Electricity and Magnetism [Ch. 4]

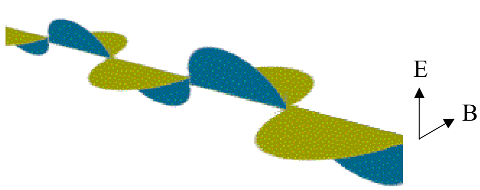
$$F_{grav} = \frac{GM_{\oplus}m}{d^2}$$

$$F_{elec} = \frac{k\, q_{p+} \cdot q_{e-}}{d^2}$$

- Electrostatic force similar to gravitational force
  - $1/r^2$ dependence
- But important differences:
  - both positive and negative electrical charges
    - positive or negative force (like charges repel, opposites attract)
  - coupled to magnetic force
    - moving electrical charges cause magnetic field (electric motor)
    - changing magnetic field causes electrical current (generator)

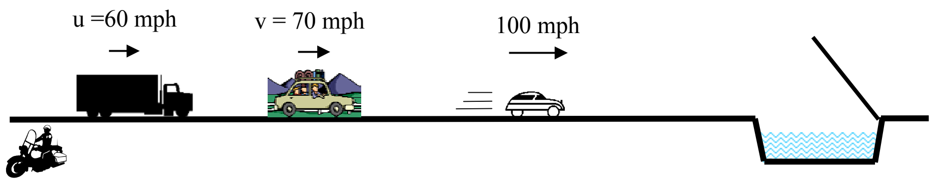
Electromagnetism

- Maxwell (1860's) showed that *light* can be described as an *electromagnetic* wave:
  - changing electrical field creates magnetic field.
  - changing magnetic field creates electrical field.
  - the two fields together can propagate forever through space, at the speed of light.



The E-M wave in action link

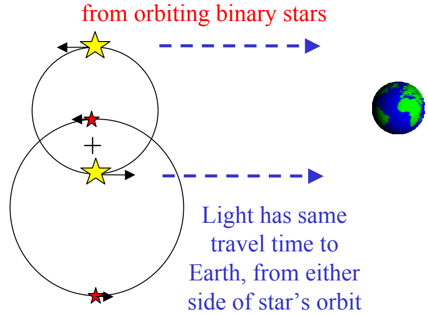
The Speed of Traffic $v' = (v-u)$



The Speed of Light

- Maxwell's results only describe electromagnetism ***if*** the speed of light is the same, no matter how fast or in what direction you are moving when you measure it.

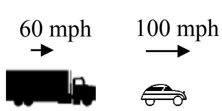
How can this be??



Special Relativity: Einstein postulated (1905):

- **The Principal of Relativity.** The laws of physics are the same in all inertial reference frames.
- **The constancy of the speed of light.** Light travels through a vacuum at a speed *c* which is independent of the light source.

➔ distance, time, velocity add up in funny ways



We see truck moving at velocity u
car moving at velocity v

- What speed v' does truck driver see car moving at?

Classical: $v' = (v-u)$

Special relativity: $v' = (v-u)/(1-uv/c^2)$

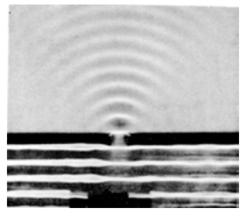
u = 60 mph   v = 100 mph
c = 669,600,000 mph
$1 - uv/c^2 = 1 - .00000000000001$

- All observers see light move at same speed.
- Observers moving at different speeds see time pass at different rates.
  - time = "4th dimension"

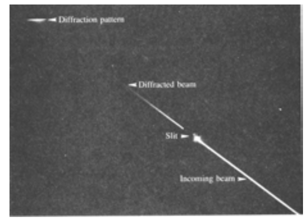
Light

- It's a wave!
  - Does same thing as water waves. Example: Diffraction.

Real water waves in real ocean, passing through narrow opening at entrance to harbor.



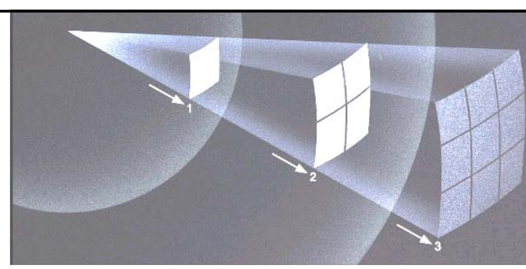
Real water waves in lab, passing through narrow slot.



Light wave in lab, passing through narrow slot.

- But no! It's a particle!
  - Called *photons.*
  - You can see them hit… one by one… each with same energy.
- ….so it's *both* a wave and a particle.

Inverse square law



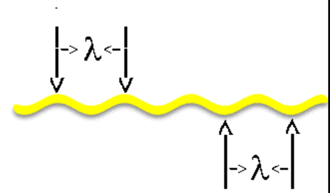
[Fig 4.4]

- A light bulb looks fainter at greater distances.
- Outgoing light wave spreads out over more and more surface area.
- If same amount of light emitted in all directions
  - *Isotropic* emission
  - surface area increases as r^2
  - light per unit surface area decreases as $1/r^2$
- *Luminosity* (L)
  - intrinsic brightness of light source
  - energy per unit time
- *Flux* (F)
  - apparent brightness of object as it appears from distance r.
  - energy per unit time per unit area

$$F = L / 4\pi r^2$$

Wavelength, Frequency and Energy

- *Wavelength*
  λ = distance between successive crests.



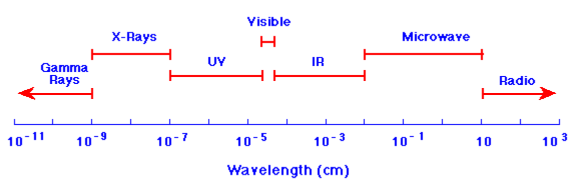
- Wave moves at speed of light c.
- *frequency* = rate at which crests pass a stationary observer.
  $f = \text{velocity/distance} = c/\lambda$ (cycles/second)
- *Energy* of each photon:
  $E = hf = hc/\lambda$ (h = Planck's constant)

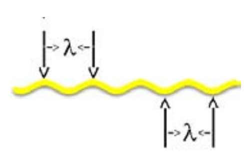
CONSUMER WARNING: most books and astronomers use ν to designate frequency.
…What's ν? c/λ.

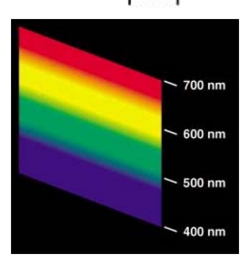
The E-M wave in action link

The Electromagnetic Spectrum

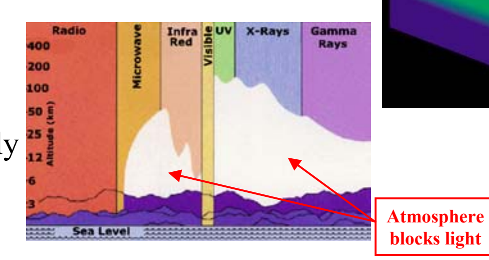
- Light is given different names according to its wavelength λ





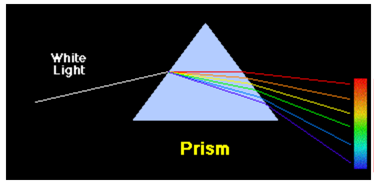


- In visible passband, different λ = different color.
  - Blue = smaller λ
  - Red = larger λ
- Only visible light and radio waves pass freely through Earth's atmosphere.



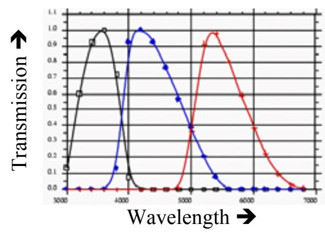
Spectroscopy

- *Spectrograph*. Instrument that measures how bright the light is at each individual wavelength.
- Prism :



Detector: measures brightness of light at each point (pixel) in vertical direction.

- Simple colored filters give coarser measurement:



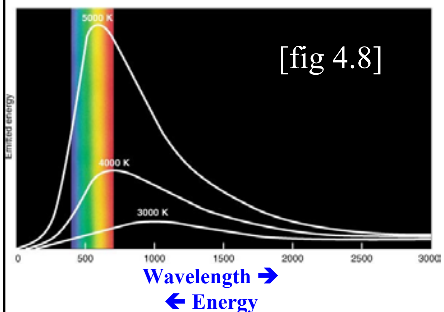
- Can make similar measurements with radio, infrared, ultraviolet, x-ray light.

Blackbodies

- Heat up a frying pan
  - It glows more brightly as it gets hotter
  - It changes color as it gets hotter

	Temperature			Color
	^{o} K	^{o} C	^{o} F	
Completely cold.	0	-273	-459	Does not emit light
Body temperature.	310	37	99	Infrared
Blowtorch.	4000	3727	6740	Red-hot
Blast furnace.	6000	5727	10,340	White-hot
Hotter still.	7500	7227	13,040	Blue-hot

Black-Body Spectrum



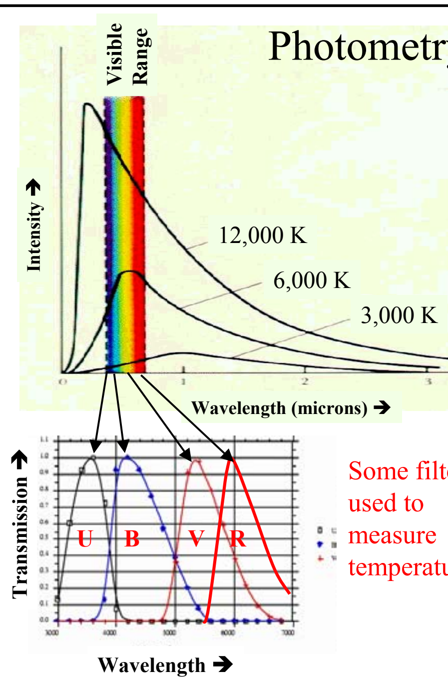
- Characteristic shape
  - Narrow peak.
  - Sharp drop towards higher energy.
  - Slow drop towards lower energy.

Slightly hotter objects put out *way* more energy per unit surface area:

T	T^4
5800	$1.1\text{x}10^{15}$
6800	$2.1\text{x}10^{15}$
10,000	$1.0\text{x}10^{16}$
100,000	$1.0\text{x}10^{20}$

- Peak wavelength given by Wien Displacement Law.
  - $\lambda_{max} = 3\text{x}10^6 / T$
  - hotter objects have peak at smaller λ.
- Total energy emitted *per unit surface area* is given by Steffan-Boltzmann Law: $E = \sigma T^4$

Photometry& Colors



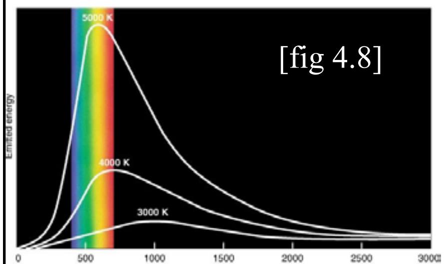
Some filters used to measure temperature.

- Measure flux from black body in 2 colors
  - blue
  - red
- Use colored glass filters in front of a photocell.

Temperature	F_{blue}/F_{red}
12,000	> 1
6,000	~ 1
3,000	< 1

- So *ratio* of fluxes measures the temperature.

Black-Body Spectrum



Wavelength →

← Energy

- Characteristic shape
  - Narrow peak.
  - Sharp drop towards higher energy.
  - Slow drop towards lower energy.

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5800	$1.1x10^{15}$
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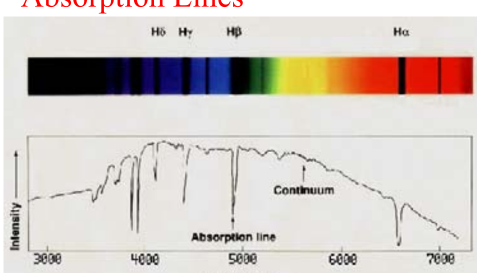
10,000	$1.0x10^{16}$
100,000	$1.0x10^{20}$

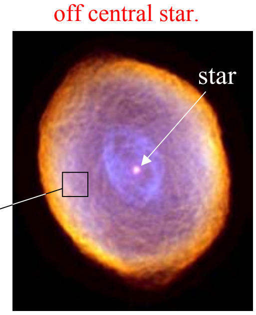
But many spectra are not smooth

- Absorption Lines

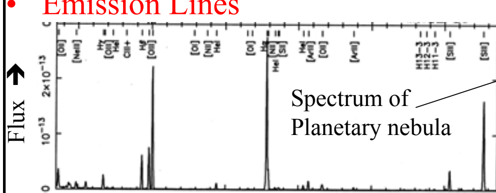


Spectrum of a star

IC 418 – shell of gas blown off central star.



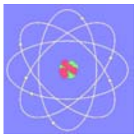
- Emission Lines

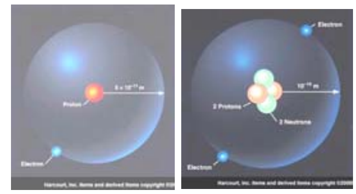


Wavelength →

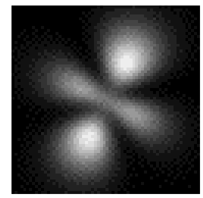
The Bohr Atom

[Figs 4.13,4.14]





- The atom as a miniature solar system



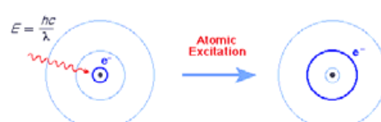
- But three special rules needed for Bohr Atom:
  - Electrons can only be in orbits at certain special radii.
  - Only one electron can be in a given orbit at one time.
  - Electron's energy stays constant while it is in orbit.
- Consequence of *quantum mechanics*.
  - Describes electrons as fuzzy probability distributions
    - not as discrete particles in discrete orbits
  - Too complicated! Bohr atom is almost right, so we'll use it

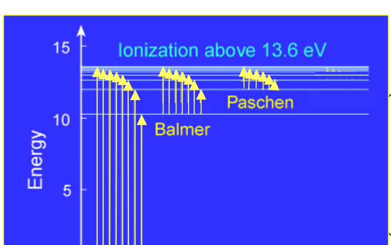
pictures

Atomic Excitation

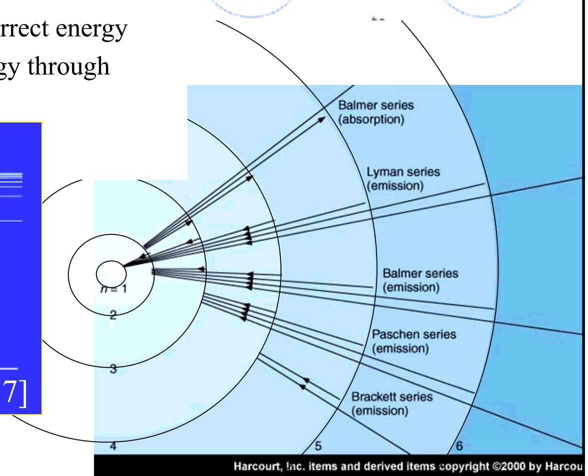
[Fig 4.16]

- Each Bohr orbit has its own distinct energy.
- For electron to move from inner orbit to one further out, it must gain exactly the energy difference between the orbits.
  - Can absorb photon with correct energy
  - Or can absorb kinetic energy through collisions.





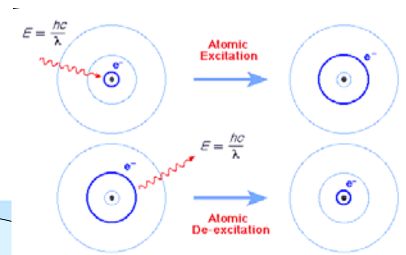
[Fig 4.17]

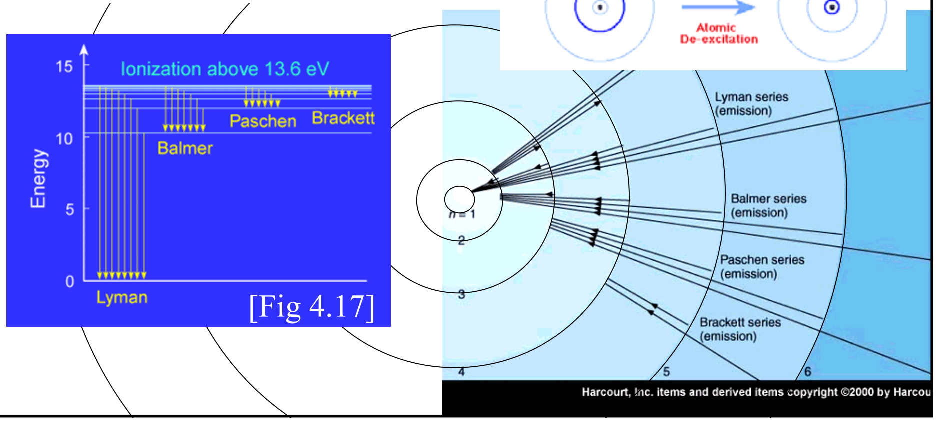


[Fig 4.16]

De-Excitation

- For electron to fall back in towards nucleus, it must *lose* exactly the energy difference between the orbits.
  - Can *emit* photon with correct energy
  - Or can *lose* energy through kinetic energy carried off by collisions.





[Fig 4.17]

Different Chemical Elements have Different Spectra

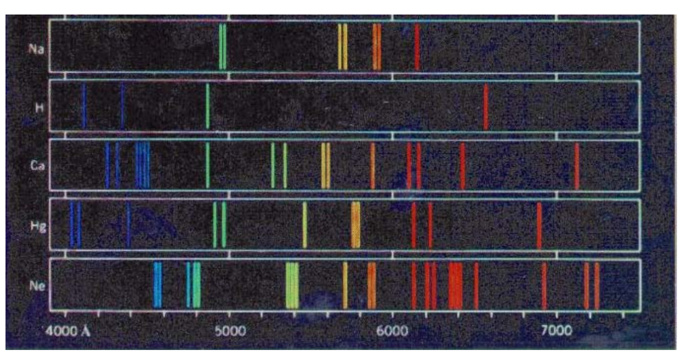
Sodium

Hydrogen

Calcium

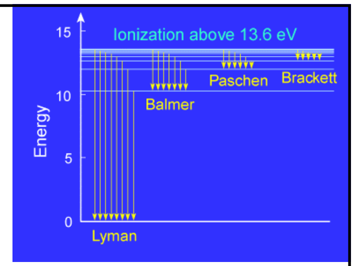
Mercury

Neon



[see Fig 4.11]

Ionization



- Very energetic photon
  ➔ electron acquires escape velocity.
  - Atom has same nucleus, but one less electron.
    - Atom is *ionized*.
  - Atom with all of its electrons is *neutral*. (neutral electrical charge)
- Elements heavier than hydrogen start out with several electrons
  - ➔ can be ionized several times
    - Example: oxygen ^{16}O
      - nucleus = 8 protons + 8 neutrons
      - O^0 or O I = nucleus with all 8 electrons.
      - O^+ or O II = nucleus with only 7 electrons.
      - O^{++} or O III = nucleus with only 6 electrons.

        etc.

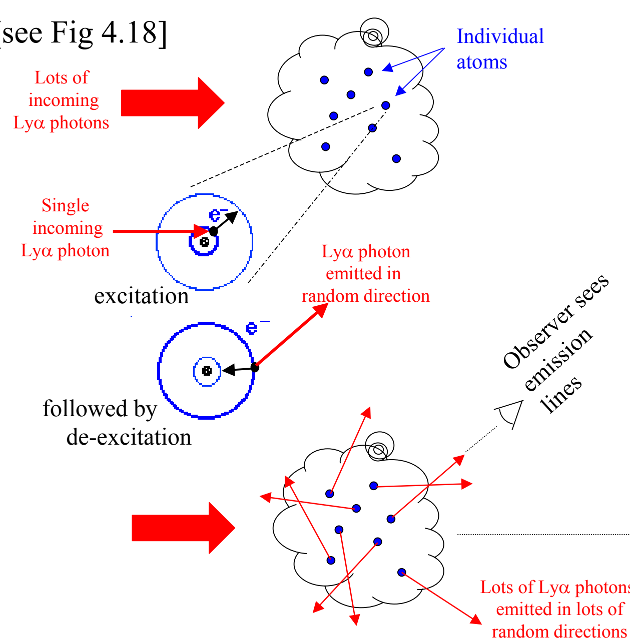
} Each have completely different spectra.

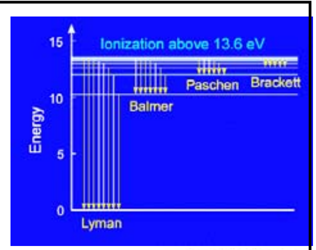
Recombination

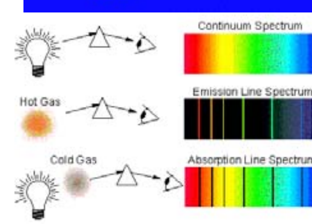
- Ion recaptures a free electron ➔ photon is emitted.

Formation of spectral lines

[see Fig 4.18]

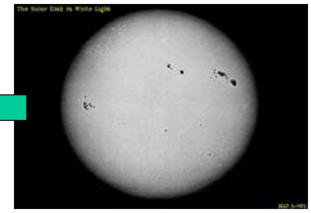






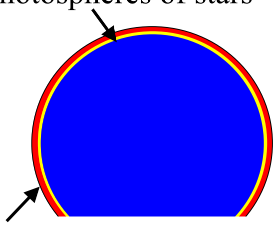
Stars vs. Gas Clouds

Continuum Spectrum



The Sun's photosphere)

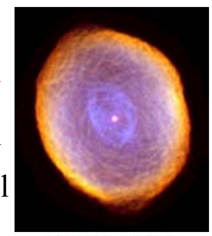
Photospheres of stars

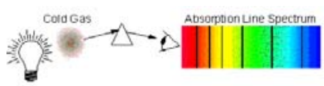


Outer, cooler layers

Absorption Spectrum

Emission spectrum: Planetary nebula shell





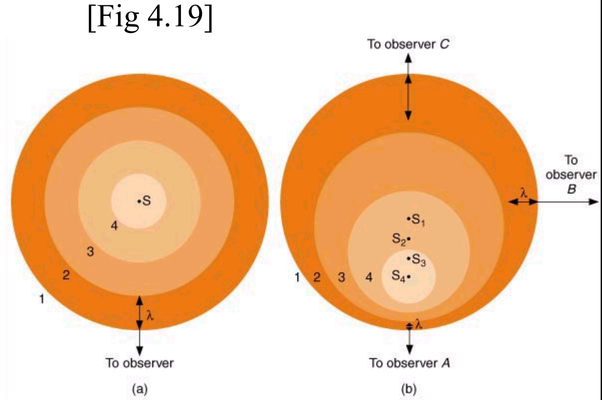
Measuring Radial Velocity: The Doppler effect

- If wave's source is moving,
  - stationary observer measures different frequency
  - = different wavelength.
- True for water waves, sound waves, and light waves.

One difference: Emitter can go faster than speed of sound, but not faster than speed of light. For result, see the Doppler Demo applet

- Shift in wavelength is
  $\Delta\lambda = \lambda_{observed} - \lambda_{rest}$
- For v = velocity of emitter,
  c = velocity of wave
  $$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$
- This *Doppler shift* only measures velocity along line of sight.

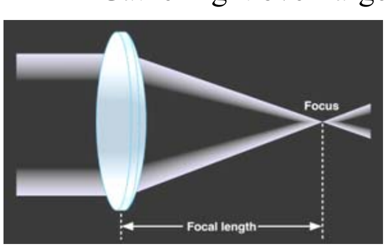
[Fig 4.19]



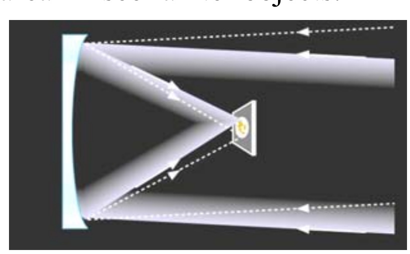
Telescopes [5]

Galileo’s telescopes: ~1” in diameter x 24-30” long

- Magnify images ➔ see details
- Gather light over large surface area ➔ see fainter objects.



Using a lens (refractor) [Fig.5.2]



Using a mirror (relector) [Fig. 5.3]

Some large ground-based optical telescopes

Lick 36" Refractor
1888

Mt. Palomar 200" Reflector
1948

Twin Keck 10m (400") reflectors
Mauna Kea, 1993

Light-gathering power

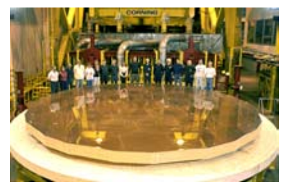
∝ (mirror area)

∝ (mirror diameter)^2

Technological advances

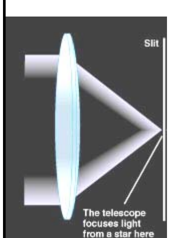
- Lenses ➔ mirrors
- Thick mirrors ➔ thin mirrors
  passive ➔ active support
- Now working on designs for 30m diameter telescopes.

Europe's Very Large Telescope
(Four 8m telescopes)

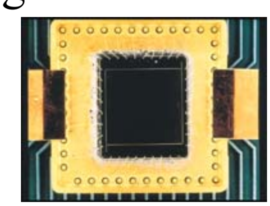


Mirror for Gemini 8m Telescope

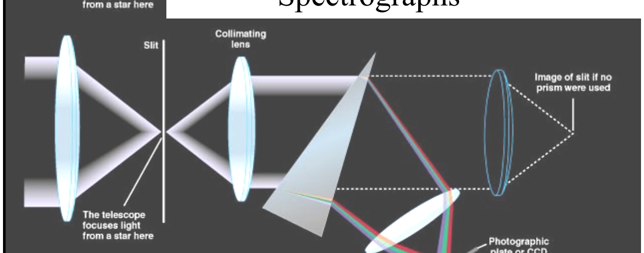
Telescopes use variety of special instruments to detect light



- CCD's in "optical" passband
- Other detectors in infrared
- Direct imaging
- Spectrographs



[Fig. 5.8]



[Fig 5.9]

SOAR: MSU's New 4m Telescope

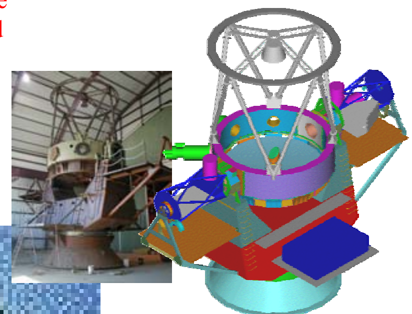
Superb image quality.
Superb site in Chile.

⇨

Highly competitive for optical/infrared observations.

SOAR on Cerro Pachón, Chile

Start operations in 2002

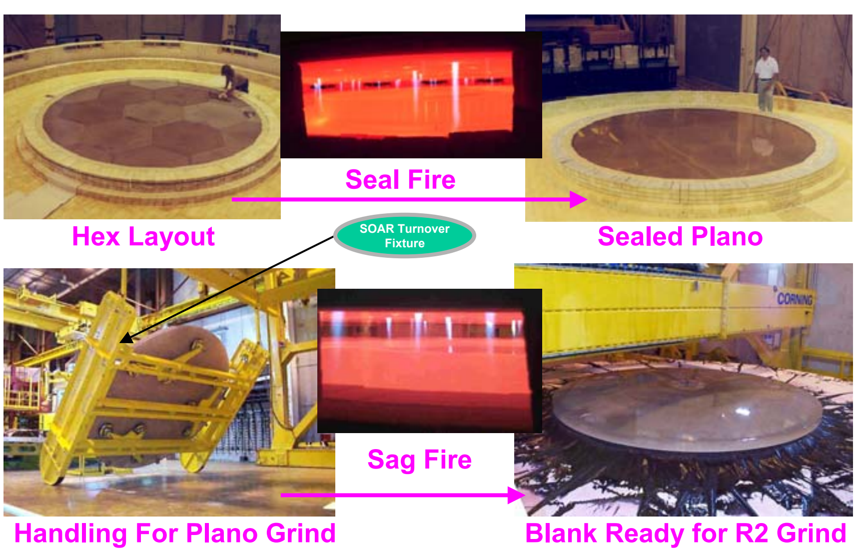


An International Partnership

- MSU
- University of North Carolina
- National Optical Astronomy Observatories
- Brazil

SOAR mirror casting

Corning Glass Works



The mirror is now being polished

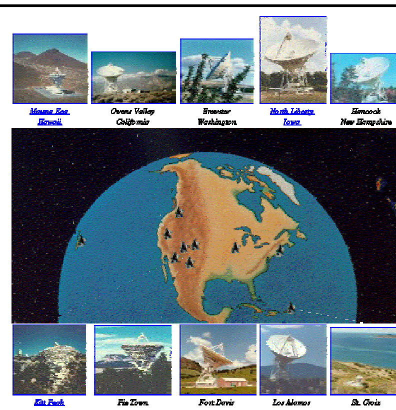
by B.F.Goodrich, in Danbury, CT

Radio telescopes

$$\text{Angular resolution} = \frac{\text{wavelength}}{\text{mirror diameter}}$$

- Radio wavelengths are large ➔ need large mirror diameter to see small-angle details.

- Arecibo, Puerto Rico….
  - **1000 ft. diameter, but same angular resolution as 0.01 ft optical telescope.**



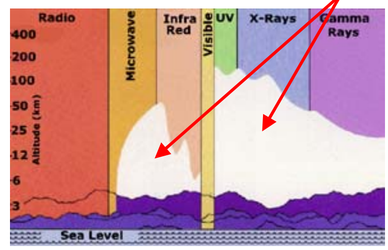
Array of smaller telescopes simulates a huge aperture.

Radio galaxy Cygnus A

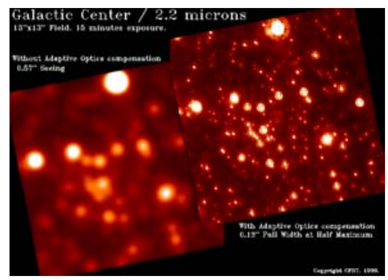
Telescopes in Space

Atmosphere blocks light

- Atmosphere blocks light at many wavelengths

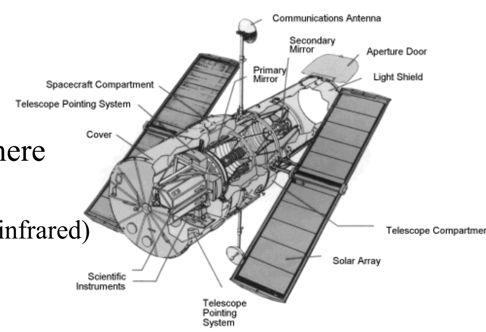


- Atmospheric turbulence smears out images.

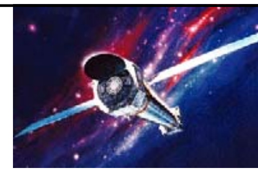


Hubble Space Telescope

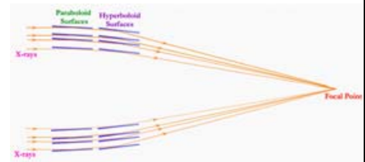
- 2.4m diameter mirror
- Ultraviolet/optical/infrared
- Above (most of) Earth's atmosphere
  - High angular resolution
  - Light not blocked in ultraviolet (or infrared)
  - Low earth orbit
    - 600 km (370 mile) altitude
    - 95 min orbits
    - Earth blocks view half of each orbit
    - But can be reached by shuttle to install new instruments
- Launched in 1990
- To be replaced by NGST in ~2008

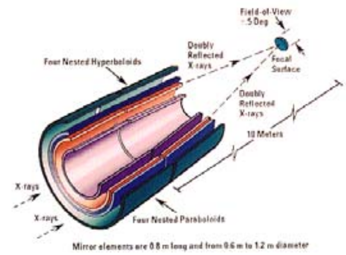


X-Ray telescopes



- Chandra
  - Named after Subrahmanvan Chandrasekhar
    - Nobel-Prize-winning astrophysicist
  - NASA “Great Observatory”
  - Far better than previous x-ray telescopes
    - Many times higher angular resolution
    - More collecting area

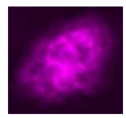




X-ray | Optical | Radio

Crab Nebula: Remnant of supernova that exploded in our Galaxy in 1054 AD





Galaxy Cluster: Hydra A, 840 million light years away.