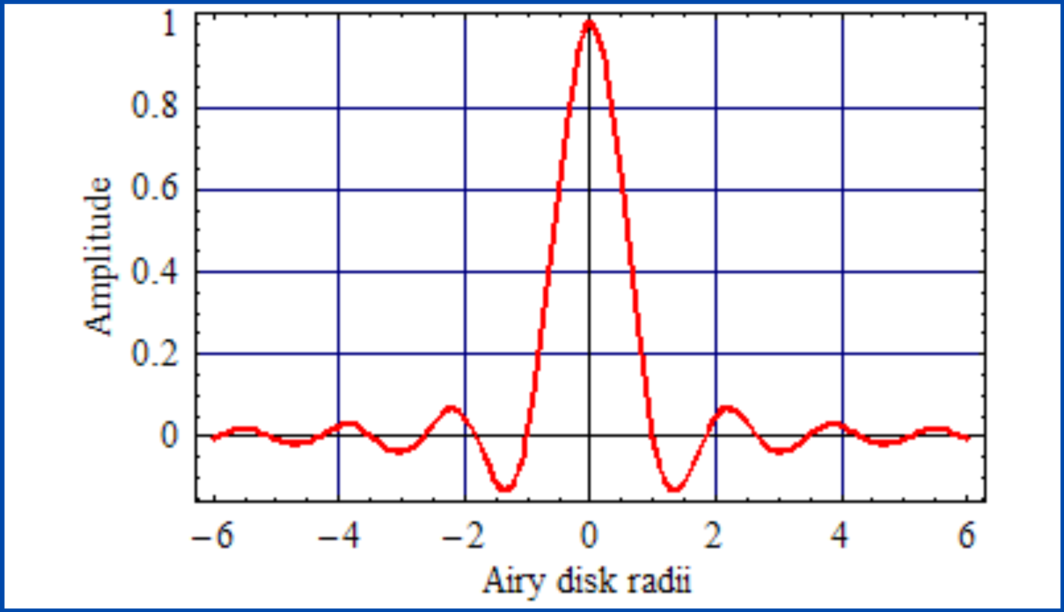
In same units!

$$\text{diffraction limit} = 2.5 \times 10^5 \left(\frac{\text{wavelength of light}}{\text{diam of telescope}}\right) \text{arc seconds}$$

Image of a point source seen through a circular telescope mirror

- At the "diffraction limit", size of central spot ~ λ / D





Diffraction limit animation

Example of diffraction limit

- **Keck Telescope, visible light**

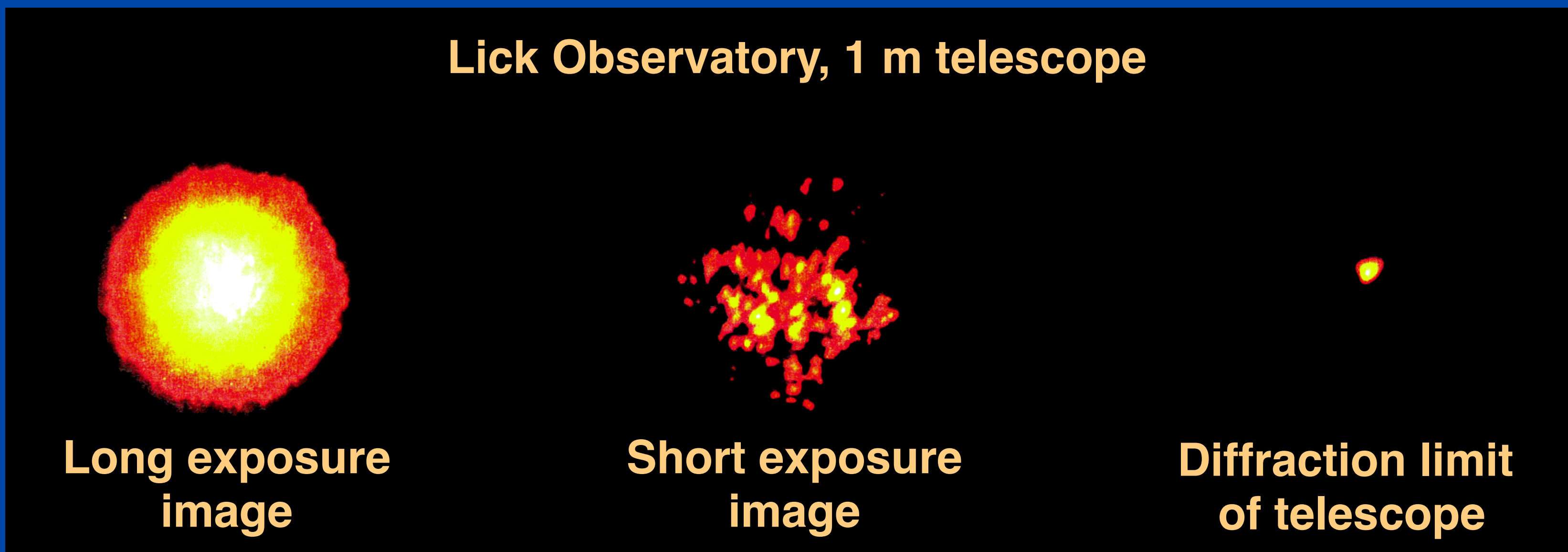
$$\text{telescope diameter } D = 10 \text{ meters}$$

$$\text{wavelength of light } \lambda = 5000 \text{ Angstroms} = 5\times10^{-7}\text{meter}$$

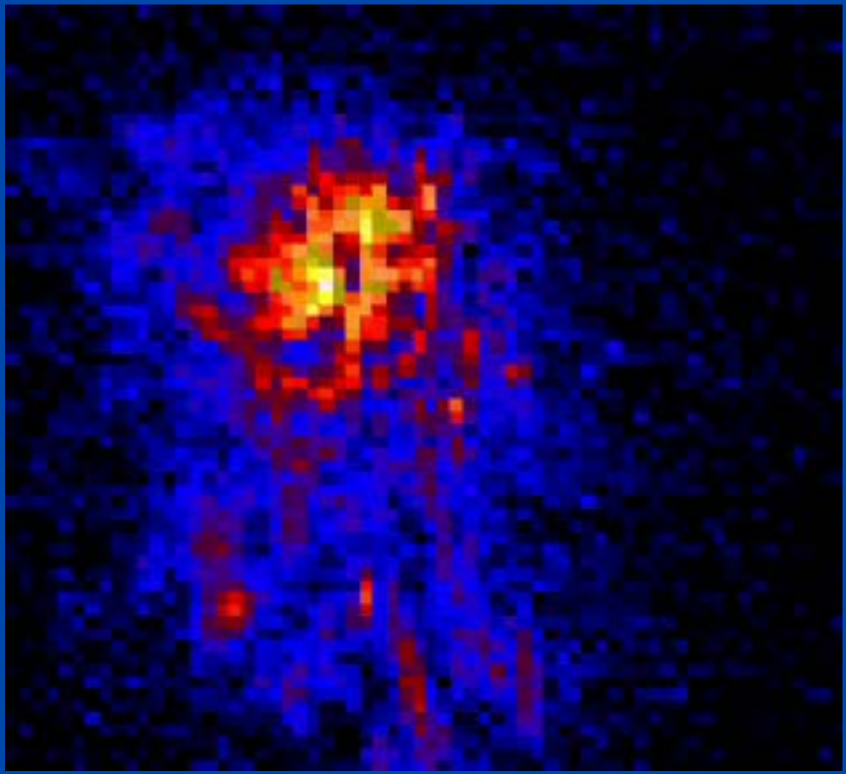
$$\text{diffraction limit} = \left(2.5\times10^{5}\right)\times\left(\frac{5\times10^{-7}}{10}\right)\text{arc seconds} = 0.0125 \text{ arc second}$$

- **BUT: Turbulence in the Earth's atmosphere blurs images, so even the largest telescopes can't "see" better than about 1 arc second**
  - **A decrease of a factor of 1 / 0.0125 = 80 in resolution!**

Images of a bright star, Arcturus



Snapshots of turbulence effects, Lick Observatory



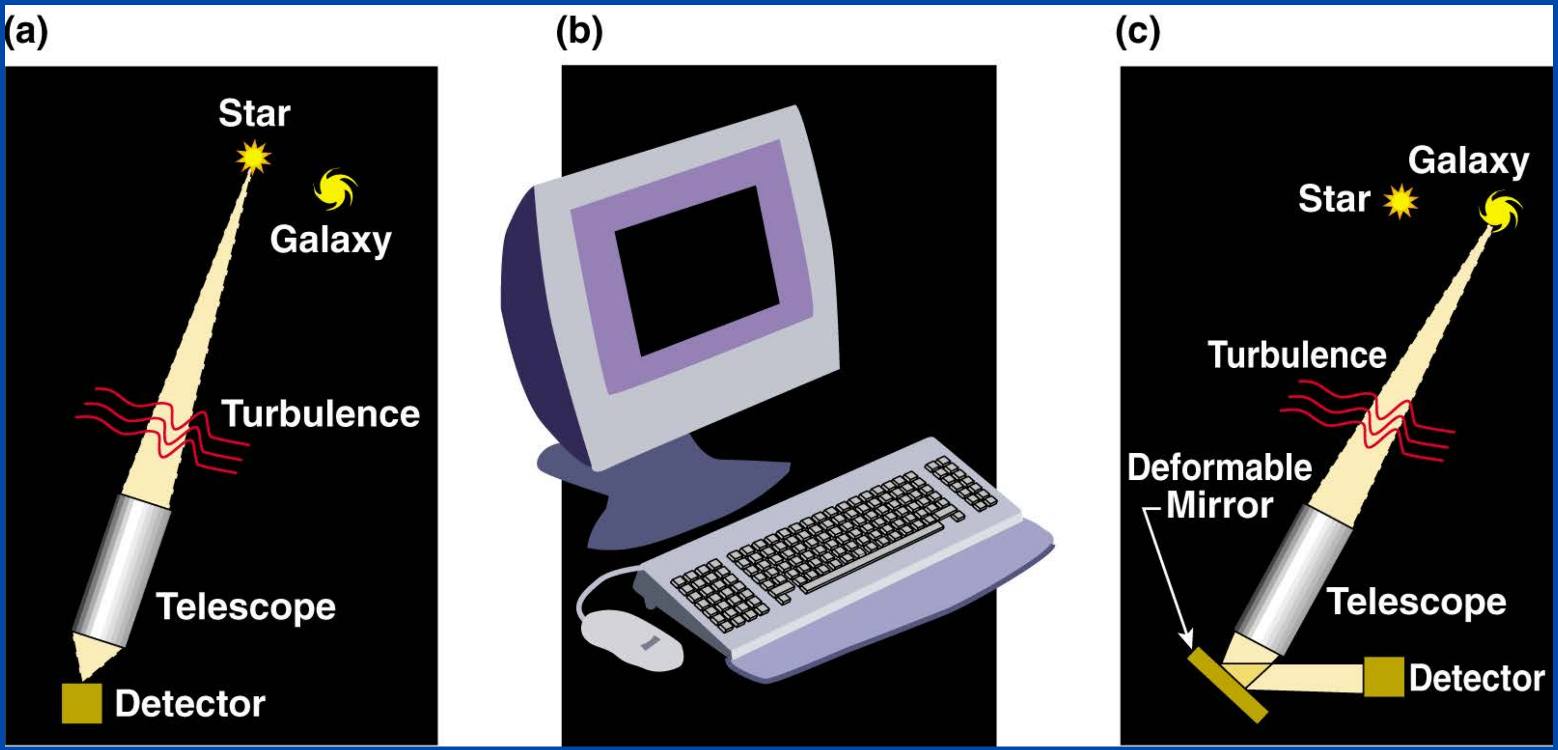
These are all images of a star, taken with very short exposure times (100 milliseconds)

How to correct for atmospheric blurring

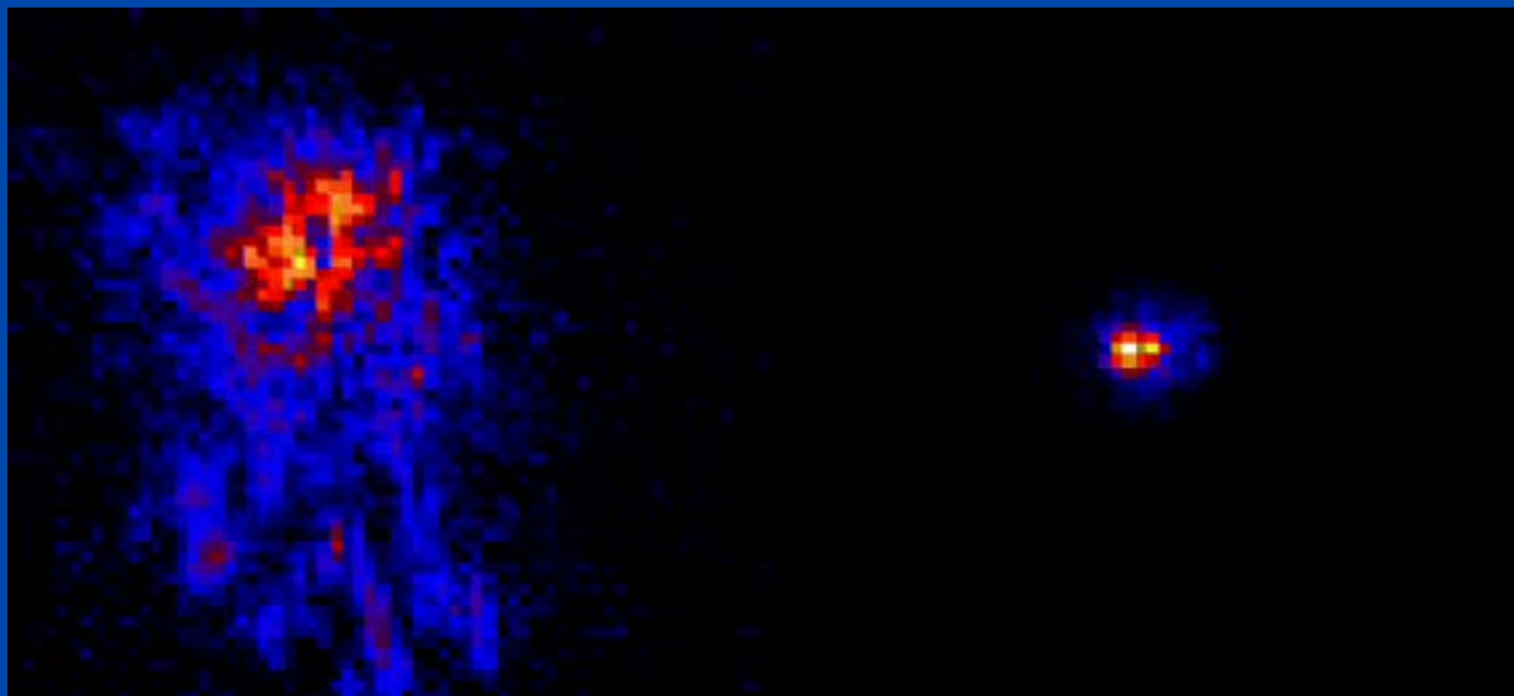
Measure details of blurring from "guide star" near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed



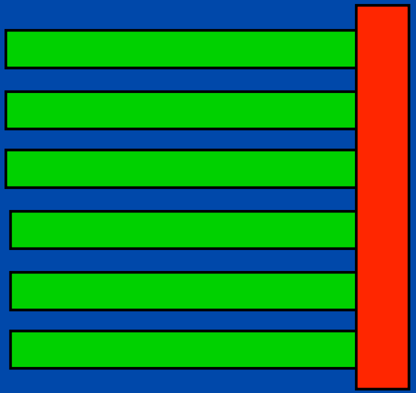
Infra-red images of a star, from Lick Observatory adaptive optics system



No adaptive optics **With adaptive optics**

Deformable mirror is small mirror behind main mirror of telescope

Mirror changes its shape because actuators push and pull on it



- **Actuators are glued to back of thin glass mirror**
- **When you apply a voltage to an actuator, it expands or contracts in length, pushing or pulling on the mirror**

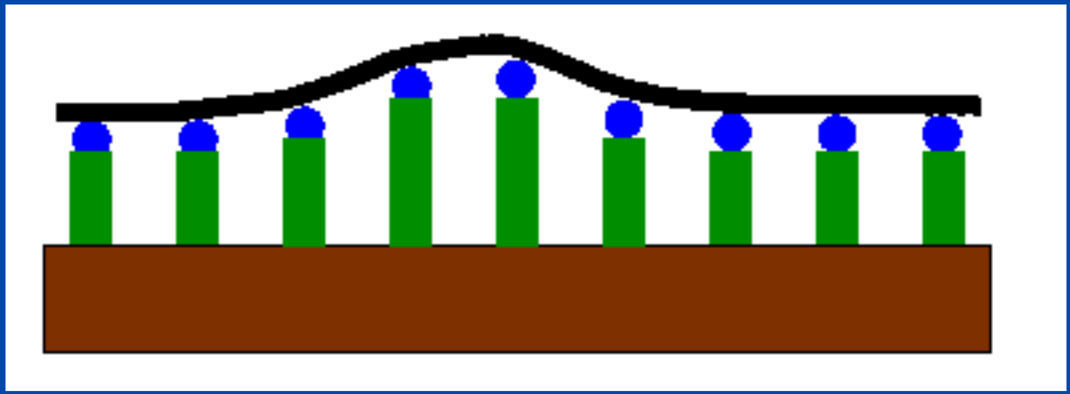
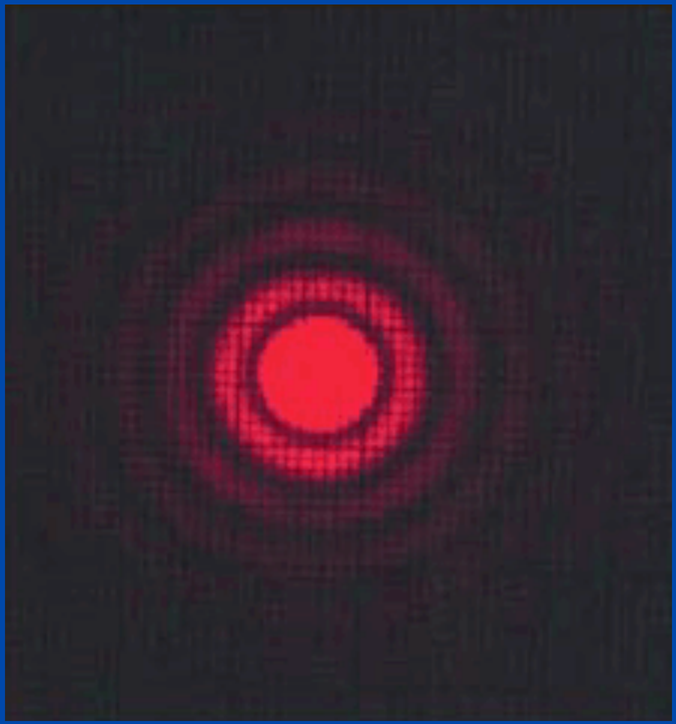
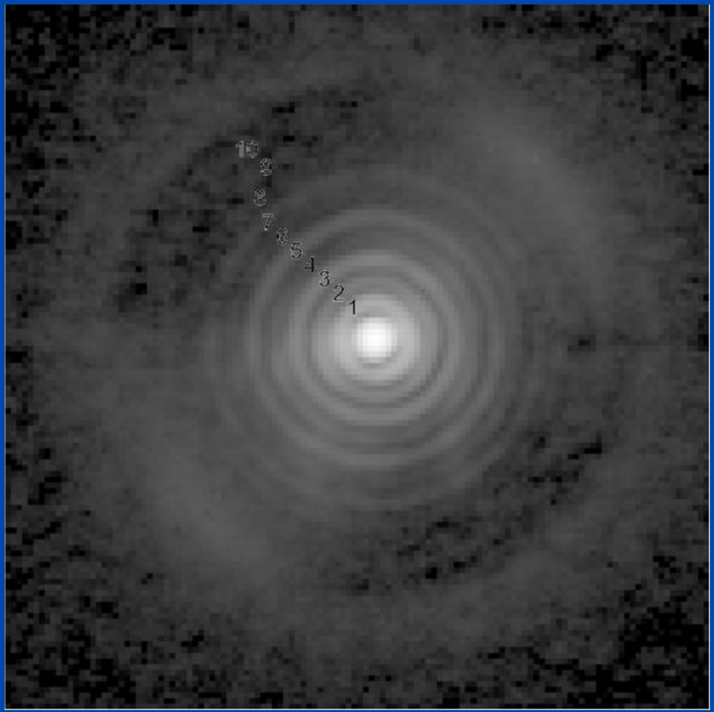


Image of a point source seen through a circular telescope mirror

- At the "diffraction limit", size of central spot ~ λ / D



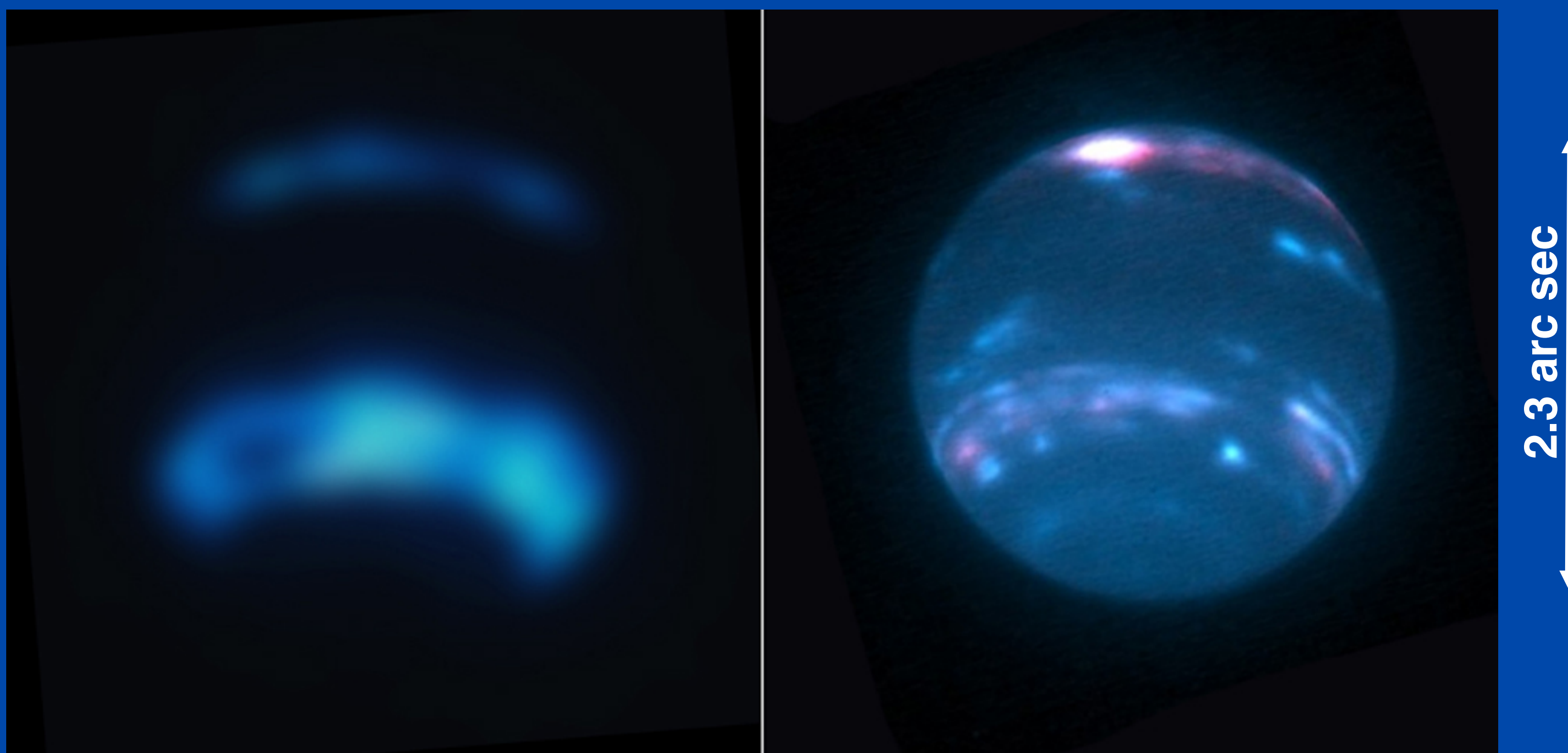


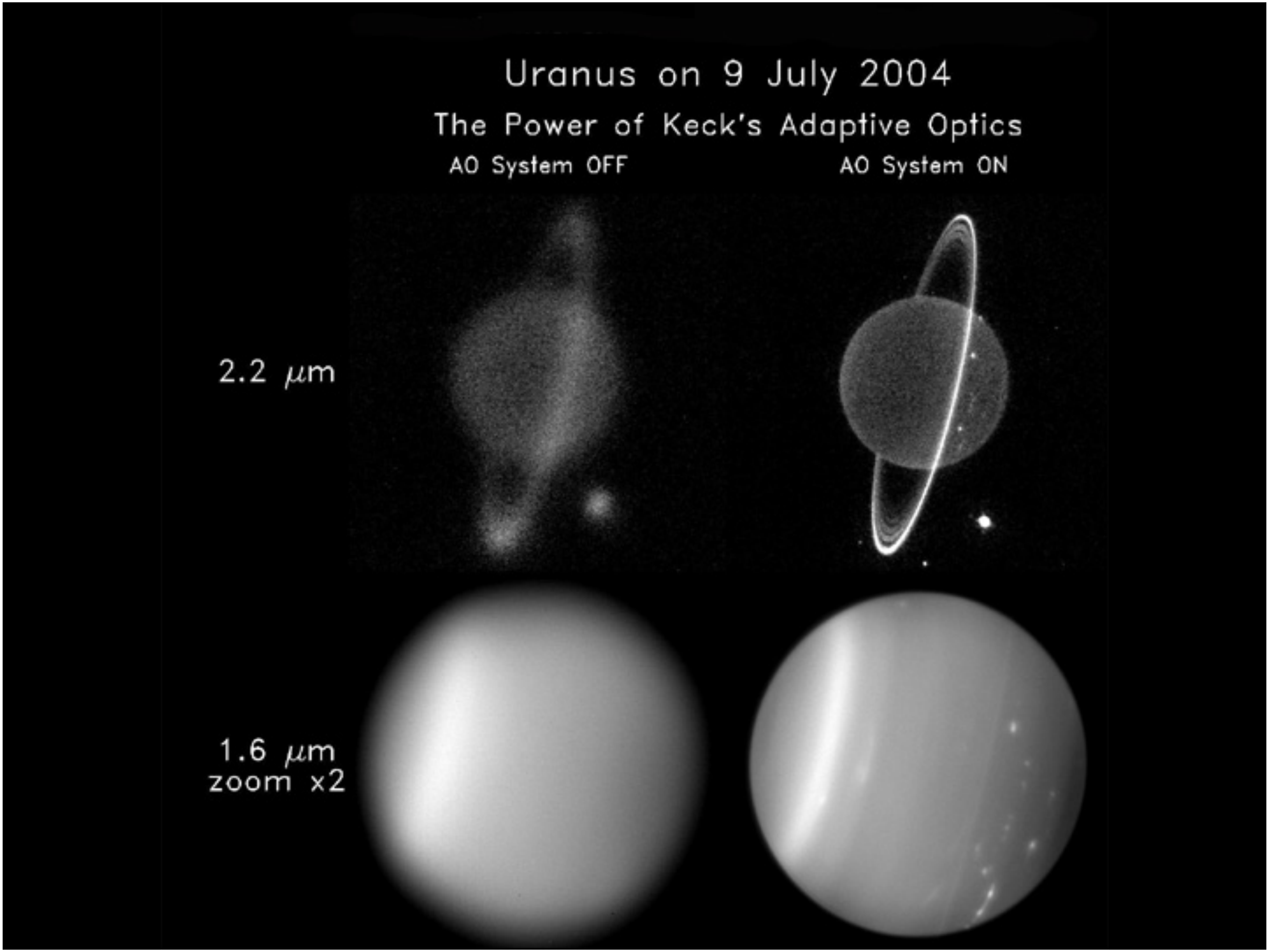
Diffraction limit animation

LBT Telescope with Adaptive Optics

Neptune in infra-red light, Keck Telescope adaptive optics

Without adaptive optics **With adaptive optics**




Uranus on 9 July 2004
The Power of Keck's Adaptive Optics
AO System OFF
AO System ON
2.2 μm
1.6 μm
zoom x2

Concept Question

- The Keck Telescope in Hawaii has a diameter of 10 m, compared with 5 m for the Palomar Telescope in California. The light gathering power of Keck is larger by a factor of

  a) 2   b) 4   c) 15   d) 50

- By what factor is Keck's angular resolution better than that of Palomar, assuming that both are using their adaptive optics systems?

  a) 2   b) 4   c) 15   d) 50

How can we observe invisible light?

- **A standard satellite dish is just a reflecting telescope for observing radio waves.**

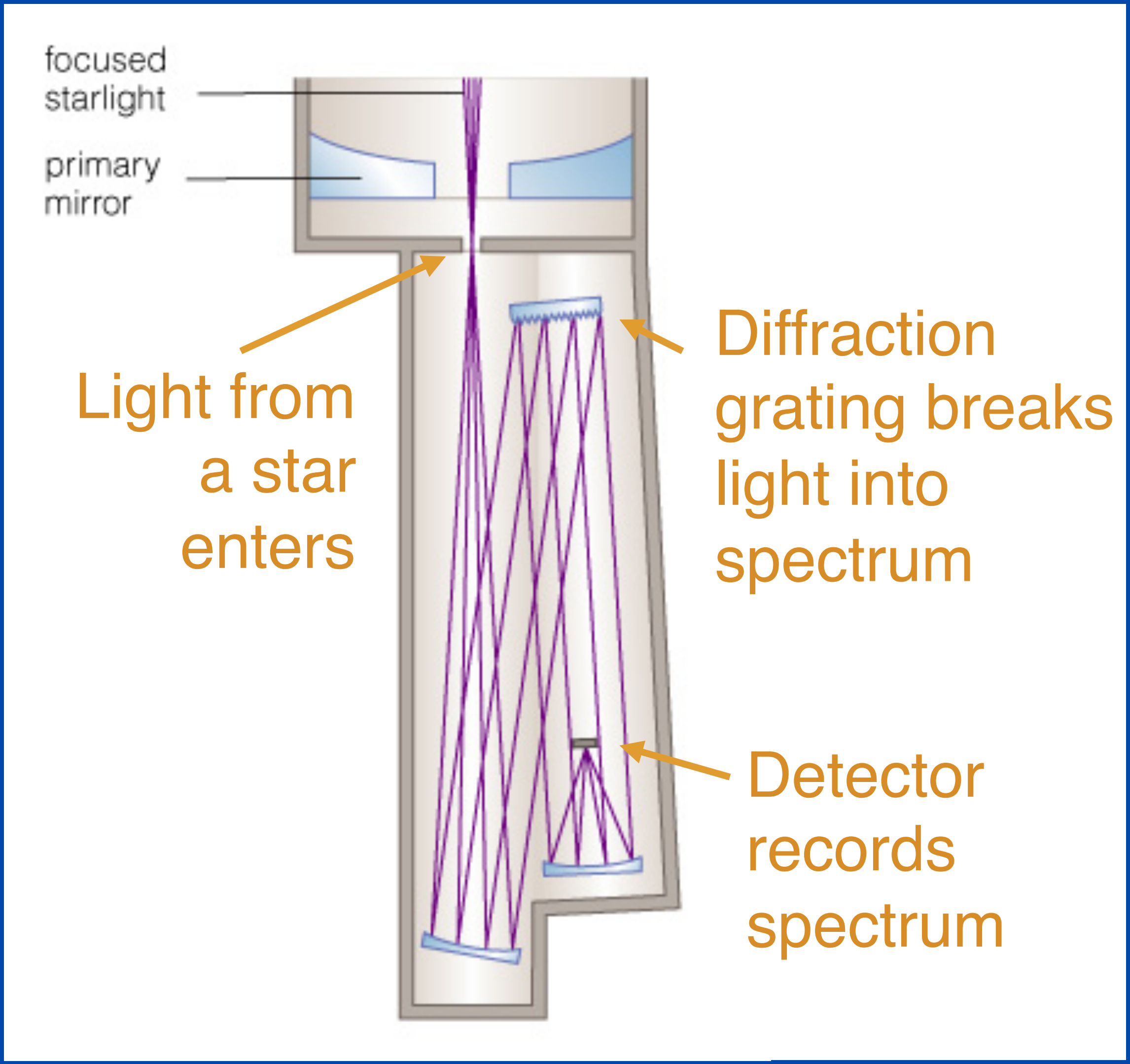
Reflecting telescopes work fine at radio wavelengths too

- **The radio telescope at Green Bank, NC**

Largest radio telescope fills a whole valley in Puerto Rico

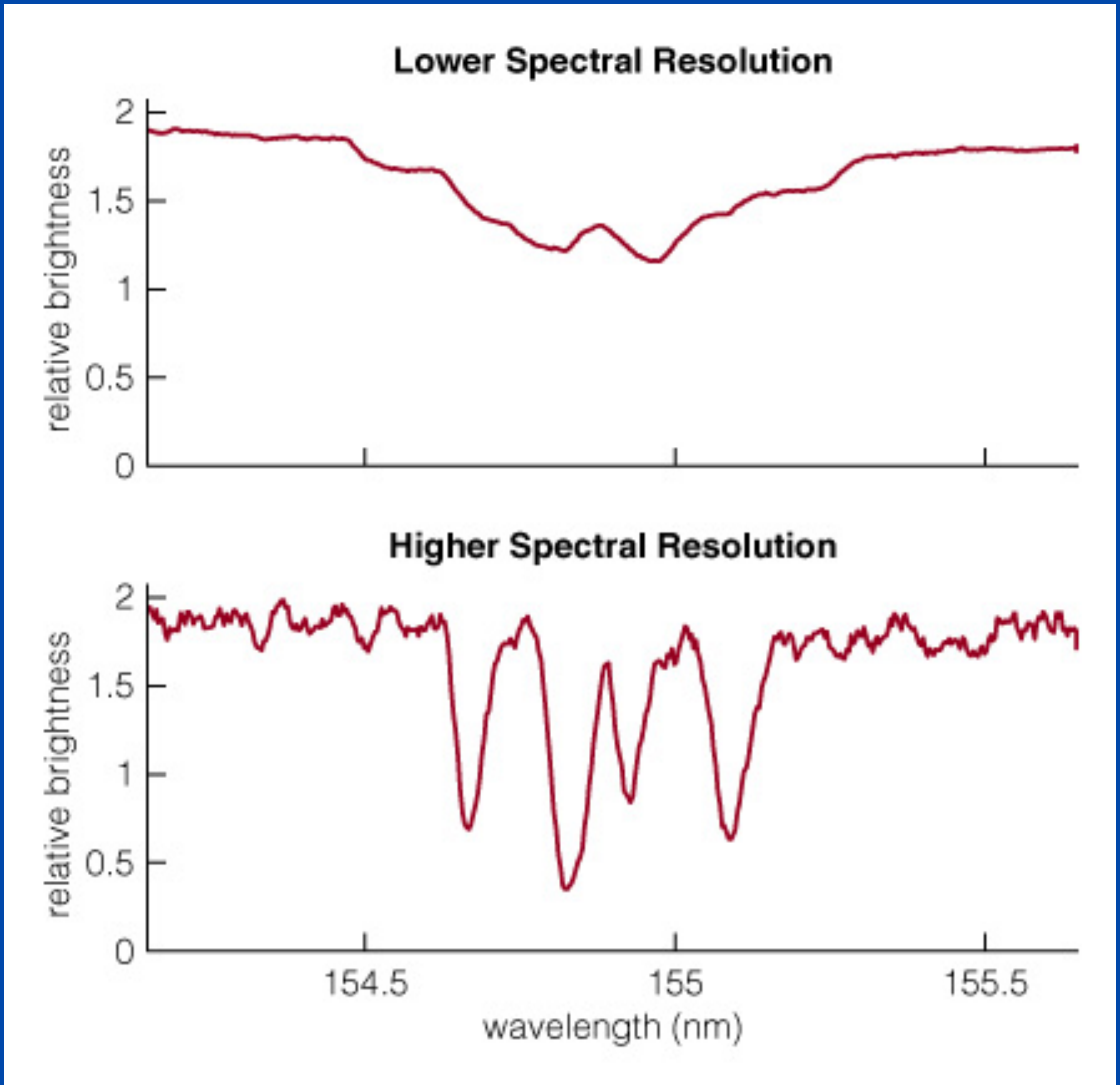
Arecibo Observatory

Spectroscopy



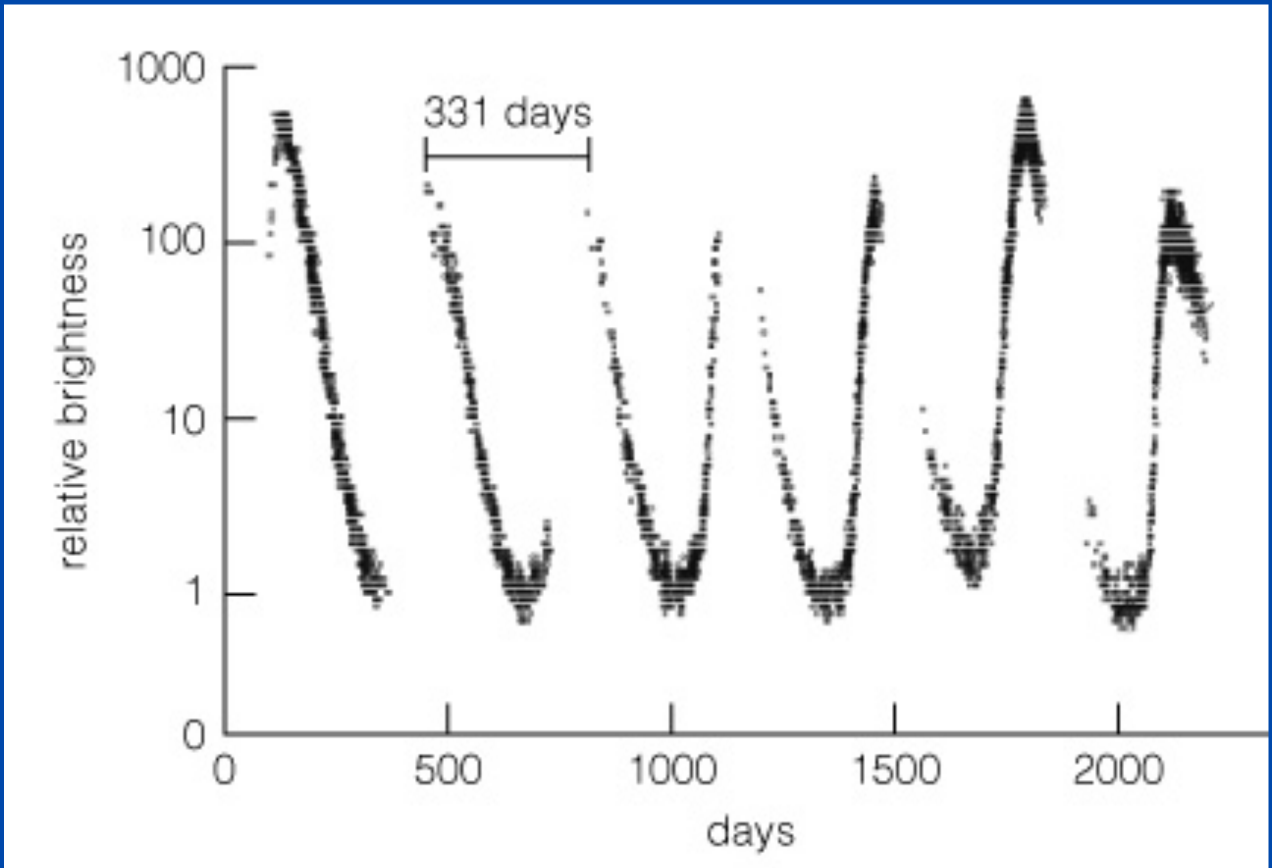
- A spectrograph separates the different wavelengths of light before they hit the detector

Spectroscopy and the effect of spectral resolution



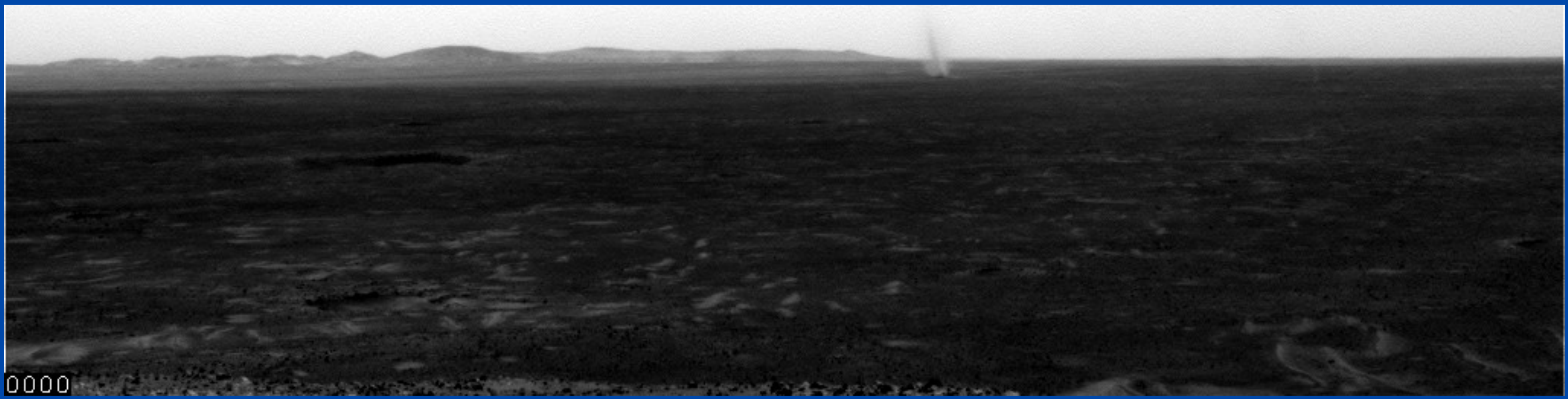
- **Graphing relative brightness of light at each wavelength shows the details in a spectrum**
- **Higher spectral resolution = more detail as a function of wavelength**

Timing



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

Timing: Dust devils on Mars seen from Spirit Rover



Want to buy your own telescope?

- Buy binoculars first (e.g. 7x35) - you get much more for the same money.
- Ignore magnification (sales pitch!)
- Notice: aperture size, optical quality, weight and portability.
- Product reviews: Astronomy, Sky & Telescope, Mercury Magazines. Also amateur astronomy clubs.
- (Probably best to avoid cheap telescopes that you see in department stores or Big Box stores)

Why do we need telescopes in space?

Why do we need telescopes in space?

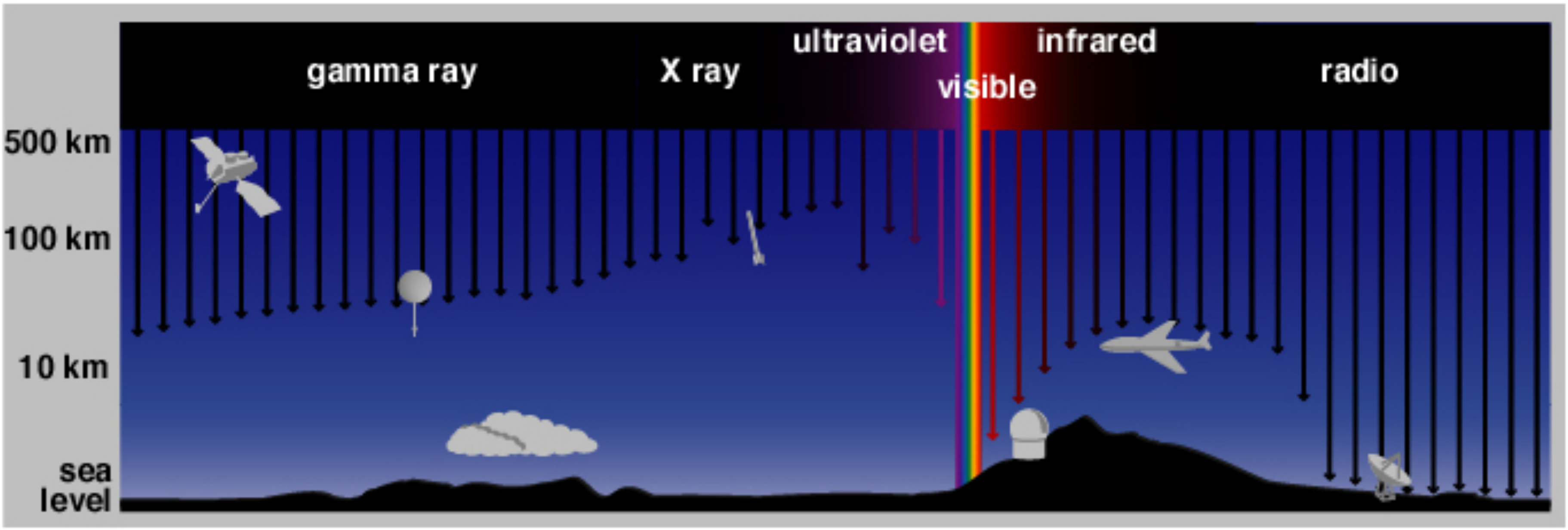
a) Some wavelengths of light don't get through the Earth's atmosphere

- Gamma-rays, x-rays, far ultraviolet, long infrared wavelengths

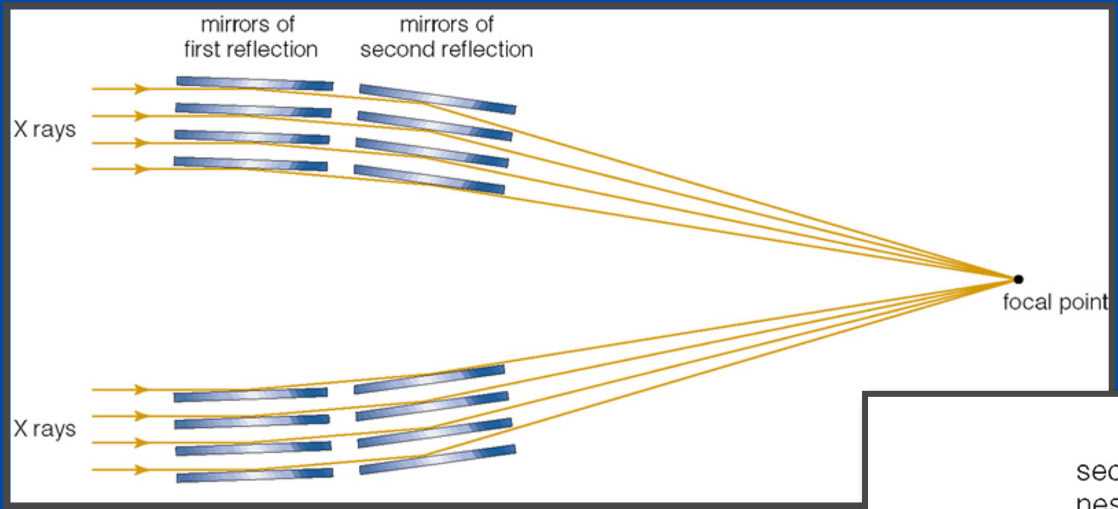
b) Going to space is a way to overcome blurring due to turbulence in Earth's atmosphere

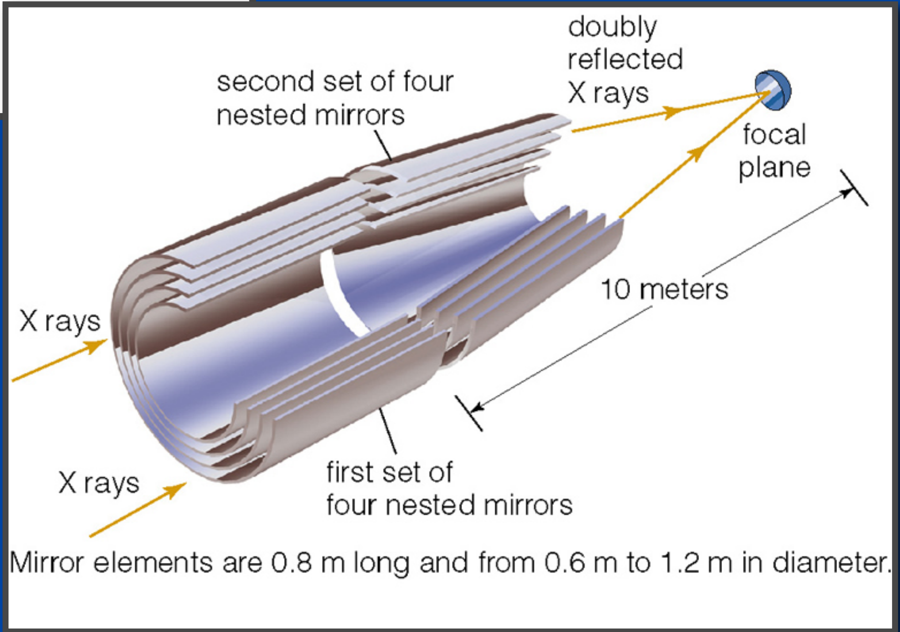
c) Planetary exploration: spacecraft can actually go to the planets, get close-up information

Depth of light penetration into atmosphere at different wavelengths



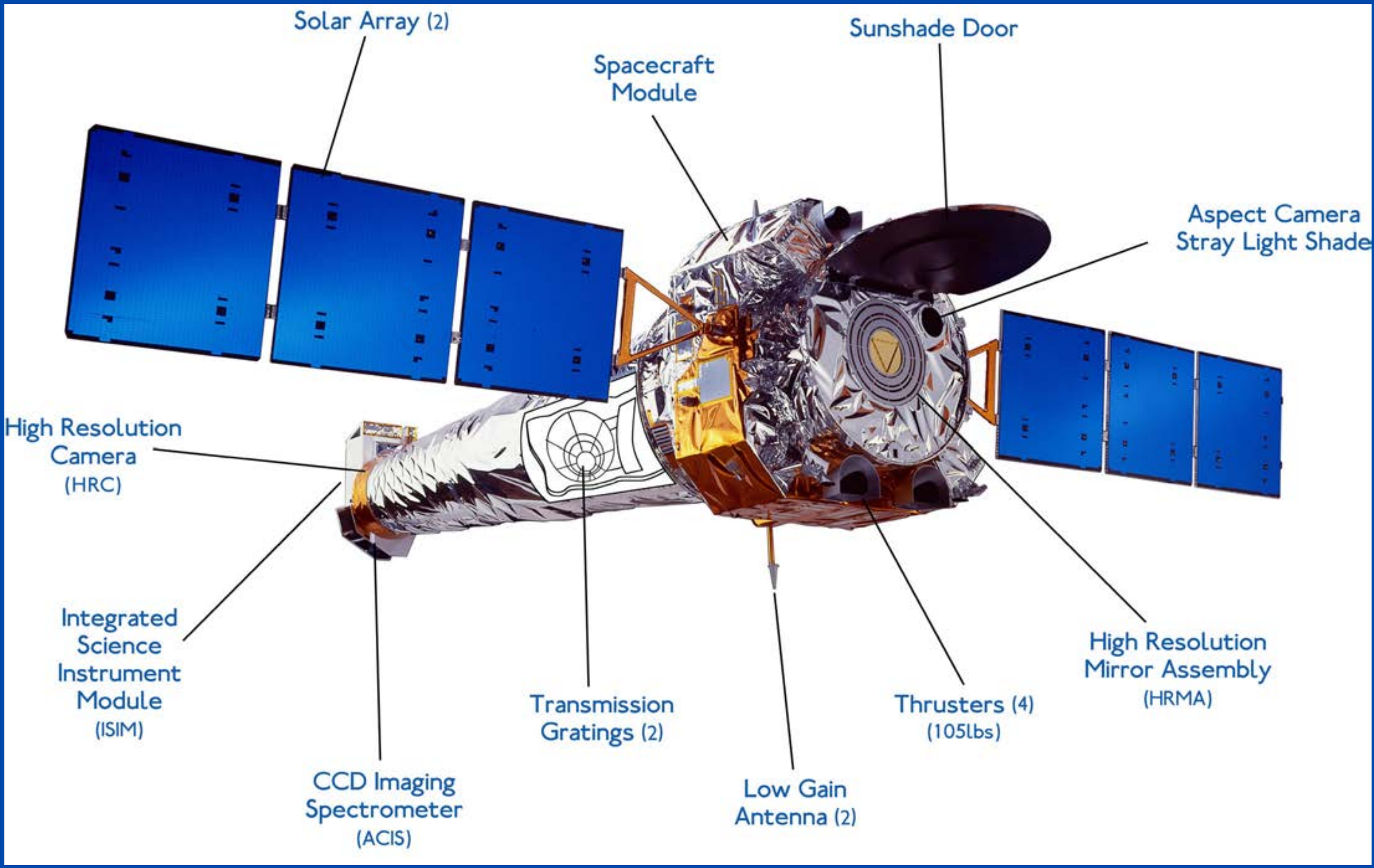
X-ray mirrors also concentrate light and bring it to a focus





- X-ray mirrors

Chandra spacecraft: x-ray telescope



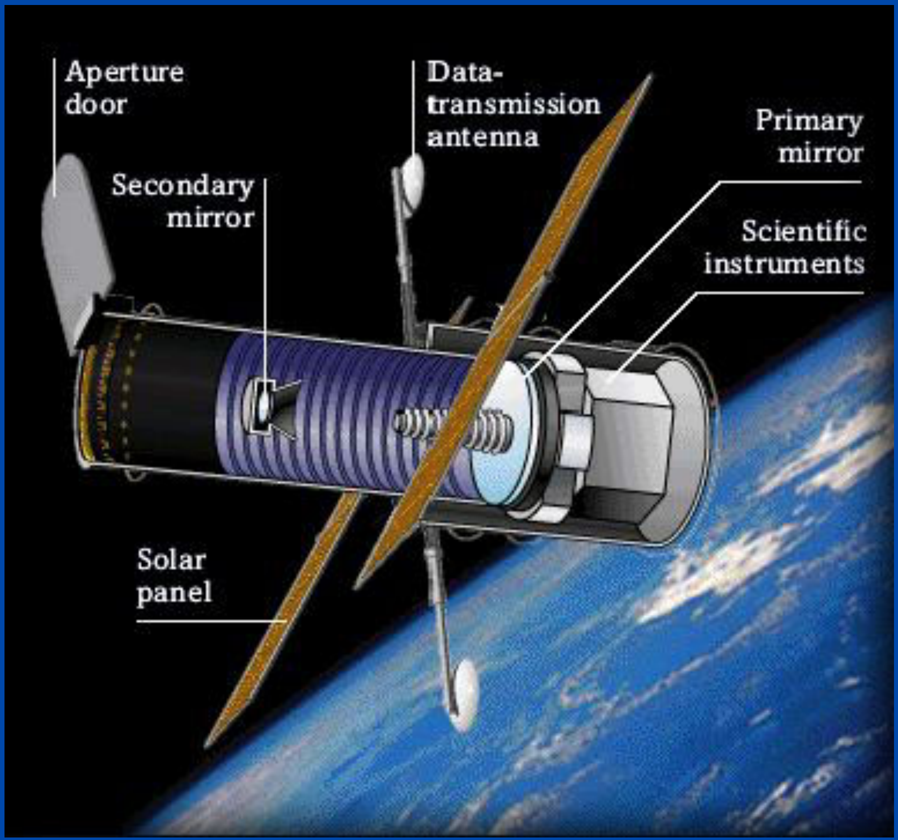
Types of space missions

- Earth orbiters
  - Hubble, Chandra space telescopes
- Planetary fly-bys
  - Mercury, Venus, Mars, Jupiter, Saturn, Uranus, Neptune so far
  - New Horizons flyby of Pluto arrives there July 14 2015
- Planetary orbiters
  - Venus, Mars, Jupiter, Saturn so far.
  - Soon: Mercury Messenger March 2011
- Probes and landers
  - Mars rovers: Spirit and Opportunity
  - Mars landers: e.g. Phoenix
  - Probes sent from orbiters of Venus, Mars, Jupiter
  - Titan lander (Huygens probe from Cassini spacecraft)

Space missions carry telescopes, other instruments as well

- **Typically planetary fly-bys and orbiters carry small telescopes**
  - **If you are close, you don't need super-big telescope to get good angular resolution**
- **Other instruments:**
  - **Particle analyzers, radio antennae, spectrographs, laser altimeters, dust detectors, ...**
  - **Mars rovers: probes to get rock samples and analyze them**

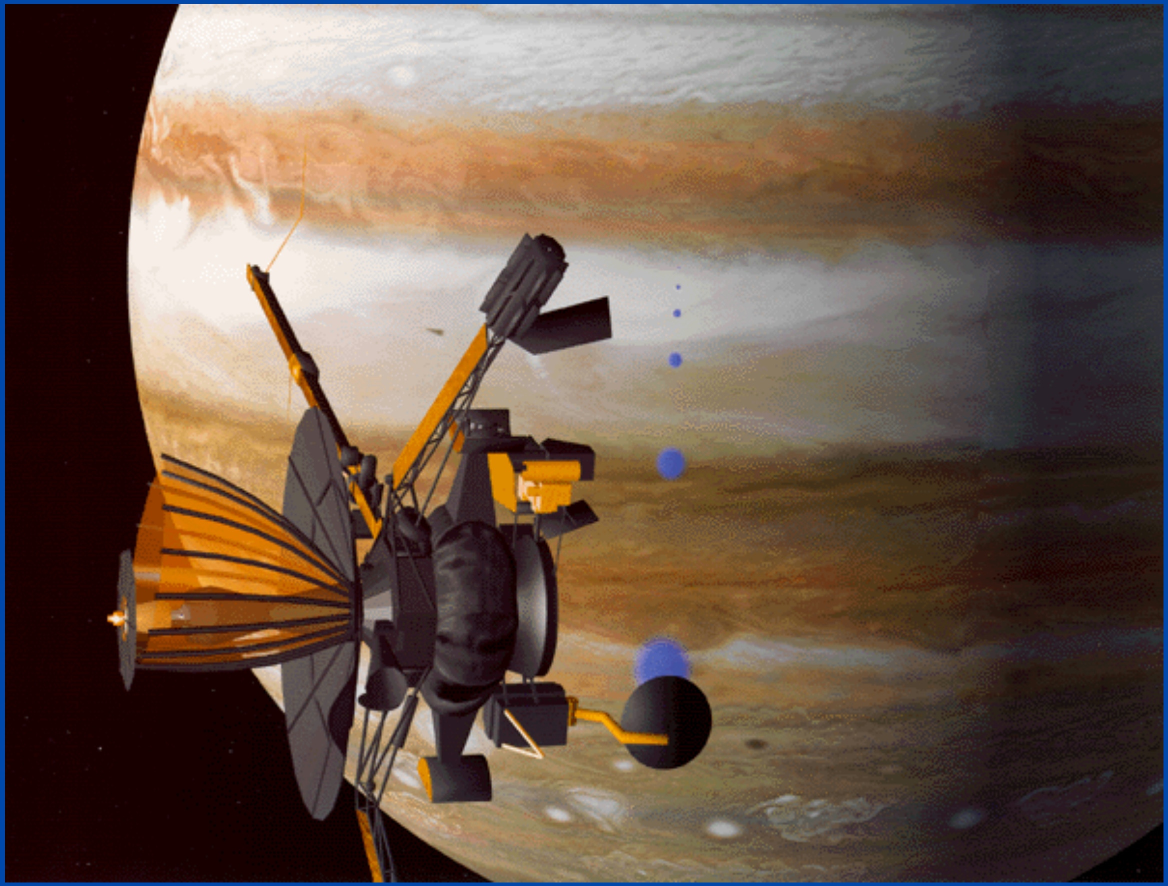
Hubble Space Telescope: clearer vision above atmospheric turbulence



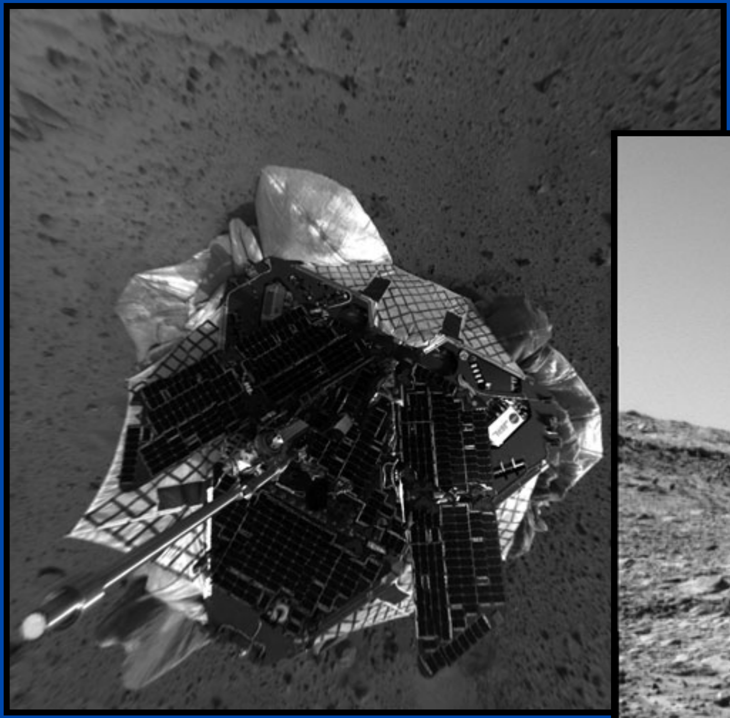
Hubble can see UV light that doesn't penetrate through atmosphere

Example of robotic planet exploration: Galileo mission to Jupiter

(Artist's conception)



Spirit Rover on Mars



Concept Question

- You are trying to decide whether to observe a new comet from a 10m telescope on the ground (without adaptive optics), or from the Hubble Space Telescope (diameter 2.4m).

- Which of the following would be better from the ground, and which from space

a) Ability to make images in ultraviolet light

b) Spatial resolution of images in infrared light

c) Ability to record images of a <u>very</u> faint (distant) comet

Telescopes: The Main Points

- Telescopes gather light and focus it
- Telescopes can be on ground, on planes, in space
- If Earth's atmosphere weren't turbulent, larger telescopes would give higher spatial resolution
  - Adaptive optics can correct for blurring due to turbulence
- Every new telescope technology has resulted in major new discoveries and surprises