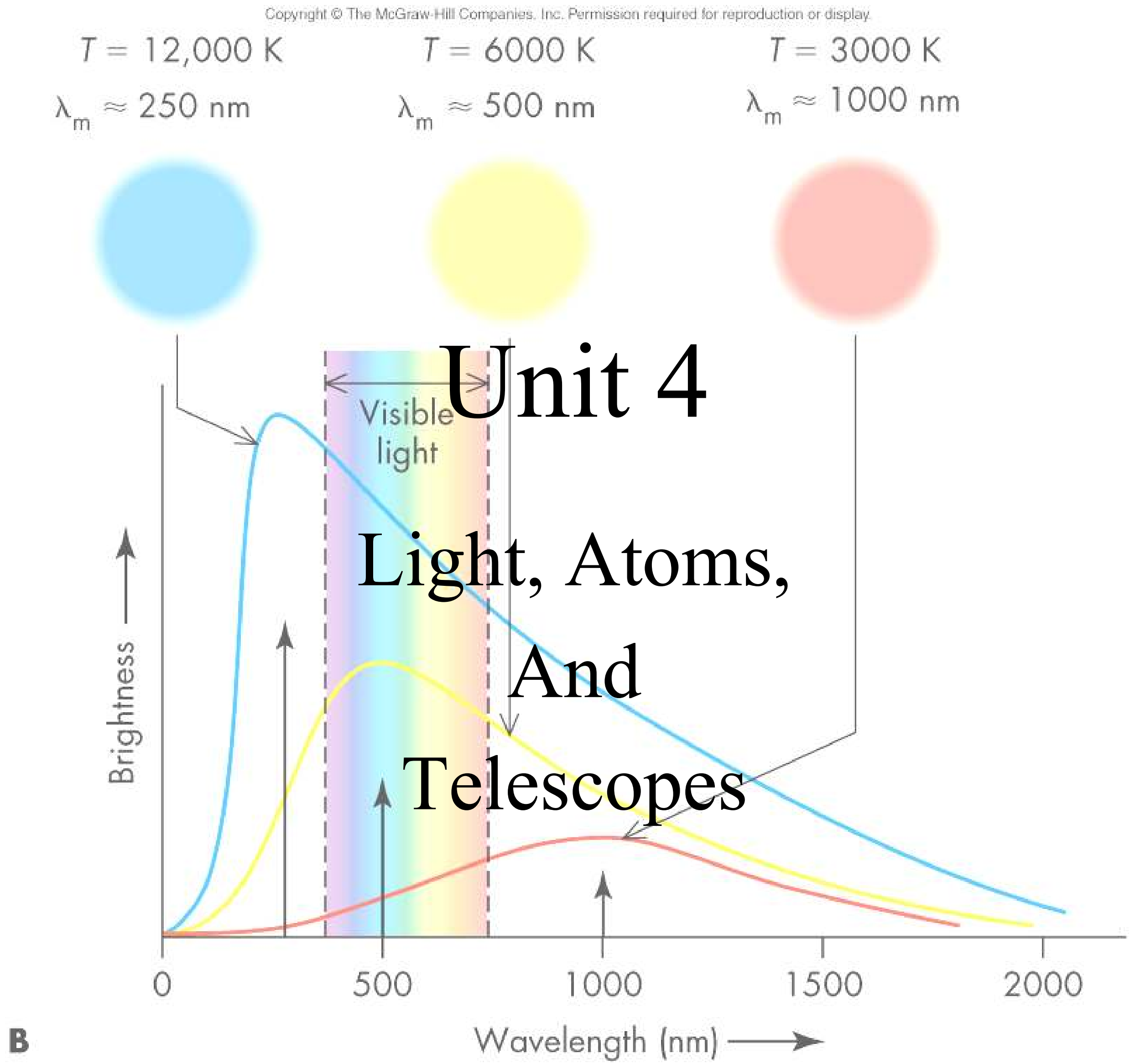
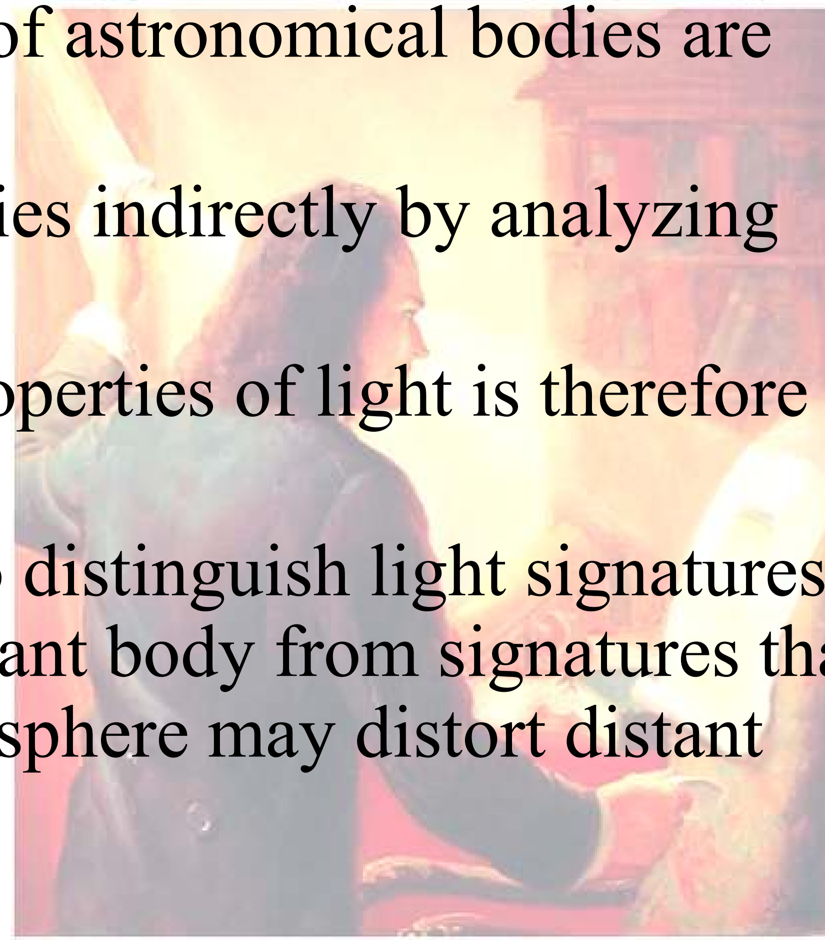
Unit 4

Light, Atoms, And Telescopes



Light – the Astronomer's Tool

- Due to the vast distances, with few exceptions, direct measurements of astronomical bodies are not possible
- We study remote bodies indirectly by analyzing their light
- Understanding the properties of light is therefore essential
- Care must be given to distinguish light signatures that belong to the distant body from signatures that do not (e.g., our atmosphere may distort distant light signals)

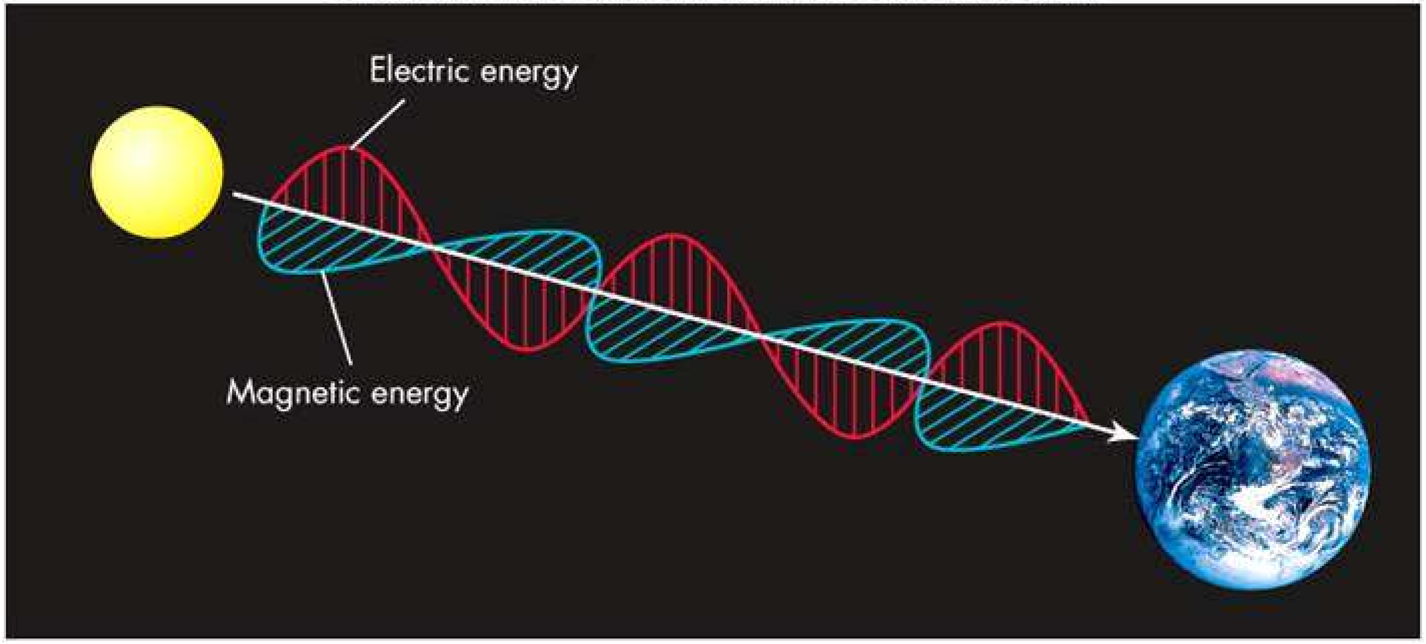


Properties of Light

- *Light* is radiant energy: it does not require a medium for travel (unlike sound!)

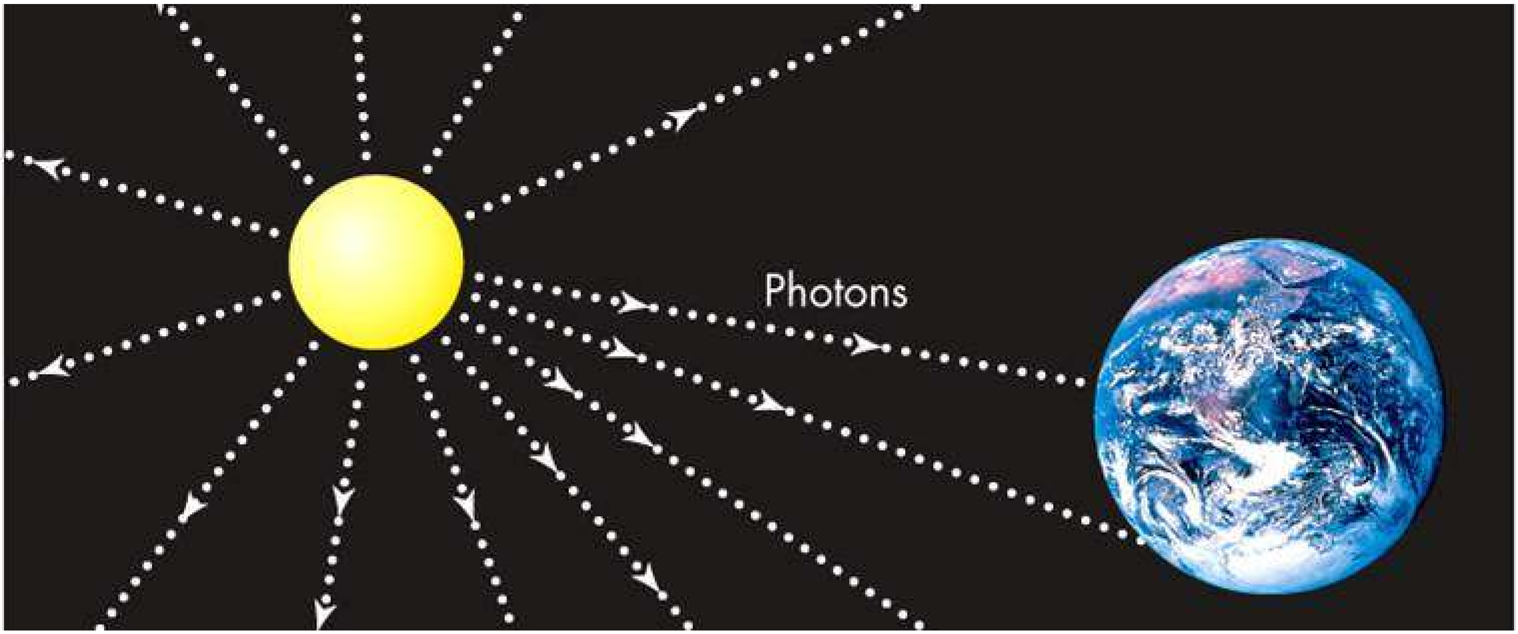
- Light travels at 299,792.458 km/s (or 186,282 miles/sec) in a vacuum (fast enough to circle the Earth 7.5 times in one second)
  - Speed of light *in a vacuum* is constant and is denoted by the letter “c”
  - However, the speed of light is reduced as it passes through transparent materials
    - The speed of light in transparent materials is dependent on color
    - Fundamental reason telescopes work the way they do!

Sometimes light can be described as a wave…



- The wave travels as a result of a fundamental relationship between electricity and magnetism
- A changing magnetic field creates an electric field and a changing electric field creates a magnetic field

…and sometimes it can be described as a particle!

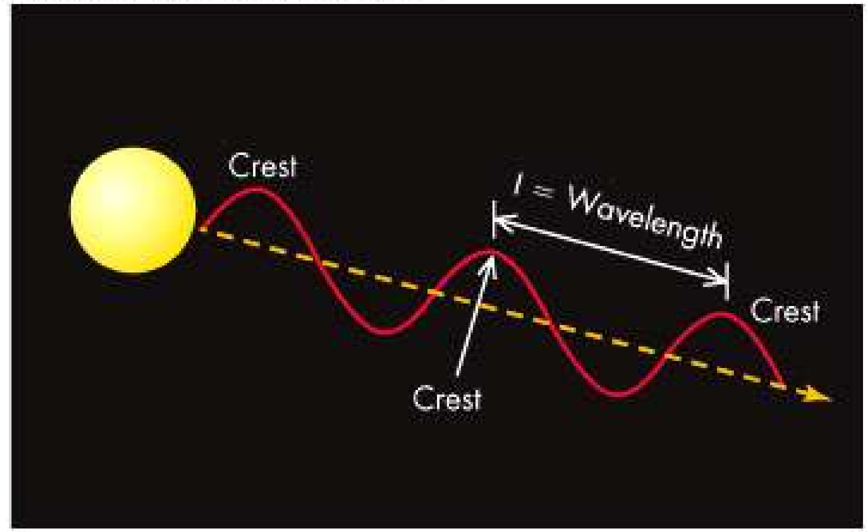


– Light thought of as a stream of particles called ***photons***
– Each photon particle carries energy, depending on its ***frequency*** or ***wavelength***

So which model do we use?

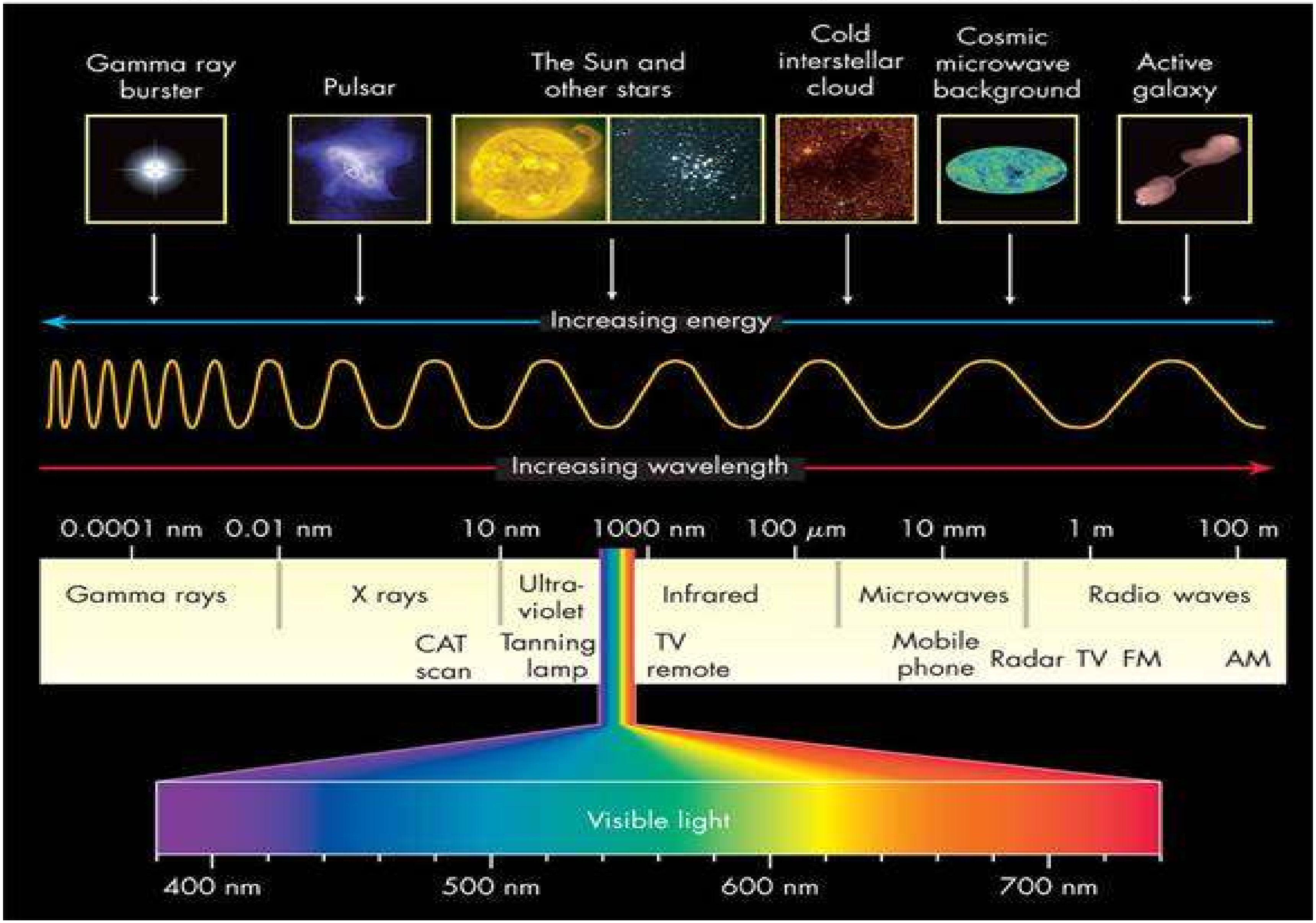
– Well, it depends!
  - In a vacuum, photons travel in straight lines, but behave like waves
  - Sub-atomic particles also act as waves
  - *Wave-particle duality:* All particles of nature behave as both a wave and a particle
  - Which property of light manifests itself depends on the situation
  - We concentrate on the wave picture henceforth

Light and Color



- Colors to which the human eye is sensitive is referred to as the ***visible spectrum***
- In the wave theory, color is determined by the light's ***wavelength*** (symbolized as λ)
  - The ***nanometer*** (10^{-9} m) is the convenient unit
  - Red = 700 nm (longest visible wavelength), violet = 400 nm (shortest visible wavelength)

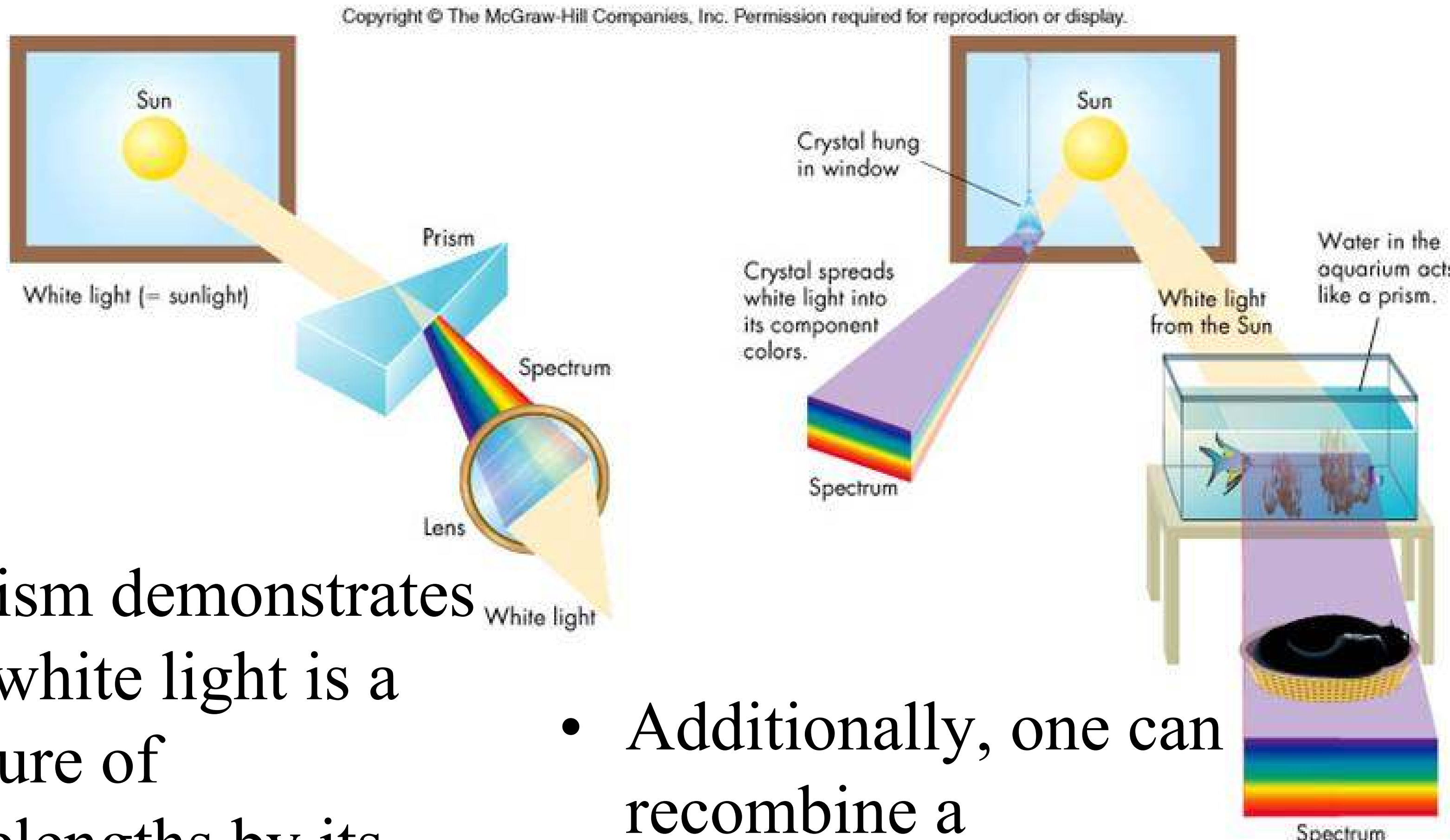
The Visible Spectrum



Frequency

- Sometimes it is more convenient to talk about light's frequency
  - ***Frequency*** (or ν) is the number of wave crests that pass a given point in 1 second (measured in Hertz, Hz)
  - Important relation: $\nu\lambda = c$
  - Long wavelenth = low frequency, low energy
  - Short wavelength = high frequency, high energy

White light – a mixture of all colors



- A prism demonstrates that white light is a mixture of wavelengths by its creation of a spectrum

- Additionally, one can recombine a spectrum of colors and obtain white light

The Electromagnetic Spectrum

- The ***electromagnetic spectrum*** is composed of radio waves, microwaves, infrared, visible light, ultraviolet, x rays, and gamma rays
- Longest wavelengths are more than 10^3 km
- Shortest wavelengths are less than 10^{-18} m
- Various instruments used to explore the various regions of the spectrum

Infrared Radiation

- Sir William Herschel (around 1800) showed heat radiation related to visible light
- He measured an elevated temperature just off the red end of a solar spectrum – ***infrared*** energy
- Our skin feels infrared as heat

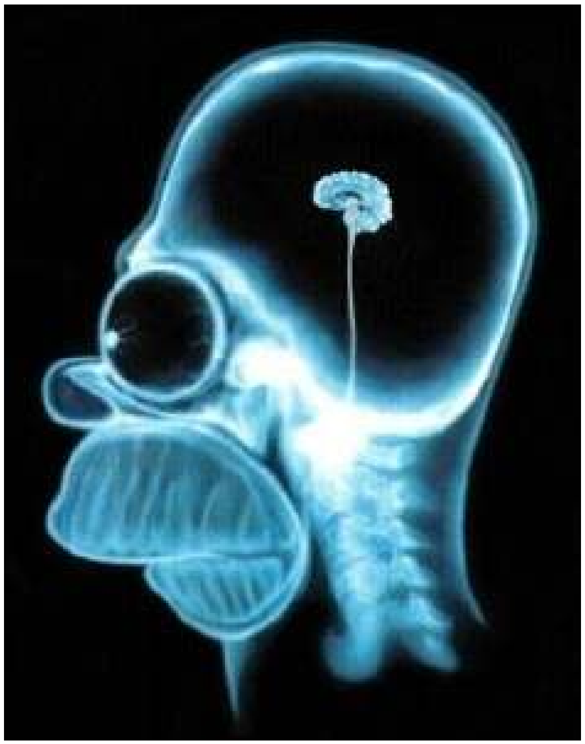
Ultraviolet Light

- J. Ritter in 1801 noticed silver chloride blackened when exposed to “light” just beyond the violet end of the visible spectrum
- Mostly absorbed by the atmosphere
- Responsible for suntans (and burns!)

Radio Waves

- Predicted by Maxwell in mid-1800s, Hertz produced ***radio waves*** in 1888
- Jansky discovered radio waves from cosmic sources in the 1930s, the birth of radio astronomy
- Radio waves used to study a wide range of astronomical processes
- Radio waves also used for communication, microwave ovens, and search for extraterrestrials

X-Rays



– Roentgen discovered X rays in 1895
– First detected beyond the Earth in the Sun in late 1940s
– Used by doctors to scan bones and organs
– Used by astronomers to detect black holes and tenuous gas in distant galaxies

Gamma Rays

- Gamma Ray region of the spectrum still relatively unexplored
- Atmosphere absorbs this region, so all observations must be done from orbit!
- We sometimes see bursts of gamma ray radiation from deep space

Energy Carried by Electromagnetic Radiation

- Each photon of wavelength λ carries an energy E given by:

$$E = hc/\lambda$$

  where h is Planck's constant
- Notice that a photon of short wavelength radiation carries more energy than a long wavelength photon
- Short wavelength = high frequency = high energy
- Long wavelength = low frequency = low energy

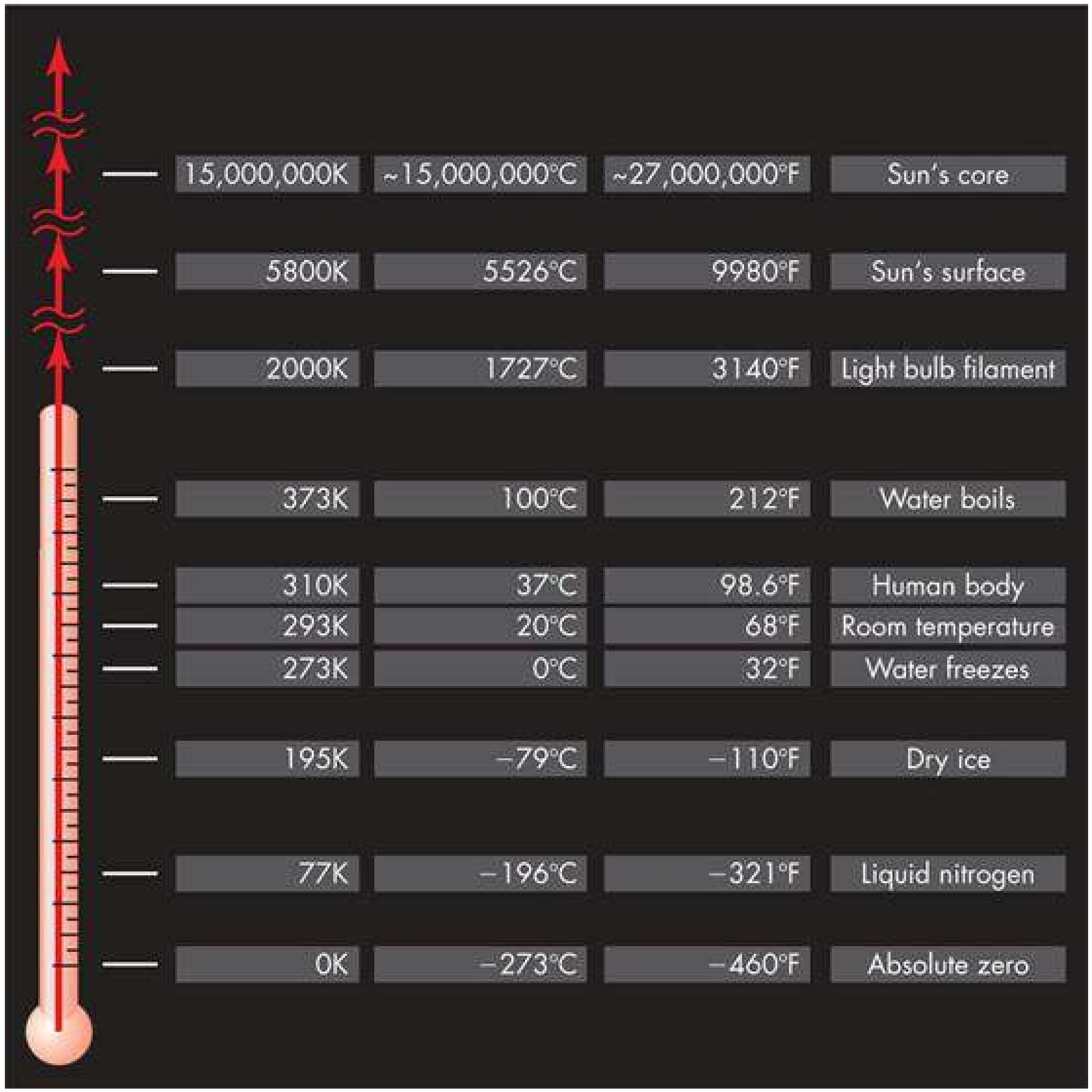
Matter and Heat

- The Nature of Matter and Heat
  - The ancient Greeks introduced the idea of the atom (Greek for “uncuttable”), which today has been modified to include a nucleus and a surrounding cloud of electrons
  - Heating (transfer of energy) and the motion of atoms was an important topic in the 1700s and 1800s

A New View of Temperature

- The Kelvin Temperature Scale
  - An object's temperature is directly related to its energy content and to the speed of molecular motion
  - As a body is cooled to zero Kelvin, molecular motion within it slows to a virtual halt and its energy approaches zero $\Rightarrow$ no negative temperatures
  - Fahrenheit and Celsius are two other temperature scales that are easily converted to Kelvin

The Kelvin Temperature Scale

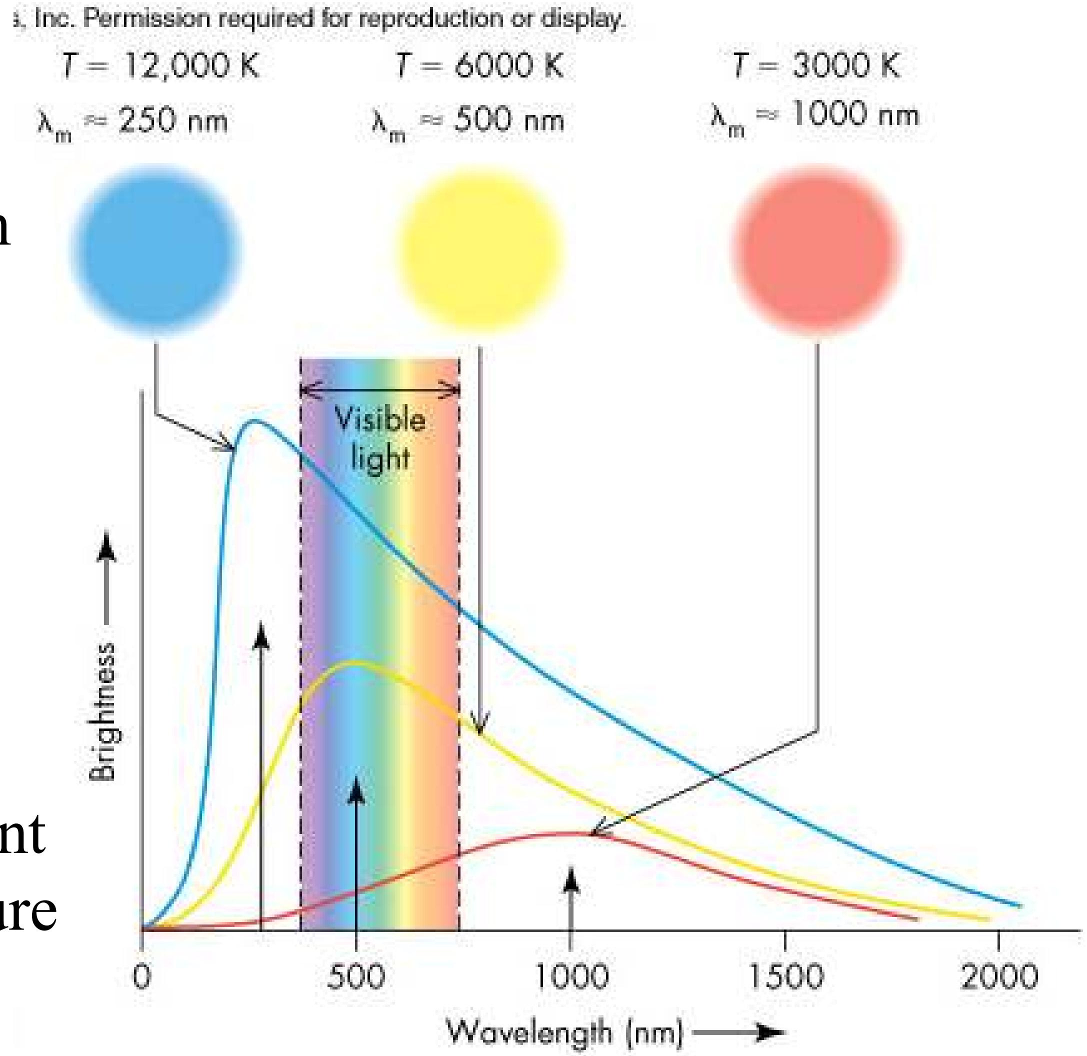


Radiation and Temperature

- Heated bodies generally radiate across the entire electromagnetic spectrum
- There is one particular wavelength, λ_m, at which the radiation is most intense and is given by ***Wien's Law:***

$$\lambda_m = k/T$$

Where k is some constant and T is the temperature of the body



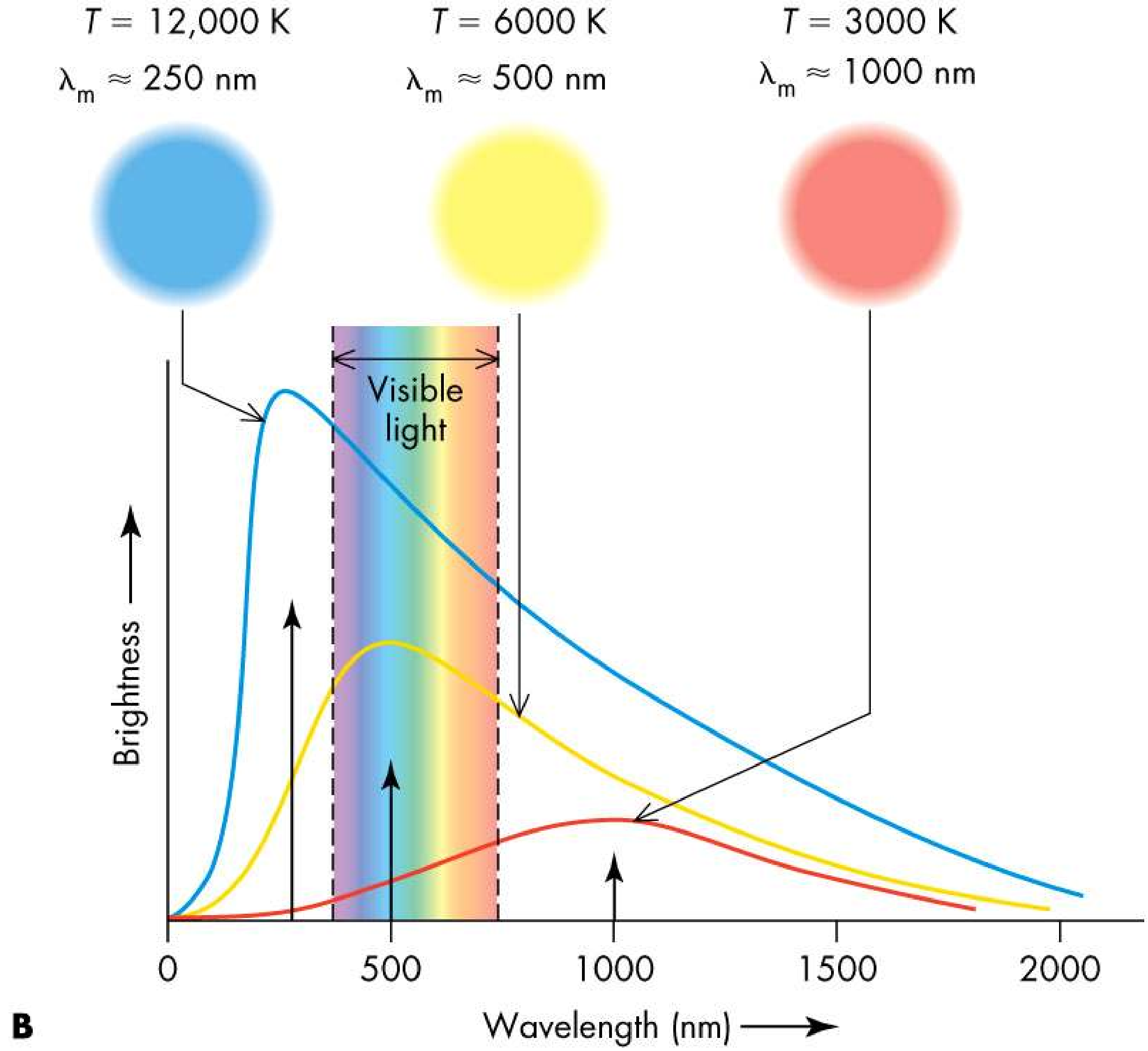
Radiation and Temperature

- Note hotter bodies radiate more strongly at shorter wavelengths
- As an object heats, it appears to change color from red to white to blue
- Measuring λ_m gives a body's temperature
- Careful: Reflected light does not give the temperature

Blackbodies and Wien's Law

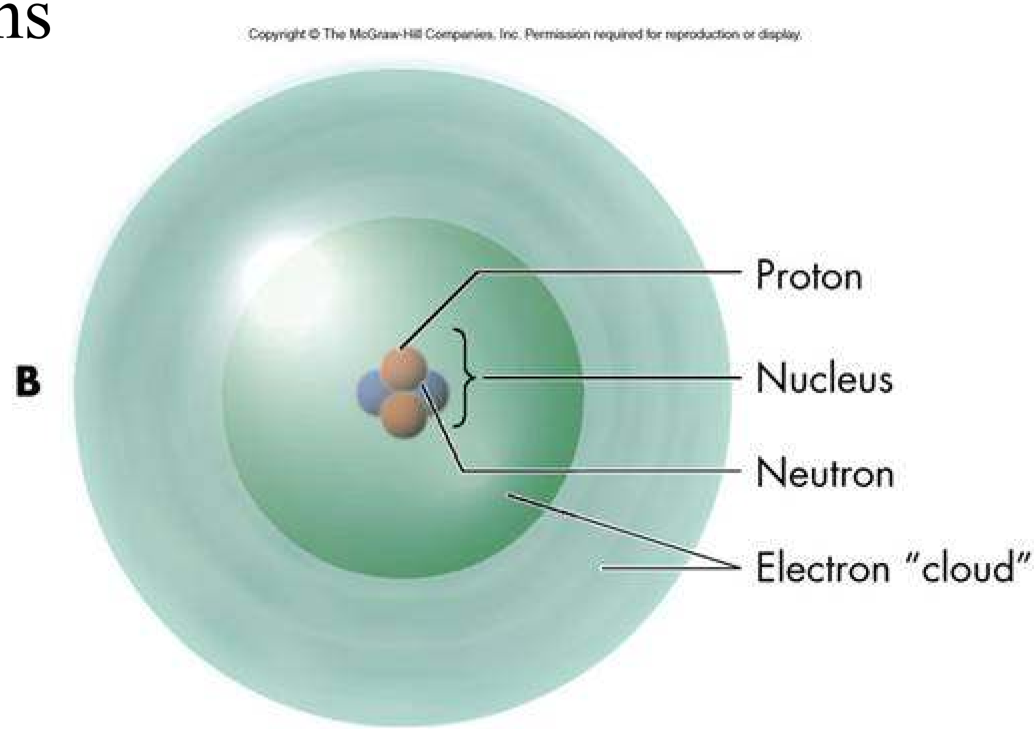
- A ***blackbody*** is an object that absorbs all the radiation falling on it
- Since such an object does not reflect any light, it appears black when cold, hence its name
- As a blackbody is heated, it radiates more efficiently than any other kind of object
- Blackbodies are excellent absorbers and emitters of radiation and follow Wien's law
- Very few real objects are perfect blackbodies, but many objects (e.g., the Sun and Earth) are close approximations
- Gases, unless highly compressed, are not blackbodies and can only radiate in narrow wavelength ranges

Blackbodies and Wien's Law



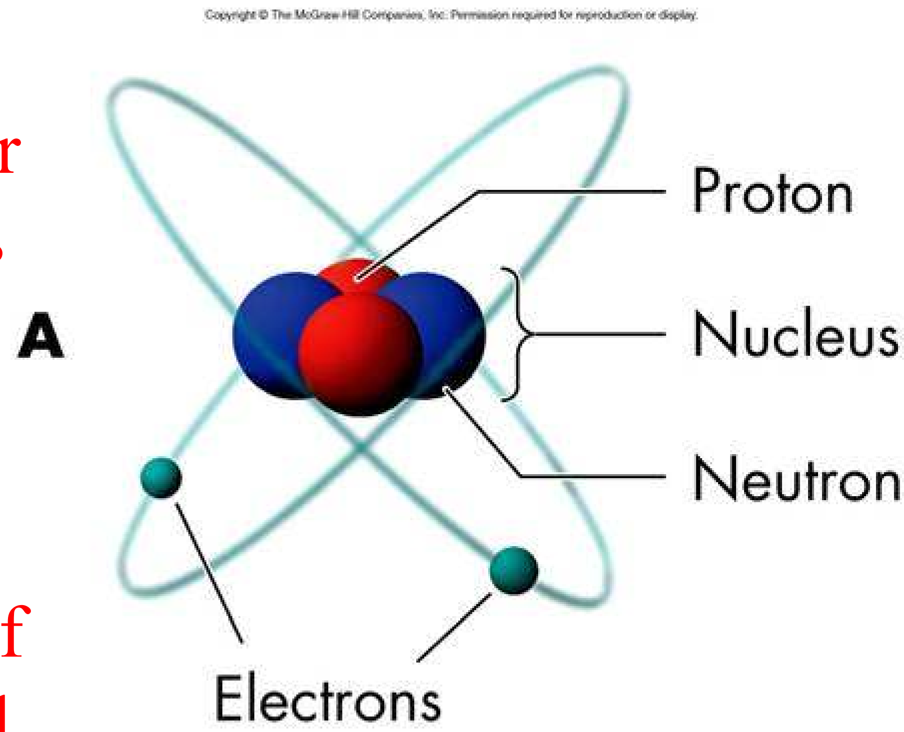
The Structure of Atoms

- Nucleus – Composed of densely packed neutrons and positively charged protons
- Cloud of negative electrons held in orbit around nucleus by positive charge of protons
- Typical atom size: 10^{-10} m (= 1 Å = 0.1 nm)

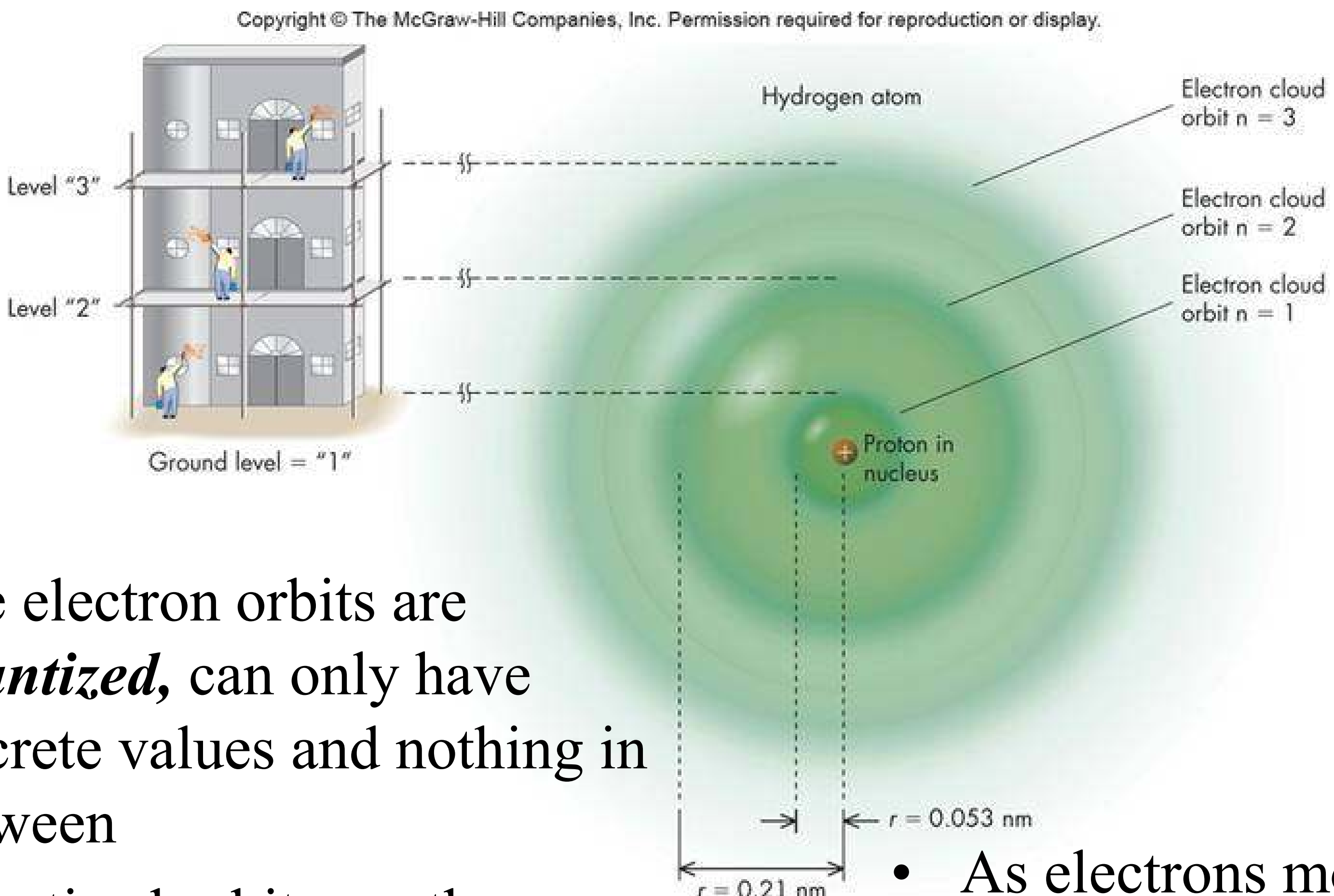


The Chemical Elements

- An ***element*** is a substance composed only of atoms that have the same number of protons in their nucleus
- A neutral element will contain an equal number of protons and electrons
- The chemical properties of an element are determined by the number of electrons



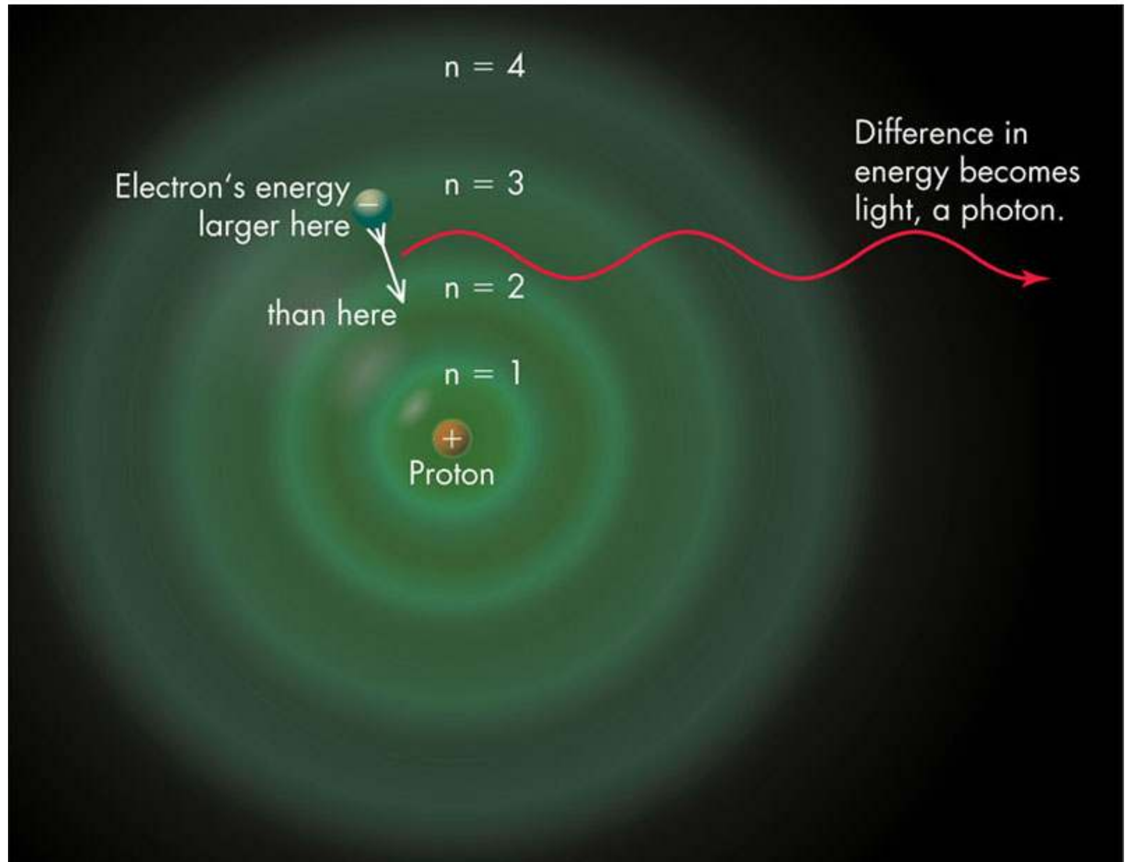
Electron "Orbits"



- The electron orbits are ***quantized,*** can only have discrete values and nothing in between
- Quantized orbits are the result of the wave-particle duality of matter
- As electrons move from one orbit to another, they change their energy in discrete amounts

Energy Change in an Atom

- An atom's energy is increased if an electron moves to an outer orbit – the atom is said to be ***excited***
- An atom's energy is decreased if an electron moves to an inner orbit

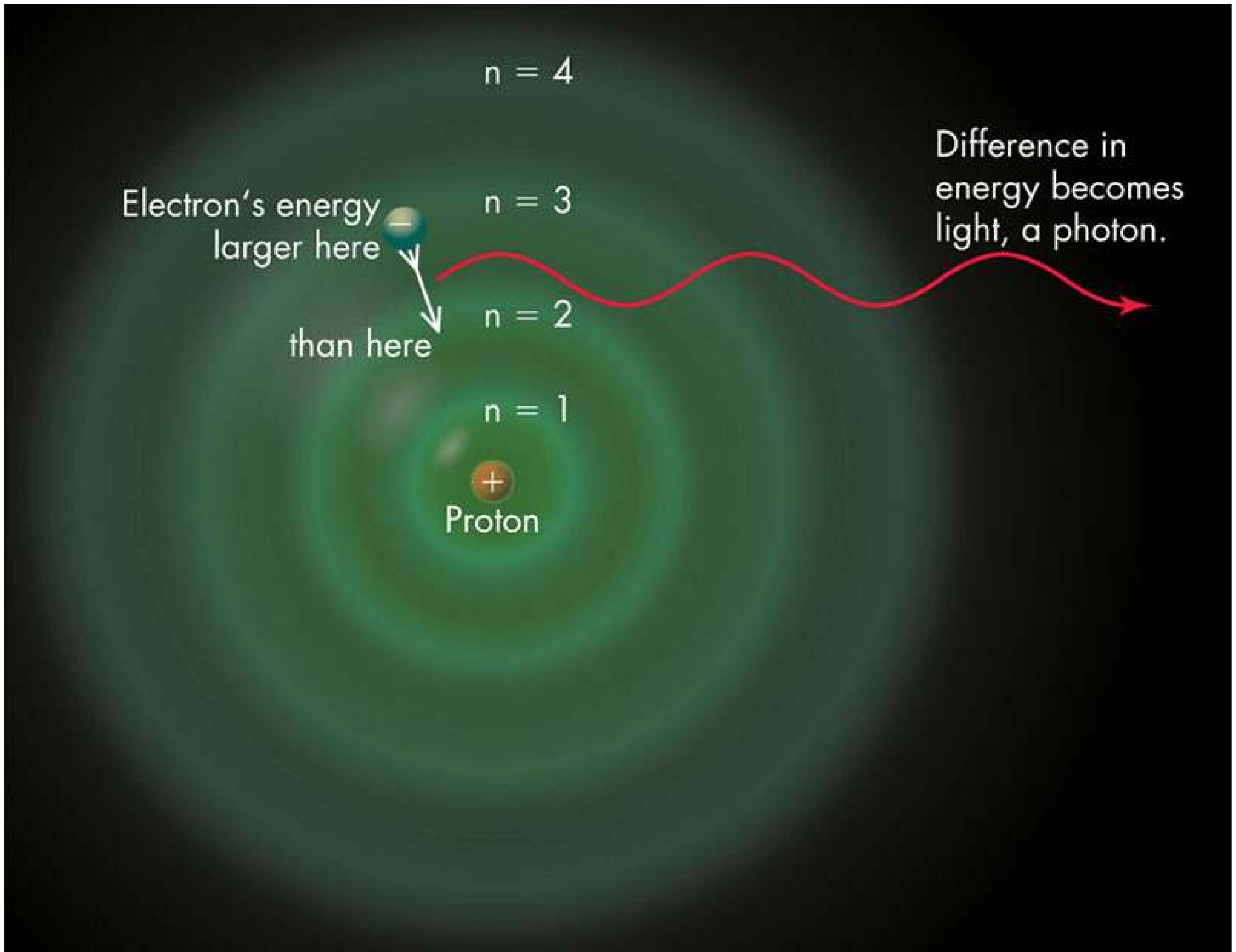


Emission of light by a hydrogen atom

Conservation of Energy

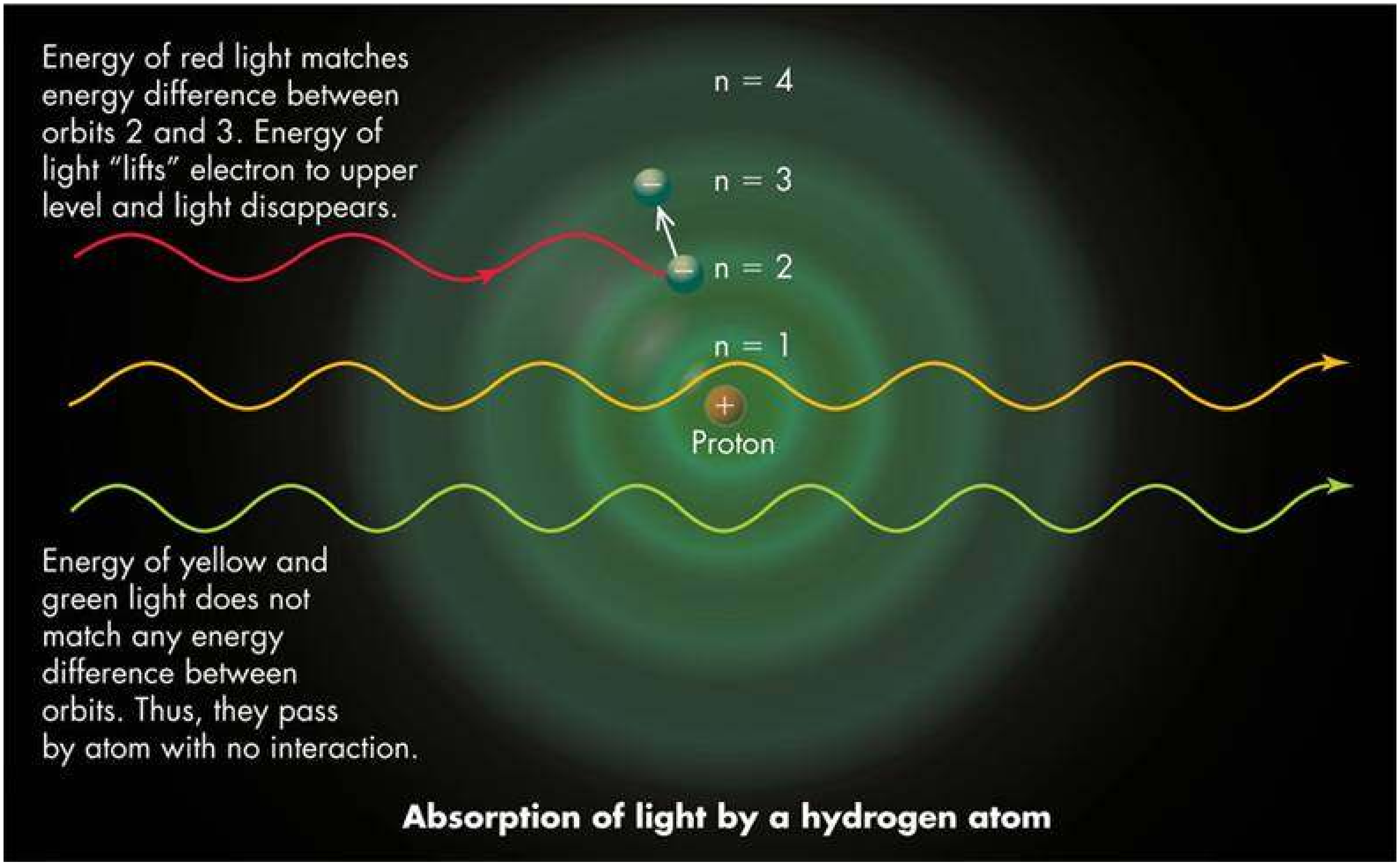
- The energy change of an atom must be compensated elsewhere – ***Conservation of Energy***
- ***Absorption*** and ***emission*** of EM radiation are two ways to preserve energy conservation
- In the photon picture, a photon is absorbed as an electron moves to a higher orbit and a photon is emitted as an electron moves to a lower orbit

Emission

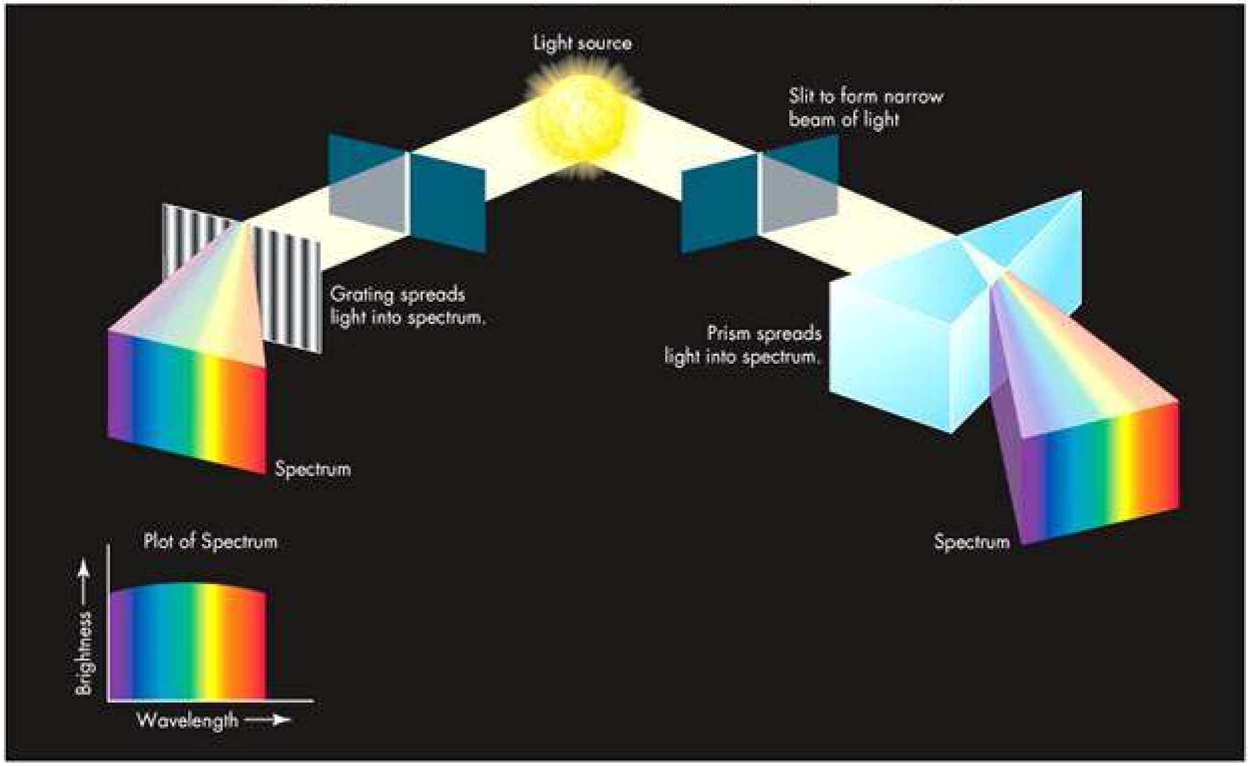


Emission of light by a hydrogen atom

Absorption

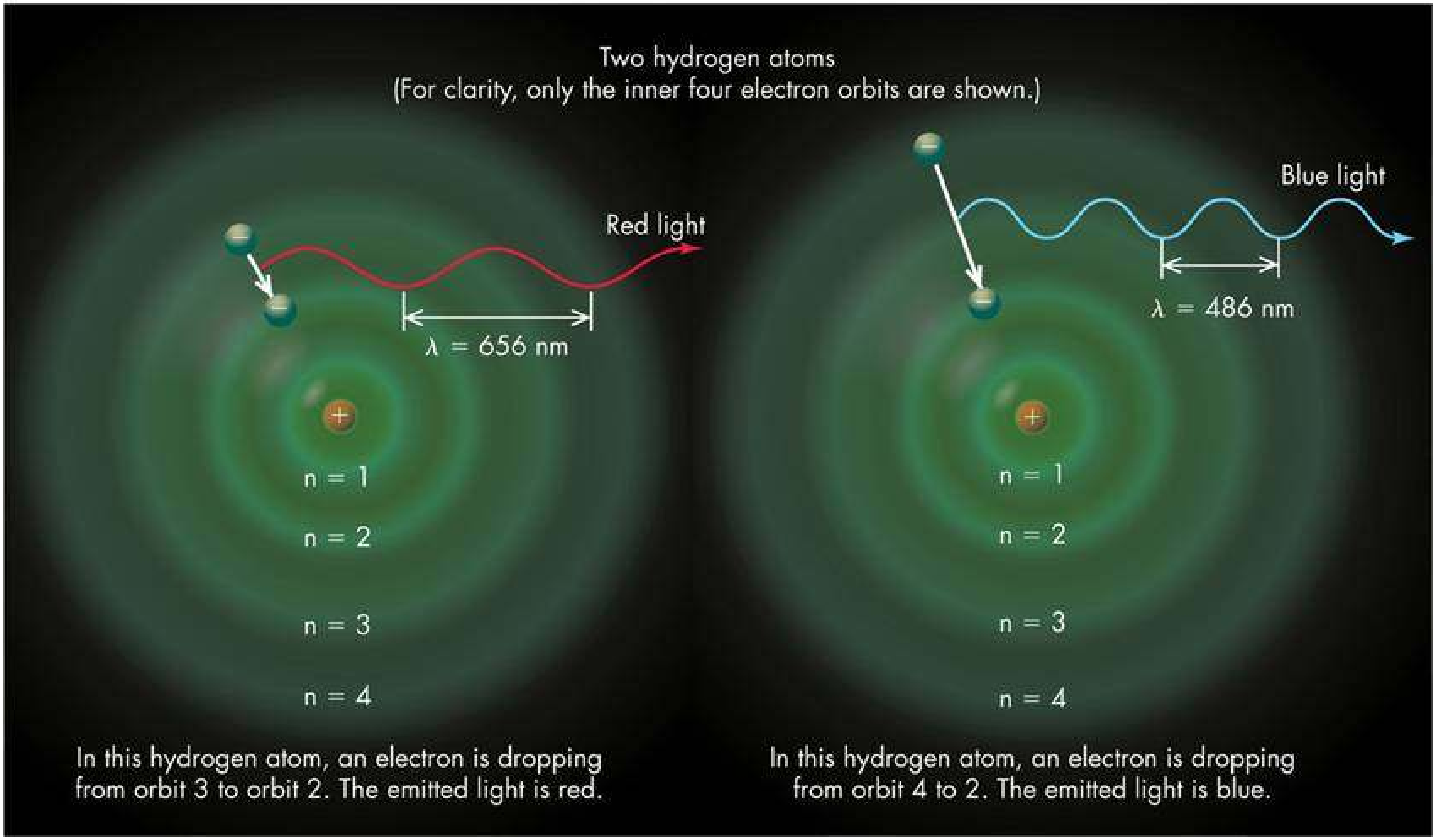

Energy of red light matches energy difference between orbits 2 and 3. Energy of light "lifts" electron to upper level and light disappears.
n = 4
n = 3
n = 2
n = 1
Proton
Energy of yellow and green light does not match any energy difference between orbits. Thus, they pass by atom with no interaction.
Absorption of light by a hydrogen atom

Spectroscopy



- Allows the determination of the composition and conditions of an astronomical body
- In ***spectroscopy,*** we capture and analyze a spectrum
- Spectroscopy assumes that every atom or molecule will have a unique spectral signature

Formation of a Spectrum

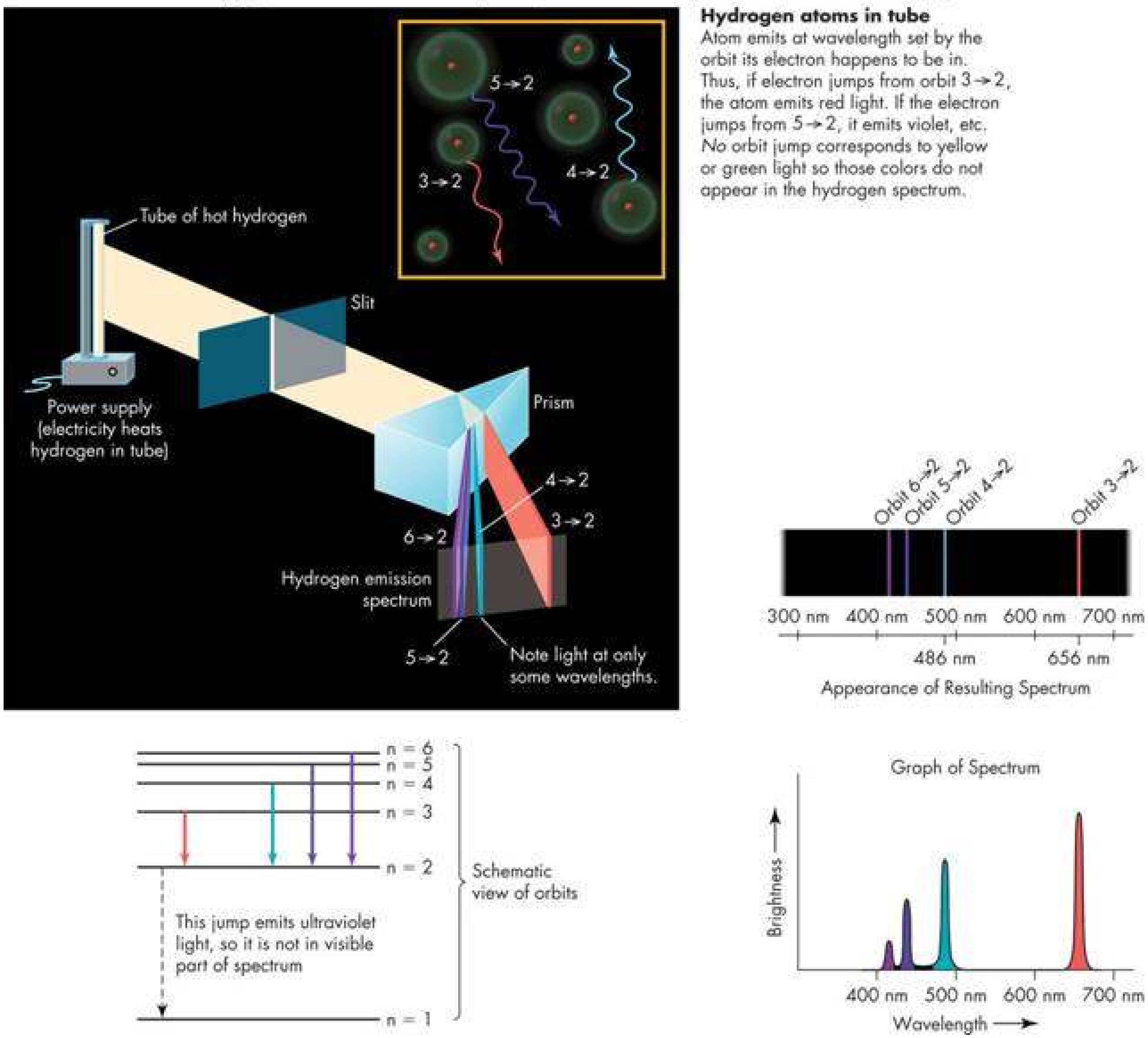


- A transition in energy level produces a photon

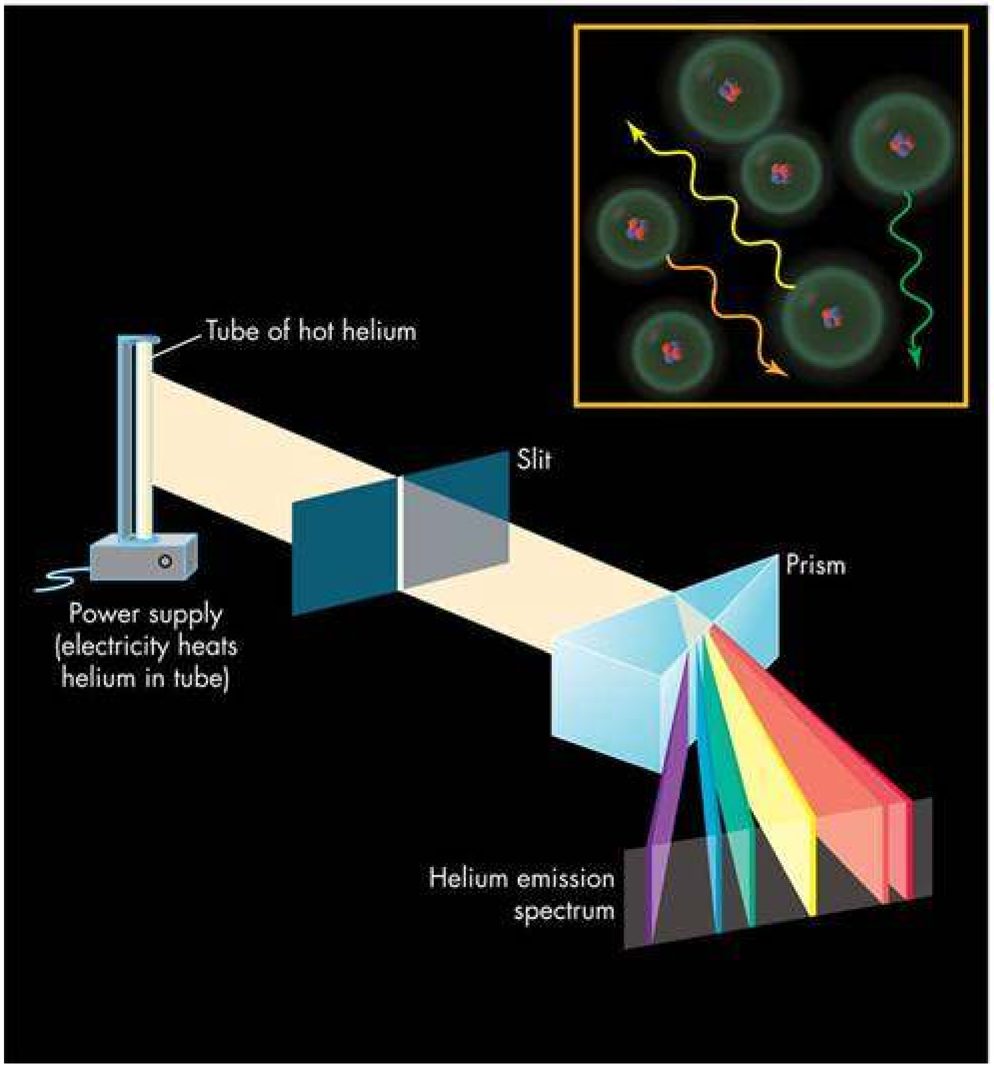
Types of Spectra

- ***Continuous spectrum***
  - Spectra of a blackbody
  - Typical objects are solids and dense gases
- ***Emission-line spectrum***
  - Produced by hot, tenuous gases
  - Fluorescent tubes, aurora, and many interstellar clouds are typical examples
- ***Dark-line*** or ***absorption-line spectrum***
  - Light from blackbody passes through cooler gas leaving dark absorption lines
  - Fraunhofer lines of Sun are an example

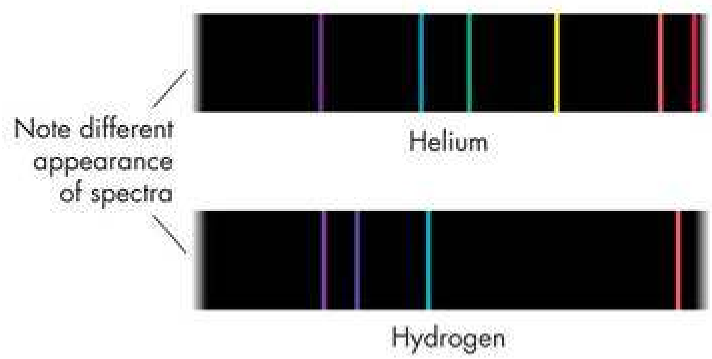
Emission Spectrum



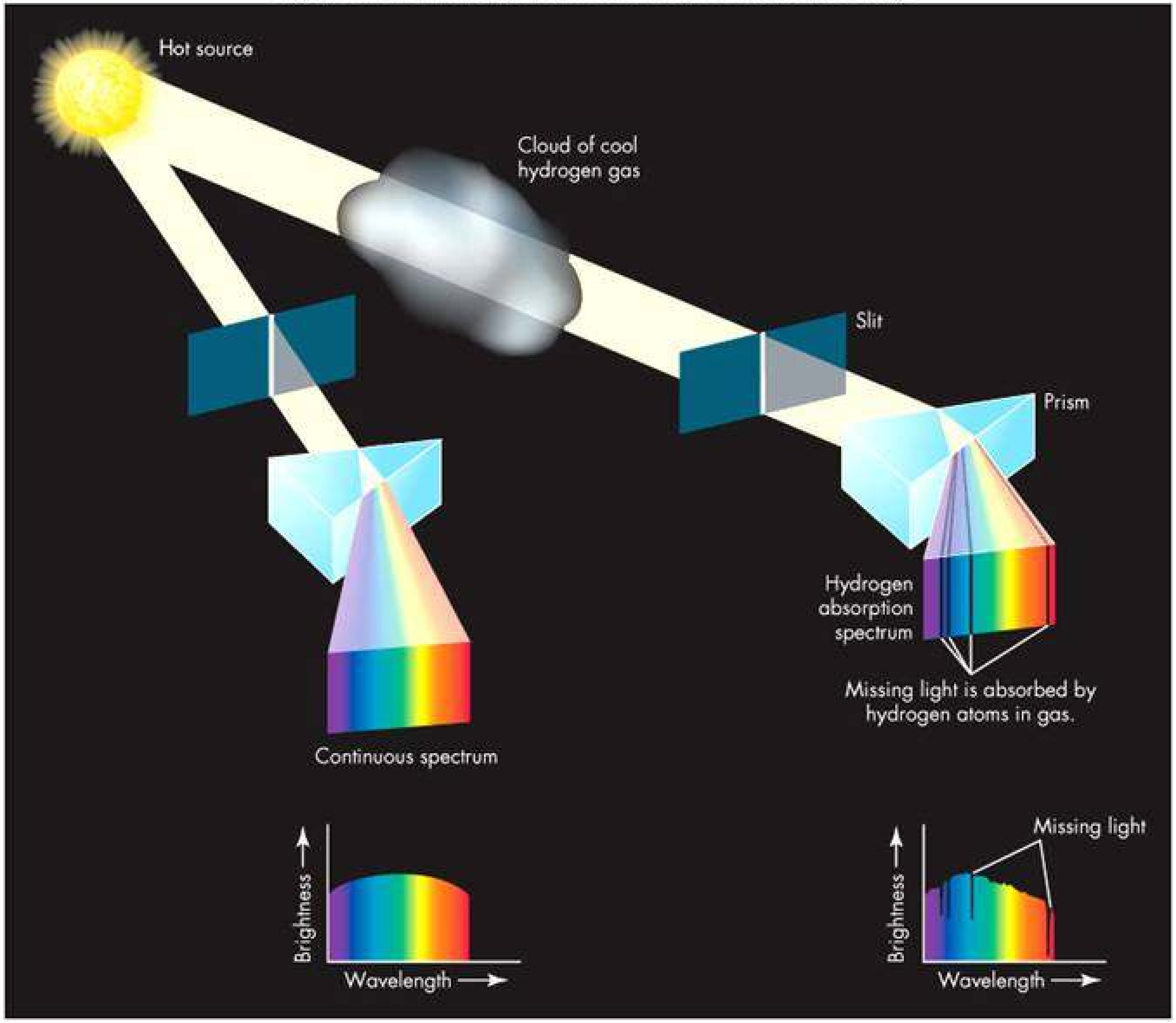
Emission Spectrum



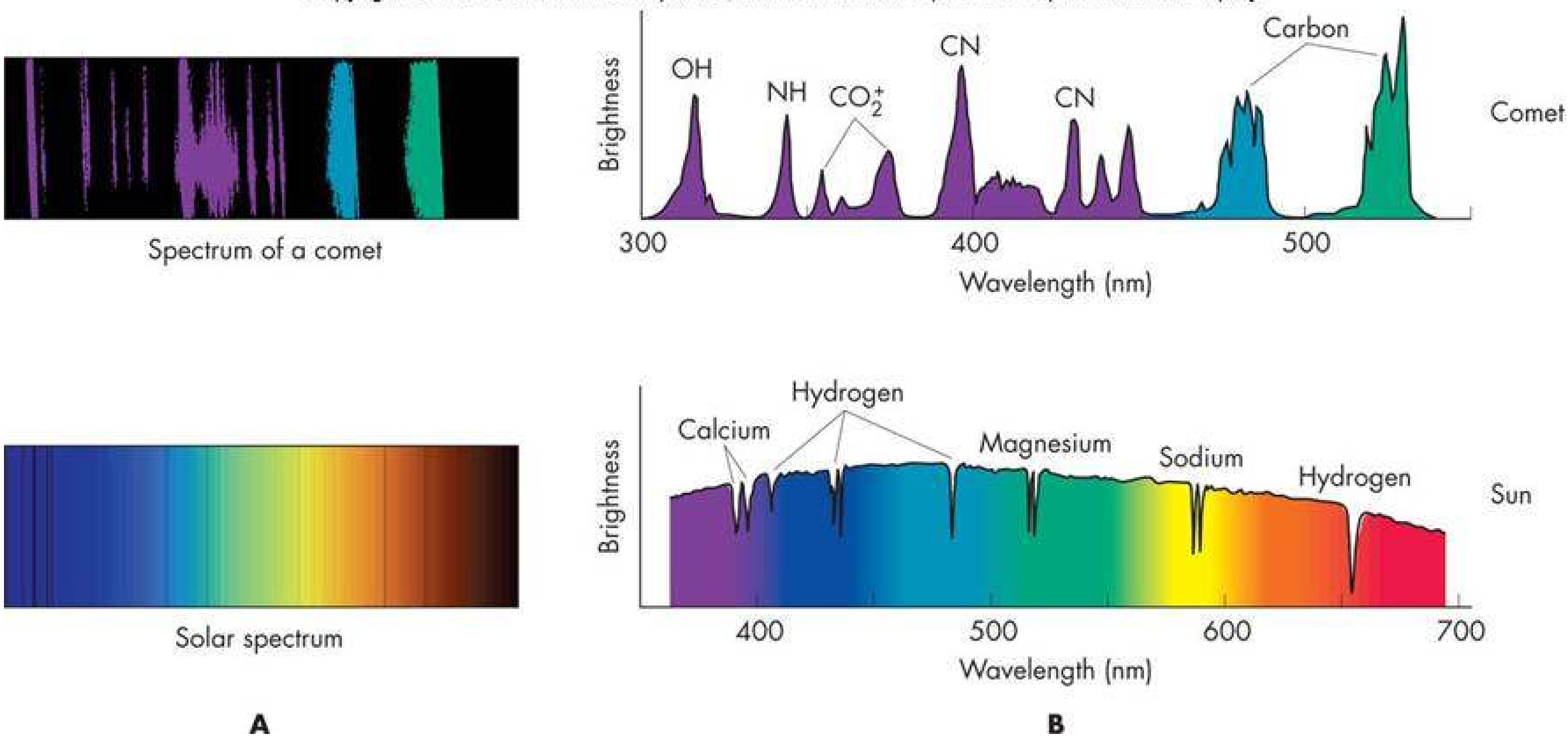
Helium atoms in tube
The electron orbits for helium atoms are different from the orbits in hydrogen. The light they emit therefore differs from that of hydrogen.



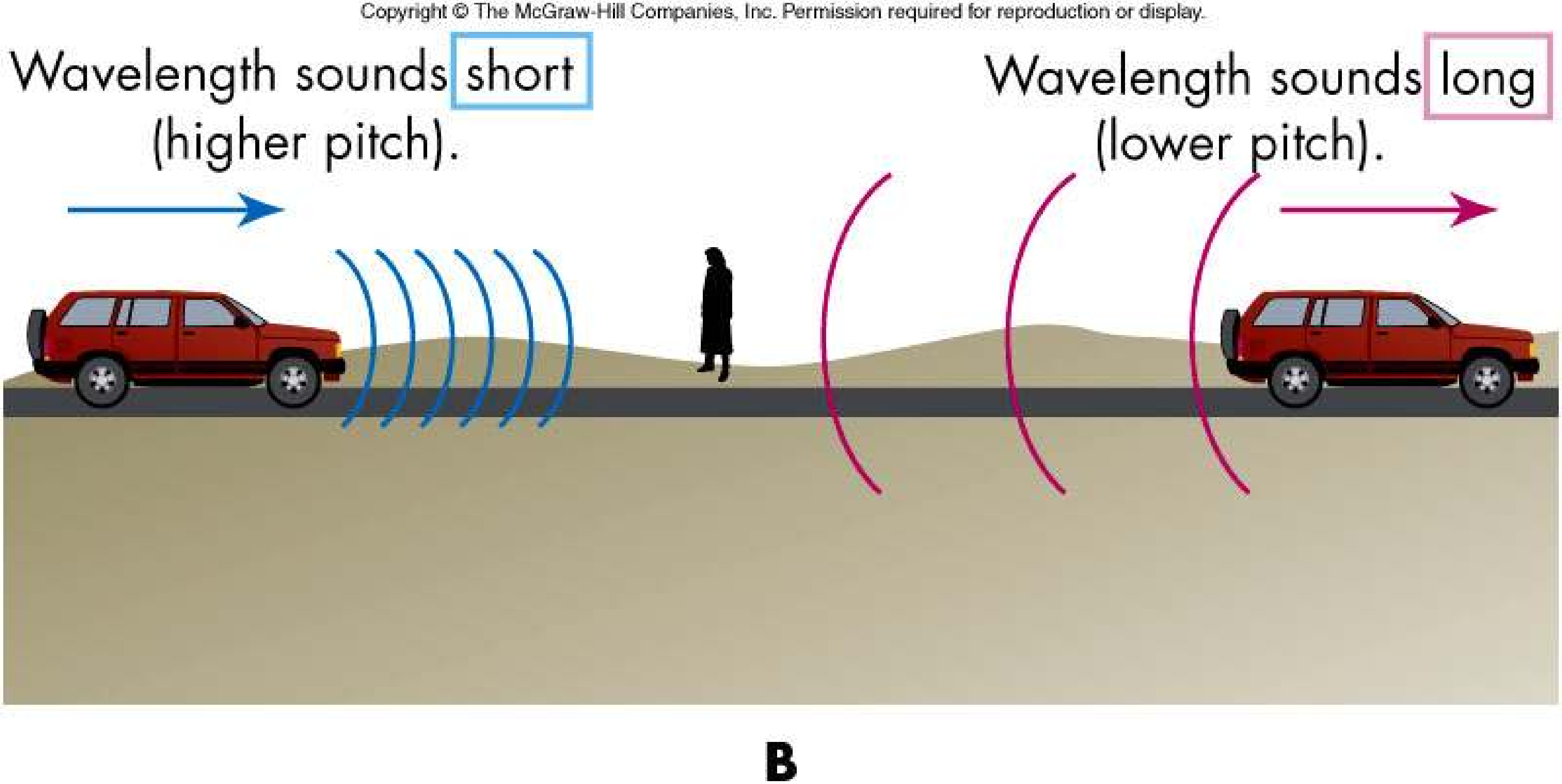
Continuous and Absorption Spectra



Astronomical Spectra

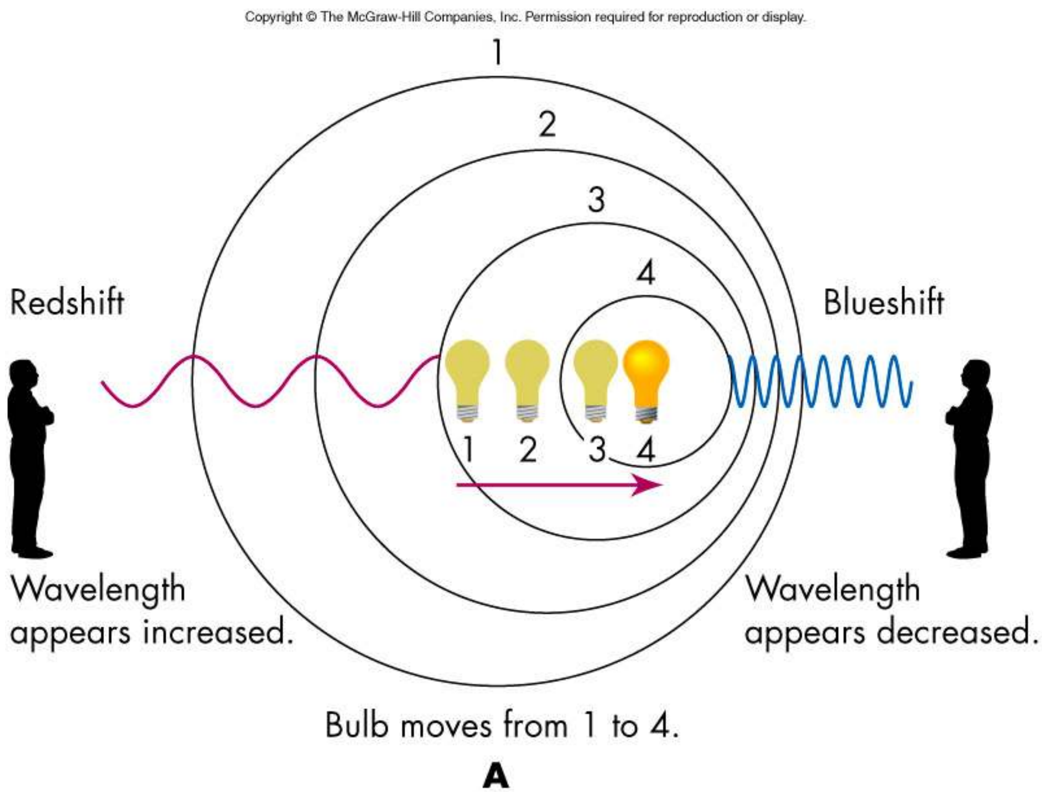


Doppler Shift in Sound



- If the source of sound is moving, the pitch changes!

Doppler Shift in Light



- If a source of light is set in motion relative to an observer, its spectral lines shift to new wavelengths in a similar way

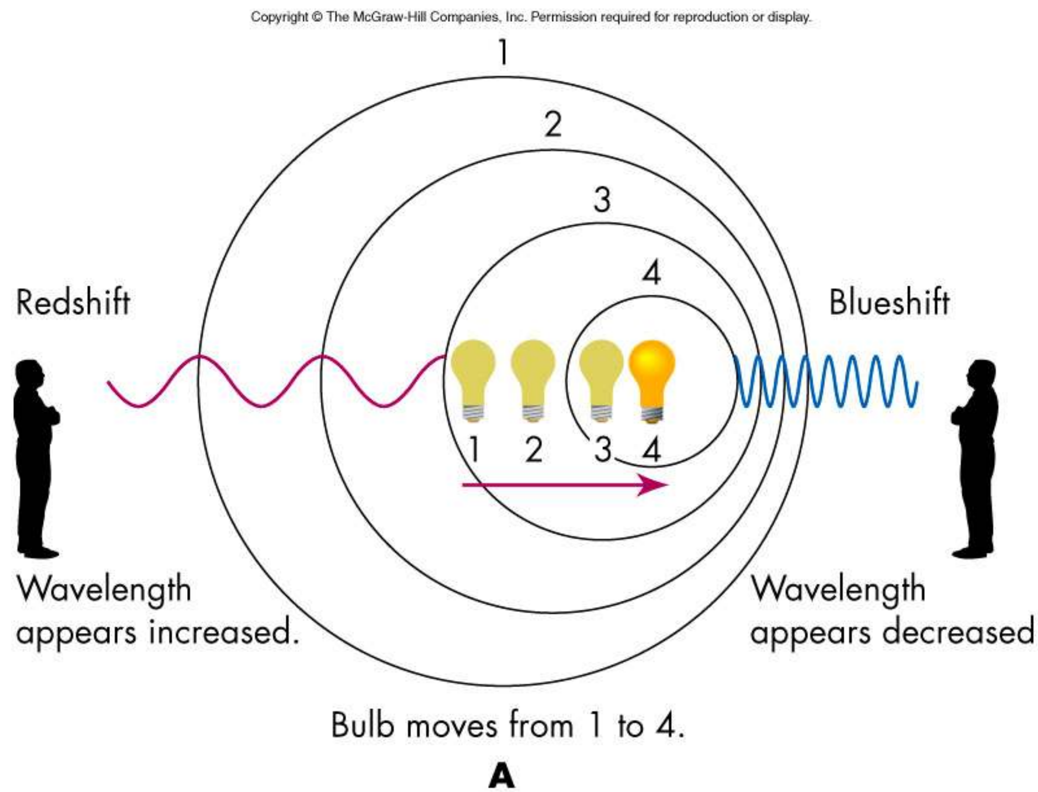
- The shift in wavelength is given as

$$\Delta\lambda = \lambda - \lambda_o = \lambda_o v/c$$

where λ is the observed (shifted) wavelength, λ_o is the emitted wavelength, v is the source non-relativistic <u>radial velocity</u>, and c is the speed of light

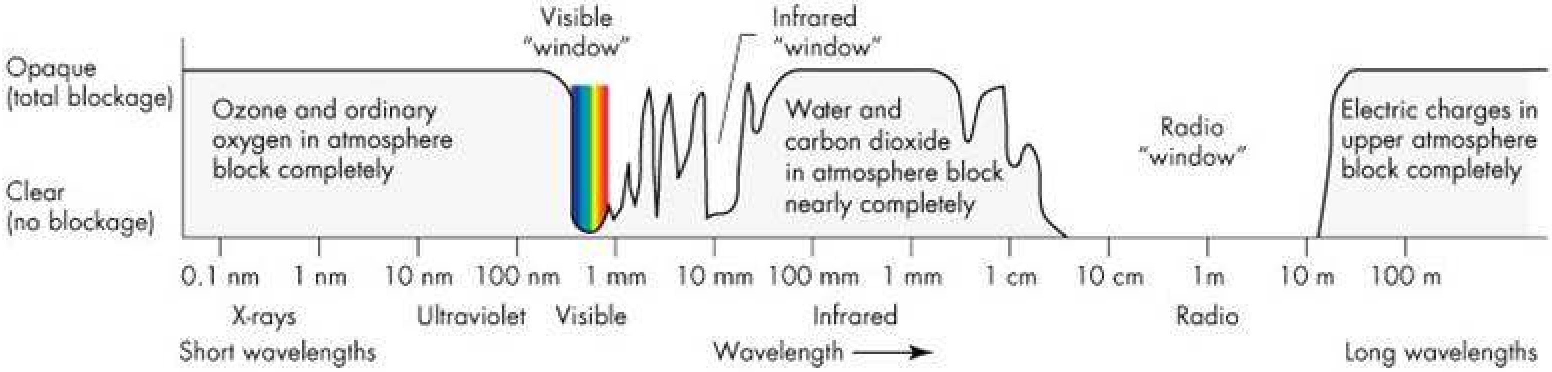
Redshift and Blueshift

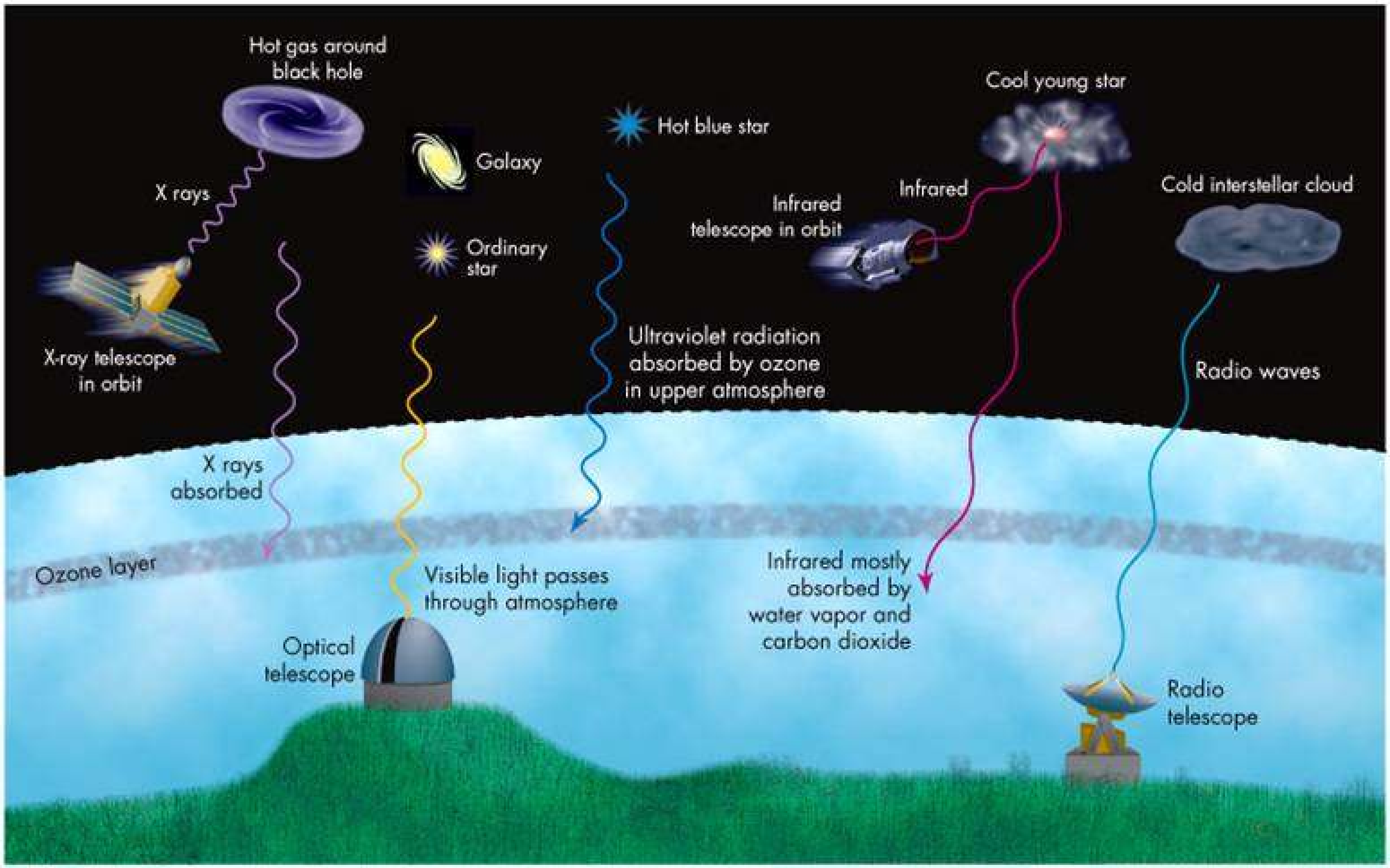
- An observed increase in wavelength is called a redshift, and a decrease in observed wavelength is called a blueshift (regardless of whether or not the waves are visible)
- Doppler shift is used to determine an object's velocity

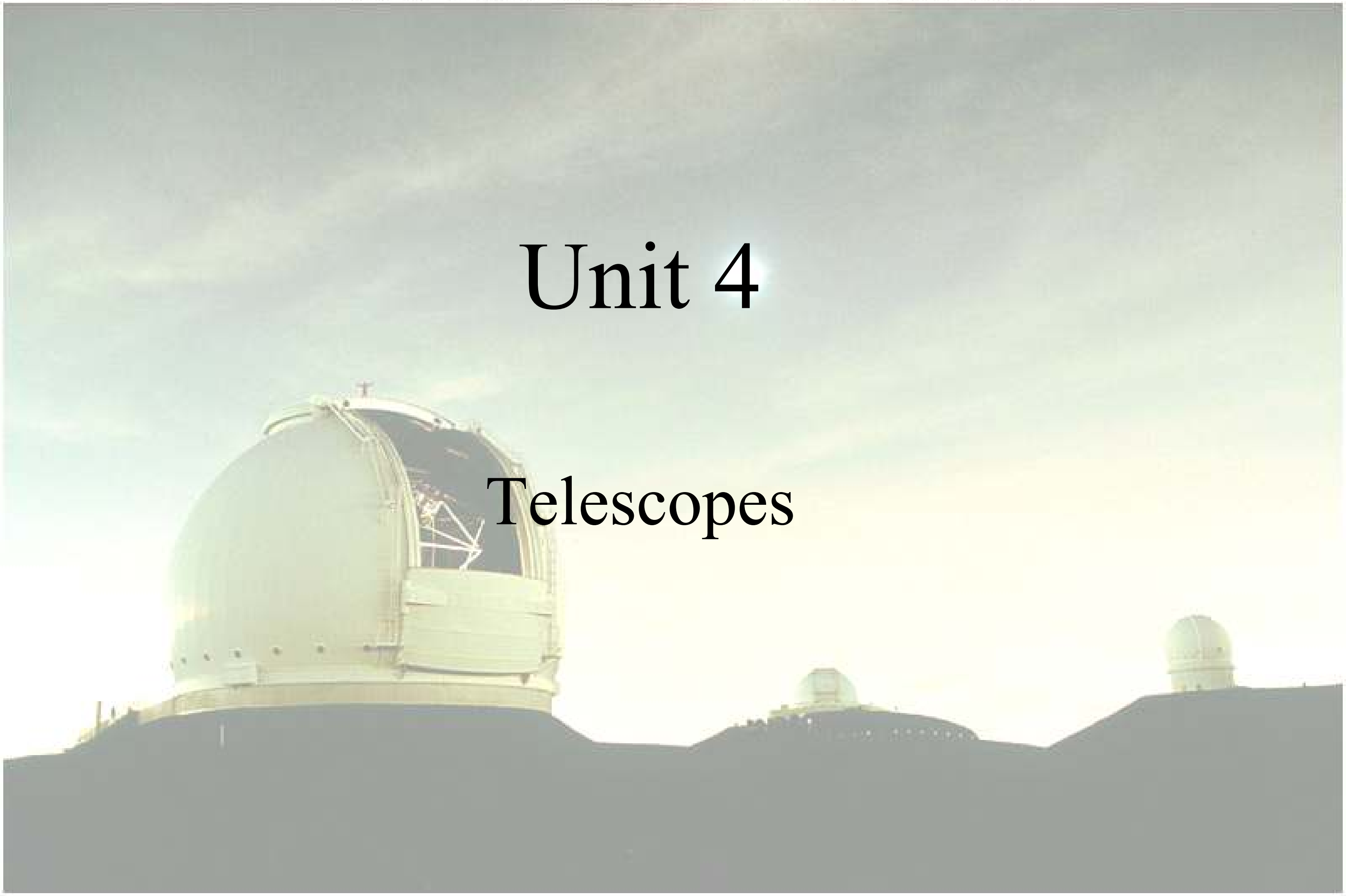


Absorption in the Atmosphere

- Gases in the Earth's atmosphere absorb electromagnetic radiation to the extent that most wavelengths from space do not reach the ground
- Visible light, most radio waves, and some infrared penetrate the atmosphere through ***atmospheric windows,*** wavelength regions of high transparency
- Lack of atmospheric windows at other wavelengths is the reason for astronomers placing telescopes in space


Visible
"window"
Infrared
"window"
Opaque
(total blockage)
Clear
(no blockage)
Ozone and ordinary
oxygen in atmosphere
block completely
Water and
carbon dioxide
in atmosphere block
nearly completely
Radio
"window"
Electric charges in
upper atmosphere
block completely
0.1 nm
1 nm
10 nm
100 nm
1 mm
10 mm
100 mm
1 mm
1 cm
10 cm
1m
10 m
100 m
X-rays
Ultraviolet
Visible
Infrared
Radio
Short wavelengths
Wavelength
Long wavelengths


Hot gas around
black hole
X rays
X-ray telescope
in orbit
Galaxy
Ordinary
star
Hot blue star
Cool young star
Infrared
Infrared
telescope in orbit
Cold interstellar cloud
Ultraviolet radiation
absorbed by ozone
in upper atmosphere
Radio waves
X rays
absorbed
Ozone layer
Visible light passes
through atmosphere
Infrared mostly
absorbed by
water vapor and
carbon dioxide
Optical
telescope
Radio
telescope

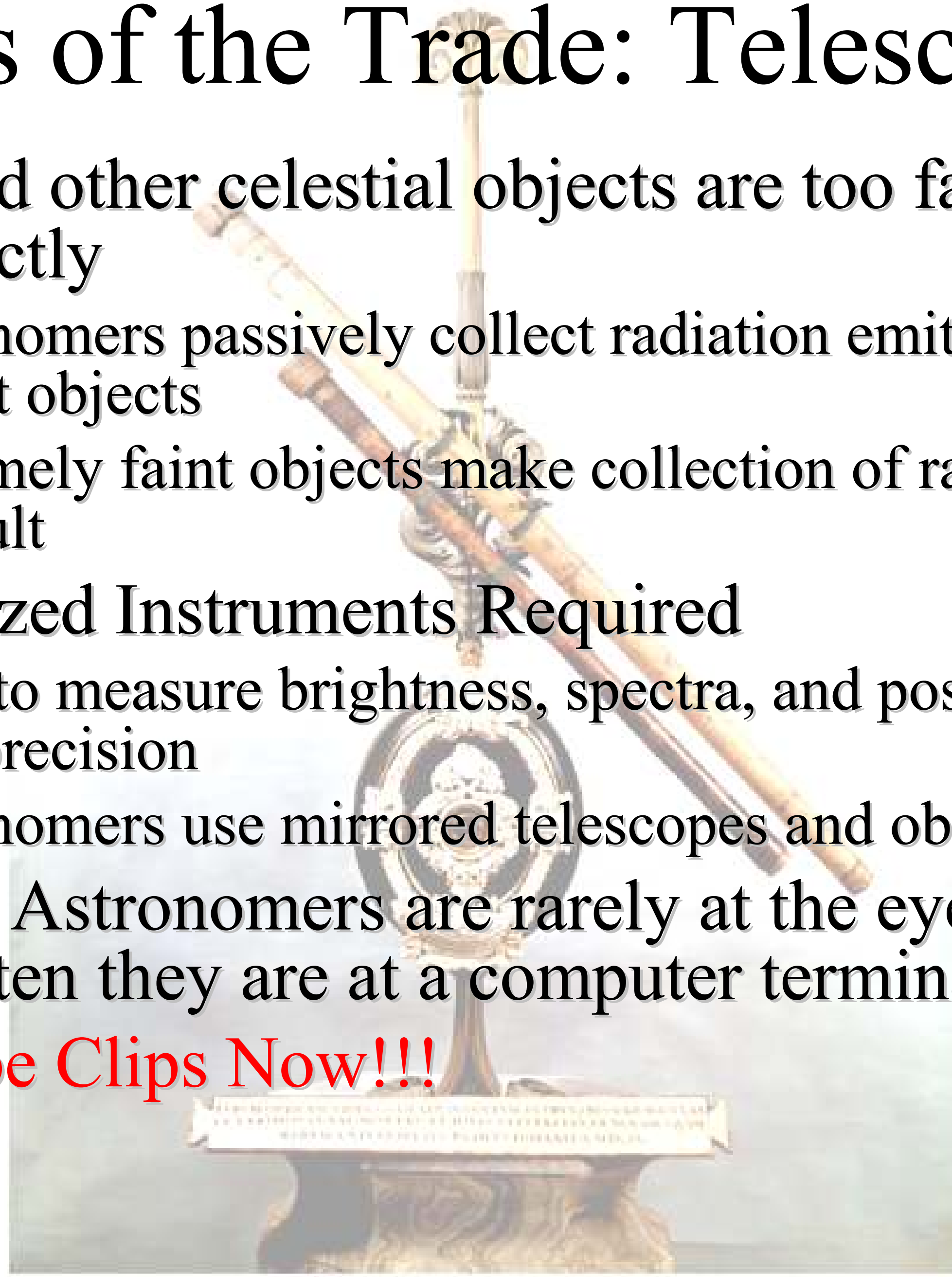


Unit 4

Telescopes

Tools of the Trade: Telescopes

- Stars and other celestial objects are too far away to test directly
  - Astronomers passively collect radiation emitted from distant objects
  - Extremely faint objects make collection of radiation difficult
- Specialized Instruments Required
  - Need to measure brightness, spectra, and positions with high precision
  - Astronomers use mirrored telescopes and observatories
- Modern Astronomers are rarely at the eyepiece, more often they are at a computer terminal!
- YouTube Clips Now!!!

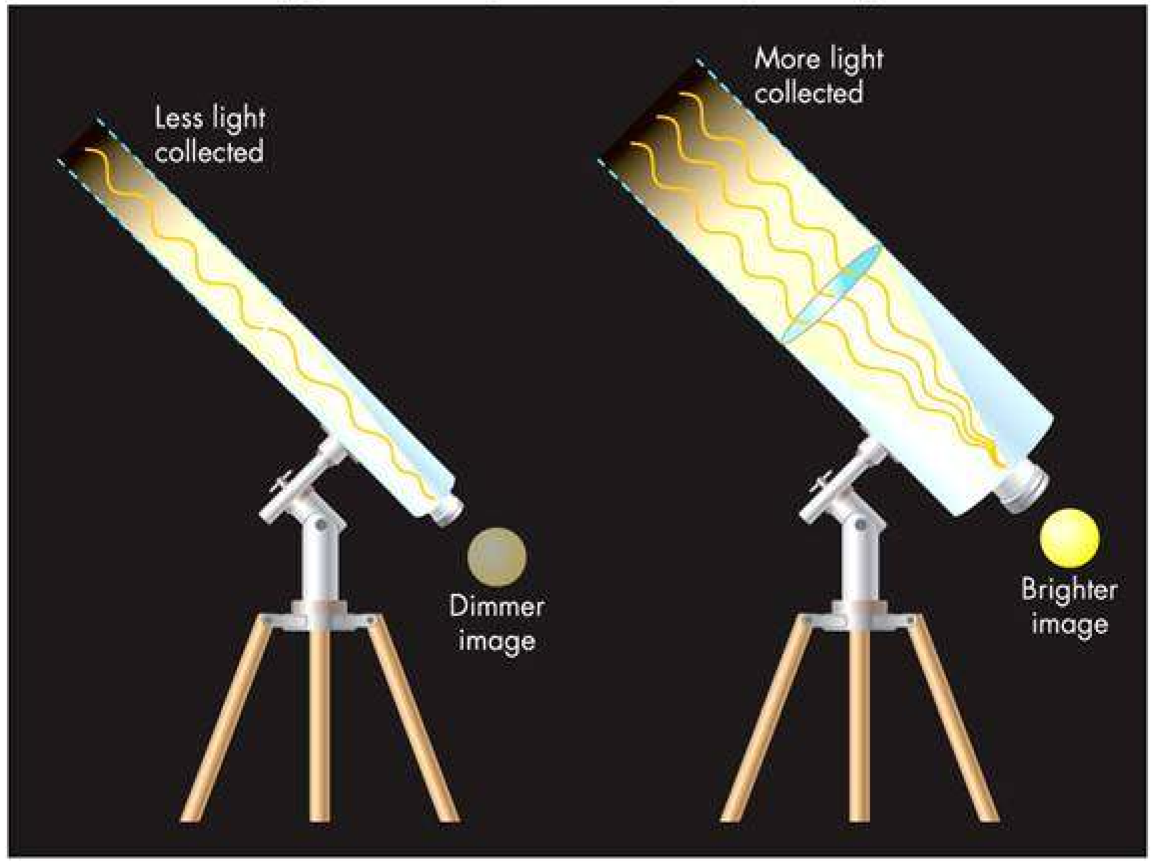


The Powers of a Telescope

- Collecting Power
  - Bigger telescope, more light collected!
- Focusing Power
  - Use mirrors or lenses to bend the path of light rays to create images
- Resolving Power
  - Picking out the details in an image

Light Gathering Power

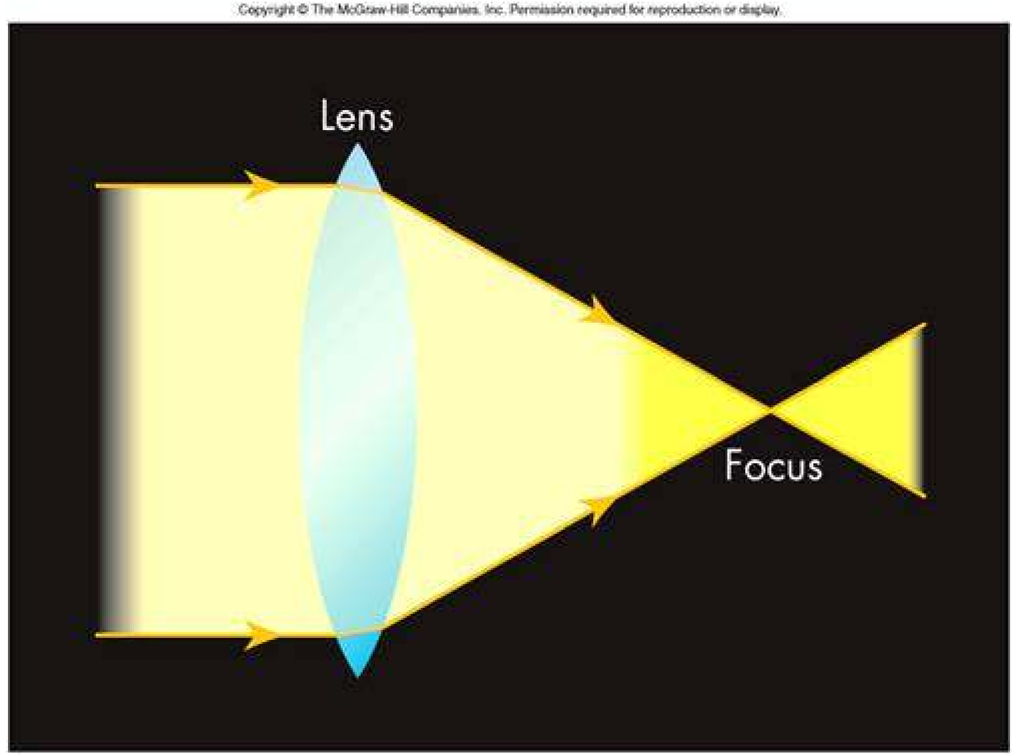
- Light collected proportional to "collector" area
  - Pupil for the eye
  - Mirror or lens for a telescope
- Telescope "funnels" light to our eyes for a brighter image
- Small changes in "collector" radius give large change in number of photons caught



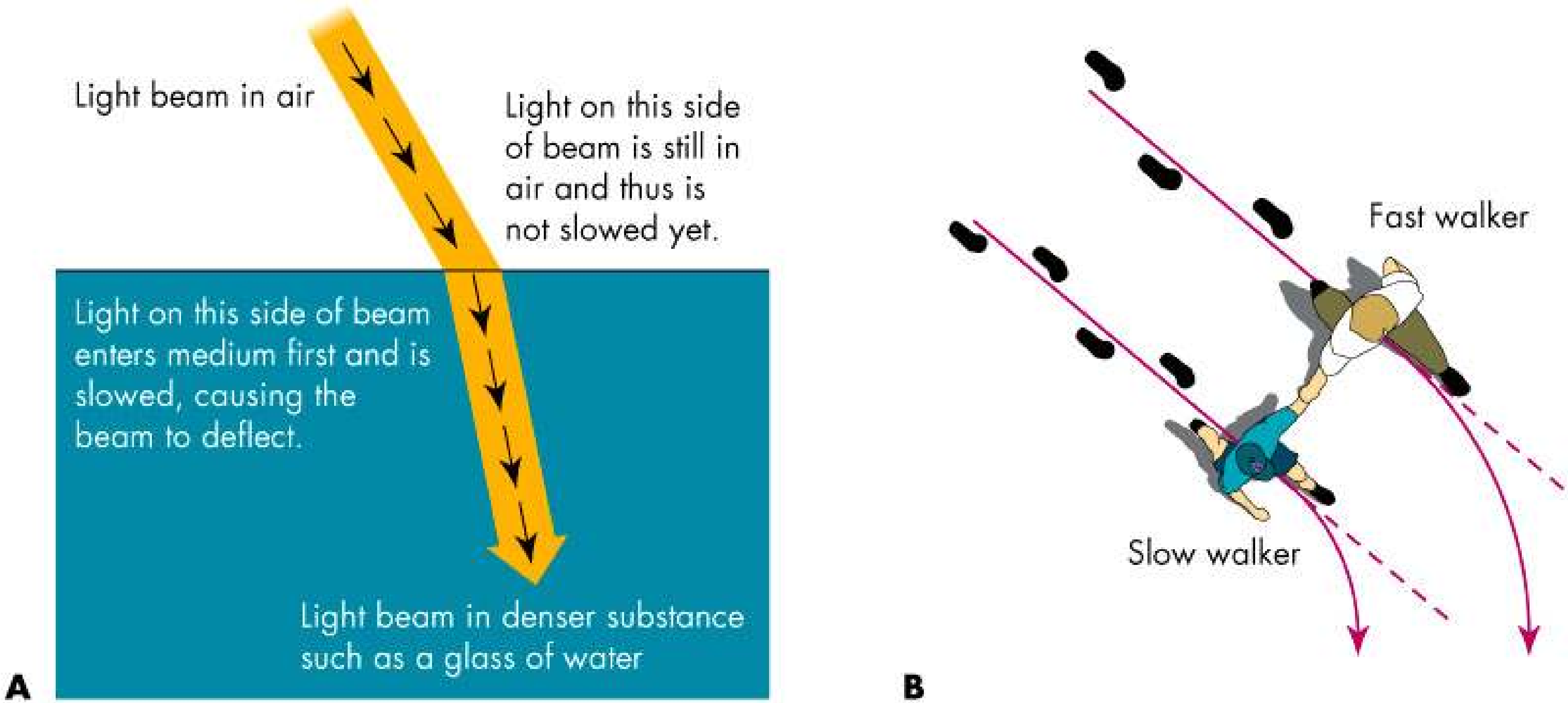
- Telescopes described by lens or mirror diameter (inches)

Focusing Power

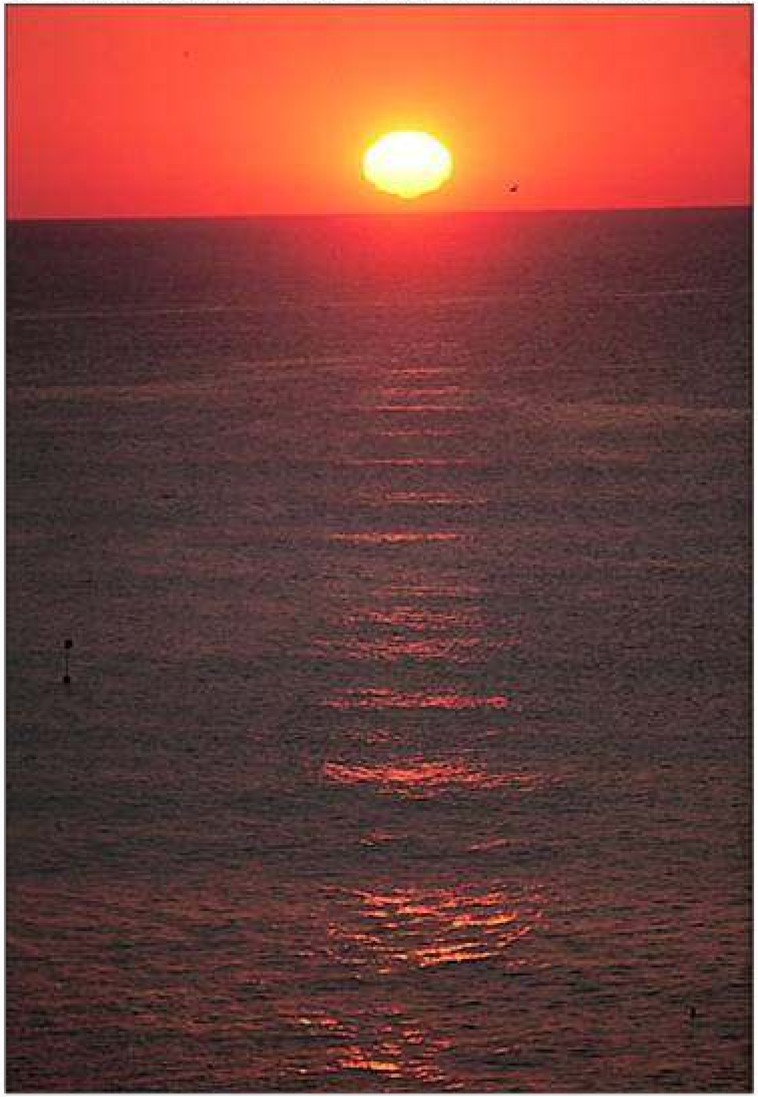
- Refraction
  - Light moving at an angle from one material to another will bend due to a process called ***refraction***
  - Refraction occurs because the speed of light is different in different materials



Refraction


Light beam in air
Light on this side of beam is still in air and thus is not slowed yet.
Light on this side of beam enters medium first and is slowed, causing the beam to deflect.
Light beam in denser substance such as a glass of water
A
Fast walker
Slow walker
B

Refraction

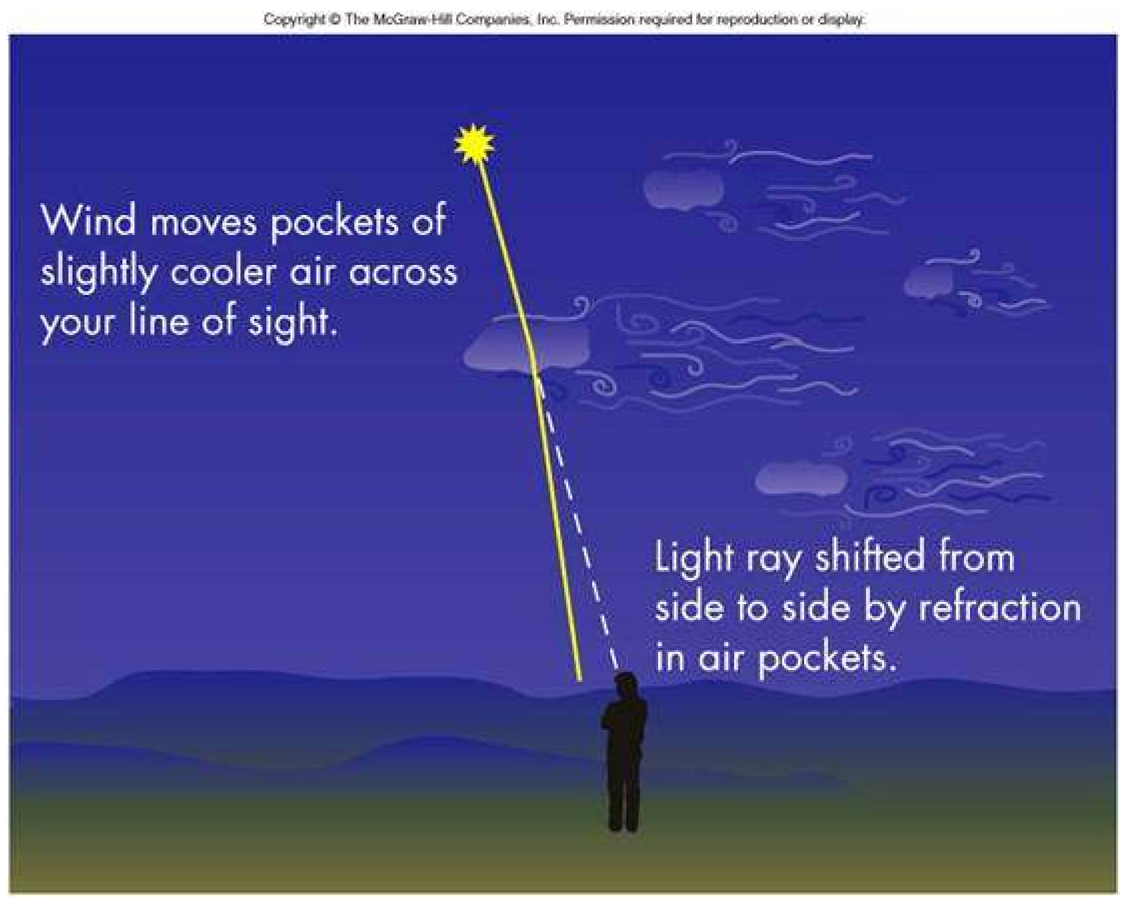


c

- ***Dispersion*** causes different colors to travel at different speeds through the same material
- Refraction is responsible for the distortion of the Sun near the horizon, but not the ***Moon illusion***

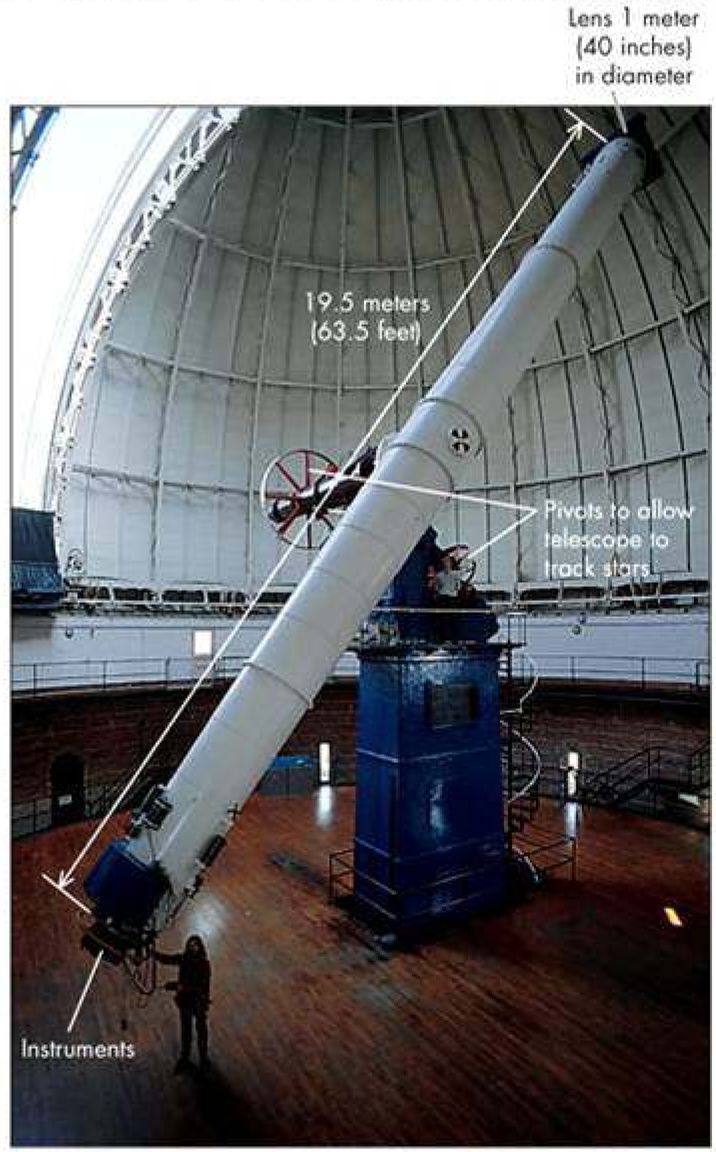
Refraction

- Refraction is also responsible for *seeing*
  - Twinkling of stars
  - AKA ***Scintillation***
- Temperature and density differences in pockets of air shift the image of the star



Refracting Telescopes

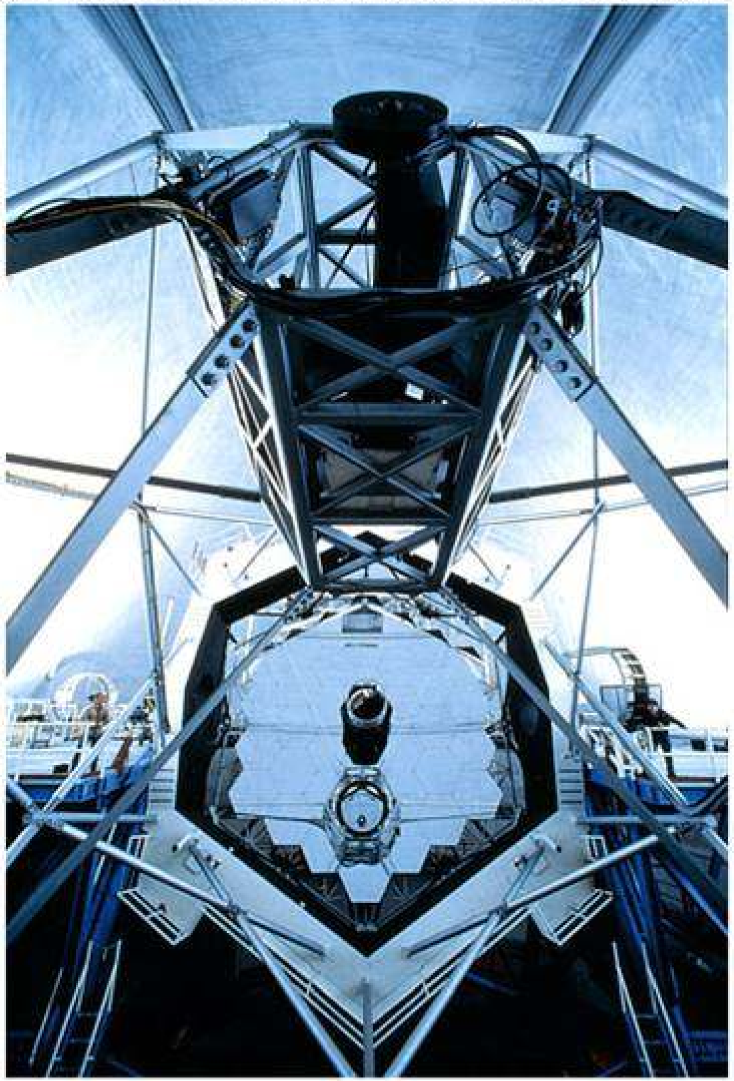
- A lens employs refraction to bend light
- Telescopes that employ lenses to collect and focus light are called ***refractors***



Disadvantages to Refractors

- Lenses have many disadvantages in large telescopes!
  - Large lenses are extremely expensive to fabricate
  - A large lens will sag in the center since it can only be supported on the edges
  - Dispersion causes images to have colored fringes
  - Many lens materials absorb short-wavelength light

Reflecting Telescopes

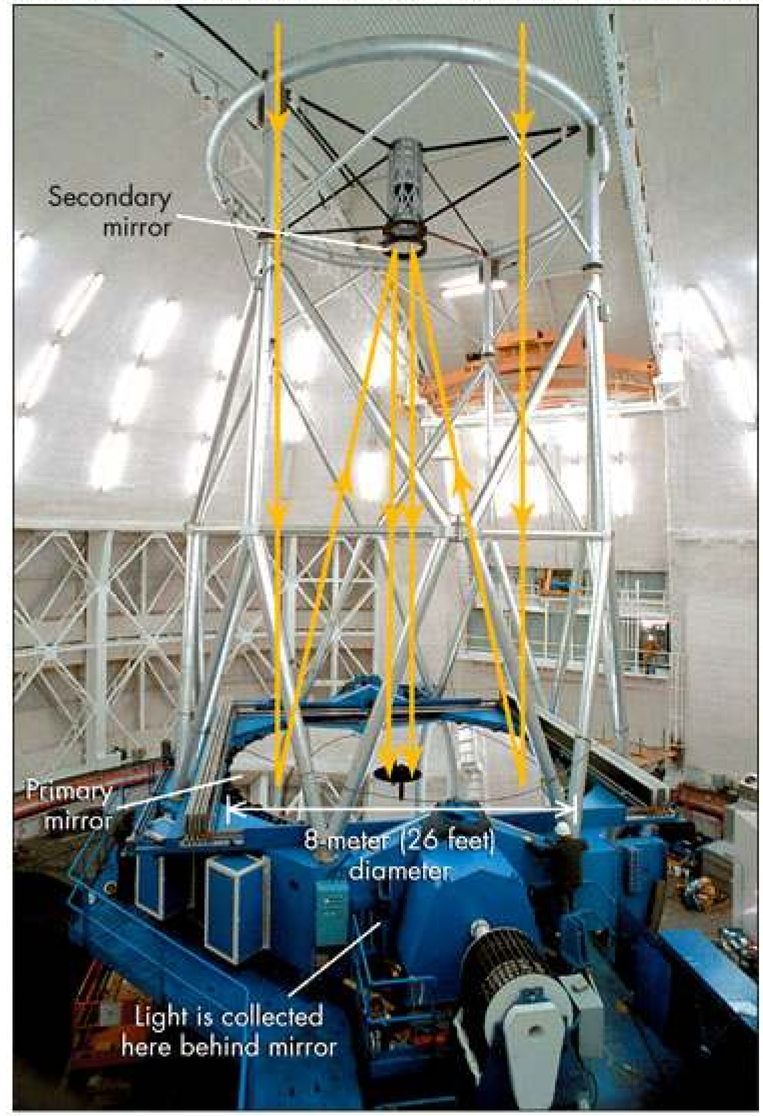


A

- Reflectors
  - Used almost exclusively by astronomers today
  - Twin Keck telescopes, located on the 14,000 foot volcanic peak Mauna Kea in Hawaii, have 10-meter collector mirrors!
  - Light is focused in front of the mirror

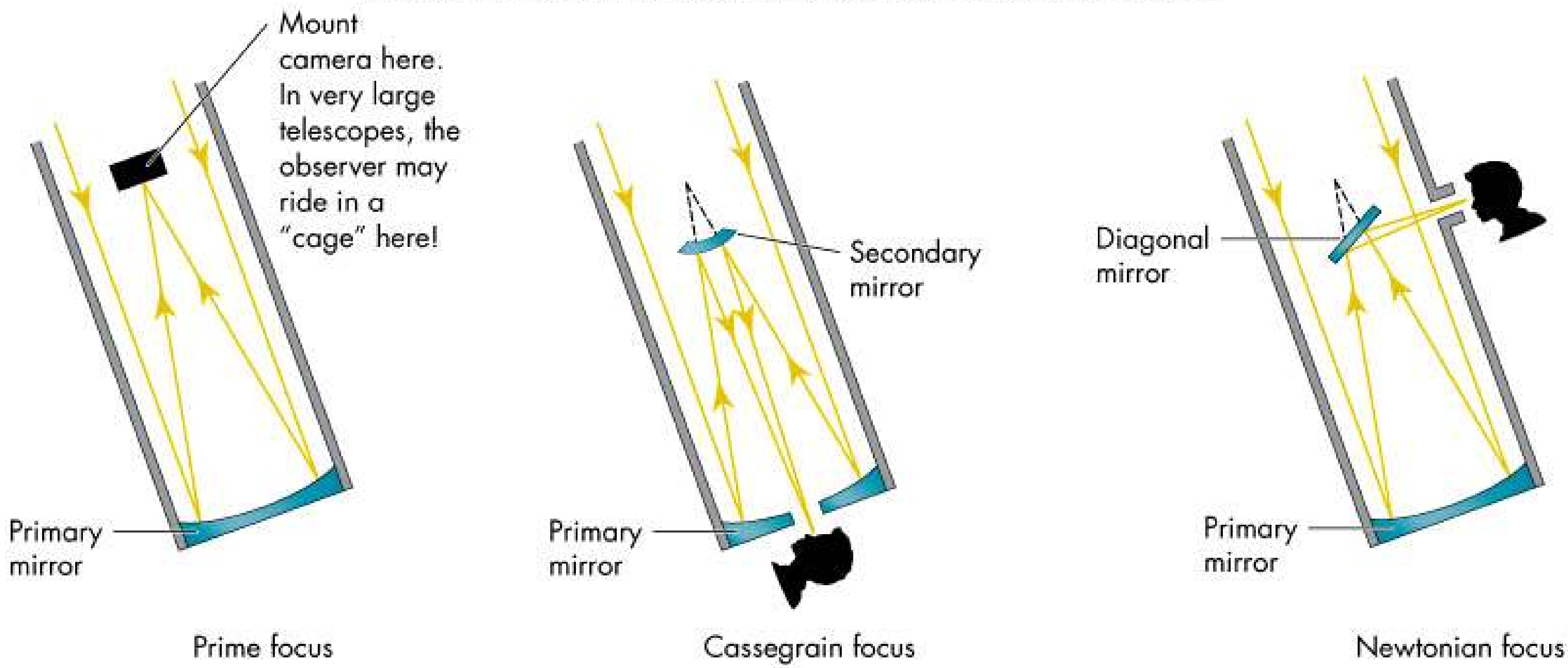
Reflecting Telescopes

- A ***secondary mirror*** may be used to deflect the light to the side or through a hole in the ***primary mirror***
- ***Multi-mirror instruments*** and ***extremely thin mirrors*** are two modern approaches to dealing with large pieces of glass in a telescope system

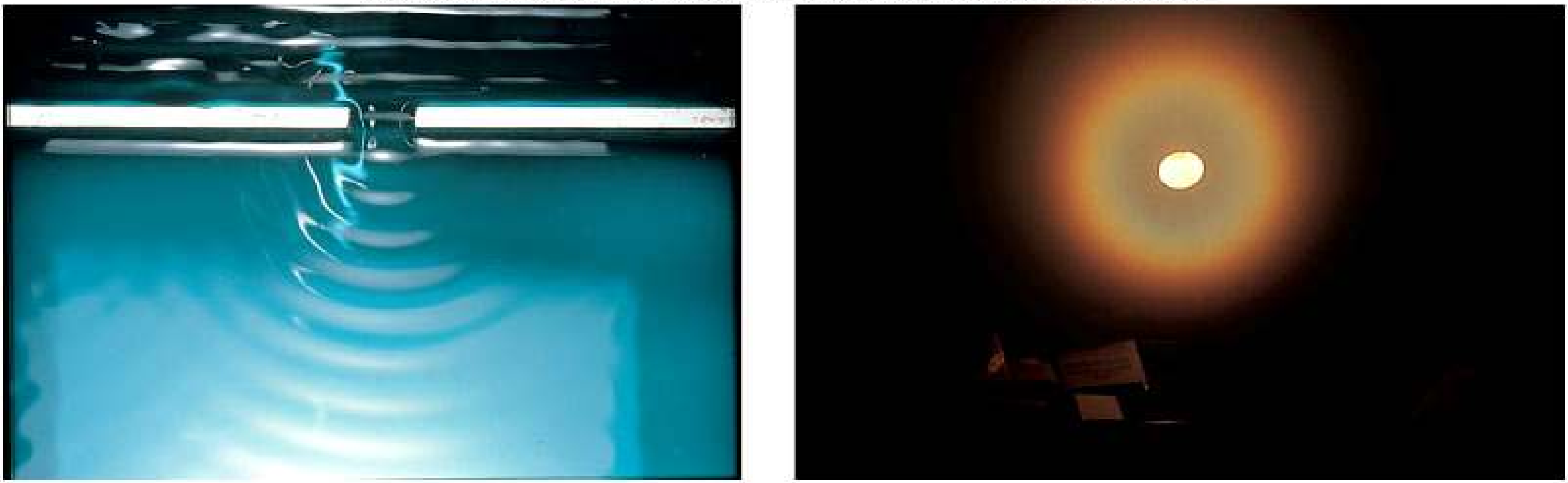


B

Styles of Refractors



Resolving Power

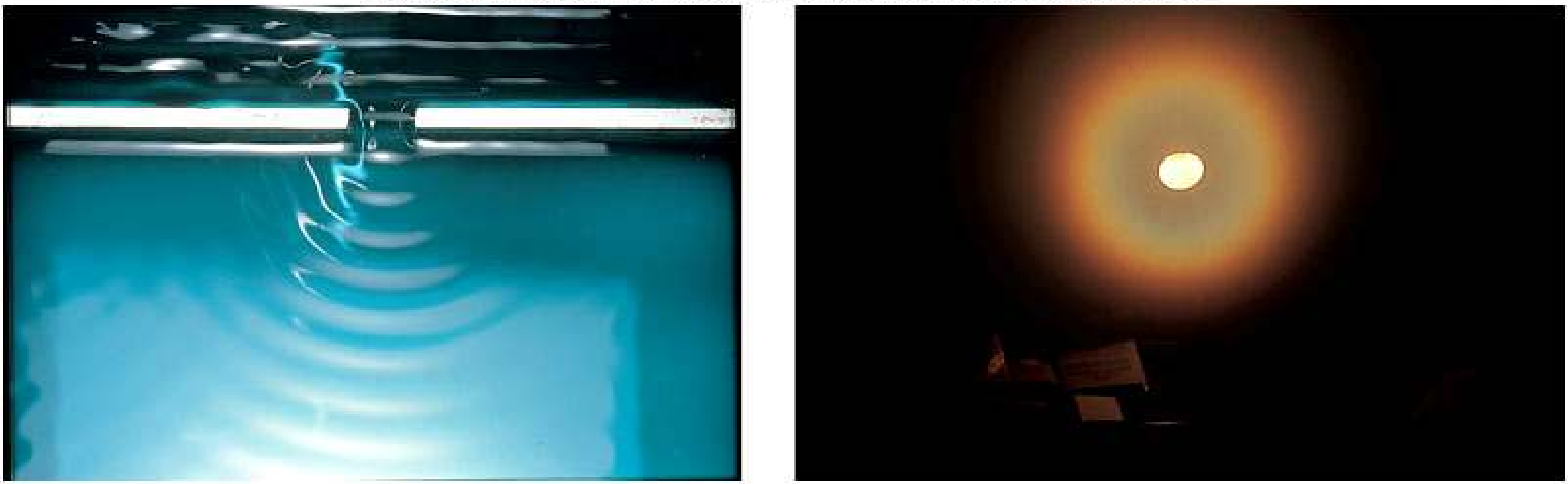


A B

- A telescope's ability to discern detail is referred to as its ***resolving power***
- Resolving power is limited by the wave nature of light through a phenomenon called ***diffraction***

- Waves are diffracted as they pass through narrow openings
- A diffracted point source of light appears as a point surrounded by rings of light

Resolving Power and Aperture



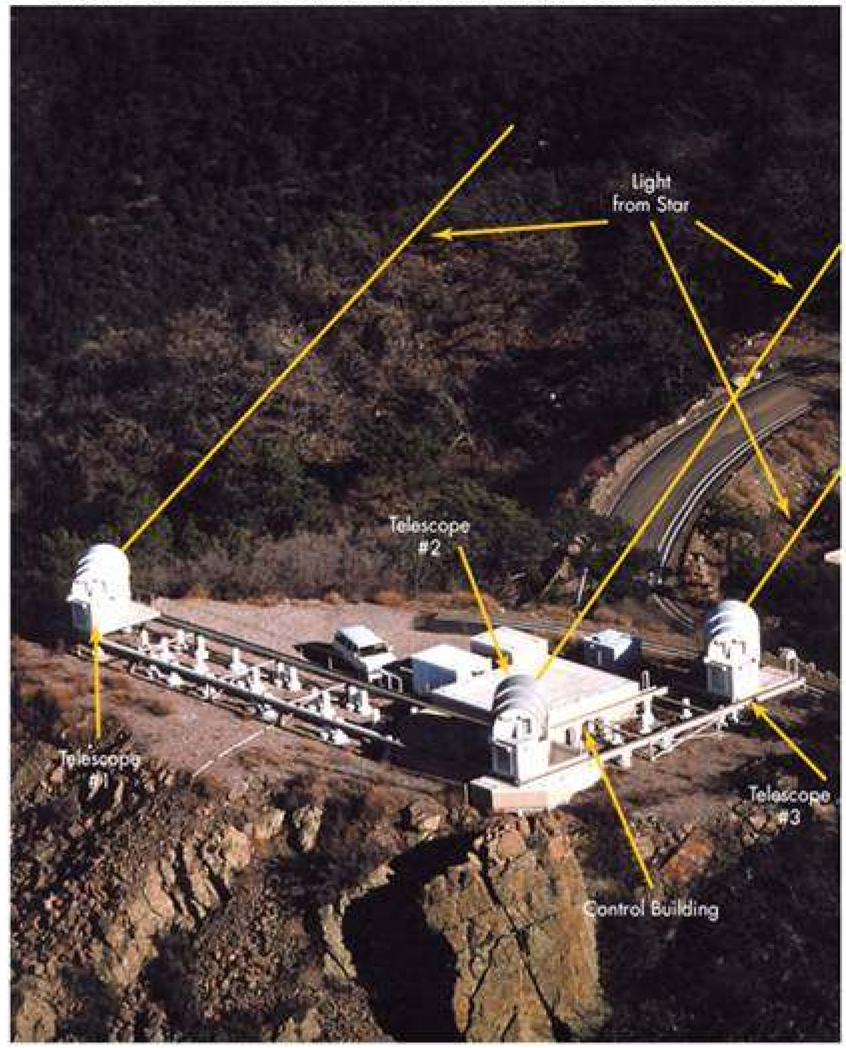
A B

- Two points of light separated by an angle α (in arcsec) can be seen at a wavelength λ (in nm) only if the telescope diameter D (in cm) satisfies:

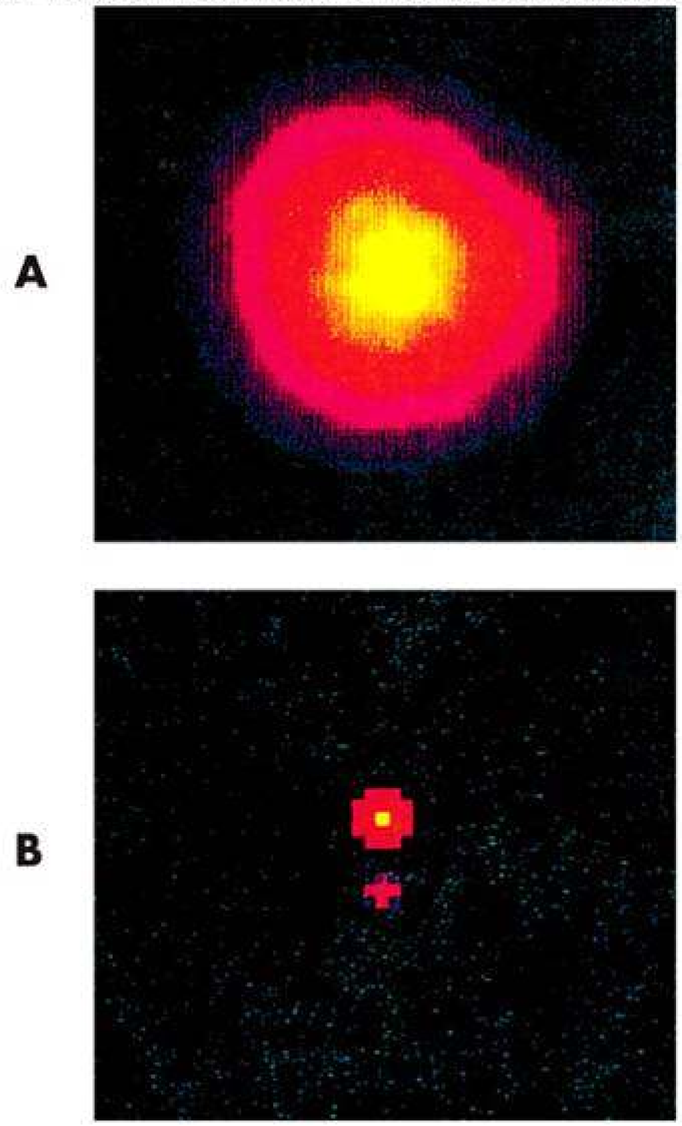
$$D > 0.02\ \lambda/\alpha$$

Increasing Resolving Power: Interferometers

- For a given wavelength, resolution is increased for a larger telescope diameter
- An ***interferometer*** accomplishes this by simultaneously combining observations from two or more widely-spaced telescopes



Interferometers



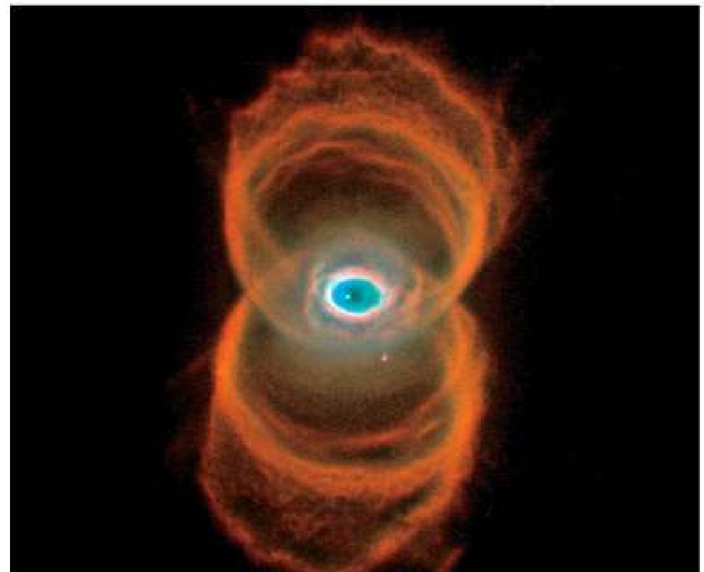
- The resolution is determined by the individual telescope separations and not the individual diameters of the telescopes themselves
- Key to the process is the wave nature of interference and the electronic processing of the waves from the various telescopes

Detecting the Light

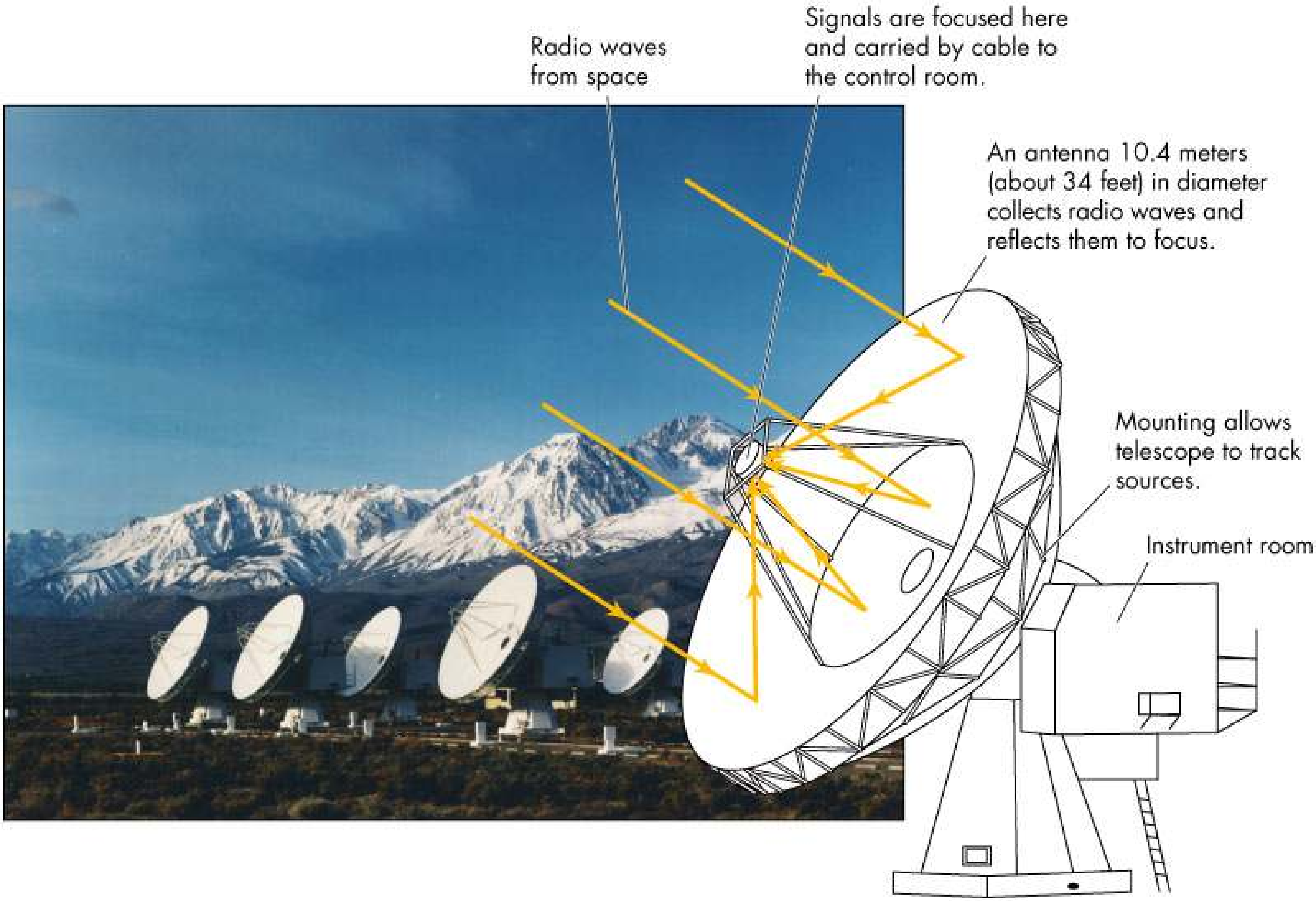
- The Human Eye
  - Once used with a telescope to record observations or make sketches
  - Not good at detecting faint light, even with the 10-meter Keck telescopes
- Photographic Film
  - Chemically stores data to increase sensitivity to dim light
  - Very inefficient: Only 4% of striking photons recorded on film
- Electronic Detectors
  - Incoming photons strike an array of semiconductor pixels that are coupled to a computer
  - Efficiencies of 75% possible
  - ***CCD*** (Charged-coupled Device) for pictures

Nonvisible Wavelengths

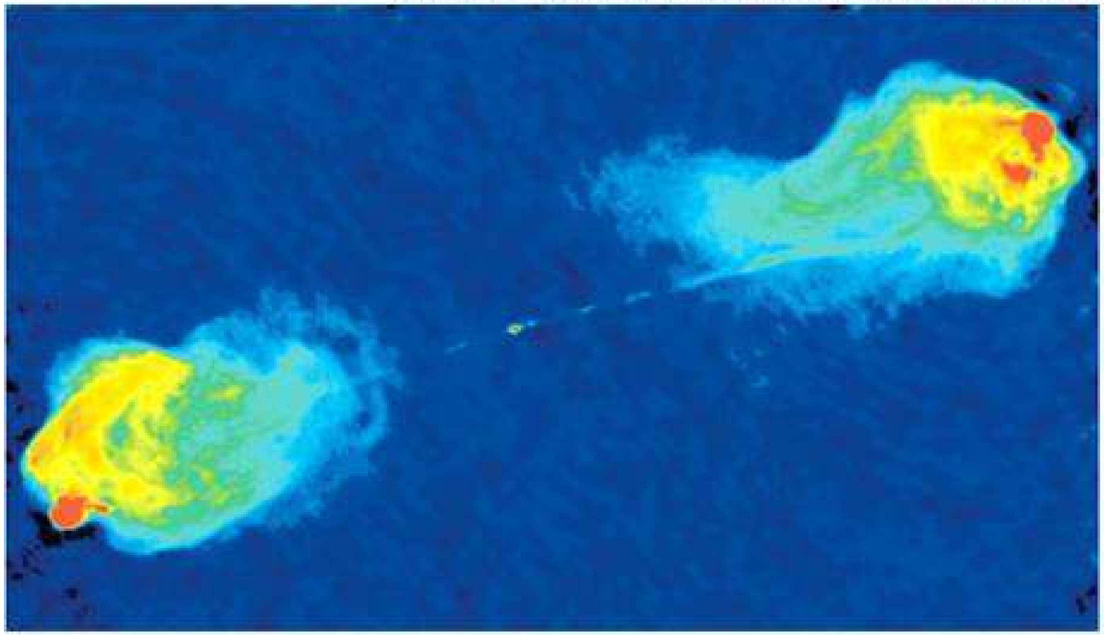
- Many astronomical objects radiate in wavelengths other visible
  - Cold gas clouds radiate in the radio
  - Dust clouds radiate in the infrared
  - Hot gases around black holes emit x-rays



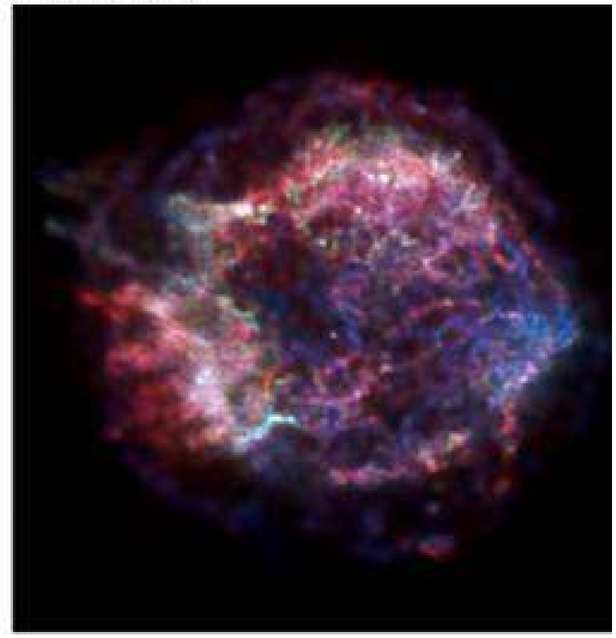
Radio Observatories



Radio Observations



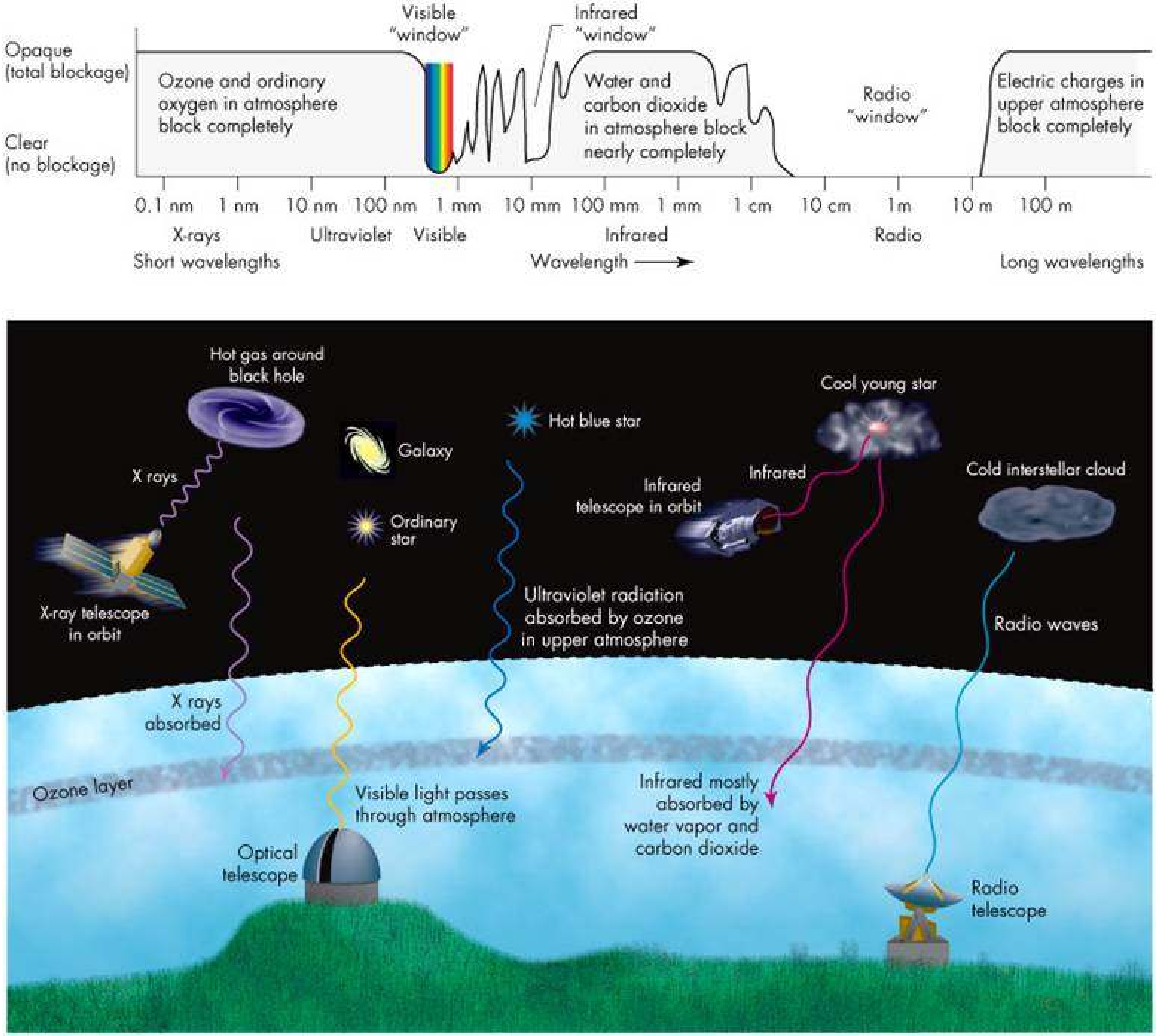
B



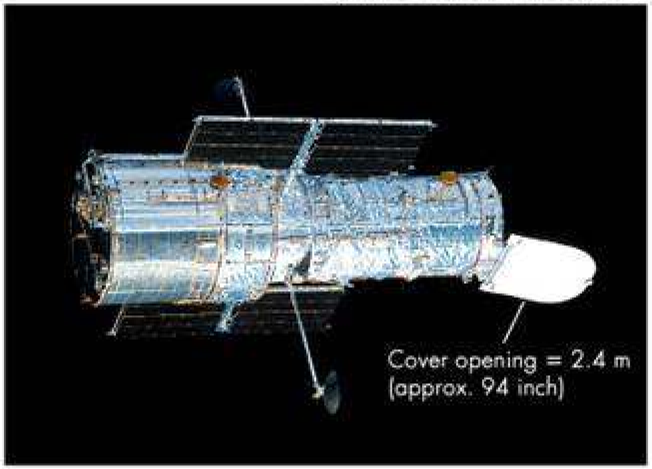
- False color images are typically used to depict wavelength distributions in non-visible observations

Gamma Rays Bursts

- Exploring New Wavelengths: Gamma Rays
  - Gamma-ray astronomy began in 1965
  - By 1970s, gamma rays found to be coming from familiar objects: Milky Way center and remnants of exploded stars
  - 1967 gamma-ray bursts from space discovered by military satellites watching for Soviet nuclear bomb explosions
  - Source of gamma-ray bursts is likely due to colliding neutron stars!

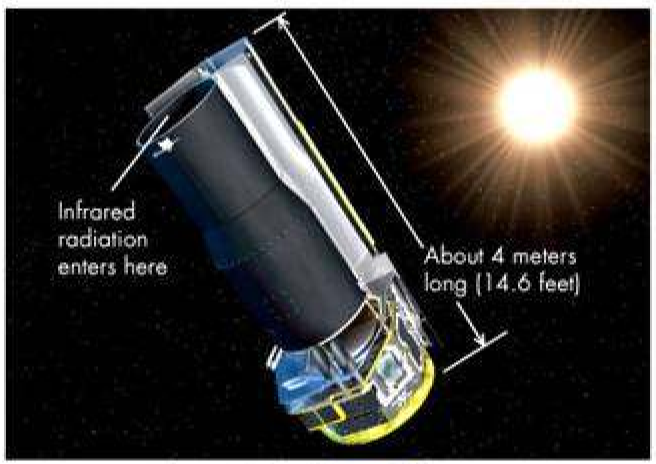

Visible "window"
Infrared "window"
Opaque (total blockage)
Clear (no blockage)
Ozone and ordinary oxygen in atmosphere block completely
Water and carbon dioxide in atmosphere block nearly completely
Radio "window"
Electric charges in upper atmosphere block completely
0.1 nm
1 nm
10 nm
100 nm
1 mm
10 mm
100 mm
1 mm
1 cm
10 cm
1m
10 m
100 m
X-rays
Ultraviolet
Visible
Infrared
Radio
Short wavelengths
Wavelength
Long wavelengths
Hot gas around black hole
Galaxy
Hot blue star
Cool young star
X rays
Infrared
Infrared telescope in orbit
Cold interstellar cloud
Ordinary star
X-ray telescope in orbit
Ultraviolet radiation absorbed by ozone in upper atmosphere
Radio waves
X rays absorbed
Ozone layer
Visible light passes through atmosphere
Infrared mostly absorbed by water vapor and carbon dioxide
Optical telescope
Radio telescope

Major Space Observatories

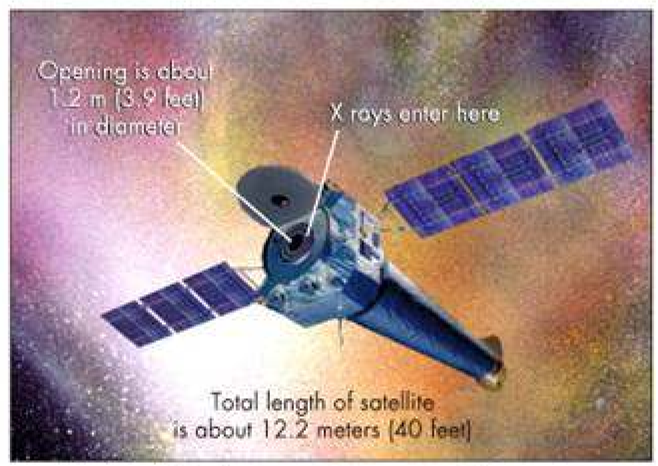


Hubble Space Telescope (13.6 m long) – HST

Extreme Ultraviolet Explorer – EUVE



Spitzer Infrared Space Telescope



Chandra X-ray Telescope Satellite

- Why put them in space?

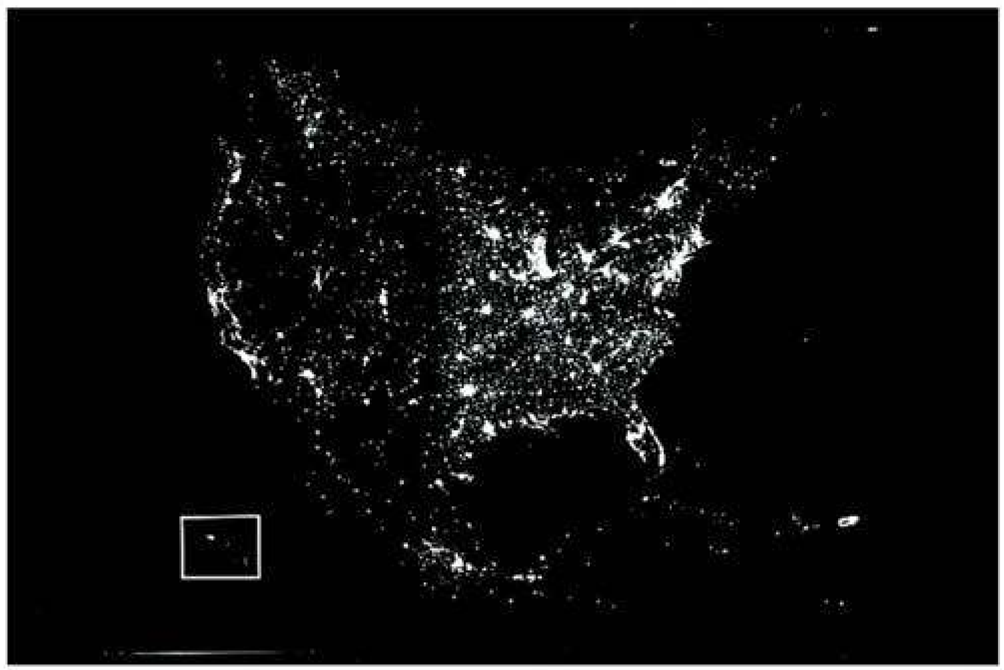
Atmospheric Blurring

- Twinkling of stars in sky, called ***scintillation,*** is caused by moving atmospheric irregularities refracting star light into a blend of paths to the eye
- The condition of the sky for viewing is referred to as the ***seeing***
- Distorted seeing can be improved by ***adaptive optics,*** which employs a powerful laser and correcting mirrors to offset scintillation

Light Pollution

A

B



C

Observatories

- The immense telescopes and their associated equipment require observatories to facilitate their use and protection from the elements
- Thousands of observatories are scattered throughout the world and are on every continent including Antarctica
- Some observatories:
  - Twin 10-meter Keck telescopes are largest in U.S.
  - The Hobby-Eberly Telescope uses 91 1-meter mirrors set in an 11-meter disk
  - Largest optical telescope, VLT (Very Large Telescope) in Chile, is an array of four 8-meter mirrors

Space vs.Ground-Based Observatories

- Space-Based Advantages
  - Freedom from atmospheric blurring
  - Freedom of atmospheric absorption
- Ground-Based Advantages
  - Larger collecting power
  - Equipment easily fixed
- Ground-Based Considerations
  - Weather, humidity, and haze
  - Light pollution

Going Observing

- To observe at a major observatory, an astronomer must:
  - Submit a proposal to a committee that allocates telescope time
  - If given observing time, assure all necessary equipment and materials will be available
  - Be prepared to observe at various hours of the day
- Astronomers may also "observe" via the Internet
  - Large data archives now exist for investigations covering certain wavelengths sometimes for the entire sky
  - http://mo-www.cfa.harvard.edu/MicroObservatory
  - http://www.lightbuckets.com/
  - slooh.com (live shows!)

Computers and Astronomy

- For many astronomers, operating a computer and being able to program are more important than knowing how to use a telescope
- Computers accomplish several tasks:
  - Solve equations
  - Move telescopes and feed information to detectors
  - Convert data into useful form
  - Networks for communication and data exchange