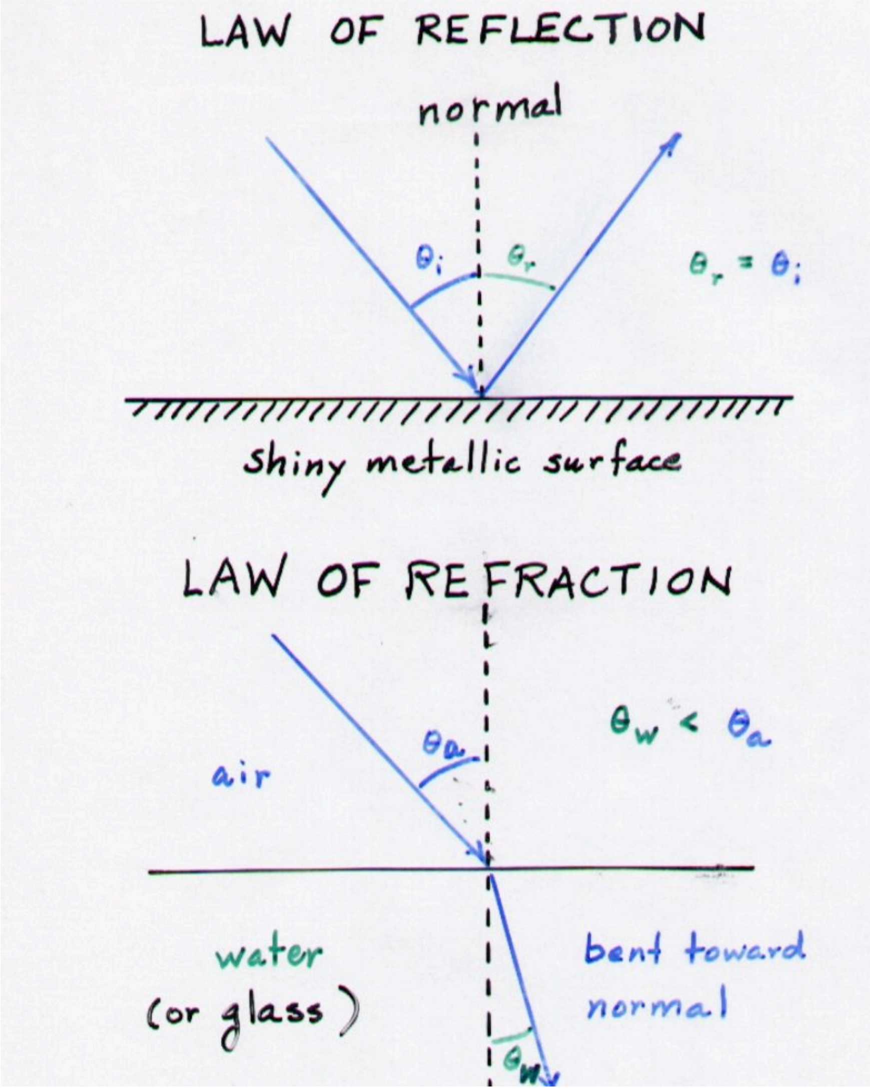
Lecture 9

Telescopes & Light

Outline of Lecture 9

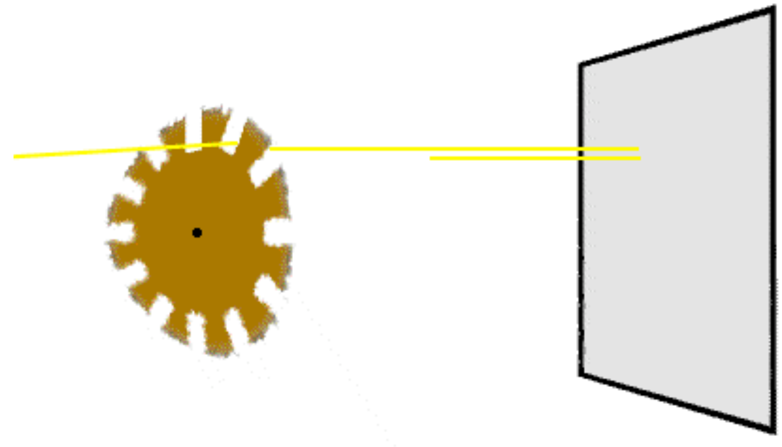
- Nature of Light:
  - Laws of refraction and reflection.
  - Wave versus particle picture of light.
  - The speed of light & Roemer’s observations of Galilean satellites
- Refracting versus reflecting telescopes:
  - Newton’s dissatisfaction with chromatic aberration of refracting telescopes.
  - Newton’s discovery of dispersion of white light into spectrum of colors.
  - Newton’s invention of a reflecting telescope.
- Angular resolution:
  - Astronomical seeing and diffraction limit.
  - Adaptive optics.
  - Aperture synthesis.

Reflection & Refraction

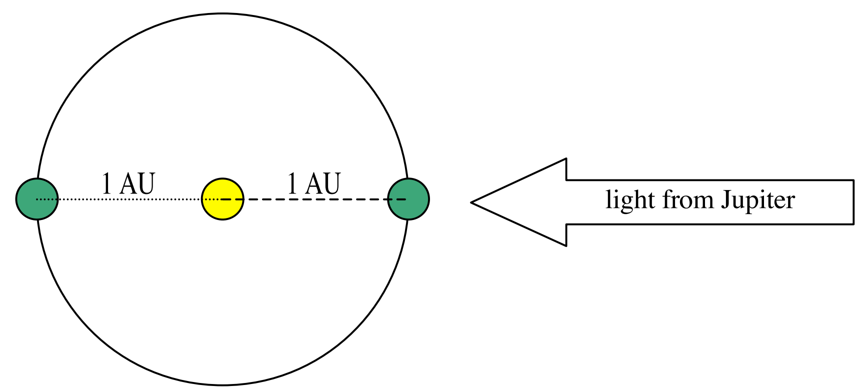


Speed of Light & Value of AU

- Galileo attempts to measure the speed of light. Eventual success with Fizeau in 1849: $c = 3.00 \times 10^{8}$ m s^{-1} (in vacuum).
- Galileo suggests using transits/eclipses of moons of Jupiter as clock for determining longitude at sea (cf. concept of time zones).
- Ole Roemer (1644-1710) tries to get very accurate predictions of when transits/eclipses will occur. Find discrepancies of about 1000 s depending on whether Jupiter is in conjunction or opposition from the Sun. Concludes diameter of circular orbit of Earth around Sun = 1000 lt-sec (i.e., light takes 1000 s to traverse 2 AU).
- With Fizeau's value for *c*, 1 AU = 500 lt-sec = 1.50×10^{11} m.

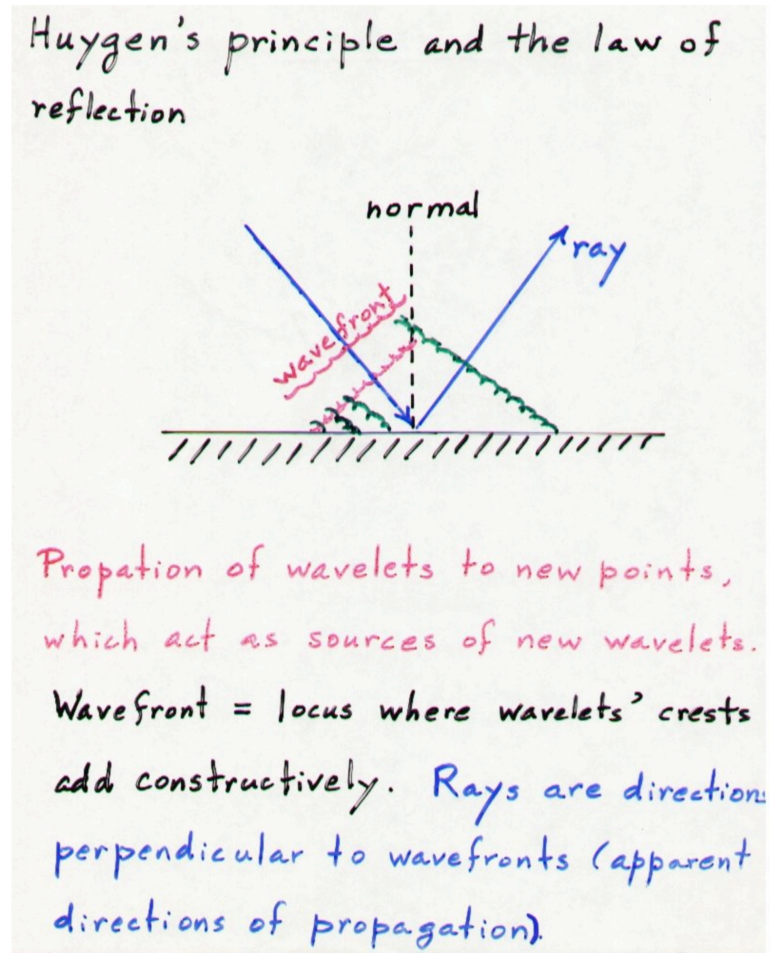


Prentice-Hall

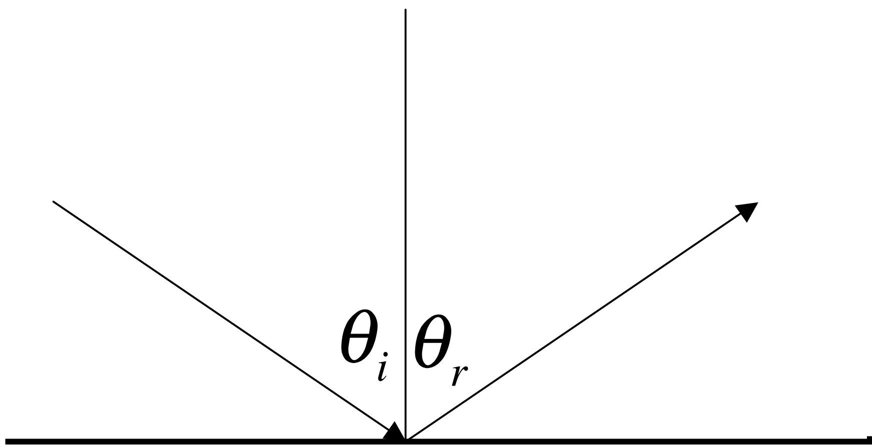


Nature of Light

- Huygens: Light is a *wave*, whose influence propagates by spreading from point to point, reinforcing or destroying the influence of other waves.
- Newton: Light is a *particle* (termed by Newton, a *corpuscle*), which propagates in a straight line from point to point, unless it *reflects* from obstacles, or *refracts* upon entering a different medium inside of which it slows down or speeds up. Rays are paths traced by particles of light.



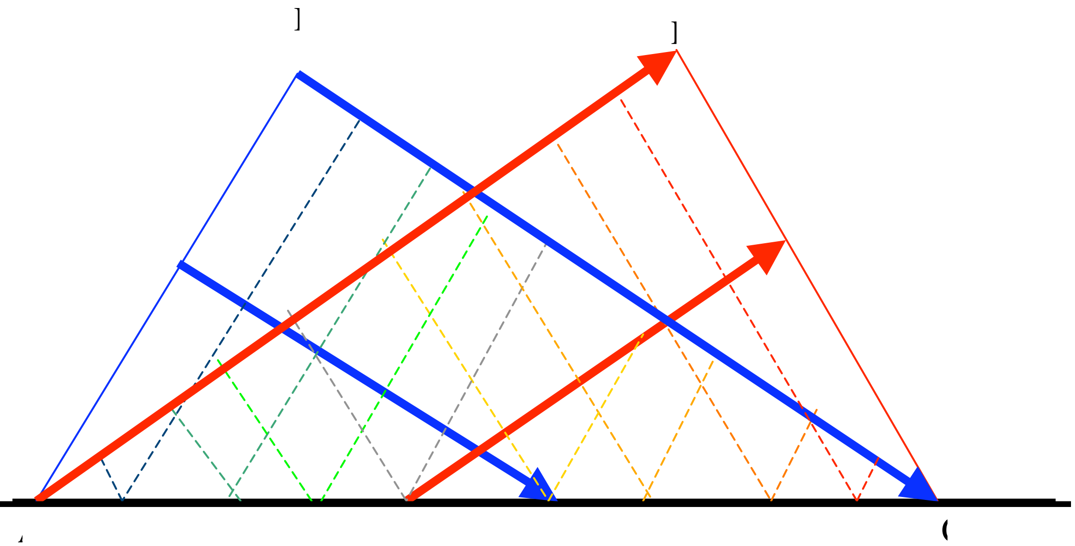
Reflection



Corpuscular reflection

$$\theta_r = \theta_i$$

for an elastic bounce in which perpendicular velocity is reversed.

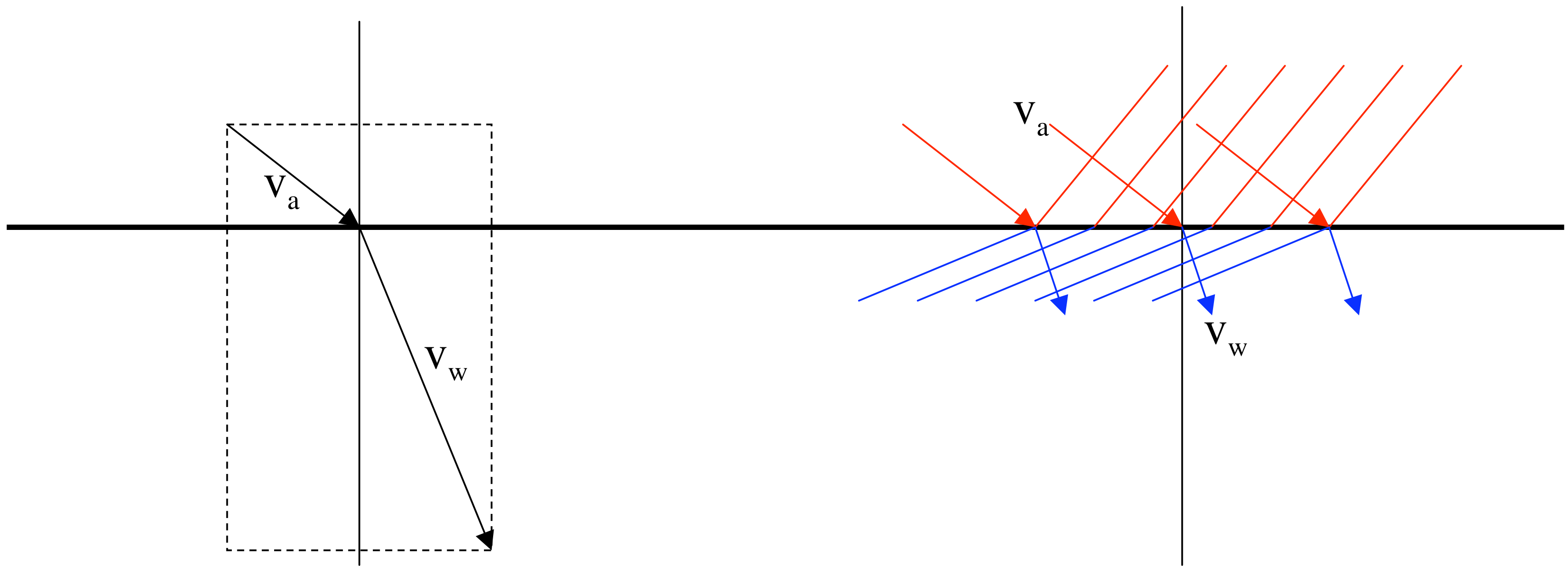


Wave reflection from (infinite) mirror according to Huygen's principle also gives

$$\theta_r = \theta_i$$

No difference because of light is propagating in same medium (air) before and after reflection.

Refraction

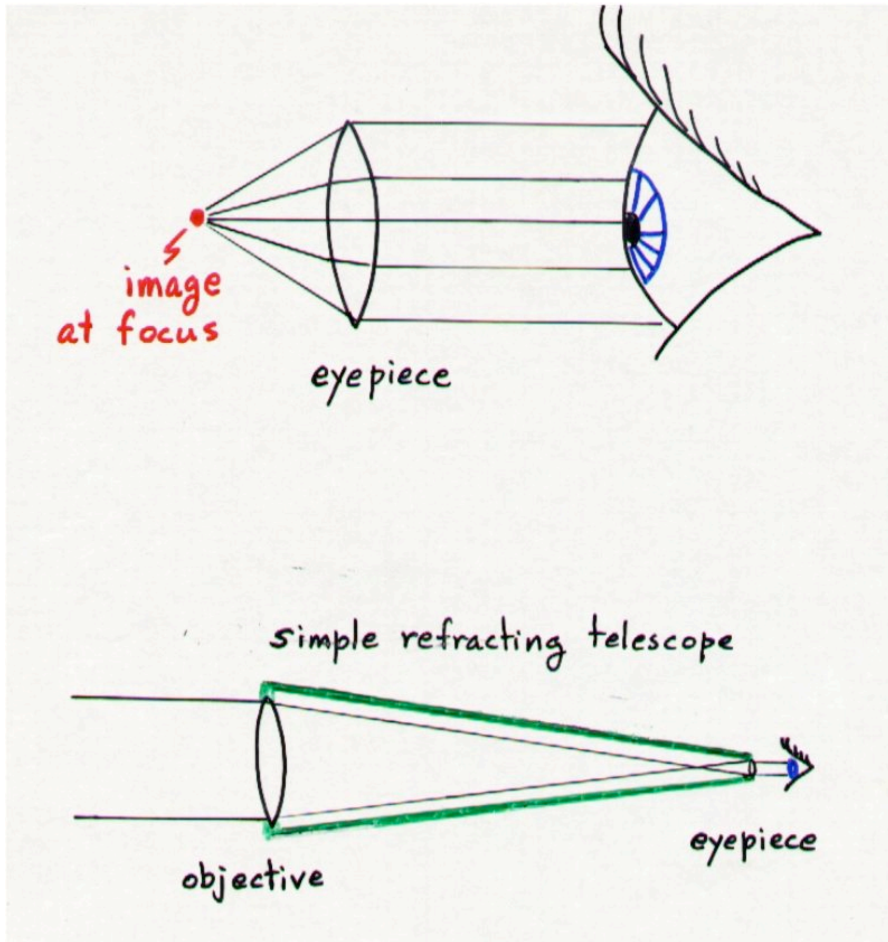


To explain observed behavior, speed of light corpuscle in water v_w must be greater than its speed in air v_a.

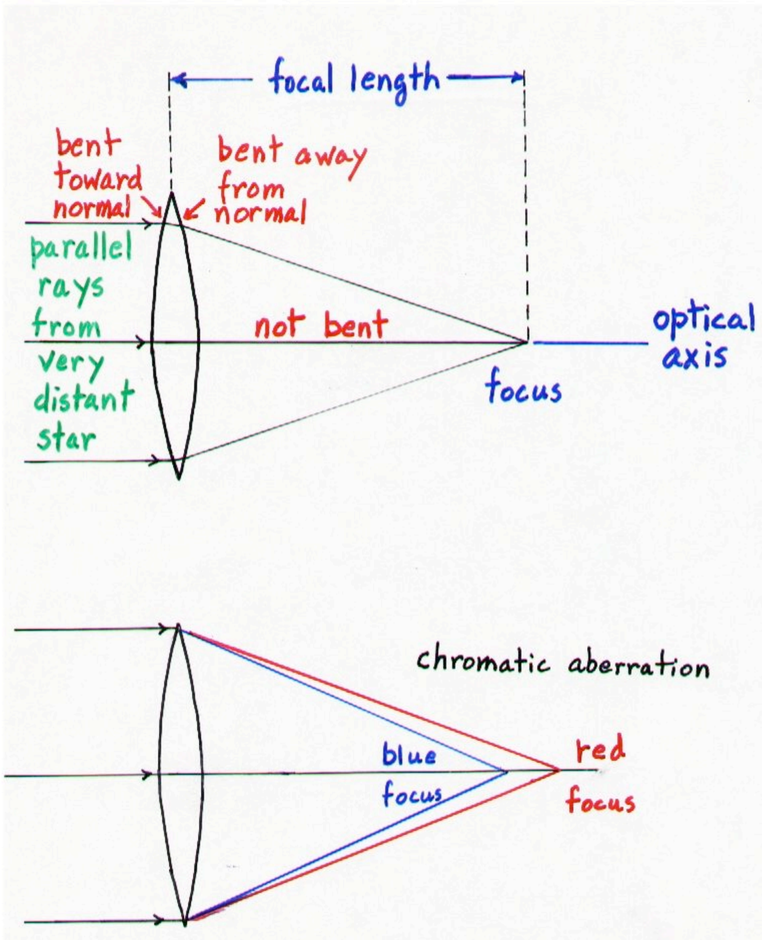
To explain observed behavior, speed of light wave in water v_w must be smaller than its speed in air v_a.

Now known that $v_w < v_a$, which favors wave theory of light

Lens as Eyepiece and Simple Refracting Telescope

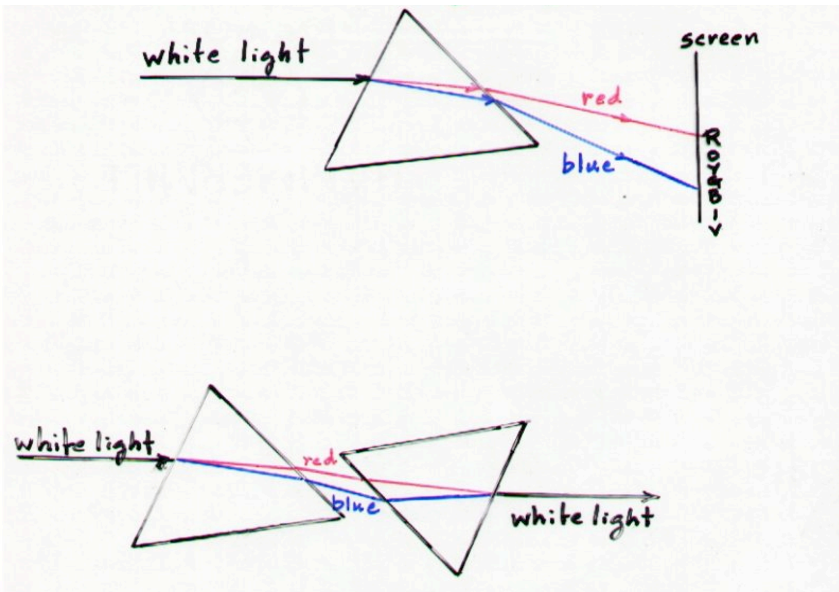


Principle of Lens



Natural Light Is Made of Spectrum of Colors

Dispersion of white light by a prism:



Newton's use of two prisms shows that colors were not added by prism to colorless (white) light. Instead color is an intrinsic part of the different components of light. (Natural light contains a *spectrum*.)

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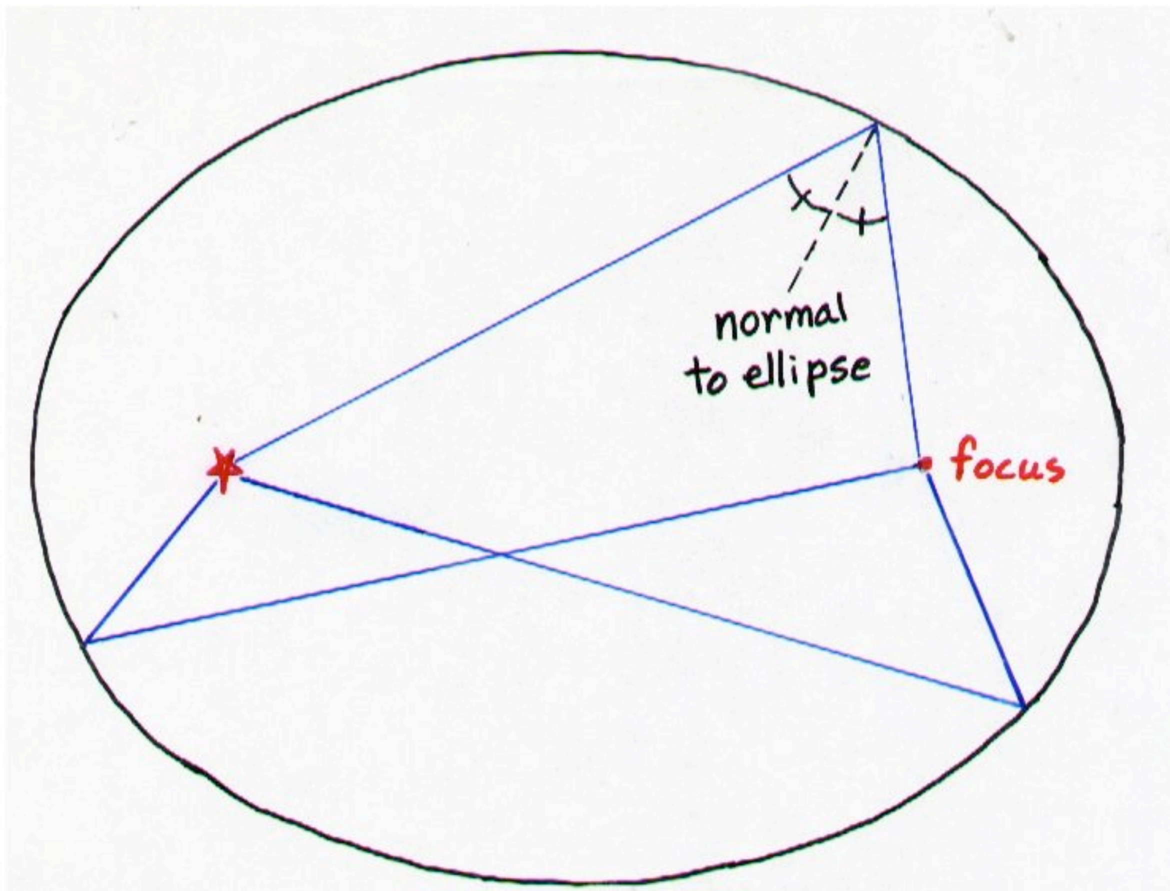
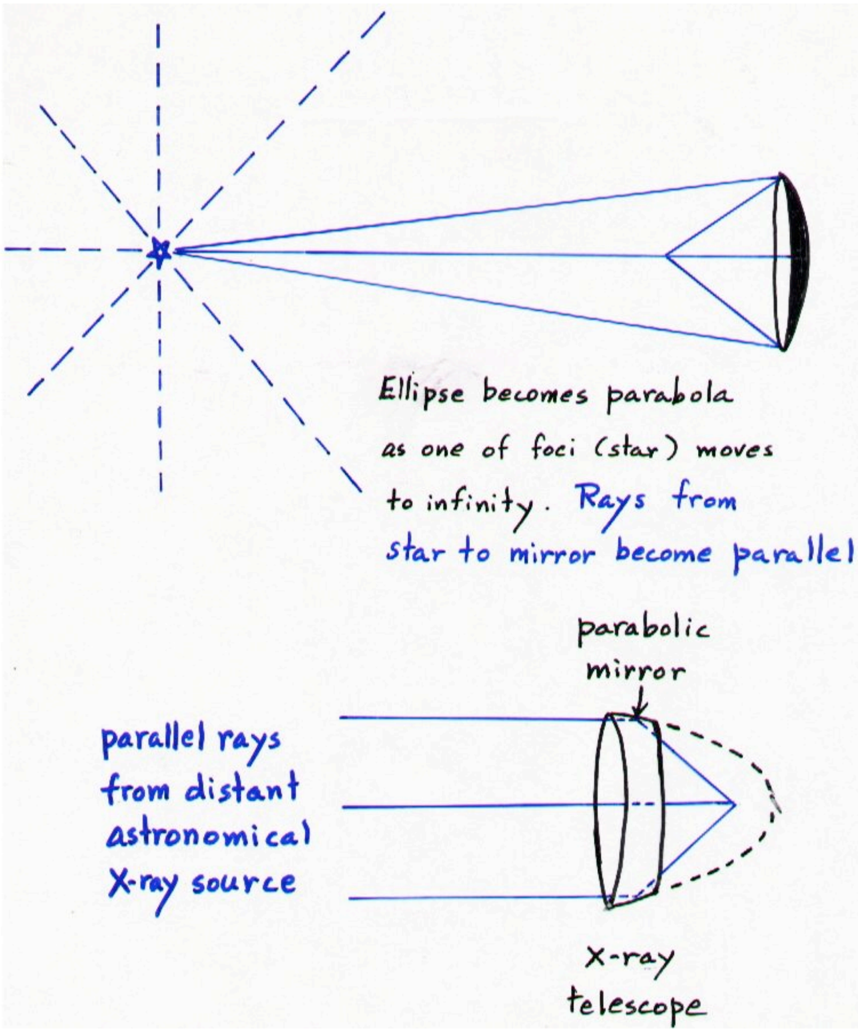
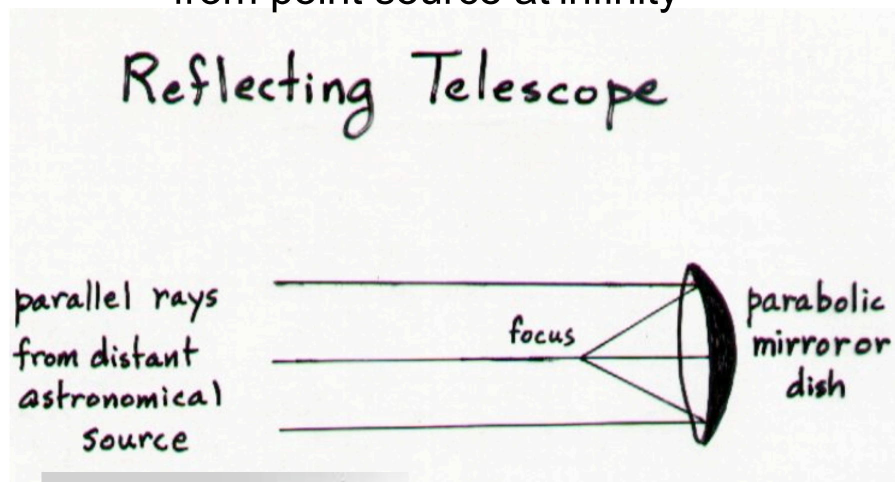
Alhazen (965-1040): Ellipse Brings Light from One Focus to Other Focus



When Source Moves to Infinity, Needed Ellipse Becomes Parabola



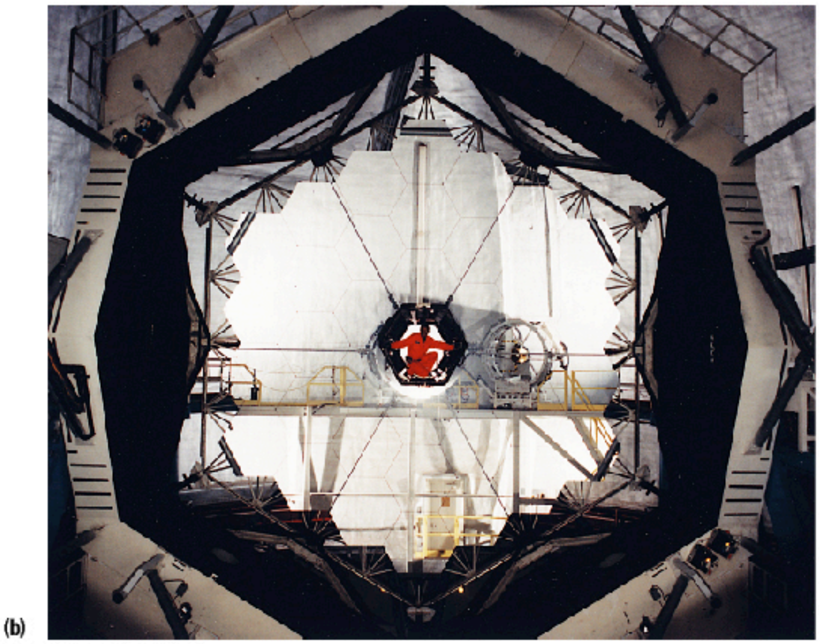
Parabolic mirror focuses light from point source at infinity

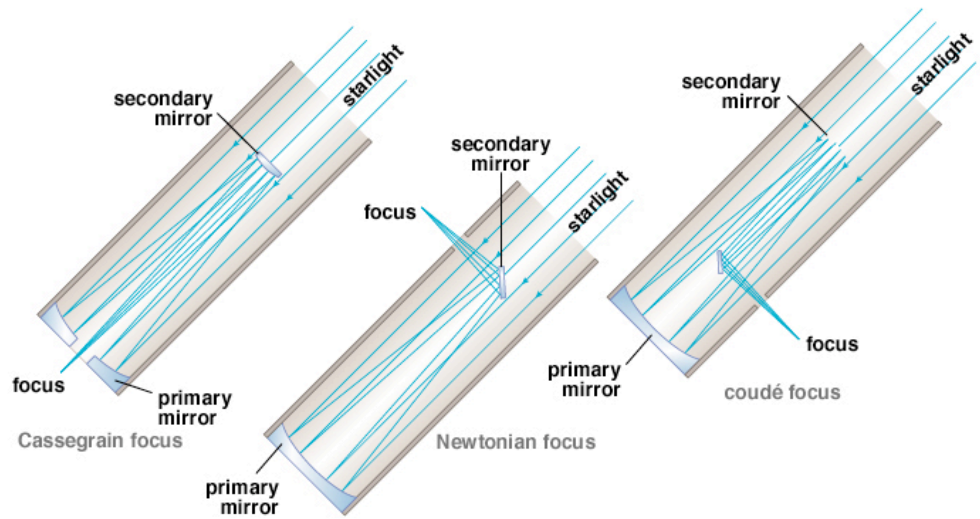


Note viewing is at Newtonian focus

Newton's reflector

All Large Telescopes Built Today Are Reflectors

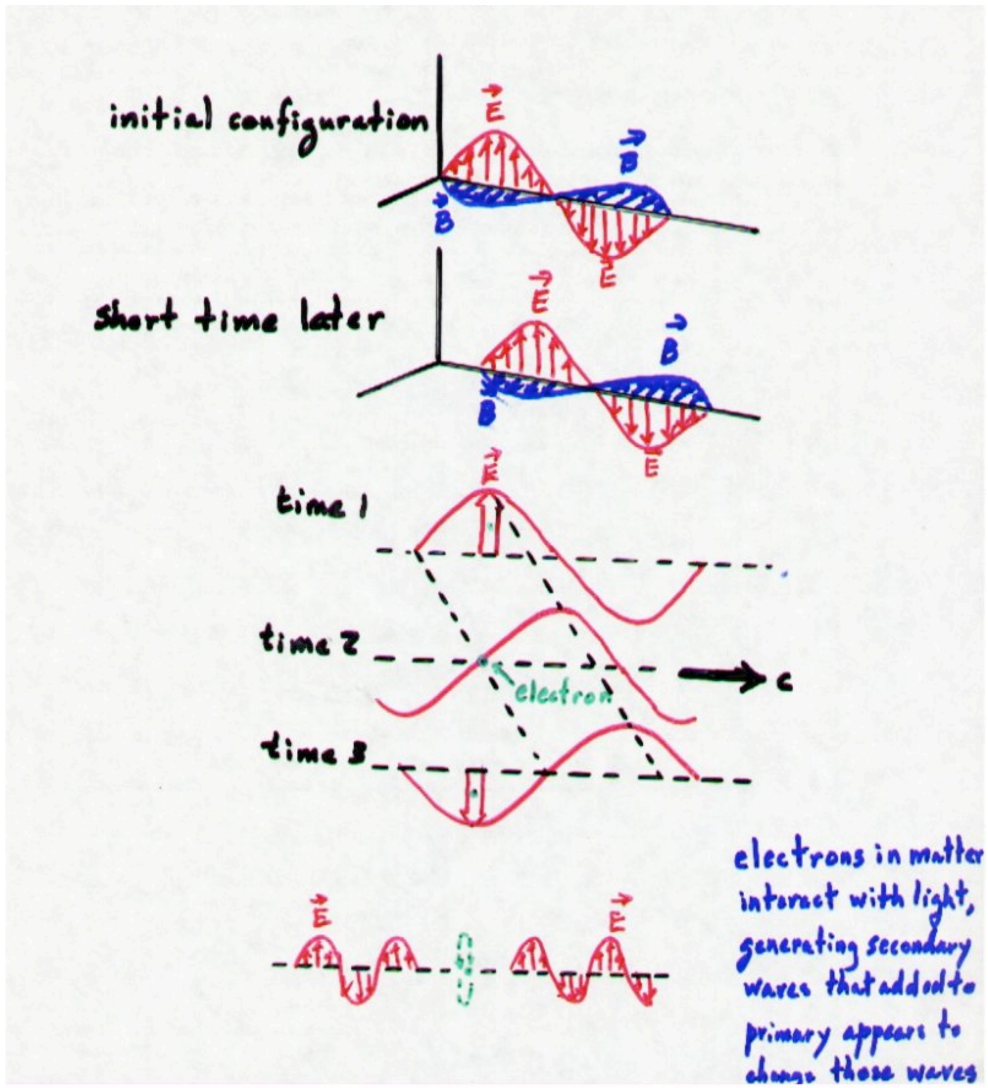




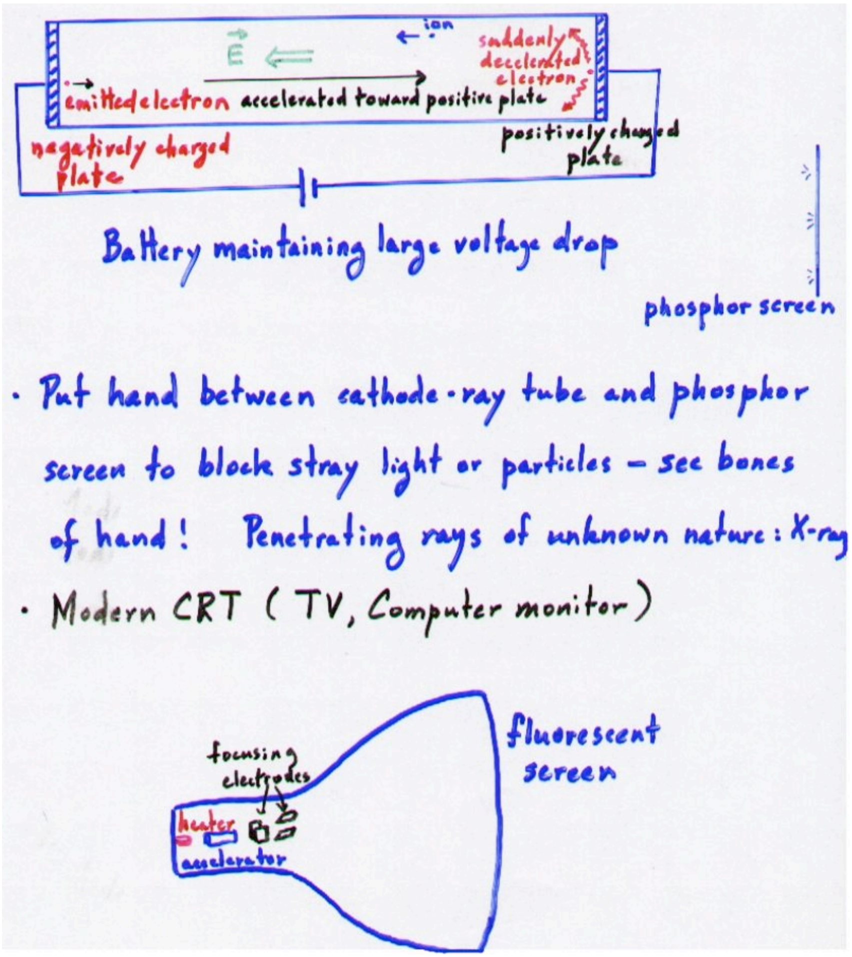
Keck telescope with 36 parabolic segments = 10 m mirror

Possible focal arrangements, apart from prime focus in front, for a modern telescope

Huygen's Principle from How a Charged Particle Interacts with Light (extra material)

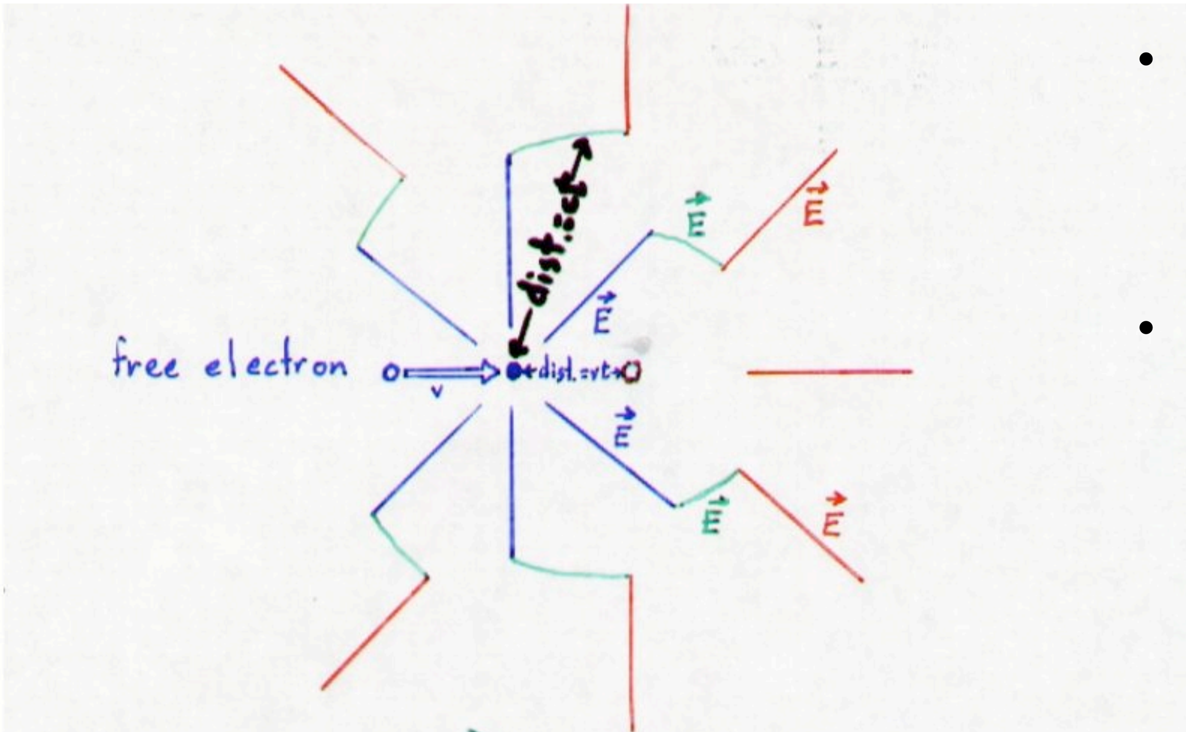


Discovery of X-Rays by Roentgen (1845-1928)



Harvard Medical School

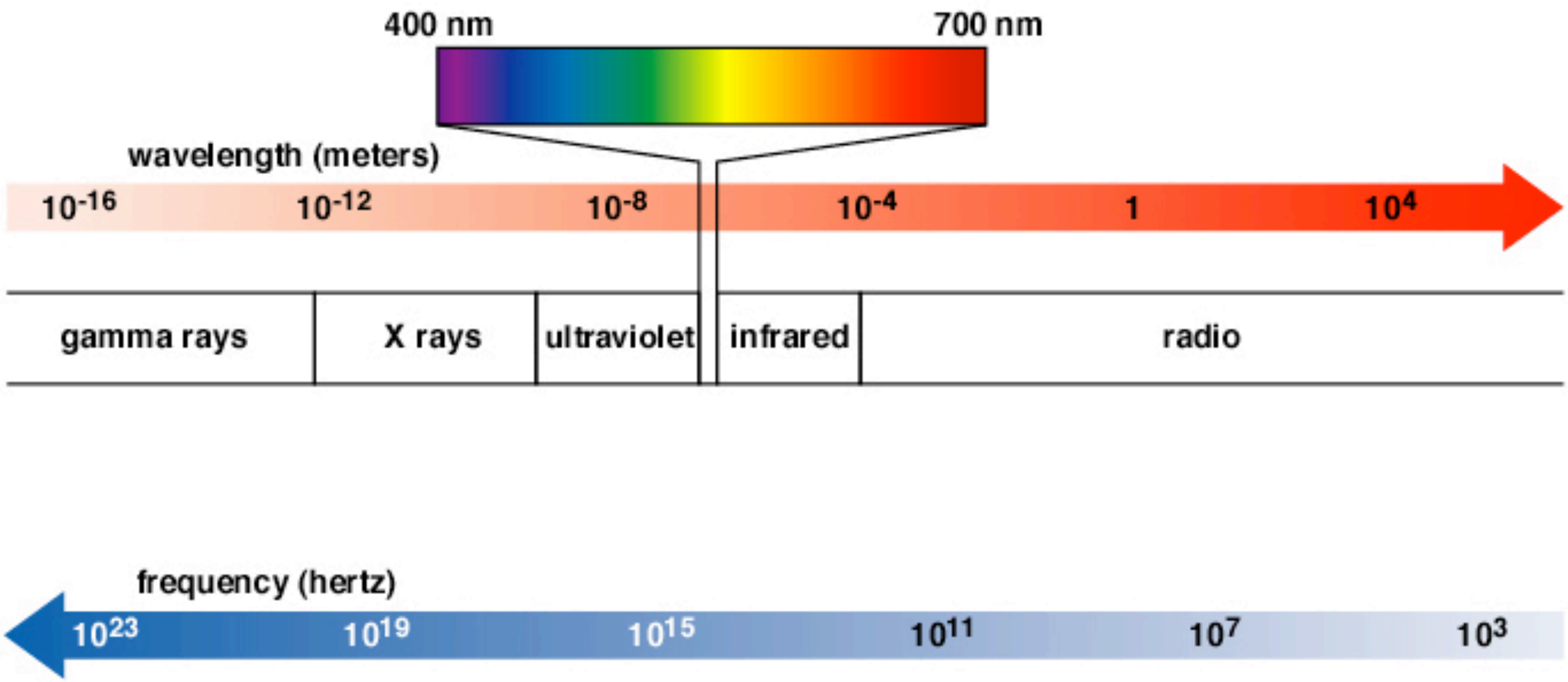
Radiation from a Suddenly Stopped Charge (extra material)



Pulse of transverse $\vec{E}$ that races radially outward from position of stopped charge at speed of light c.

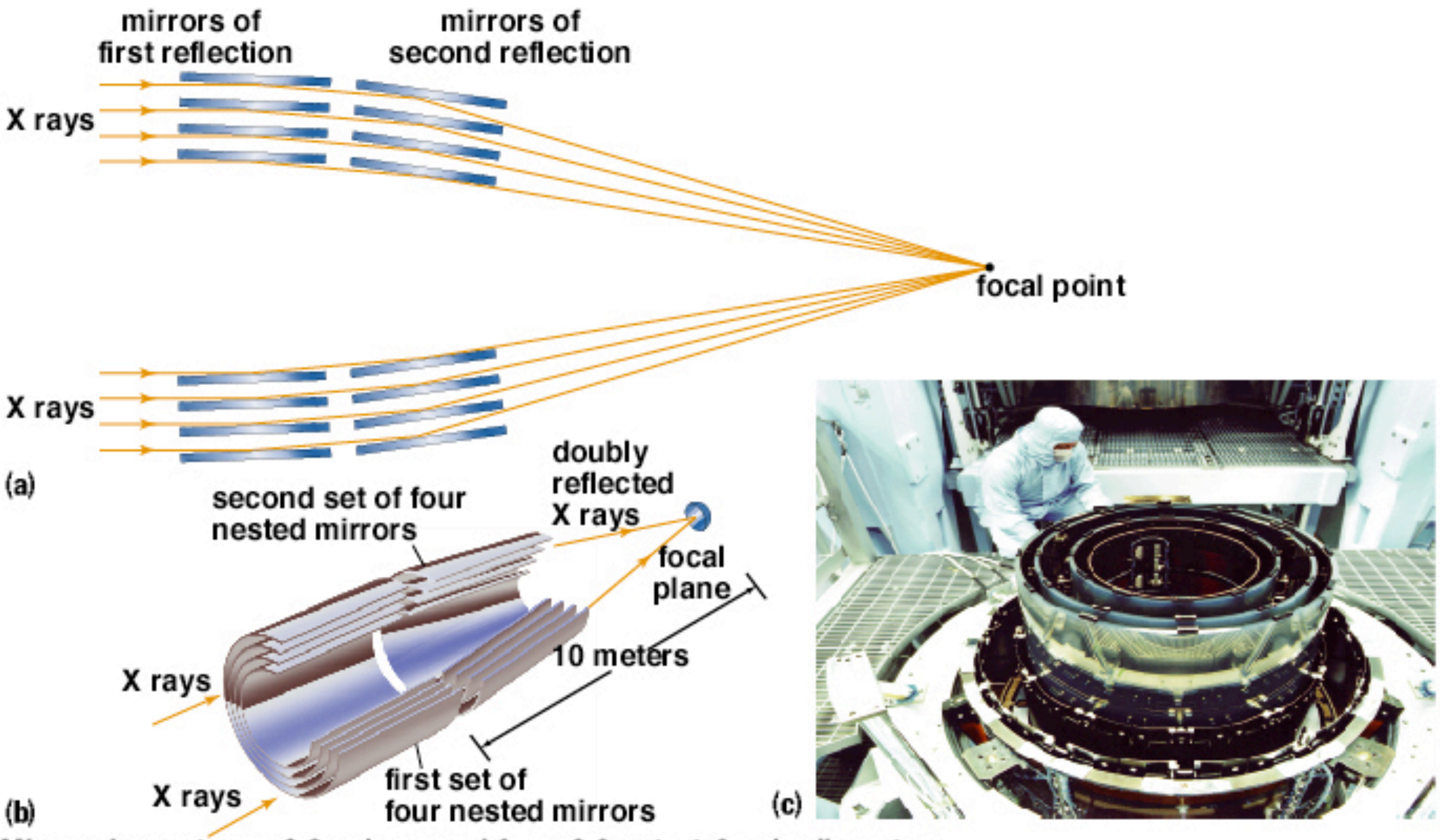
- Classically, a charged particle will emit radiation whenever it is accelerated or decelerated.
- The more violently a moving charge is accelerated or decelerated, the more kinked is the resulting transverse ***E***, i.e., the shorter is wavelength and period of the emitted radiation associated with the pulse of light.

The Electromagnetic Spectrum



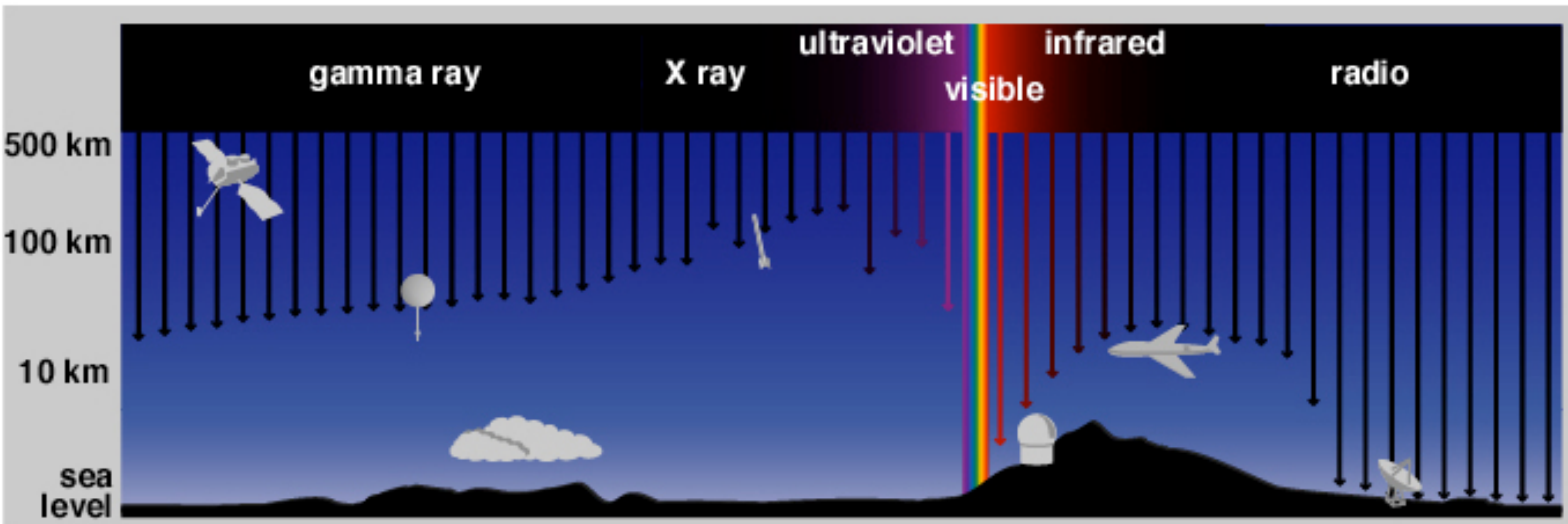
Addison-Wesley

Principle of X-Ray Telescopes (extra material)

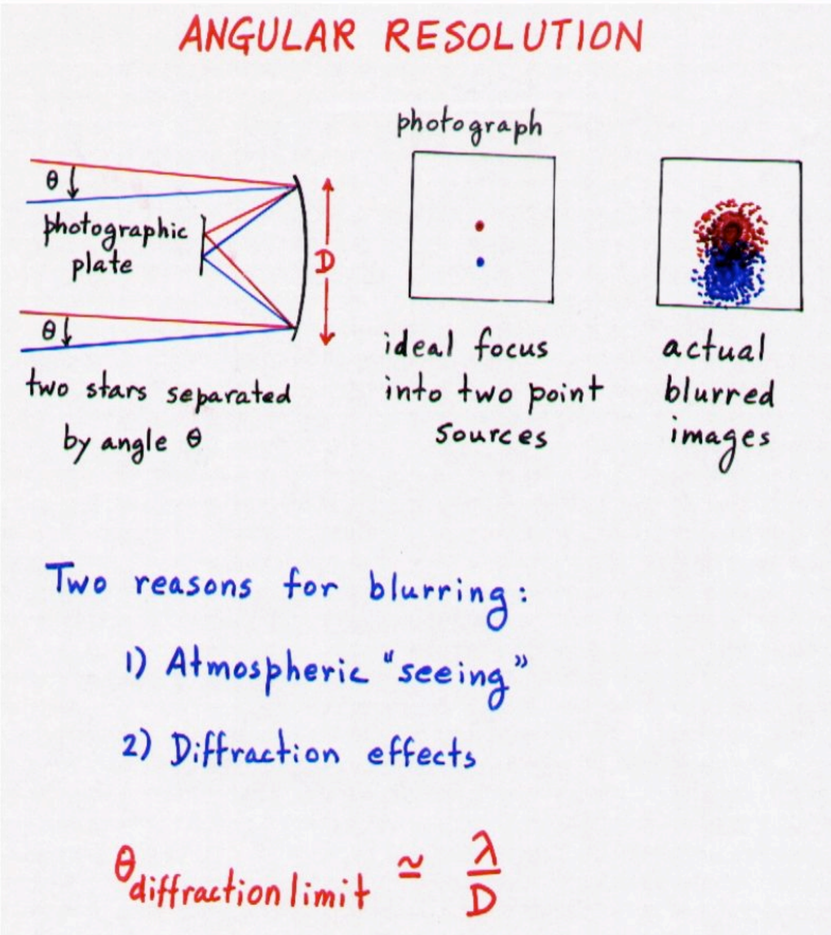


Mirror elements are 0.8 m long and from 0.6 m to 1.2 m in diameter.

Transparency of Atmosphere at Different Wavebands

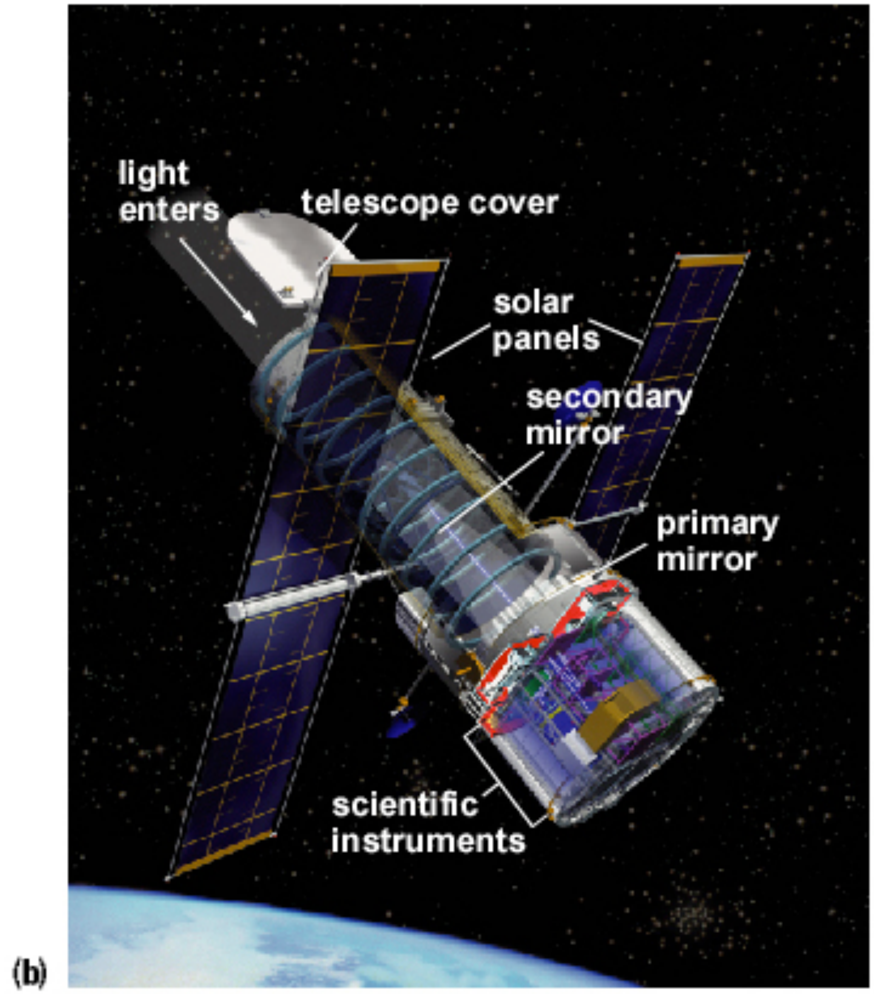


Why Human Eyes and Telescopes Do Not Form Perfect Images



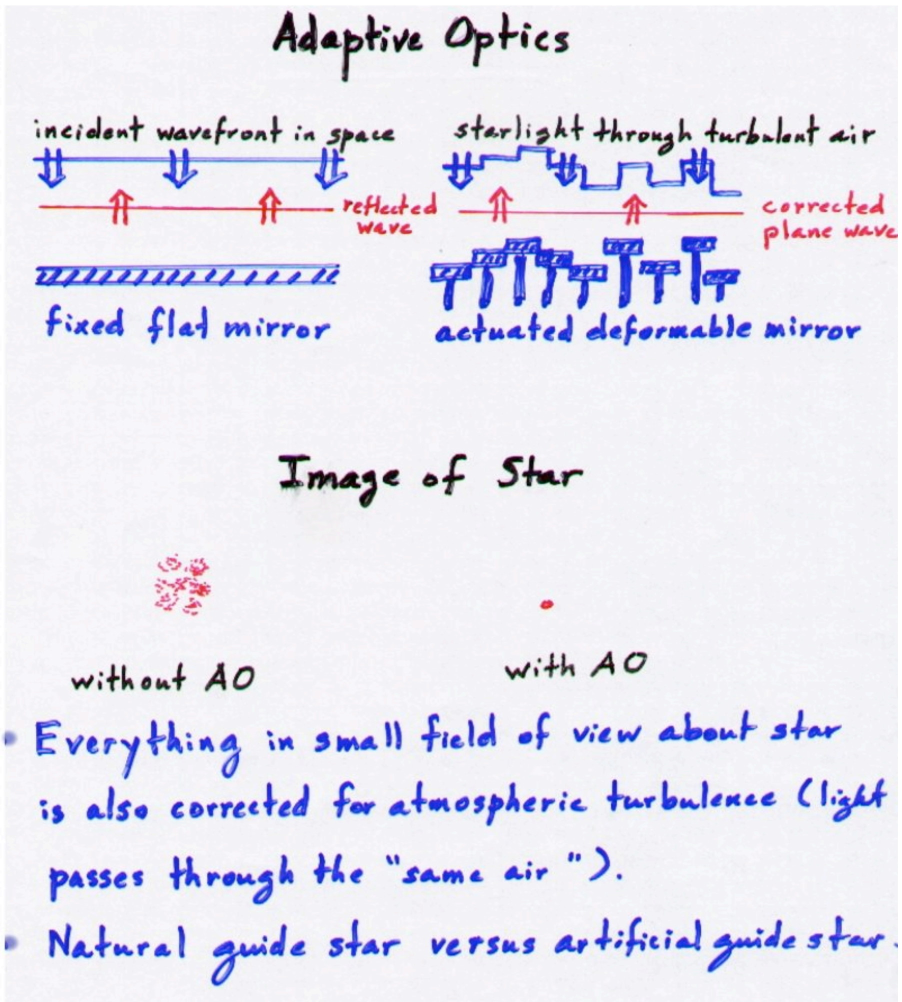
At visible wavelengths, for human pupil,,

$\lambda / D \approx 5 \times 10^{-4}$ rad = 1.5 arcmin.

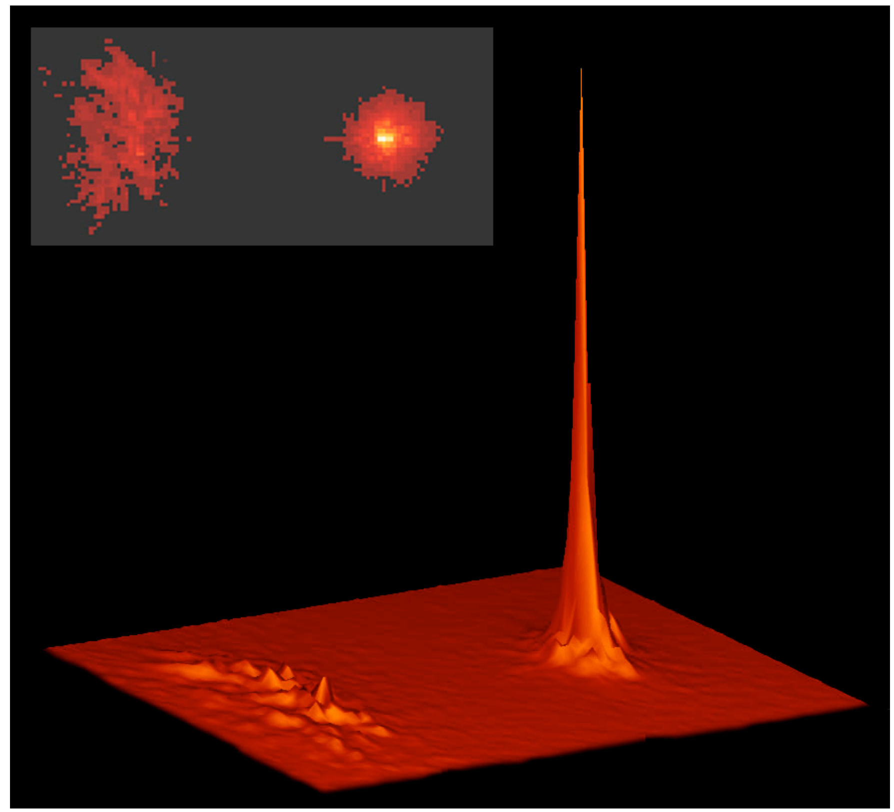


Hubble telescope gets above atmospheric turbulence.

Correction for Atmospheric Turbulence by Adaptive Optics (extra material)



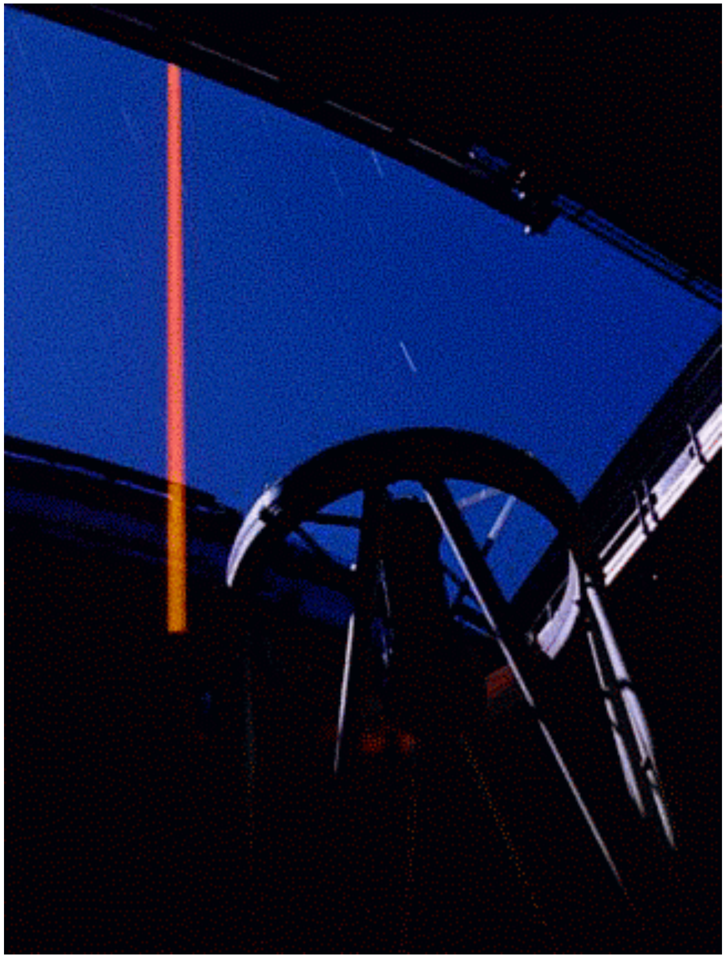
Stellar Image with and without AO



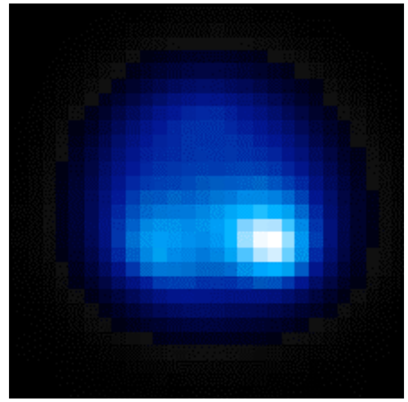
Center for Adaptive Objects

Adaptive Optics in Action (extra material)

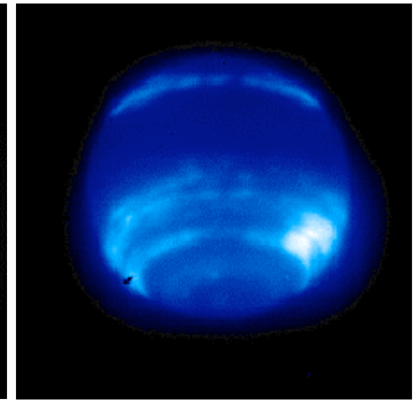
Laser guide star

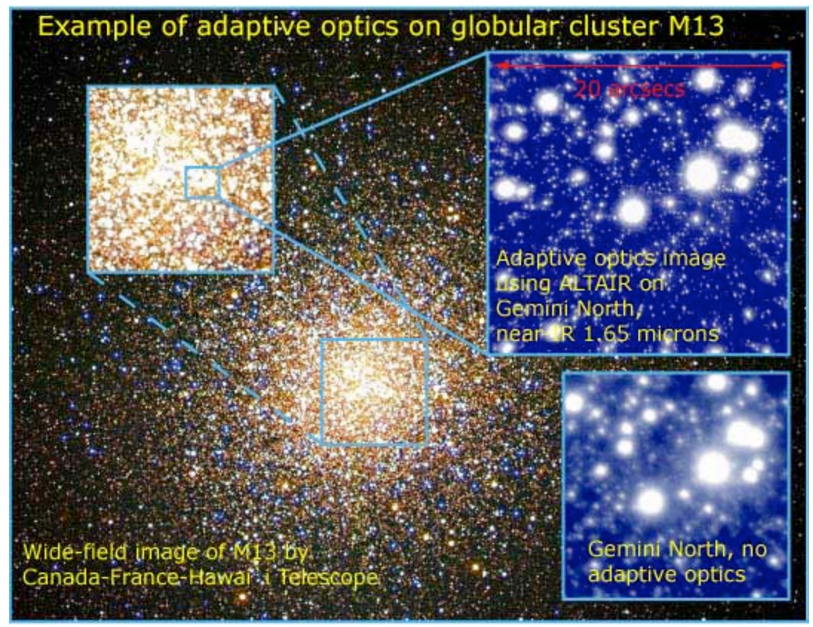


Neptune without AO



Neptune with AO





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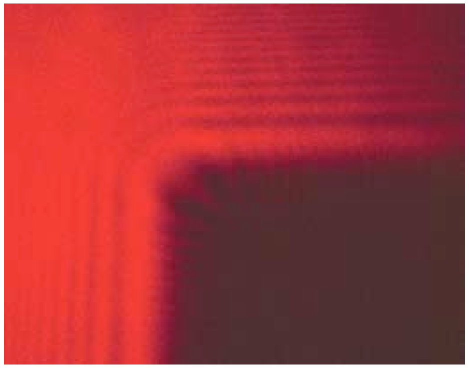
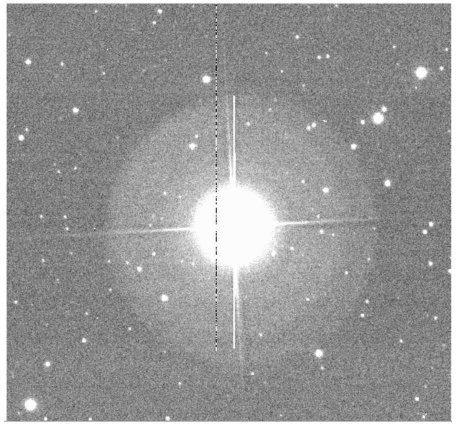
Diffraction

- Sound is a wave (alternating regions of high and low pressure).
- Light is a wave (alternating directions of electric and magnetic fields).
- Sound diffracts around corners, so we can hear a person through an open door even if we cannot see her.
- Why doesn't light bend around corners (of the door)? Answer: it does, but the effect is too subtle to notice unless we perform careful experiments.

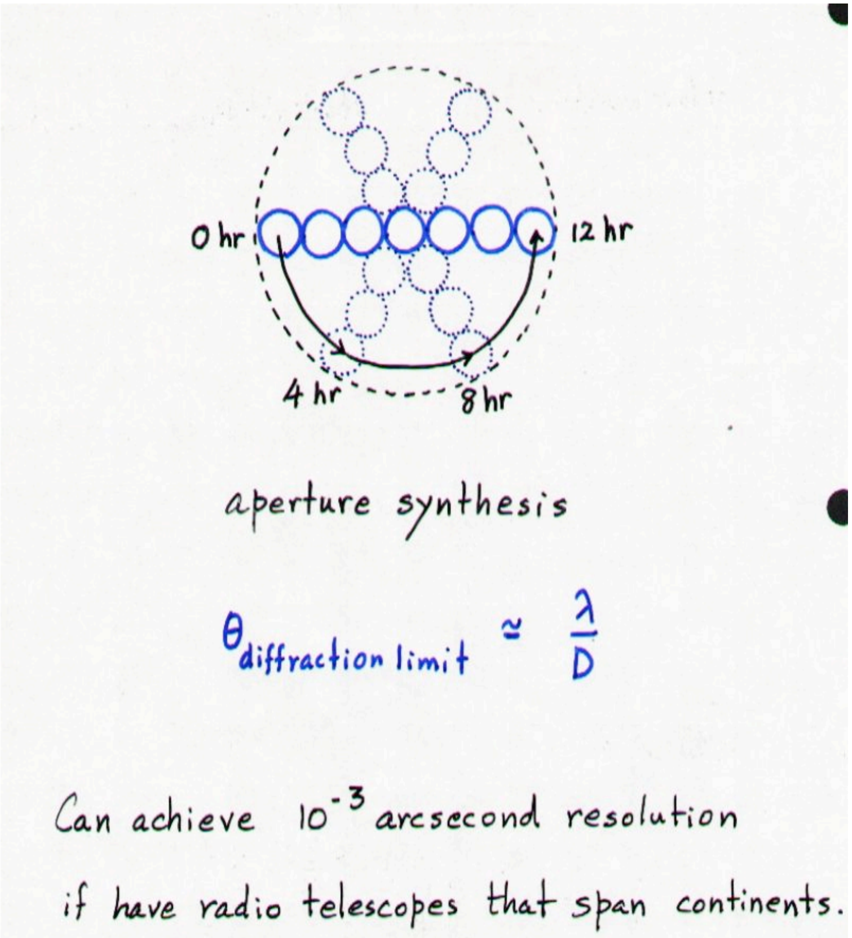
Diffraction rings as well as chromatic aberration seen through a 1 inch refractor.



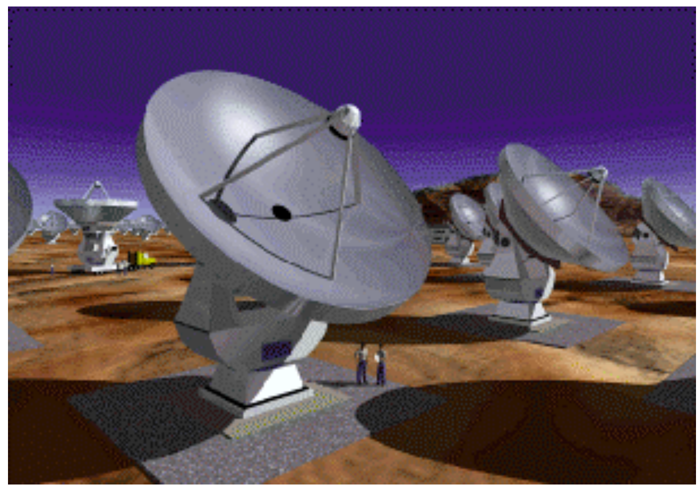


Diffraction patterns formed by corner of a razor blade and by circular aperture of a reflecting telescope and its struts.

Simulating a Large Telescope with an Array of Small Ones



VLA (Very Large Array)



ALMA (Atacama Large Millimeter Array)

NRAO

Summary
Light: Wave or Particle?

- Newton's controversies:
  - With Hooke: Who first discovered certain phenomena in optics, and who discovered $1/r^2$ law of gravitation?
  - With Leibniz: Who first discovered calculus?
  - With Huygens: Is light a wave or a particle?
- With Maxwell's theory of light discussed in lecture 8 and experiments involving interference and diffraction, the issue seems decisively settled in favor of Huygen's wave picture.
- However, it is unwise to discount the ideas of a genius completely. In a future lecture on quantum mechanics, we will see how Einstein -- the greatest opponent of Newtonian concepts in mechanics because of its conflicts with Maxwell's electromagnetic-*wave* theory of light -- comes to Newton's aid in the question of whether light is, after all, also a *particle*!