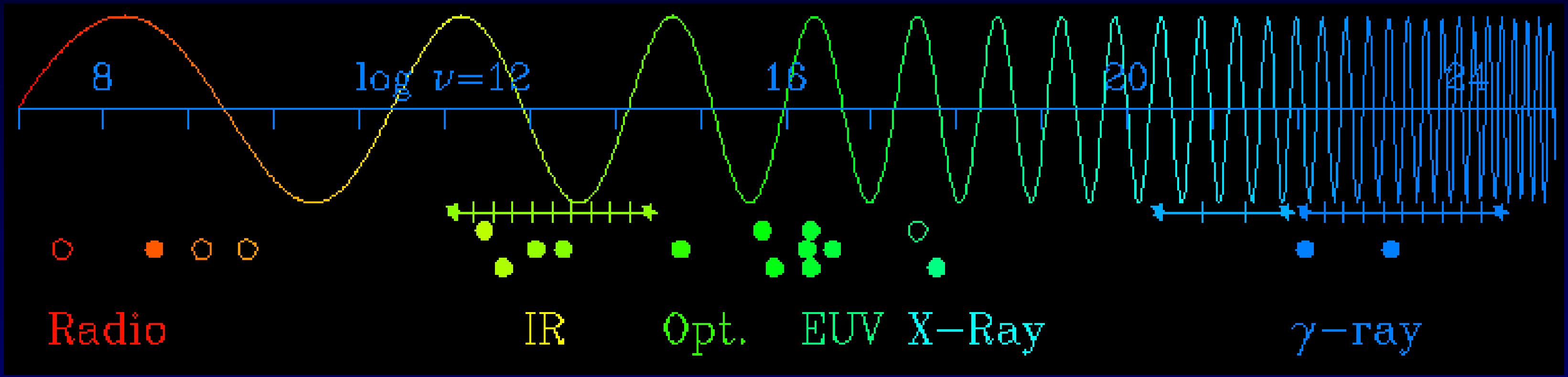
Reminders

- http://astro.ucsc.edu/~neil/ay4_s08

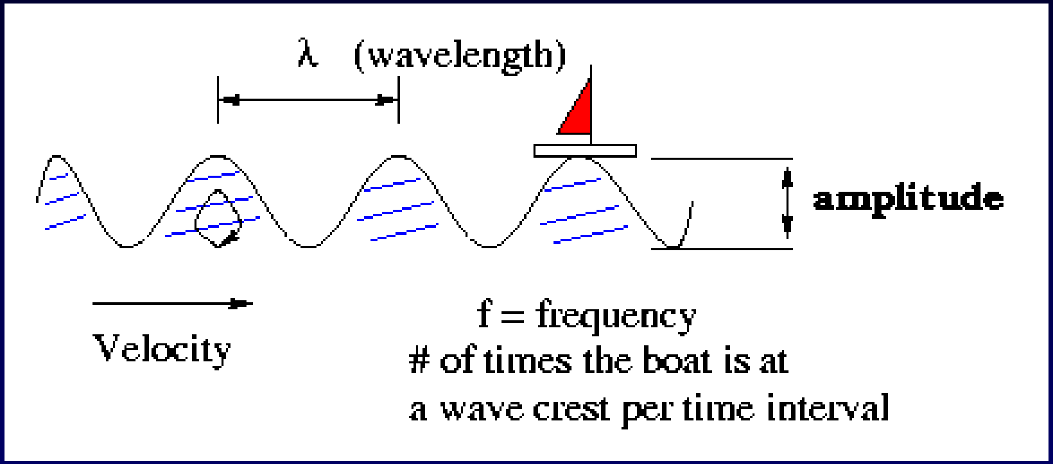
  Has all the class info. Lectures, homework, sections times/places, office hours and contact info.
- Note: by far the best way to contact Professor Brodie is via brodie@ucolick.org
- Quiz 1: Thursday, April 10th
- Observing Session: Wednesday, April 9th, 8 PM at the Music Center Balcony (2 points extra credit just for coming!!!)

Let there be Electromagnetic Radiation



- Light, radio waves, x-rays, ultra-violet radiation are all forms of a type of wave composed of oscillating electric and magnetic fields

Waves



- Think about water waves. They are characterized by their amplitude (height) and three related quantities: wavelength (λ), frequency (*f*) and speed (v).

$v = f \times \lambda$ and $\lambda = v/f$

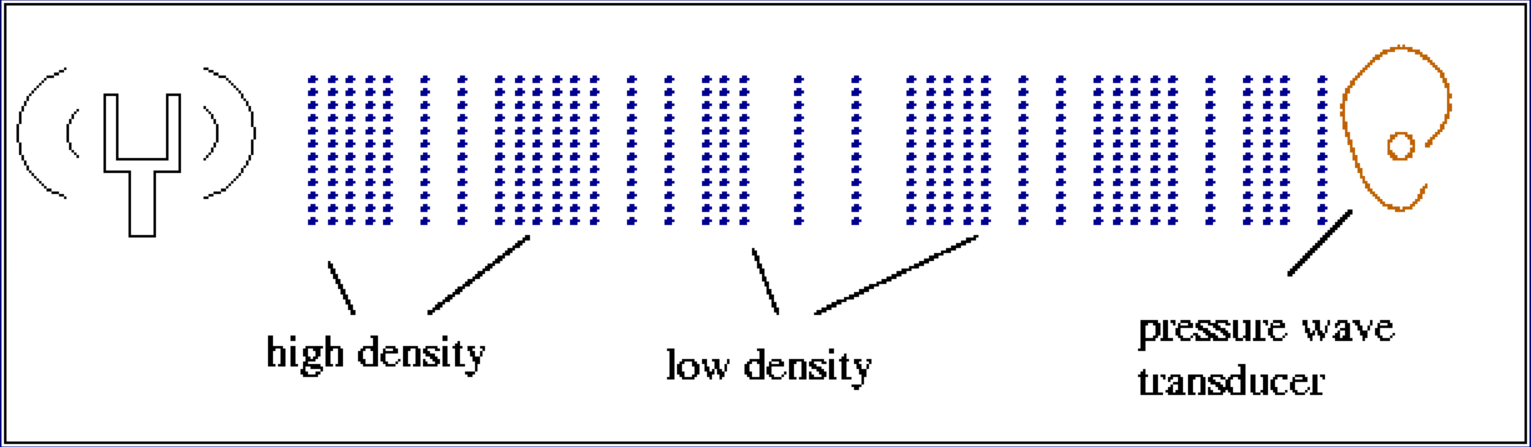
- Wavelength has units of distance
- Frequency, the number of times the boat goes up and down per unit time, has units of 1/time, e.g. 1/second.
- Speed has units of distance/time.

Q. What moves at the wave speed?

ENERGY

Other waves

- There are other kinds of waves. Ocean waves are sometimes called `gravity' waves.
- Sound waves are density/pressure waves

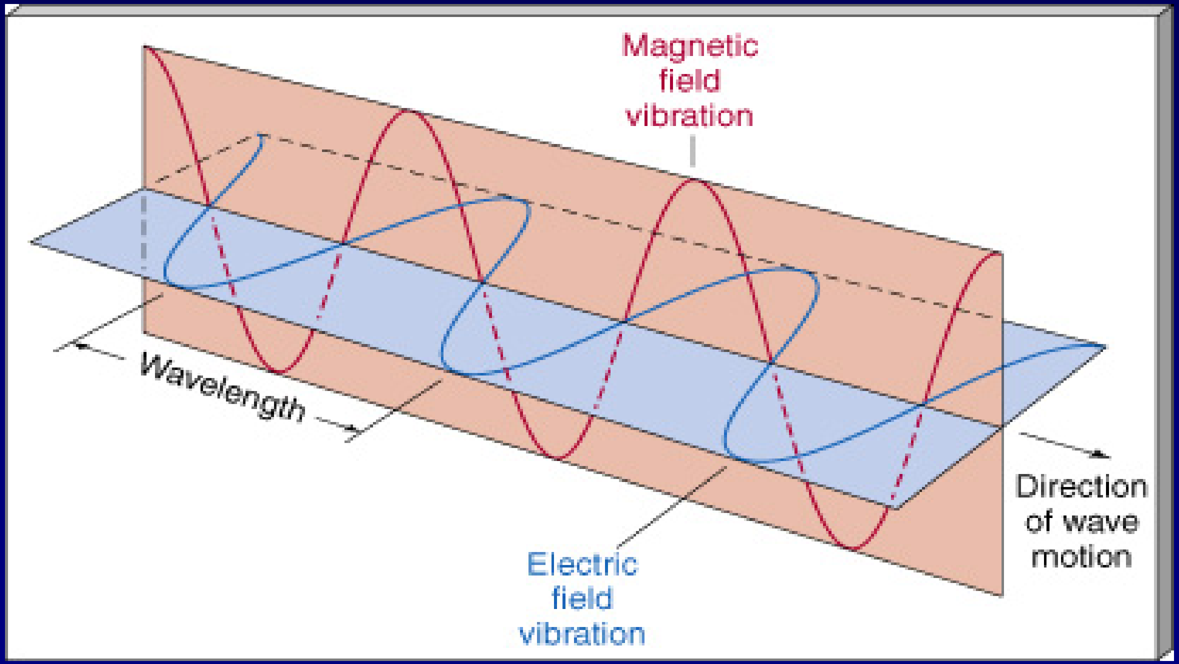


Sound waves

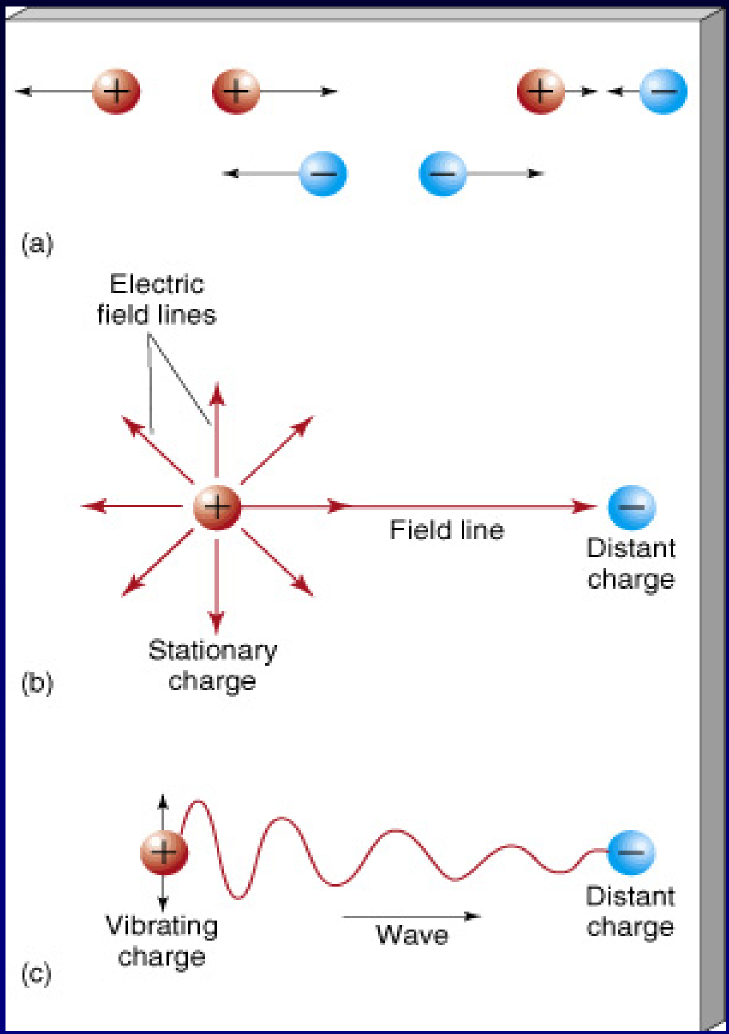
- Sound waves only travel at 1000 ft/sec in air. This is the basis of the old thunderstorm trick.
  - The light from lightning travels at the speed of light (it arrives almost instantaneously).
  - Thunder is a pressure wave triggered by the rapid expansion of the heated air near the lightning bolt. This travels at the speed of sound in air.
- So, for every second delay between seeing the lightning and hearing the thunder the storm is 1000ft away (5280 feet/mile)

E-M Radiation

- Light is a type of wave composed of oscillating electric and magnetic fields propogating through space.



E-M radiation



- This diagram is not quite right, but gives you the idea.
- Any charged particle has a radial electric field extending to infinity. If the charge moves, the center of the field has changed.
- This information propogates outward as a `kink’ in the field lines. This changing electric field induces a changing magnetic field.

- The varying electric and magnetic fields move outward at the speed of light.
- In a vacuum, this speed is:

$$c = 300{,}000 \text{ kilometers/second}$$

$$c = 3 \times 10^5 \text{ km/s}$$

Q. What is the speed of light in miles/hour?

$$c = 3\times 10^{5}\,\frac{km}{\sec}\times\frac{0.62\,miles}{1\,km} = 186{,}000\,\frac{miles}{\sec}$$

$$186{,}000\,\frac{miles}{\sec}\times\frac{60\sec}{1\min}\times\frac{60\min}{1\,hr} = 6.7\times 10^{8}\,\frac{mile}{hr}$$

Q. The Sun is 93,000,000 miles away. How long does it take for the light that leaves the Sun to reach the Earth?

$$t = D/S$$

$$t = \frac{9300000\,miles}{186{,}000\,\frac{miles}{\text{sec}}} = 500\,\text{sec} \times \frac{1\,\text{min}}{60\,\text{sec}} = 8.3\,\text{min}$$

Q. What is a Light Year?

First, this is a unit of ***distance***, not time. It is the distance light travels in a vacuum in one year.

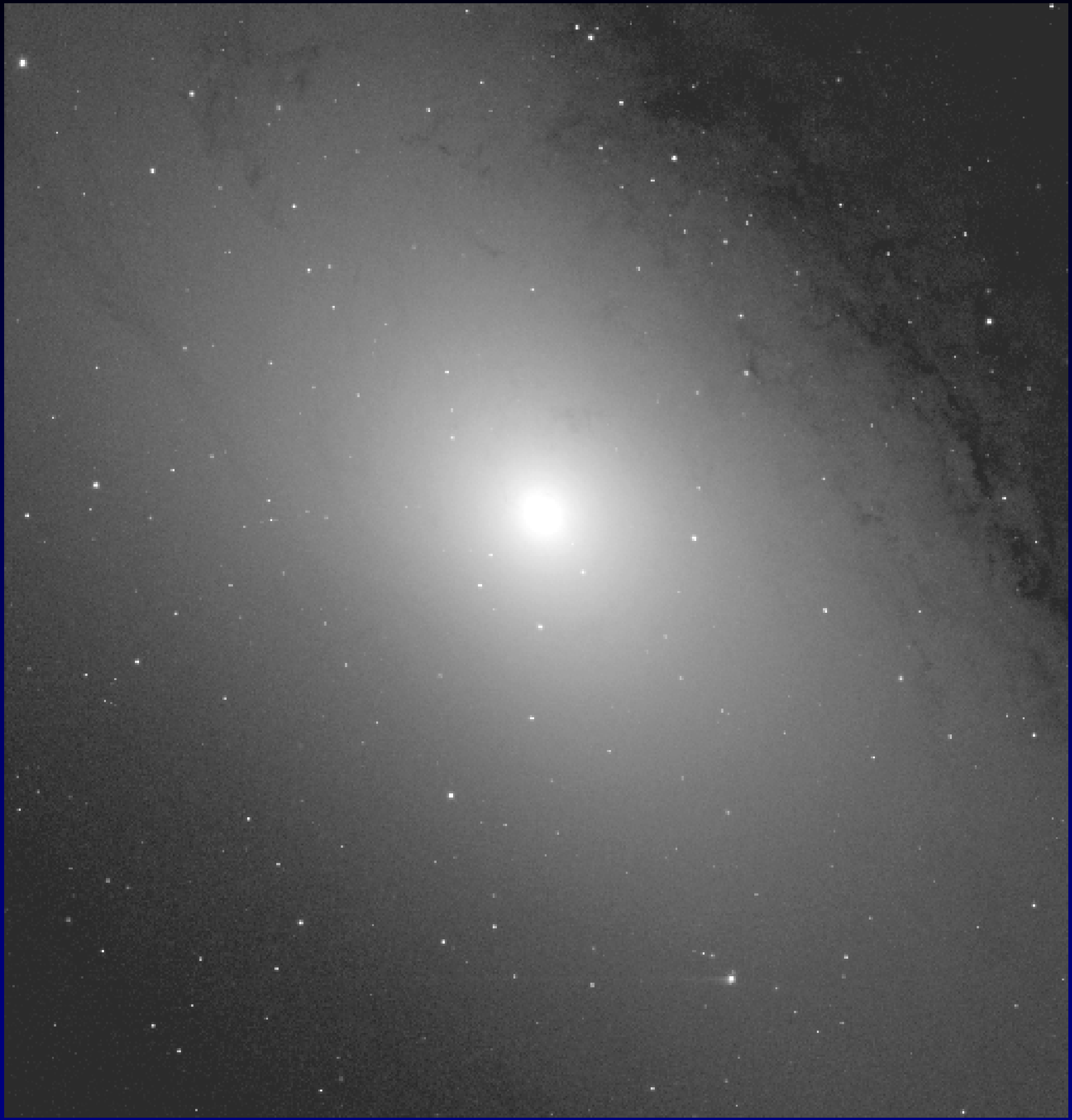
$$186{,}000\,\frac{miles}{\sec} \times \frac{60\sec}{1\min} \times \ldots$$

$$= 5.86 \times 10^{12}\, miles / year$$

$$\therefore 1LY = 5.86 \times 10^{12}\, miles$$

Lookback Time

- Because of the finite speed of light, we see all objects with a time delay.
- The Sun we see as it was 8.3 minutes in the past.
- The nearest big galaxy, the Andromeda galaxy is two million light years away -- we see it as it appeared two million years ago.



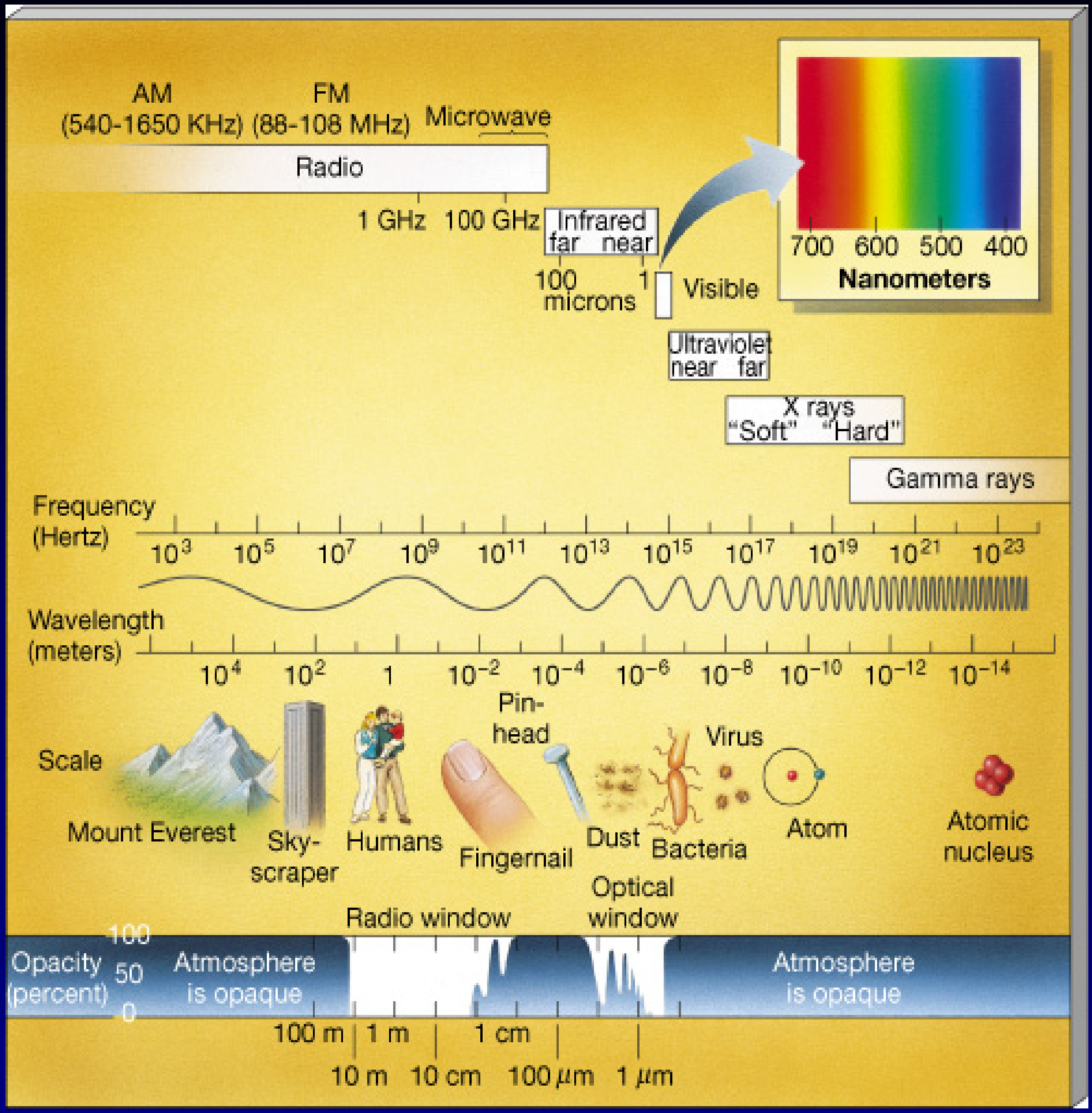
Lookback Times

In the Hubble Ultra Deep Field, some of the objects have lookback times > 12 billion LY. This provides an opportunity to view the Universe at different times in its evolution (!)

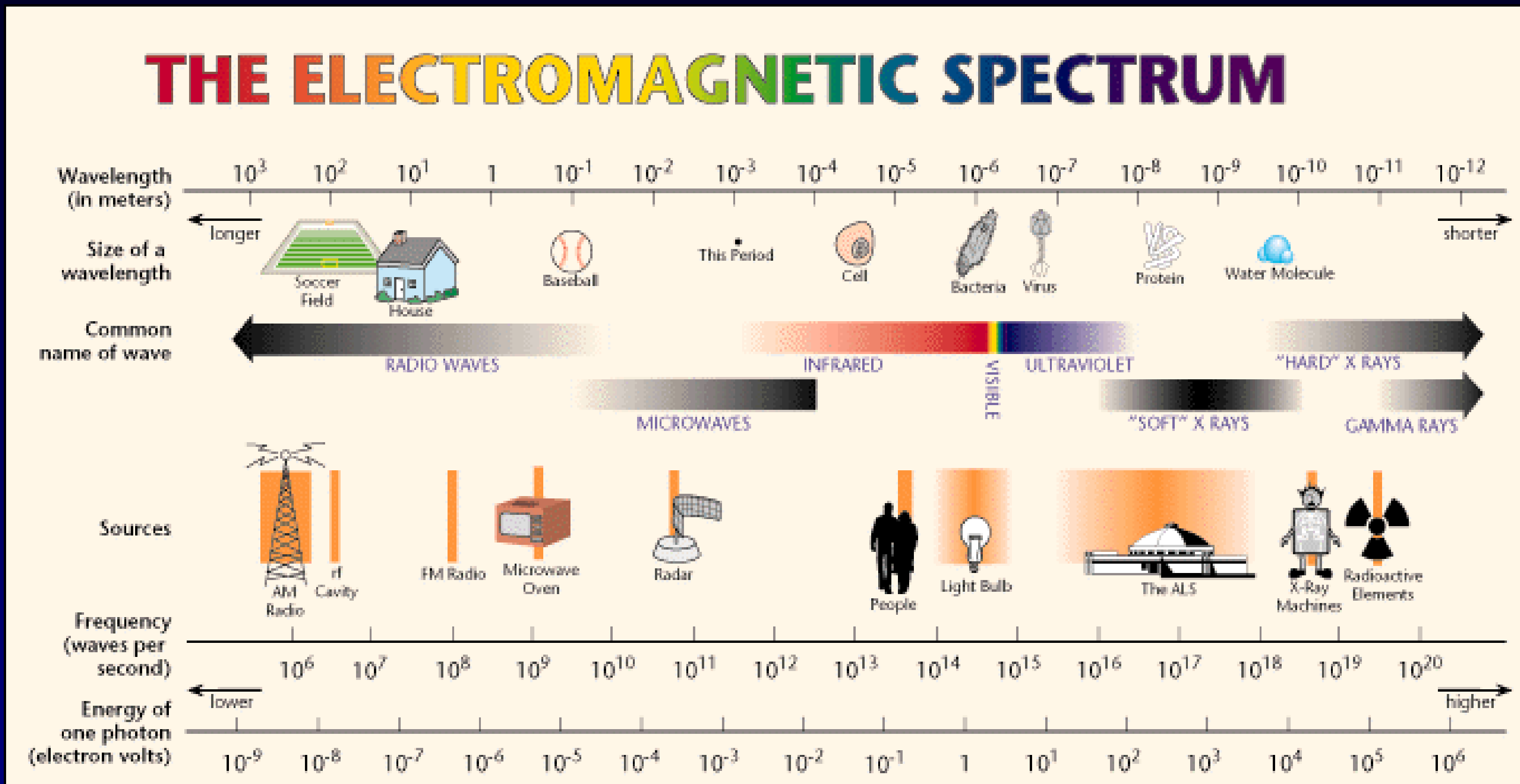
E-M Radiation

- Light is only one form of E-M radiation. There are different names for E-M radiation with different wavelength (or frequency).

X-rays
Ultraviolet
Microwaves
Infrared
Radio



AM
(540-1650 KHz)
FM
(88-108 MHz)
Microwave
Radio
1 GHz
100 GHz
Infrared
far near
100 microns
1
Visible
700 600 500 400
Nanometers
Ultraviolet
near far
X rays
"Soft" "Hard"
Gamma rays
Frequency (Hertz)
10^3 10^5 10^7 10^9 10^{11} 10^{13} 10^{15} 10^{17} 10^{19} 10^{21} 10^{23}
Wavelength (meters)
10^4 10^2 1 10^{-2} 10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14}
Scale
Mount Everest
Sky-scraper
Humans
Fingernail
Pin-head
Dust
Bacteria
Virus
Atom
Atomic nucleus
Radio window
Optical window
Opacity (percent)
100
50
0
Atmosphere is opaque
Atmosphere is opaque
100 m
1 m
1 cm
10 m
10 cm
100 μm
1 μm



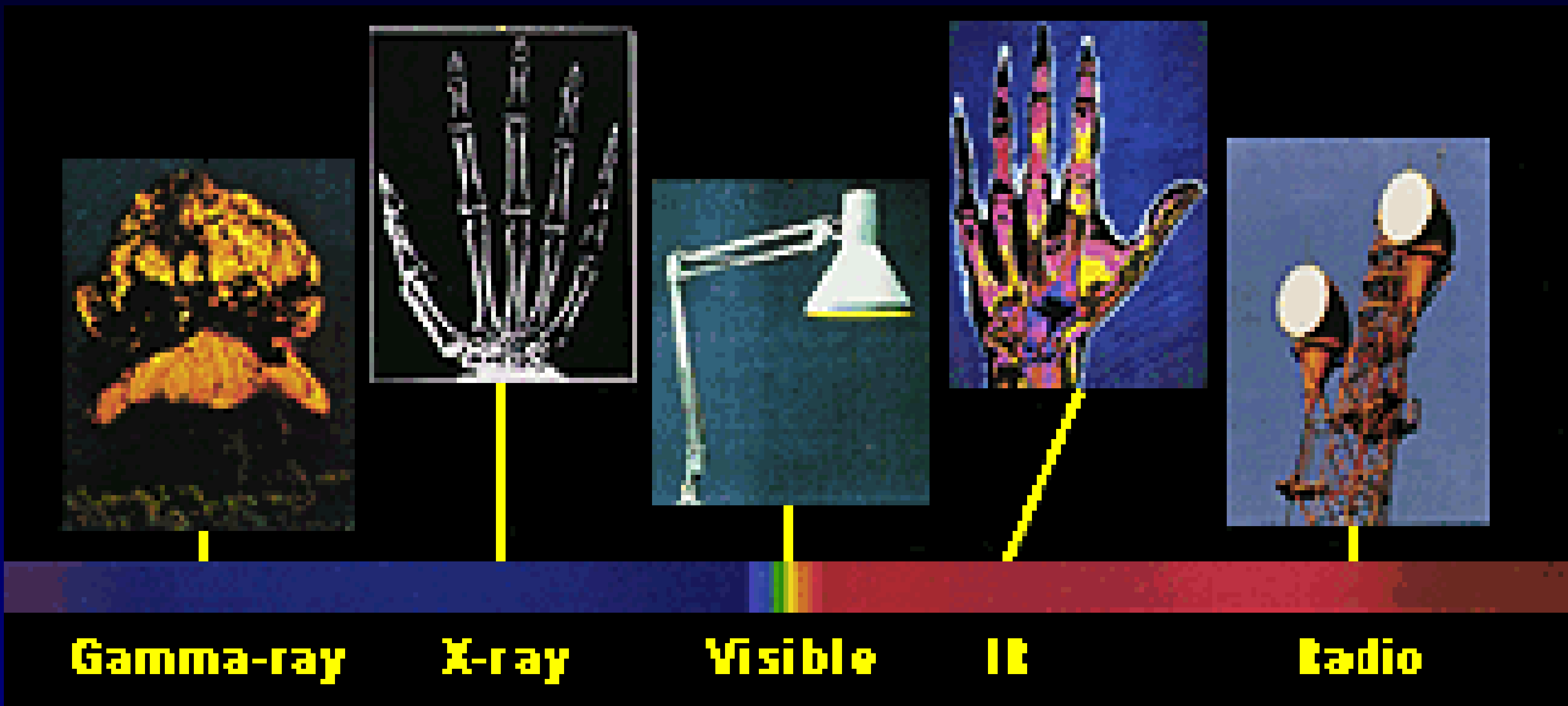
Wavelength increases, frequency decreases, energy decreases

E-M radiation

- E-M radiation with wavelength= 10^{-7} m can be detected by cells in the retina of your eye.
- E-M R between 0.5m and 1000m is used to transmit radio and television signals.
- E-M R with wavelength ~10^{-3}m (*microwaves*) is absorbed by water molecules (i.e. the energy of the E-M R is transferred to the water molecules, they heat up and your burrito in the microwave oven gets warm).

More E-M Radiation

- E-M R with wavelength ~10^{-5}m (*infrared*) can be sensed with your skin (but not eyes)
- E-M R with wavelength ~10^{-8}m (*ultraviolet*) activates pigments in your skin which causes you to tan (and triggers skin cancer).
- E-M R with wavelength ~10^{-9}m (*X-rays*) can penetrate flesh but not bones.


Gamma-ray
X-ray
Visible
IR
Radio

Q. What is the wavelength of 810 Kilohertz on your AM dial?

`kilo' > 1000; `hertz' > 1/second

$$\lambda = \frac{c}{f} = \frac{3\times10^{5}}{810{,}000}\frac{km/\text{sec}}{1/\text{sec}} = 0.37km = 1214\ ft$$

More Waves: Energy

- Radio wave, light, Infrared radiation, UV and X-rays are all E-M radiation and travel at the speed of light .
- They differ in ***wavelength*** and ***frequency.***
- Each wavelength of E-M radiation also has a unique Energy given by:

$$E = hf = \frac{hc}{\lambda}$$

$$E = hf = \frac{hc}{\lambda}$$

h is called `Planck's constant. For a given wavelength or frequency of E-M radiation this is the `unit' energy. This is not the same as the intensity of the radiation, but rather it is the energy of a single `***photon***'.

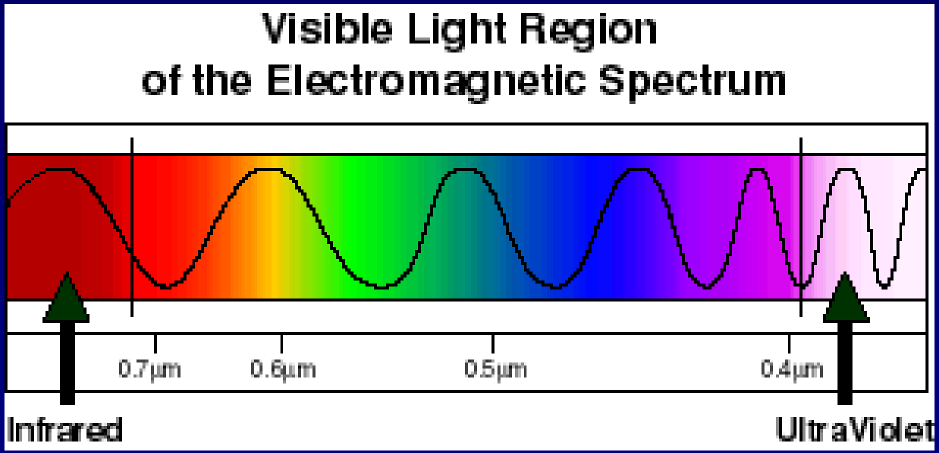
h=6.626068 x 10^{-34}Joules·sec (=m^2kg/s)

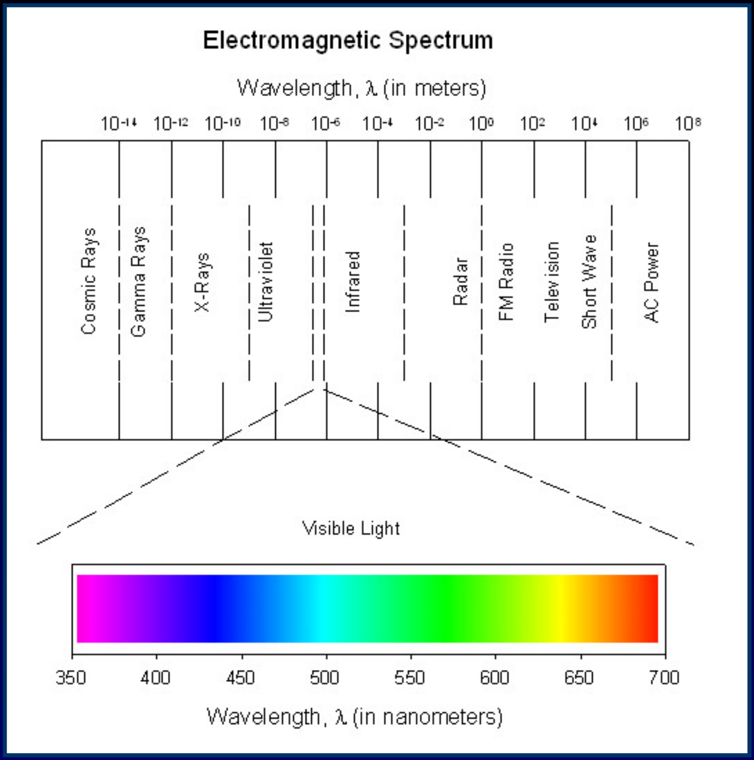
Photons

- The photon model of E-M radiation is different than the wave model.
- A photon is like a tiny E-M bullet with characteristic wavelength, frequency and energy.
- Both models are right and this is the source of many discussions on the wave-particle duality of light.

Visible Light: Some Details

- The shortest wavelength of E-M Radiation our eyes can sense is 4 x 10^{-7} meters (400 nm) which is interpreted by our brain as blue light. The longest wavelength our eyes are sensitive to is 700nm -- this is interpreted as red light

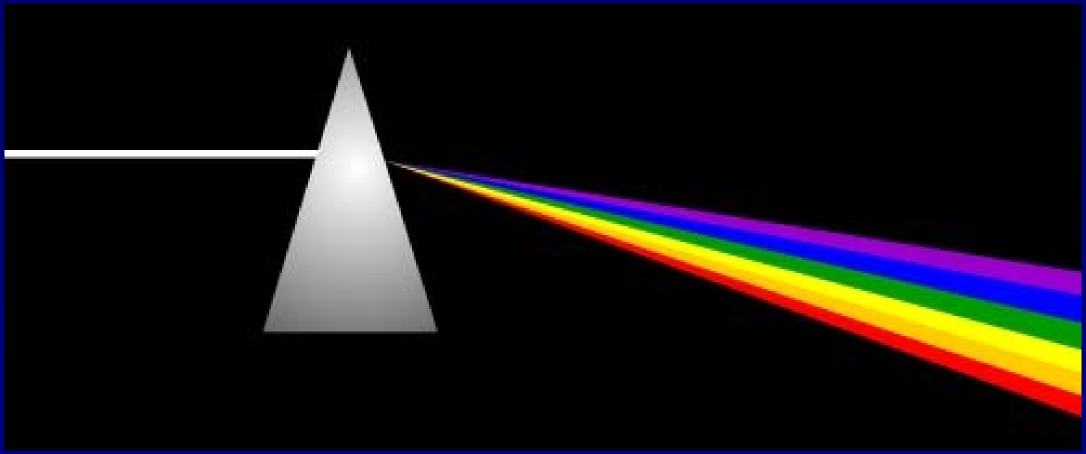




- Note that the visible part of the spectrum is only a small fraction of the E-M spectrum.
- If a source emits all the wavelengths of the visible part of the E-M spectrum, our brain interprets this as white light.

White Light

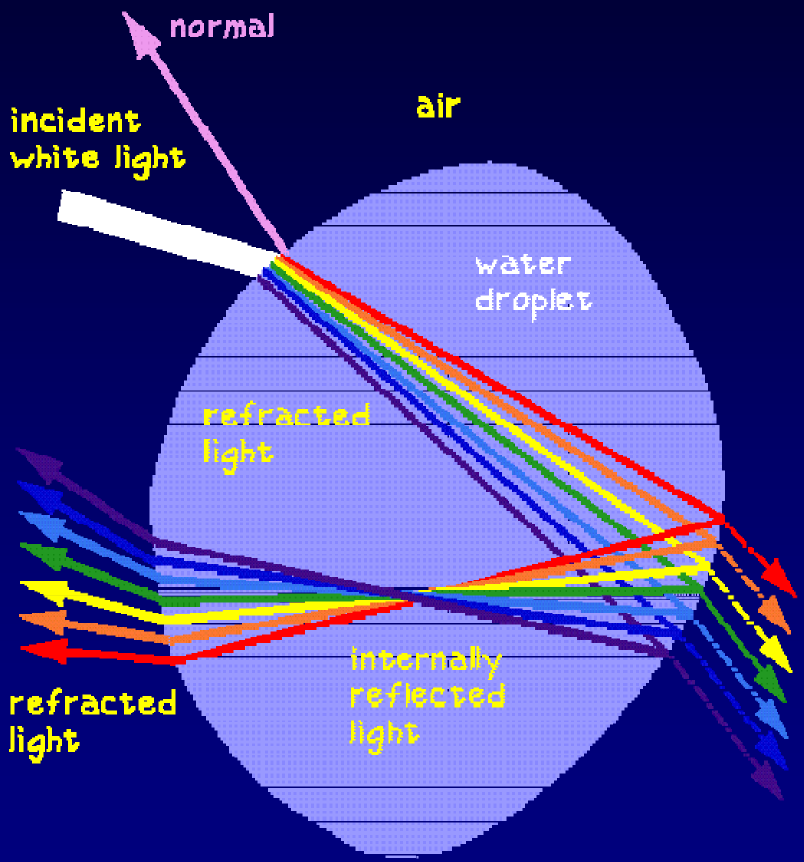
- This can be demonstrated in many ways. Newton used a prism and wrote out the first discussion of light, colors and waves.



White Light

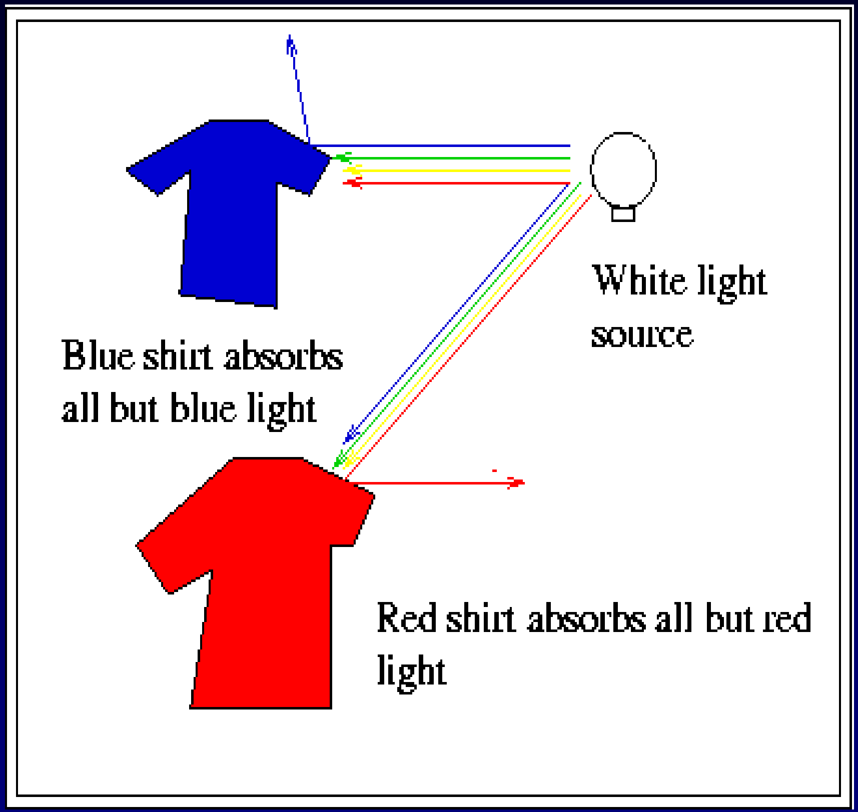
- Nature provides a beautiful means of dispersing white light into its constituent colors.

Rainbows



- Rainbows are caused when sunlight enters raindrops and reflect off the back surface. Different wavelengths of light travels at different velocity in the drop and are bent different amounts and therefore separated on the sky

Double rainbows occur for two reflections in the raindrops (note the reversed order of the colors).



- Most colors we see are in reflected light. The different colored objects in the room are reflecting come components of the white light and absorbing the rest.
- Black shirt absorbs all wavelengths
- Blue reflects blue wavelengths, absorbs the rest -- a blue shirt demonstrates that white light contains blue light.

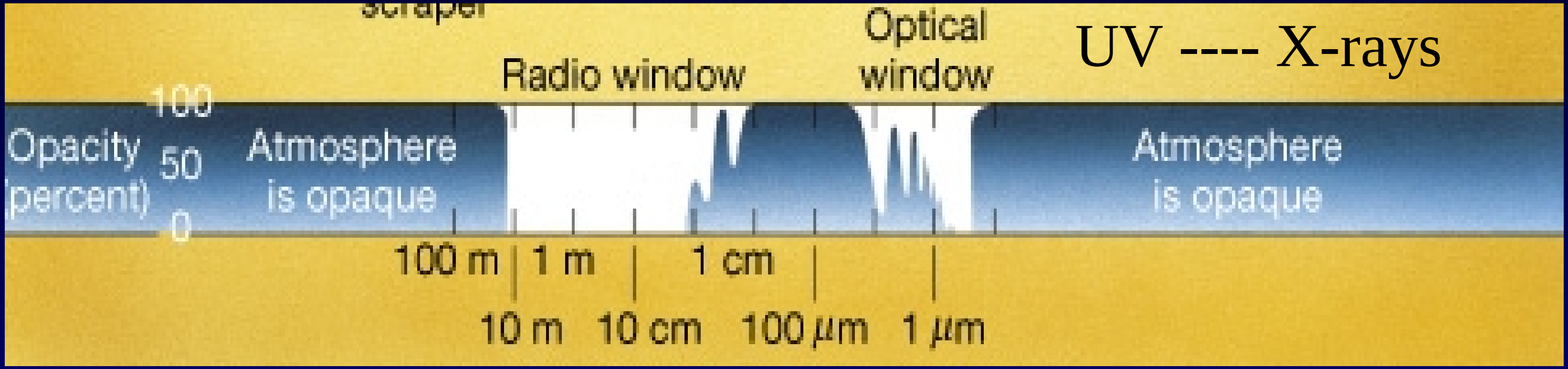
Q. What wavelengths are reflected by a white shirt?

A. All of the visible-light wavelengths.

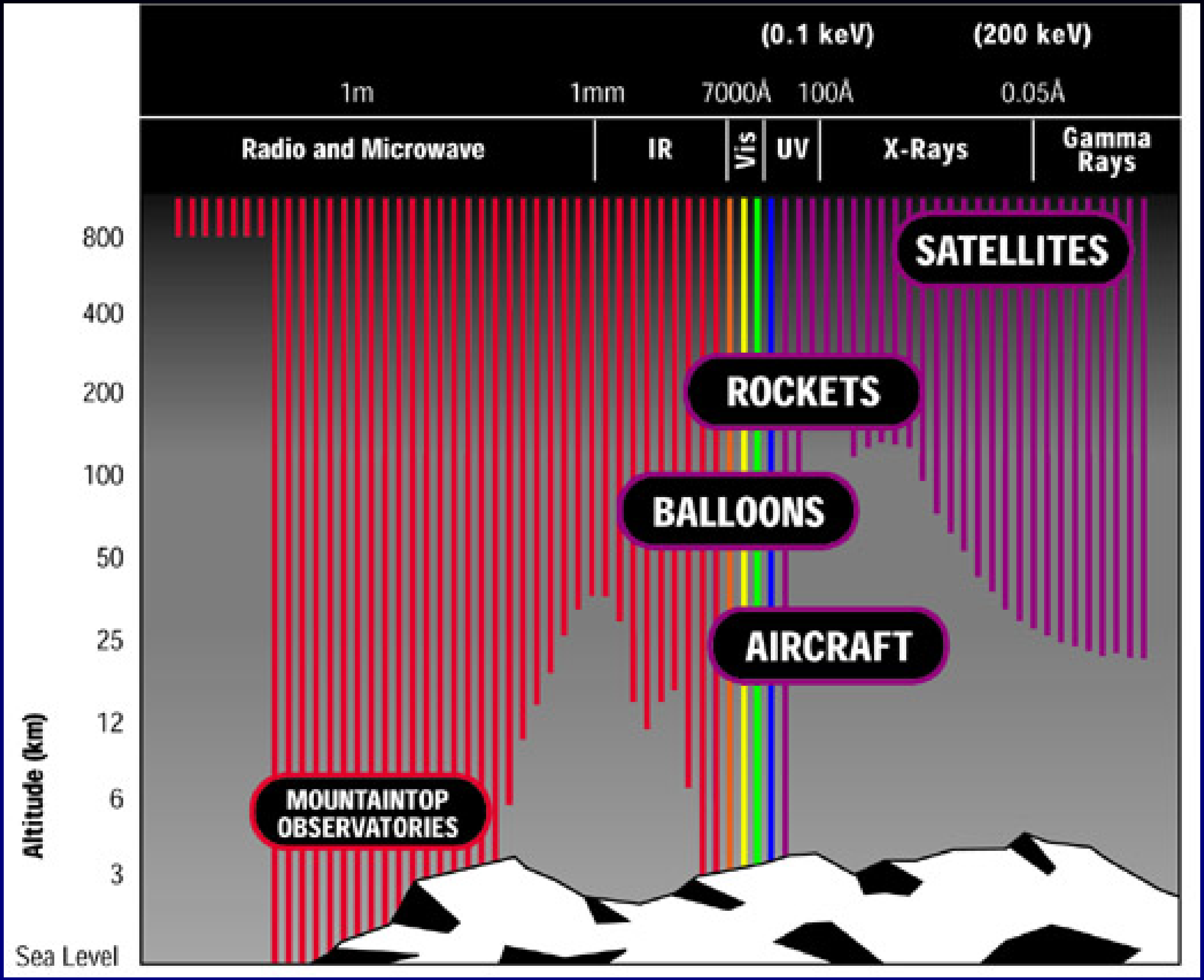
Q. What color is a yellow banana illuminated with blue light?

A. Black. It is yellow because it reflects yellow light and absorbs other colors.

E-M Radiation and the Atmosphere



- The atmosphere only passes certain `spectral windows' (either way).
- The atmosphere is transparent to visible light (do you think it is a coincidence that our eyes are sensitive to visible light?), some parts of the radio and some parts of the Infrared.


(0.1 keV)
(200 keV)
1m
1mm
7000Å
100Å
0.05Å
Radio and Microwave
IR
Vis
UV
X-Rays
Gamma Rays
800
400
200
100
50
25
12
6
3
Sea Level
Altitude (km)
SATELLITES
ROCKETS
BALLOONS
AIRCRAFT
MOUNTAINTOP OBSERVATORIES

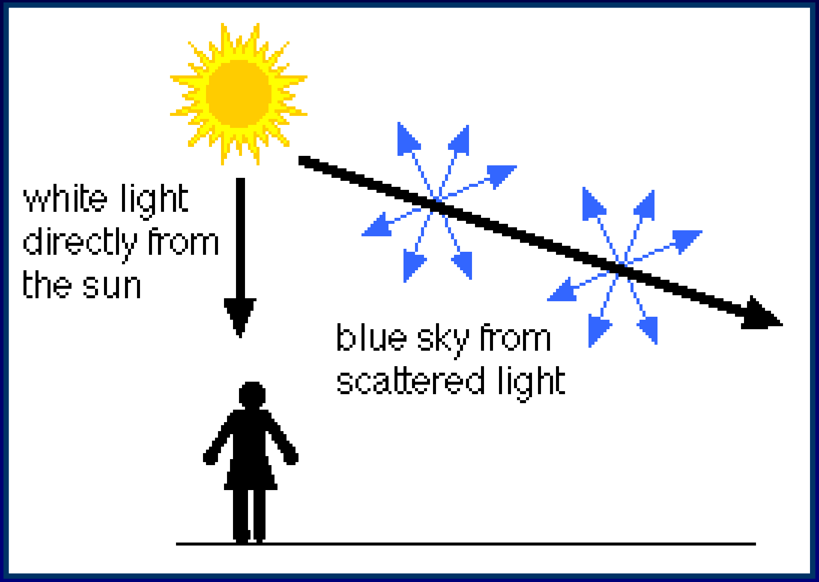
- Fortunately, the atmosphere is opaque to UV, X-rays and gamma rays. All are harmful to humans and other animals and plants.
- The Infrared between 10 and a few 100 microns is also absorbed by the atmosphere.
- To make observations of the Universe at these wavelengths requires going into space. Satellites, rockets and balloons all provide platforms.

Sidetrip: Why is the Sky Blue?

- When you look *at* the Sun, it appears yellow-white.
- When you look into the sky AWAY from the Sun, the sky *should* appear black as there is no light source.

So, why is blue?

Blue Sky cont.



- The reason the sky is blue is that molecules and small particles in the upper atmosphere scatter blue photons more efficiently than red ones.
- When you look away from the Sun, you see blue light that has bounced off the upper atmosphere into your line of sight.

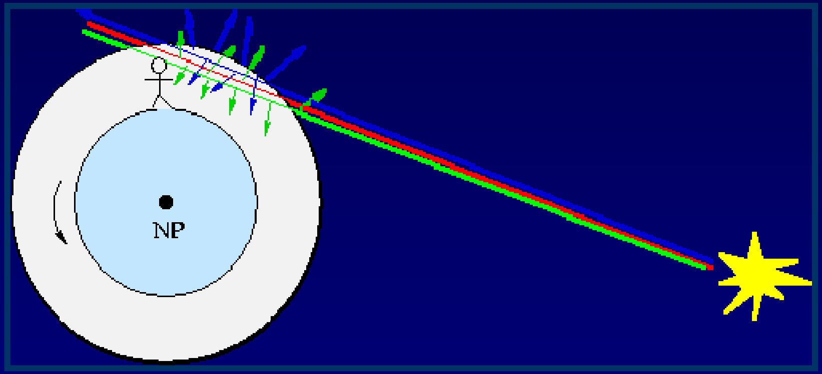
Q. What color is the sky (away from the Sun) as seen by an astronaut on the Space Shuttle?

BLACK

Q. What color is the sky (away from the Sun) as seen from the surface of the Moon?

BLACK

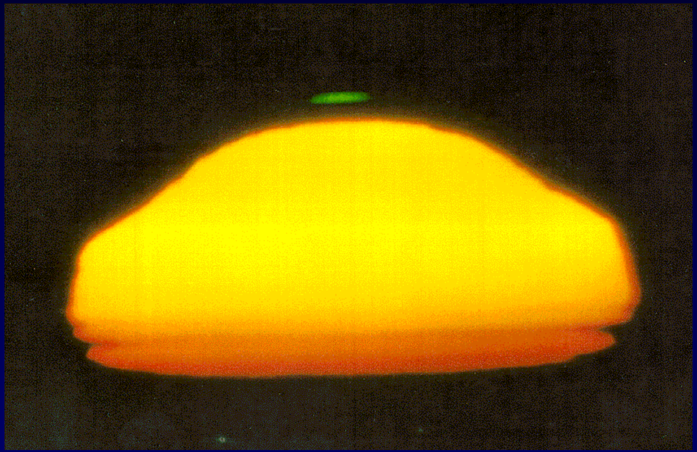
Sidetrip: Why is the Sun red at sunset?



- For the same reason the sky is blue - scattering of blue photons.
- The long pathlength through the atmosphere when the Sun is low means there are more molecules and particles to scatter out all the blue light leaving only red.

The Green Flash

- One more interesting sidelight occurs because the atmosphere acts like a prism. Red light is less bent than green light which is less bent than blue light. The image of the Sun in these different colors is therefore separated. When the Sun is low on the horizon, the red Sun sets first, then the green Sun. By then, all the blue light is scattered out so there is no `blue’ flash.

Announcements

- Quiz 1 will be held Thursday, April 10th!!
- Observing at the Music Center, April 9th (2 points extra credit!!!)

How is E-M Radiation Produced?

1. Accelerate charged particle back and forth like they do at the radio station.
2. All solids or liquids with temperature above *Absolute Zero* emit E-M radiation.
   - Absolute zero is the temperature at which all motion (on an atomic level) ceases.
   - $0K = -459^oF = -273^oC$

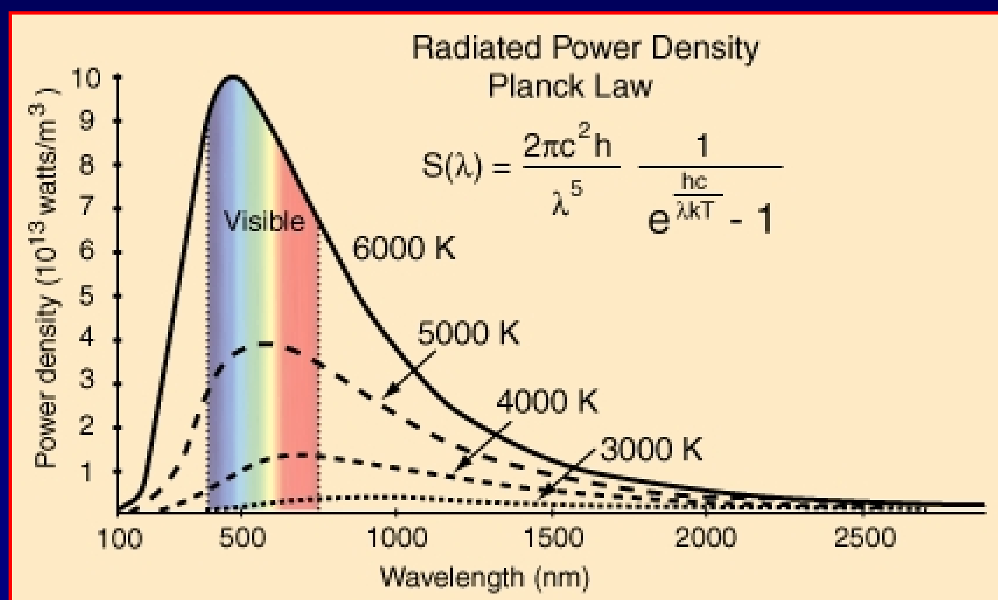
Absolute Zero

The thermo exam was quite near-o,
And he thought everything was quite clear-o;
“Why study this junk,
I’m sure I won’t flunk,”
But they gave him an Absolute Zero.

Continuous or Planck Radiation

- If the intensity of E-M radiation at each wavelength for a non-absolute-zero solid or liquid is plotted, this is called a *`spectrum'*.

Intensity



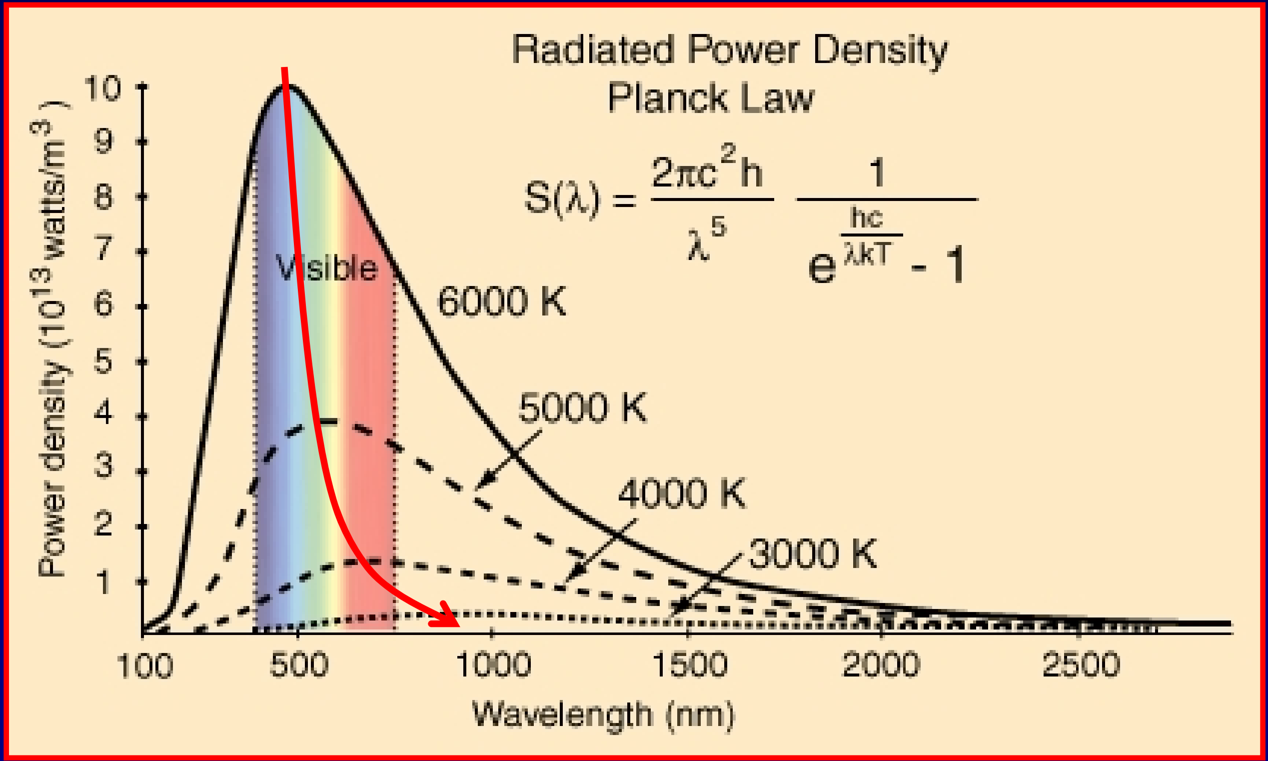
Wavelength

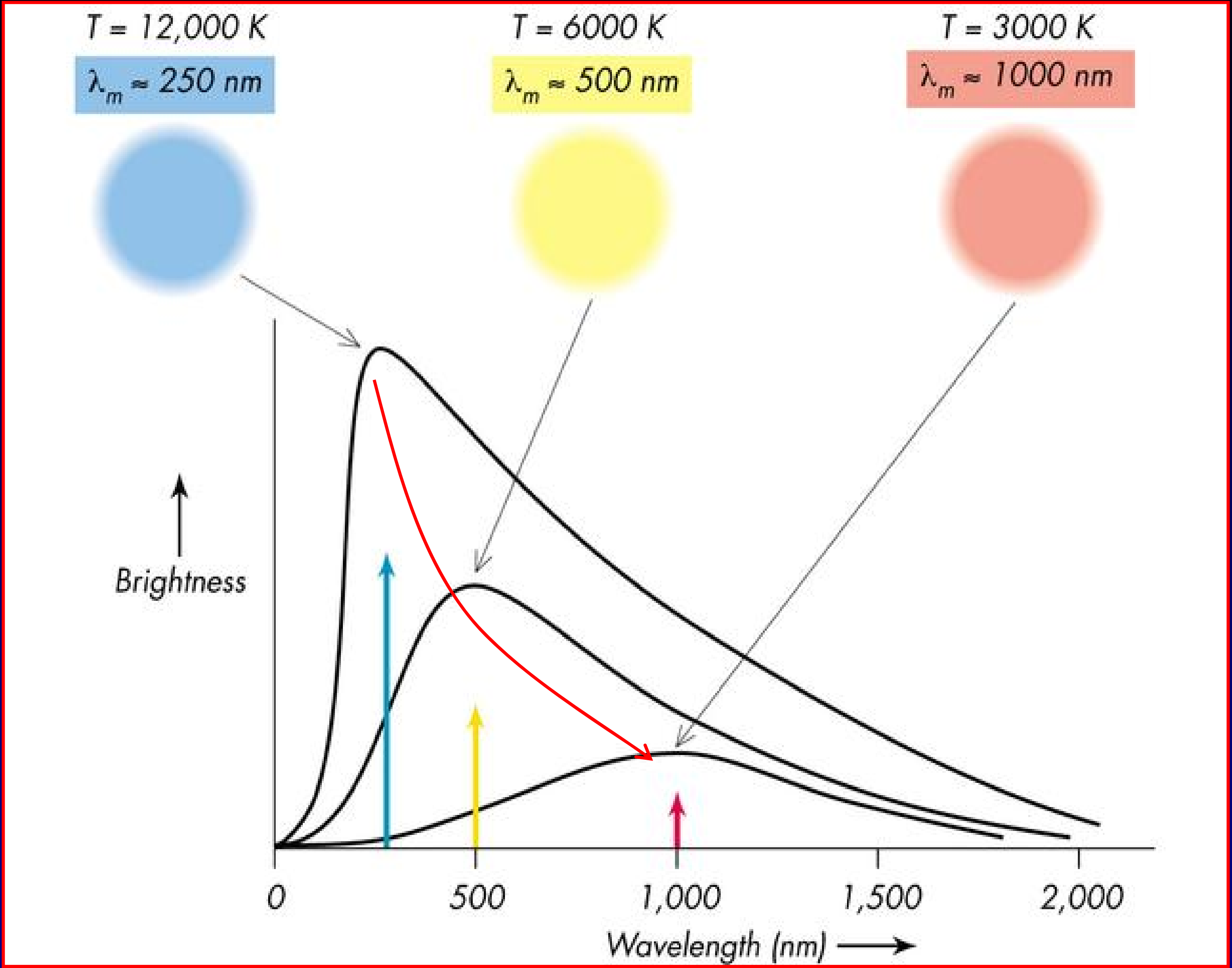
Continuous Spectra

- For a given object, as the temperature goes up:

(1) The intensity of radiation at all wavelengths increases

(2) The peak of the intensity curve moves to shorter wavelengths





T = 12,000 K
λm ≈ 250 nm
T = 6000 K
λm ≈ 500 nm
T = 3000 K
λm ≈ 1000 nm
Brightness
0
500
1,000
1,500
2,000
Wavelength (nm)

Wien's Law

- The way the peak of the Planck spectrum changes with temperature is quantified by *Wien's Law*.

$$T(K) = \frac{0.29}{\lambda_{\max}(cm)}$$

- This is very powerful!

Wien's Law

- Take a spectrum of the Sun and you discover that the peak in the spectrum is at about 5500 angstroms = 5.5 x 10^{-5}cm. Use Wien's Law to get the surface temperature of the Sun:

$$T(k) = \frac{0.29}{5.5 \times 10^{-5}} = 5200K$$

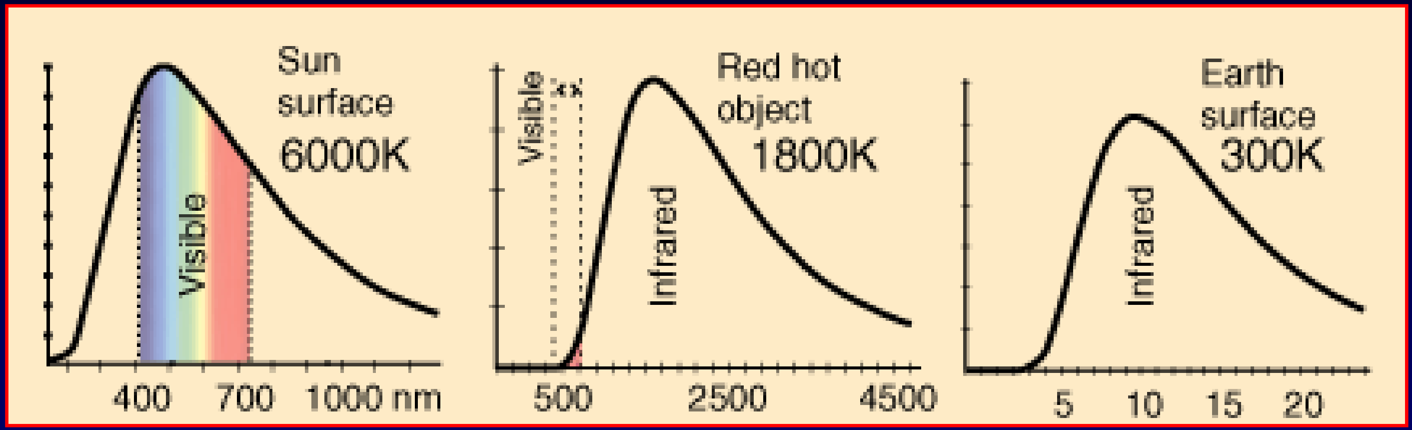
Radiation from Humans

- Note that the radiation we are using to see one another is *reflected* from the lights in the room.
- Human temperature is about 300K, so the peak radiation is:

$$\lambda_{\max}(cm) = \frac{0.29}{T(K)} = 9.8 \times 10^{-4}(cm)$$

- This is in the infrared.

``Red'' Hot vs ``White'' Hot



- Think about the stove element. When its temperature is <800K, it emits IR radiation.
- By ~1300K, it emits more IR radiation and is emitting enough radiation at shorter wavelengths to just start to glow red.

Colors and Temperature

- Simply glancing at this globular cluster you can see that there are stars with a range of temperature.

Interesting Aside: The Greenhouse Effect

- Car windows are designed to pass visible light for safety, but most glasses do not pass IR radiation.
- Visible light from the Sun passes through the car windows and is absorbed by the black leather seats.

Greenhouse Effect

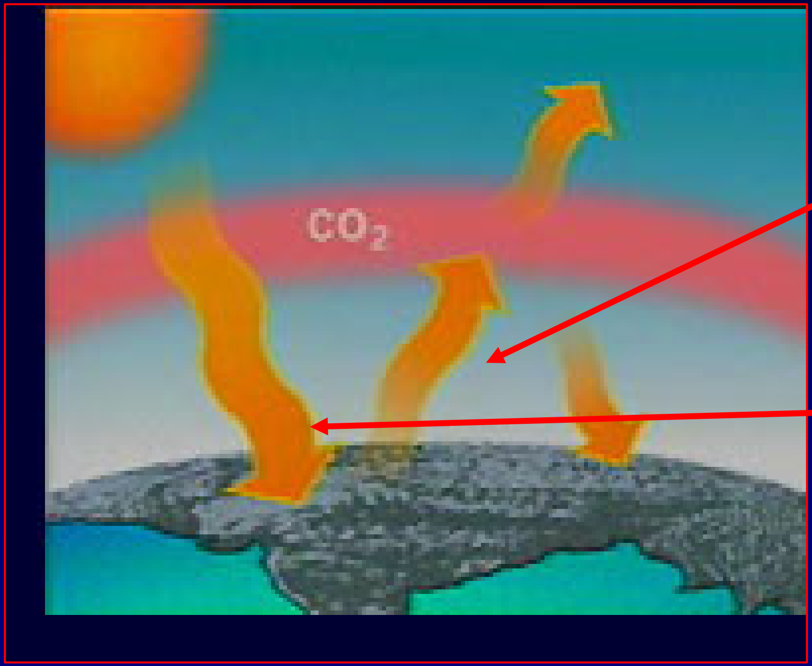
- The seats heat up to say 350K and radiate E-M radiation in what part of the spectrum?

The Infrared

- Since the window glass is opaque to IR radiation, the energy in the original visible radiation gets trapped in the car and *it gets hot in there!*

Earth's Greenhouse Effect

- The Earth's atmosphere can act like a glass window.
  - When it's not cloudy, it is transparent to visible light radiation
  - Some of the molecules in the atmosphere absorb IR radiation (CO_2)
- Much of the visible light from the Sun is absorbed by various things on the Earth's surface. These heat up and re-radiate the energy in the IR (T~250K). Some of this IR radiation is trapped by the atmosphere and a net heating is the result.

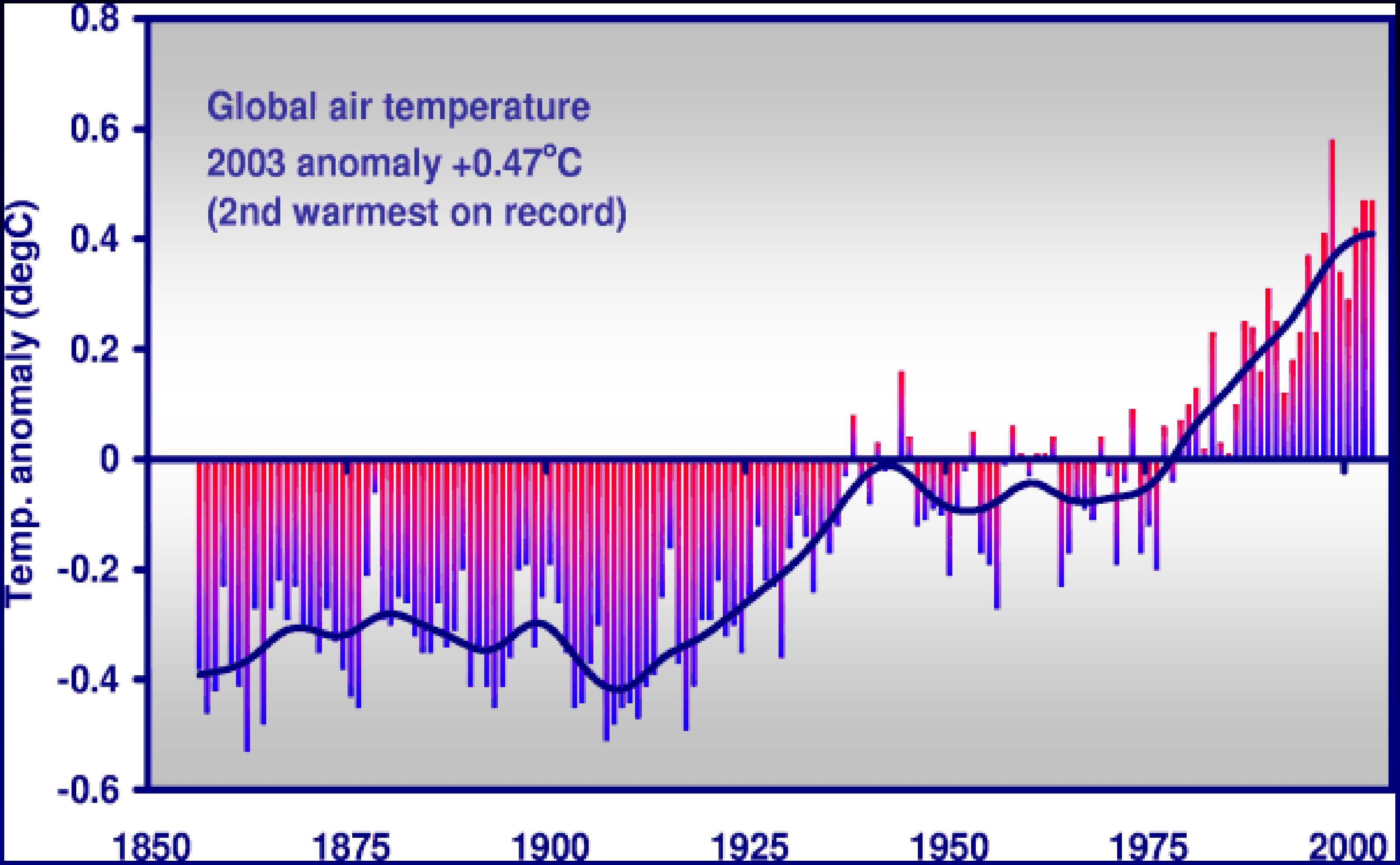


- Bad graphic that sort of shows the effect.

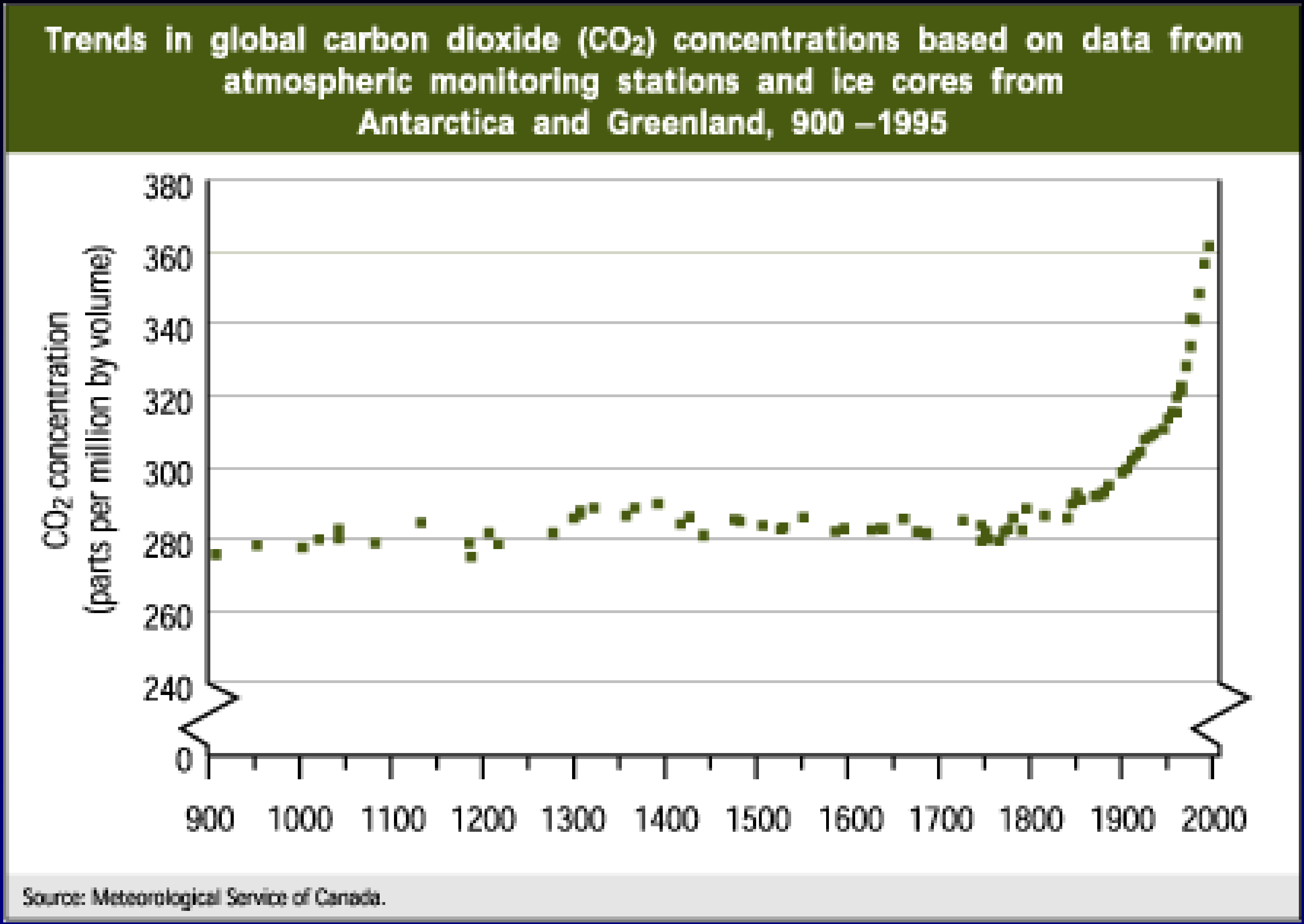
IR radiation

Visible radiation

- Is global warming happening? You bet.



Global air temperature
2003 anomaly +0.47°C
(2nd warmest on record)
Temp. anomaly (degC)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
1850
1875
1900
1925
1950
1975
2000

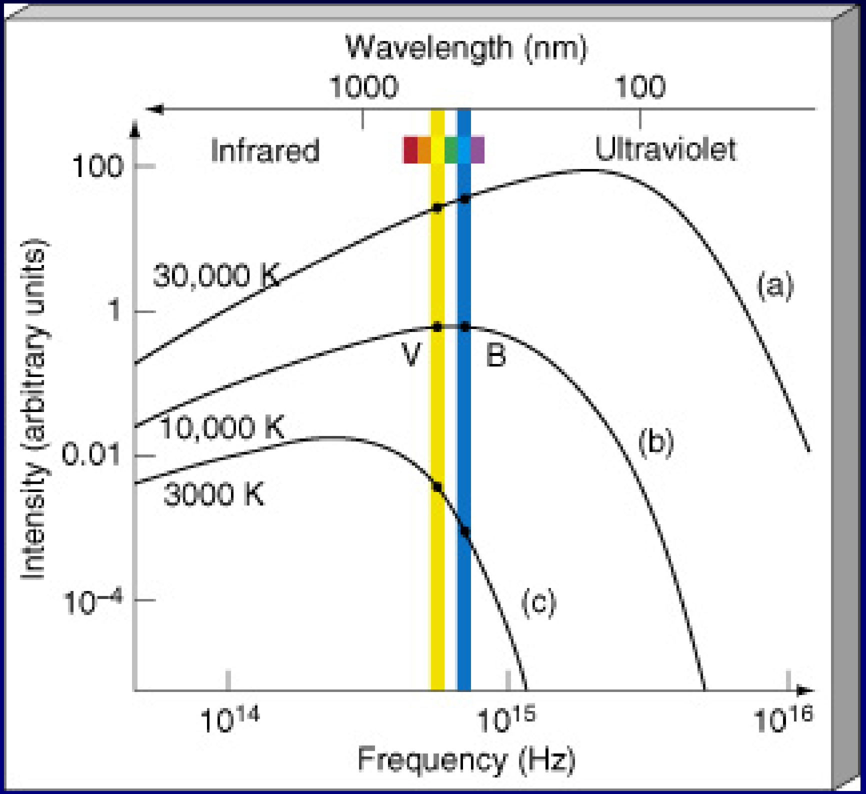


Is the warming trend due to increased CO_2? Probably

Colors and Stellar Temperatures

- Ultra-cheap trick: ``That star looks little redder than the Sun, so it's surface temperature must be less than 5200k''
- Cheap Trick: Disperse the light from a star (take a spectrum), find λ_{max} and use Wien's Law
- One of the two ways it's done in practice: measure colors

Photometric Colors

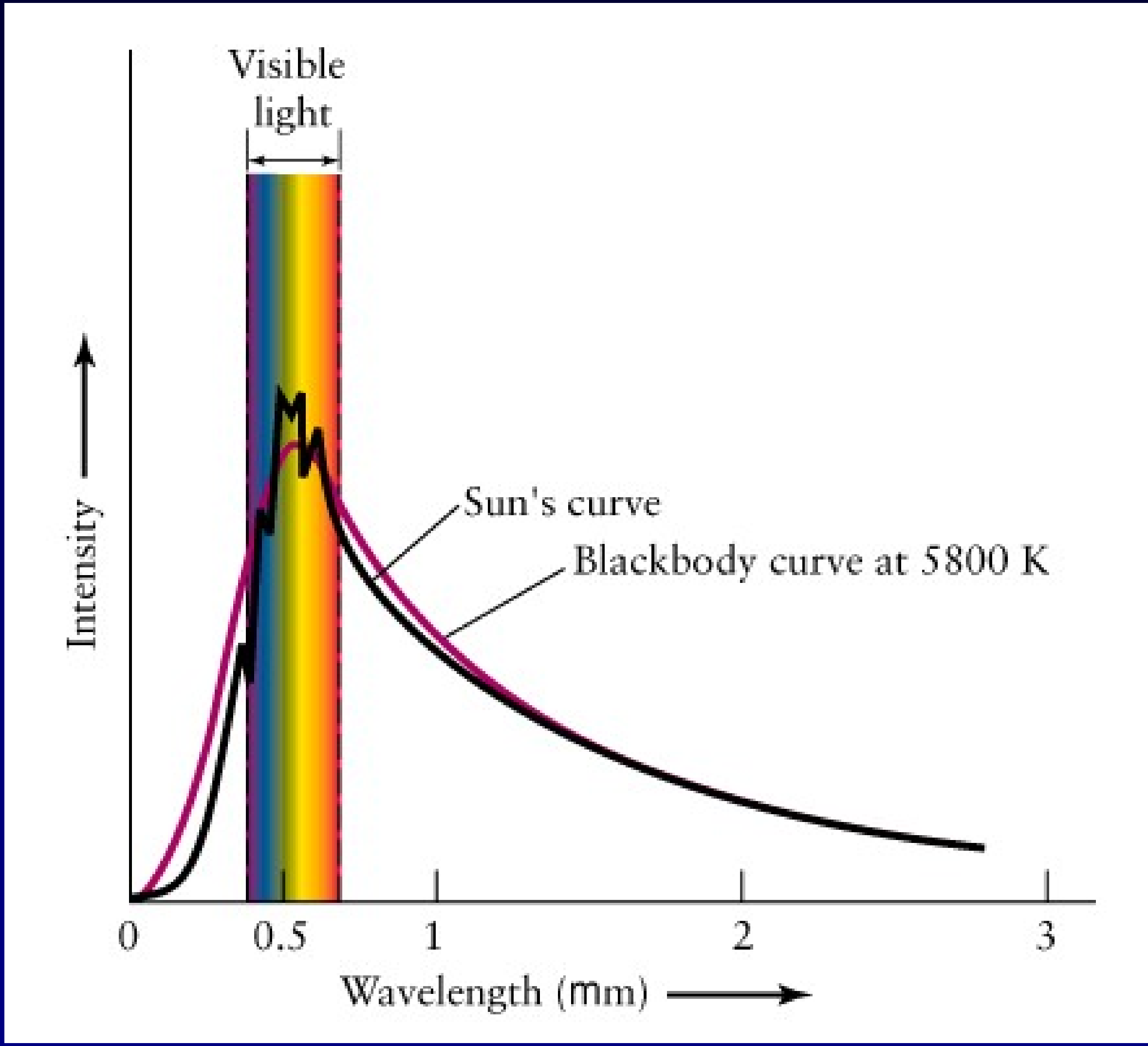


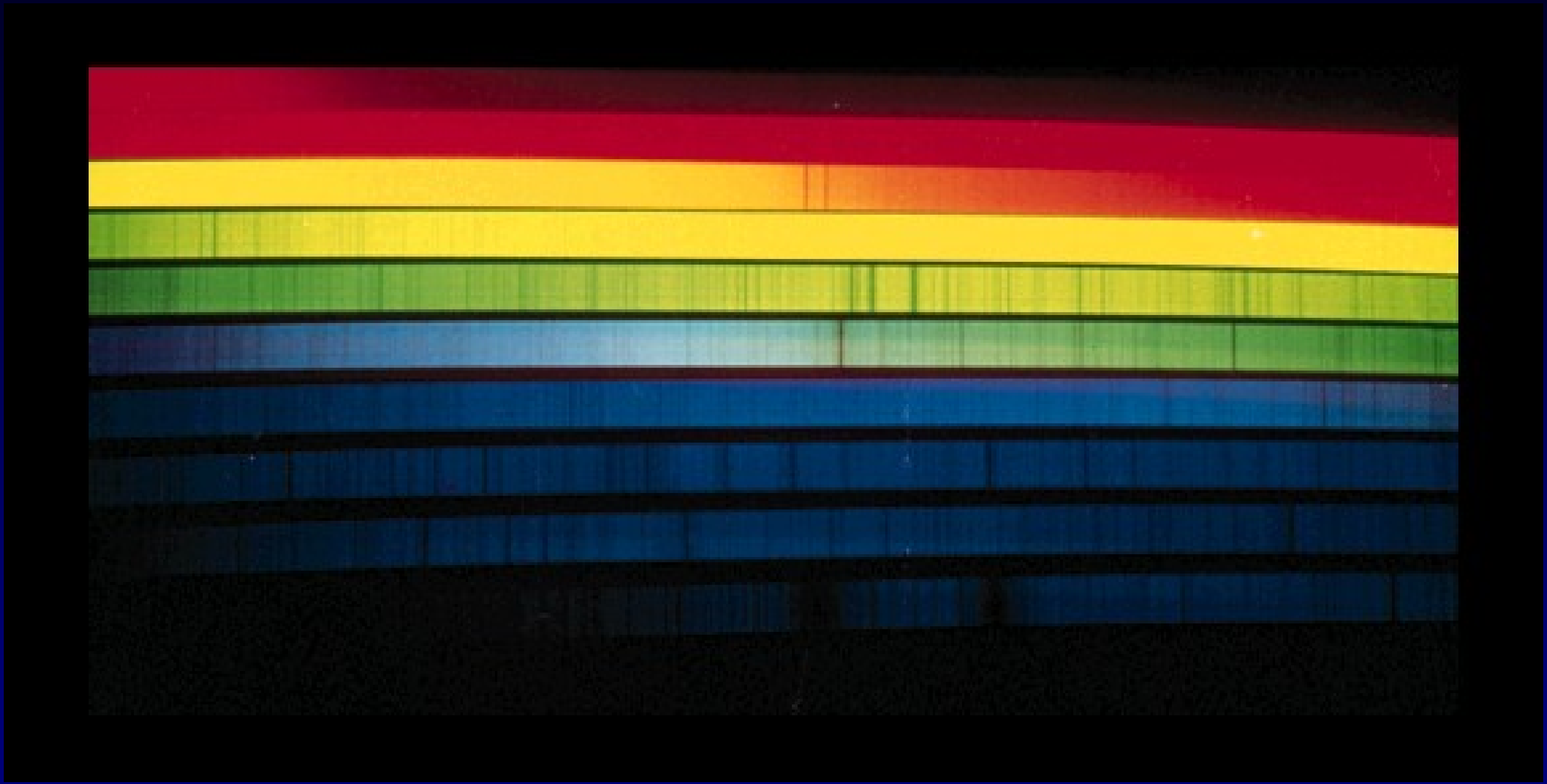
- For Planck spectra the ratio of the light in two different color filters unambiguously give the temperature of the radiating object.

Stellar Colors

- To the extent that stellar spectra look like Planck spectra (spectra of solid objects), accurately measured colors can give quantitative stellar temperatures.
- What do stellar spectra look like?
- Back in the 1800's, spectra of the Sun showed that it was similar to a Planck spectrum, but there was missing light at certain wavelengths -- `absorption spectra'

Stellar Spectra



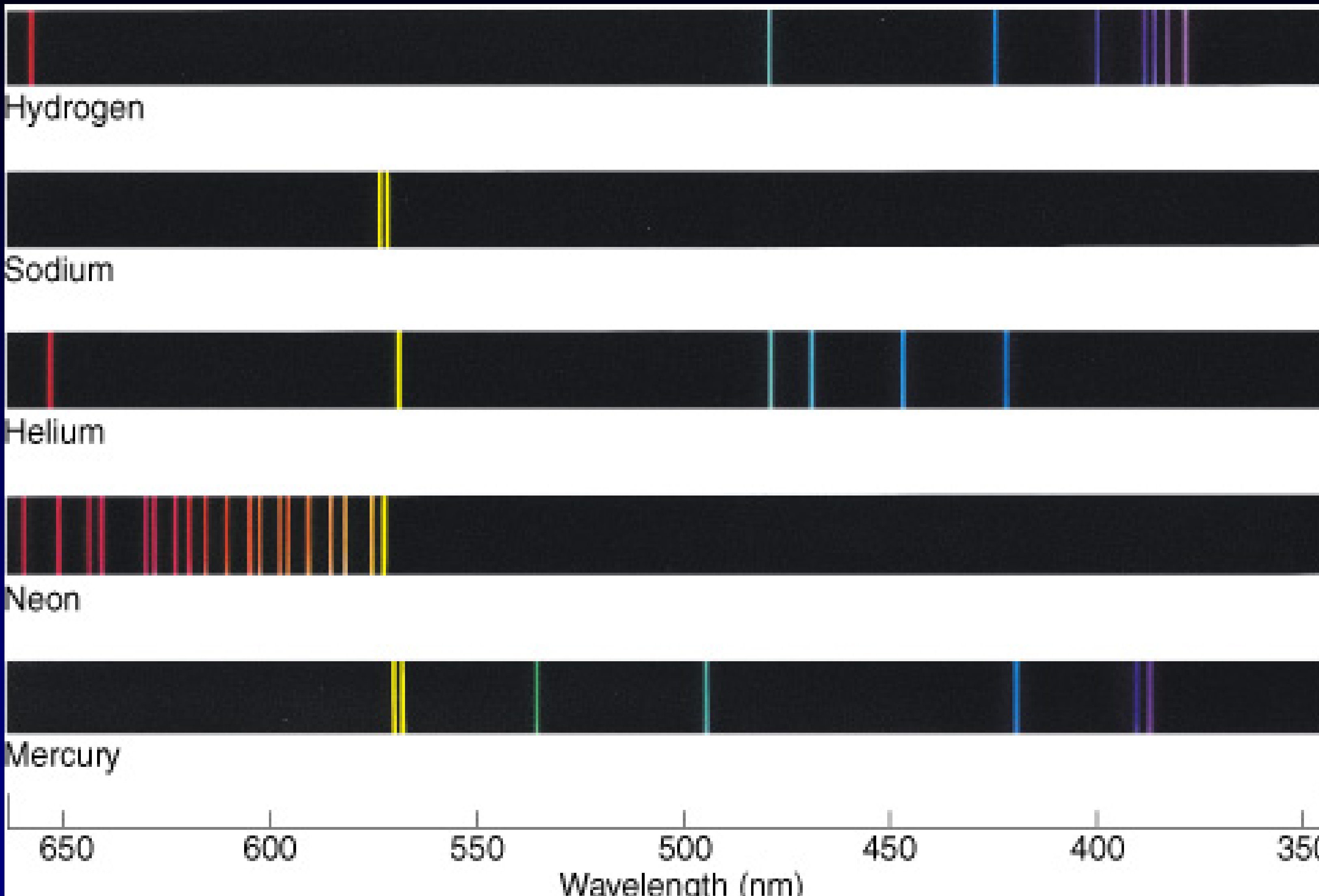


- Because the spectra of stars are pretty close to being Planck Curves, stellar colors can be used to measure stellar temperatures. The process is:

1. Use computer models of spectra generated for stars of different temperature and calibrate a color-temperature relation
2. Measure the brightness of a star through two filters and compare the ratio of red to blue light

Absorption and Emission Lines

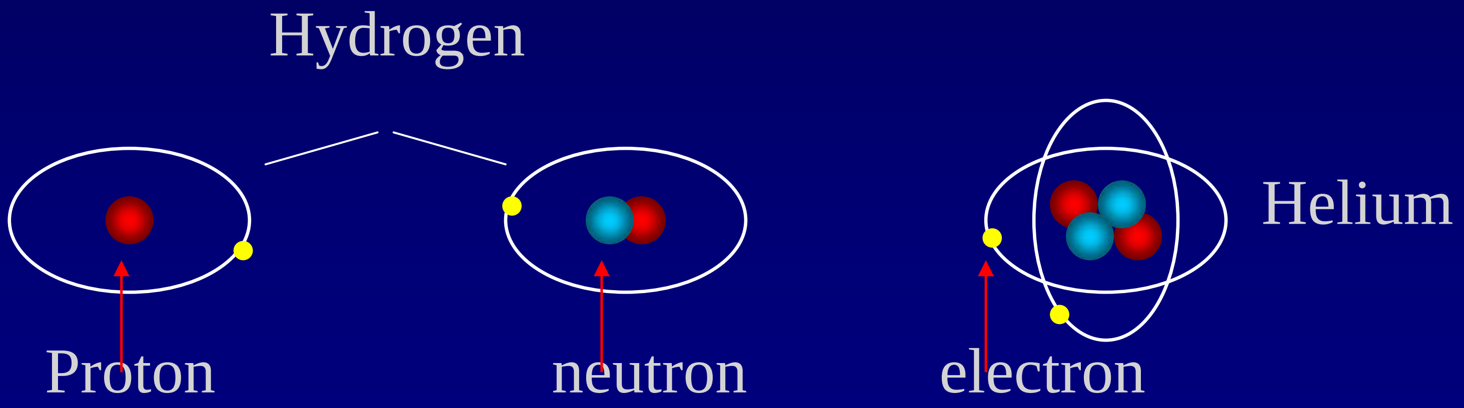
- The wavelengths with missing light in stellar spectra turned out to be very interesting and important.
- When chemists heated gases to the point where they (the gases) began to glow, the resulting spectra were not continuous, but had light at discrete wavelengths that matched the wavelengths of missing light in stellar spectra.
- *Different elements had different sets of emission/absorption lines!*



Hydrogen
Sodium
Helium
Neon
Mercury
650
600
550
500
450
400
350
Wavelength (nm)

Light and Atoms

- The understanding of spectral lines had to await the development of Atomic Physics.
- What makes an *element*?
  - The number of protons in the nucleus of an atom uniquely specifies the element.



Elements

- Hydrogen has one proton-- $^{1}H_{1}$
- Hydrogen with a neutron is a `heavy' isotope of hydrogen called deuterium -- $^{2}H_{1}$
- Add a second proton and you have the next element in the Periodic Table -- Helium

$$2p^{+} + 1n^{o} = {}^{3}He_{2}$$

total # of nucleons   # of protons

Q. How many neutrons in $^{238}U_{92}$?

Looks like p + n = 238 and there are 92 protons.
So, must have 238 - 92 = 146 neutrons.

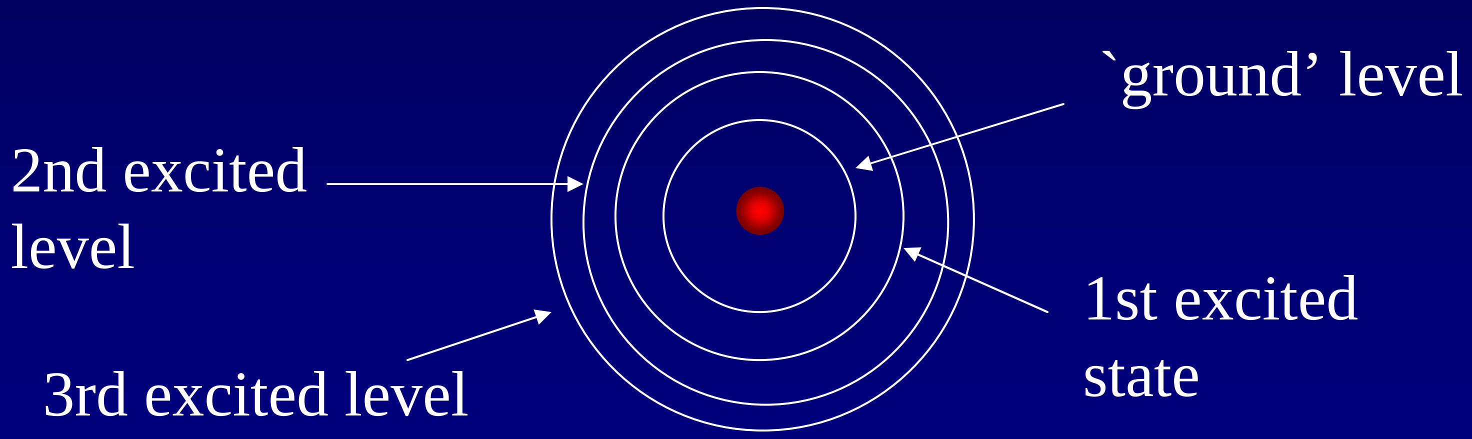
Atoms and Spectra

- What does this have to do with spectral lines?
- Lots of clever experiments in the early 1900s demonstrated:

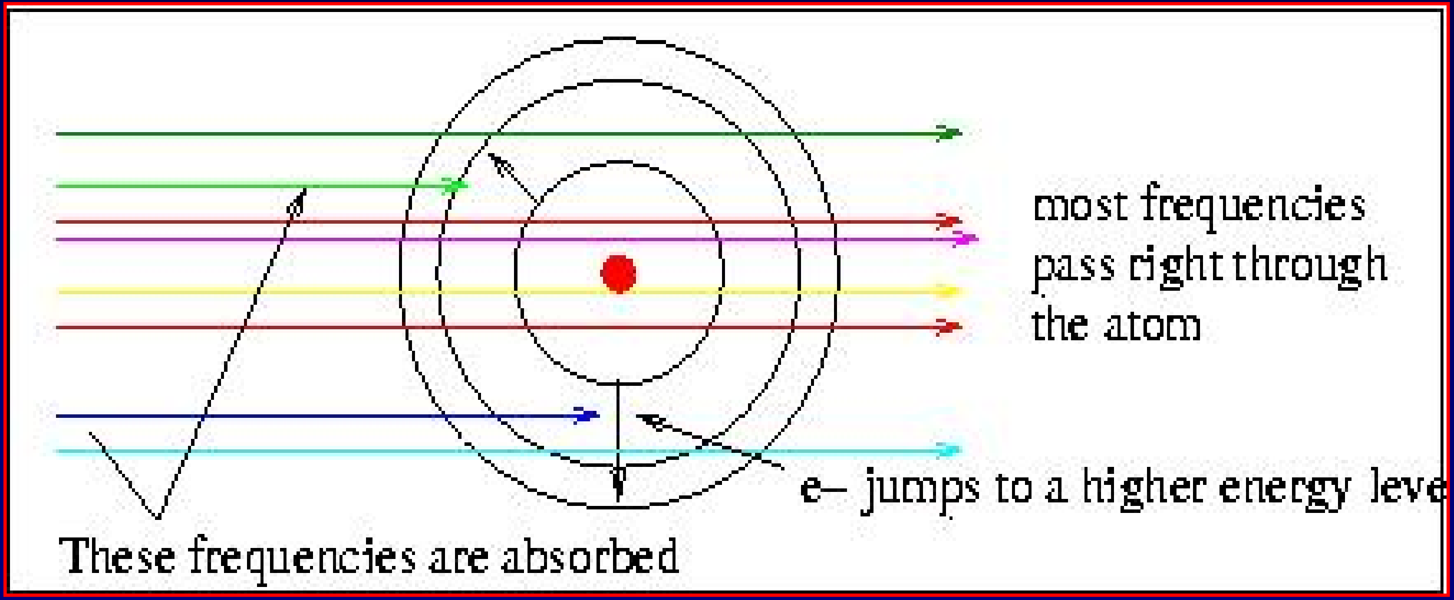
1. Light can be modeled as a stream of `quanta'called photons. Each photon carries and energy $E=h\nu$ where h is `Planck's constant' and ν is the frequency of light.

Hydrogen Schematic: 4 lowest energy levels

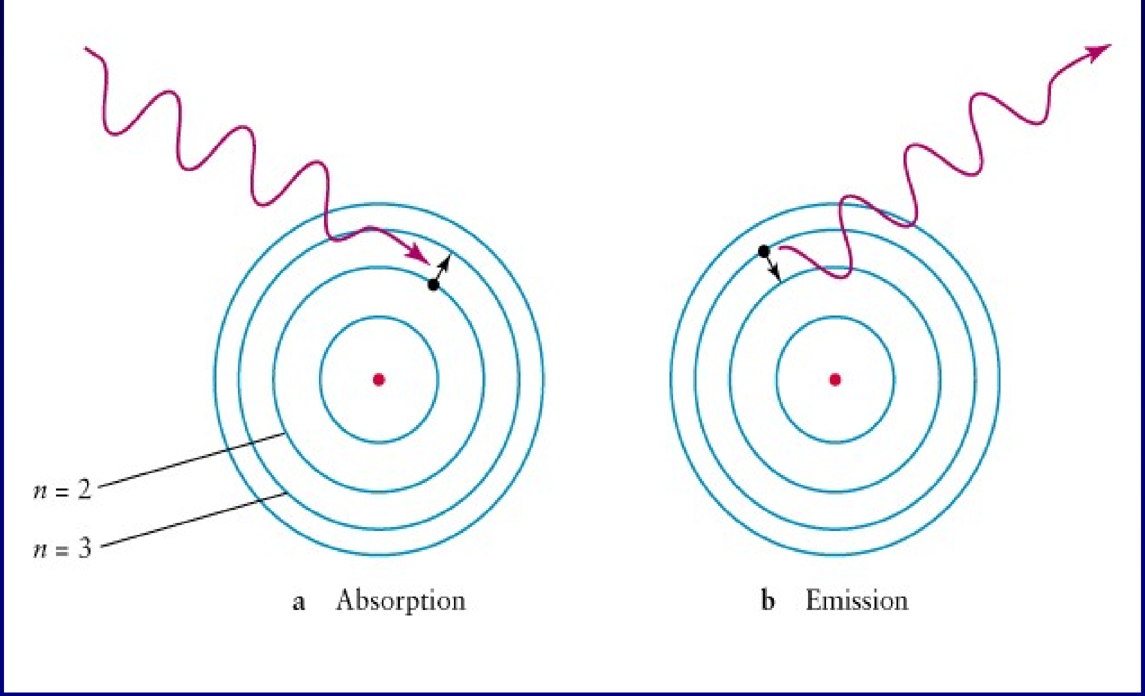
2. Atoms have a crazy structure in which only certain orbits are `allowed' for the electrons. Atomic orbits and energy levels are said to be *quantized*.

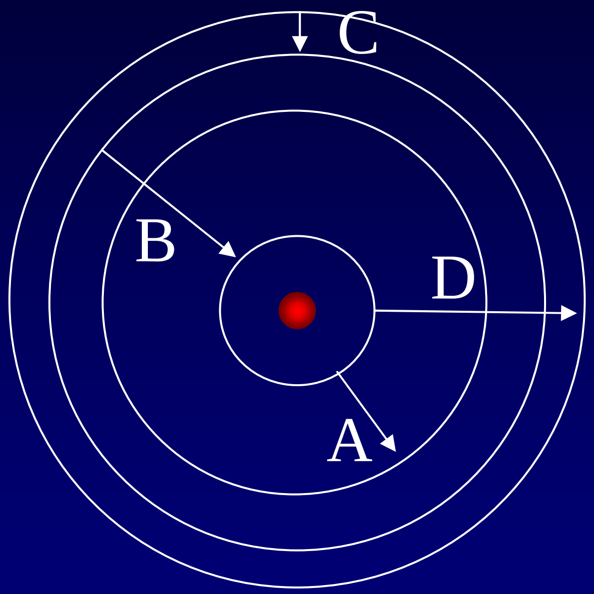


- Now, fire photons with a range of energy, frequency and wavelength at an atom and the majority of them go right through the atom.
- *But, a photon with energy equal to an energy level difference between two allowed states in the atom will be absorbed, boosting the e- into the higher level.*



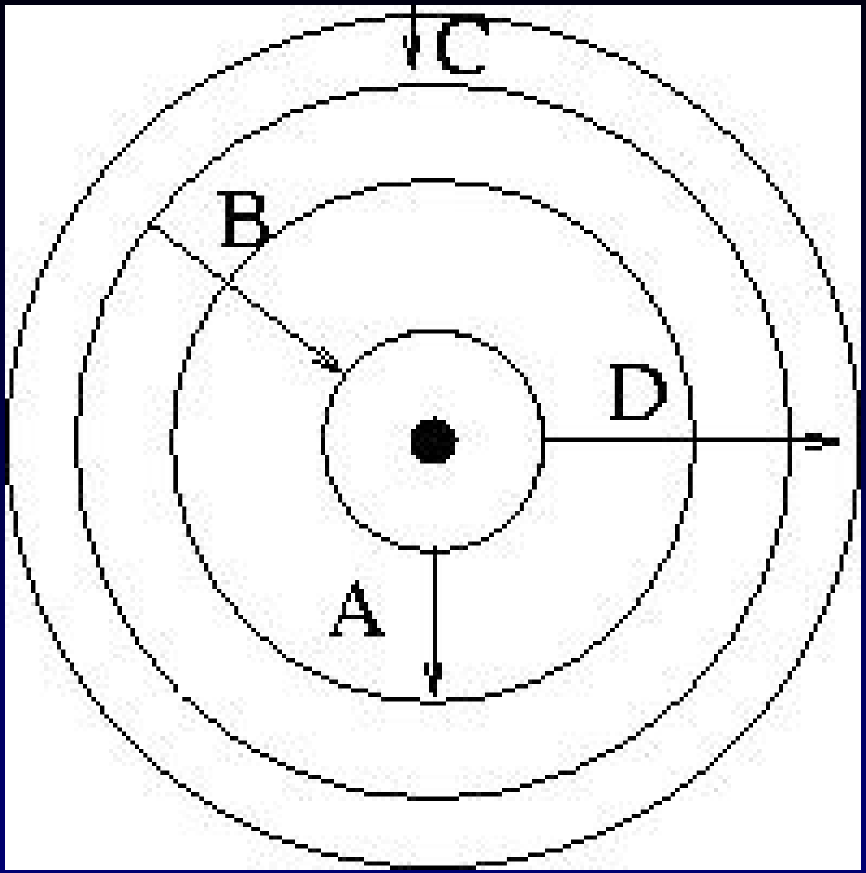
- Now, one of Nature’s favorite rules is that systems always seek the lowest available energy state.
- This means that atoms with electrons in excited levels will rapidly `de-excite’ and spit out a photon to conserve energy.





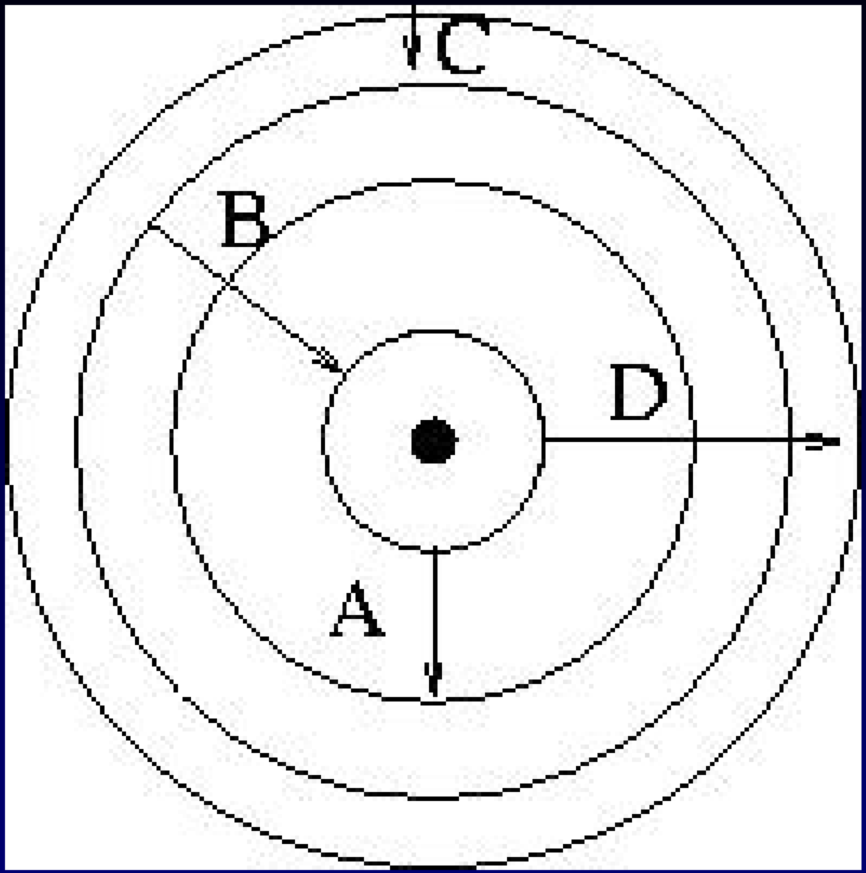
Q. Which transition(s) correspond to ABSORPTIONS of photons?

A, D

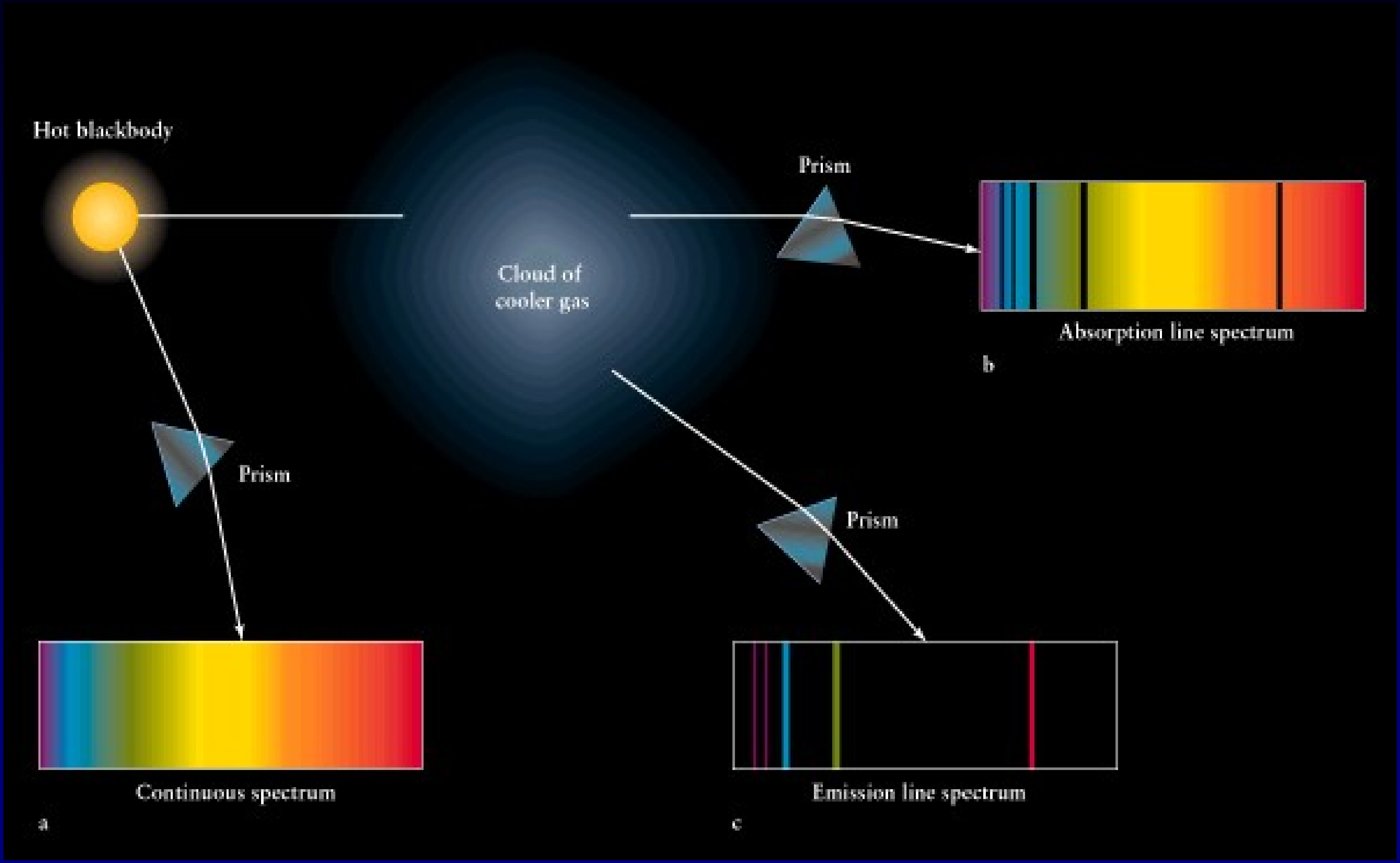


Q. Which transition(s) correspond to the highest energy photon EMITTED?

B



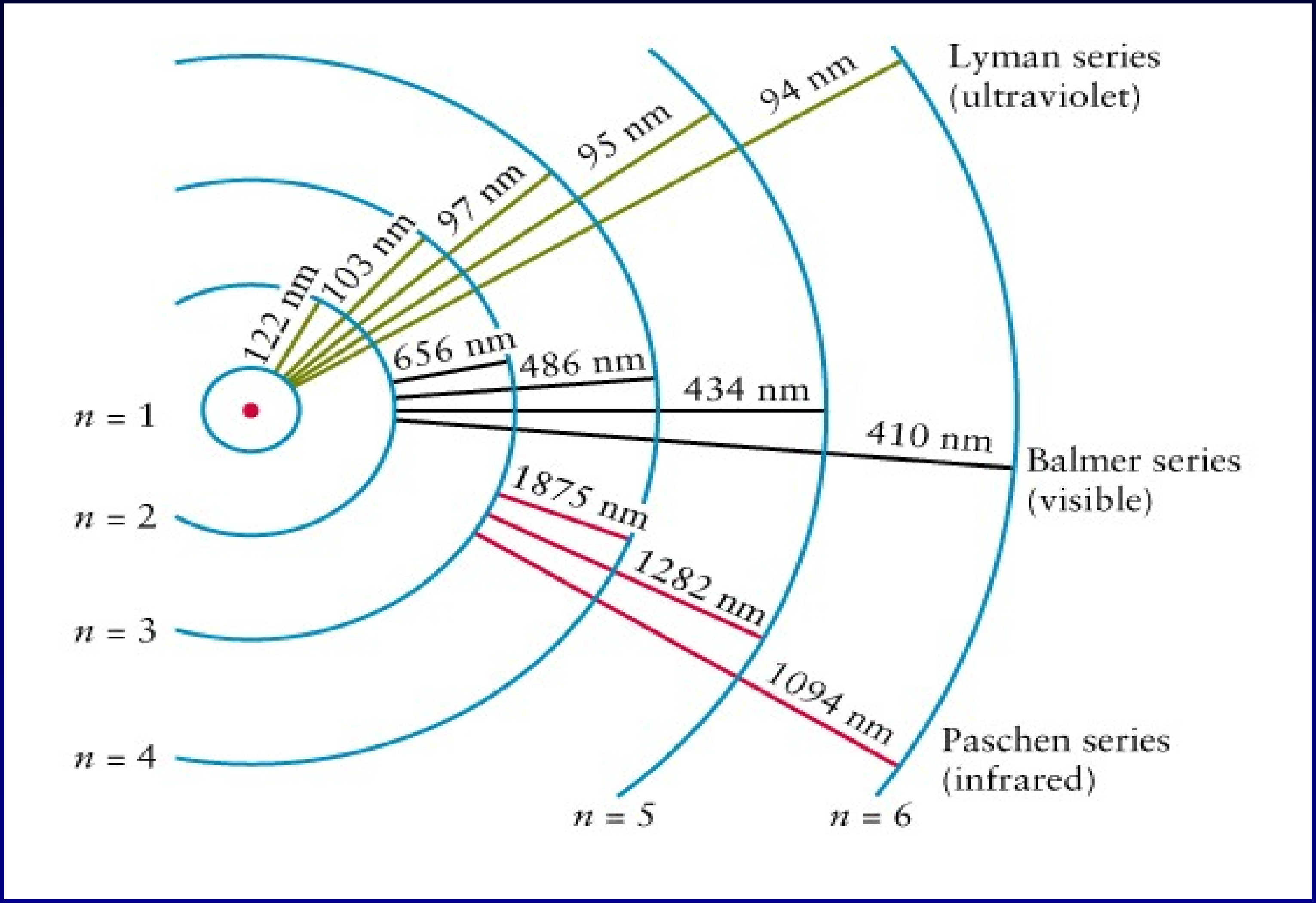
Q. Which transition corresponds to the longest wavelength photon emitted? C


Hot blackbody
Cloud of cooler gas
Prism
Absorption line spectrum
b
Prism
Prism
Continuous spectrum
a
Emission line spectrum
c

The allowed energy levels in an atom depend mostly on the electric field in the atom. So, different elements, with different numbers of e- and p+ have distinct allowed energy levels and energy level differences.

By identifying absorption/emission lines in the spectra of stars and hot gases we can determine the chemical composition of the stars and gases (!)

Hydrogen Atom Levels



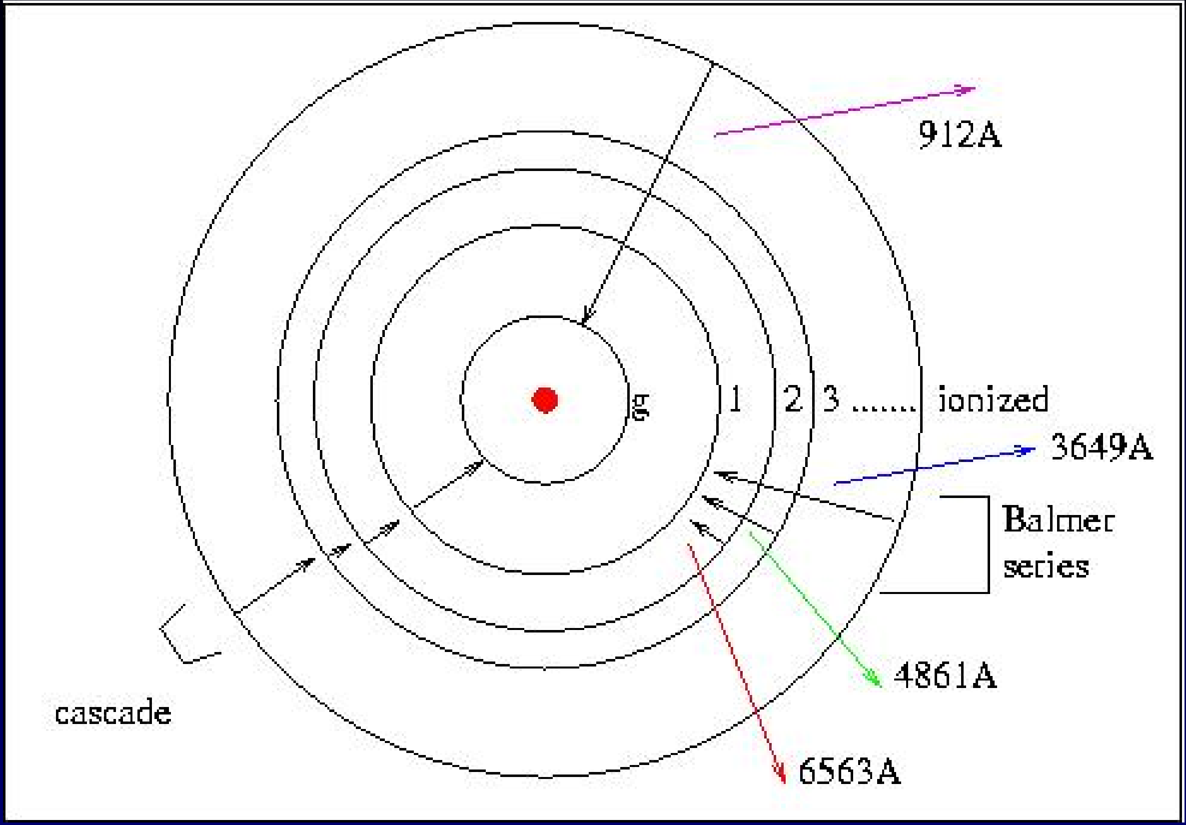
Emission from Gas Clouds

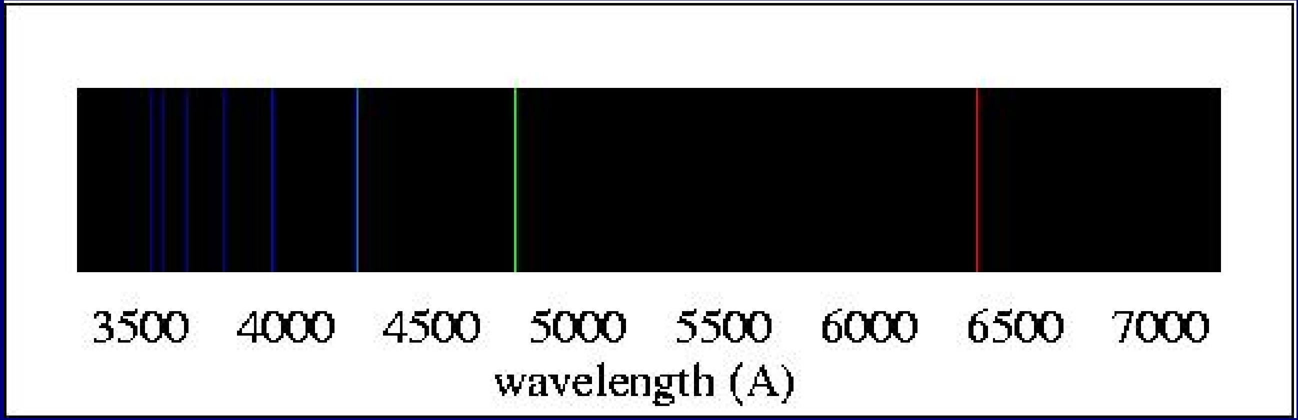
- Atoms in a gas cloud can be `collisionally' excited. Imagine atoms flying around in a gas cloud, bumping into one another. Sometimes part of the energy of the collision will bump an electron into an excited level. On de-excitation, a photon is emitted (cooling the gas).

Hydrogen Recombination Series

- If collisions are energetic enough (hot enough gas) or the photons firing through a gas cloud are energetic enough, H atoms are *ionized.*
- The free e- recombines with a free p+ and the e-drops down to the ground state via one of many paths.

Balmer Series





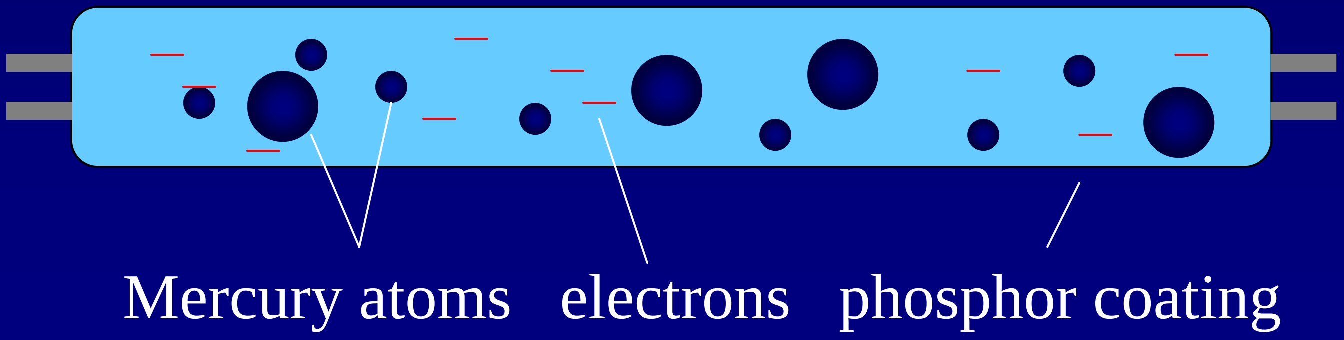
Lights around the House

- Incandescent lights work by running electrons through a filament till it heats up to around 4000K. What kind of spectrum would you expect from an incandescent light?

Planck curve

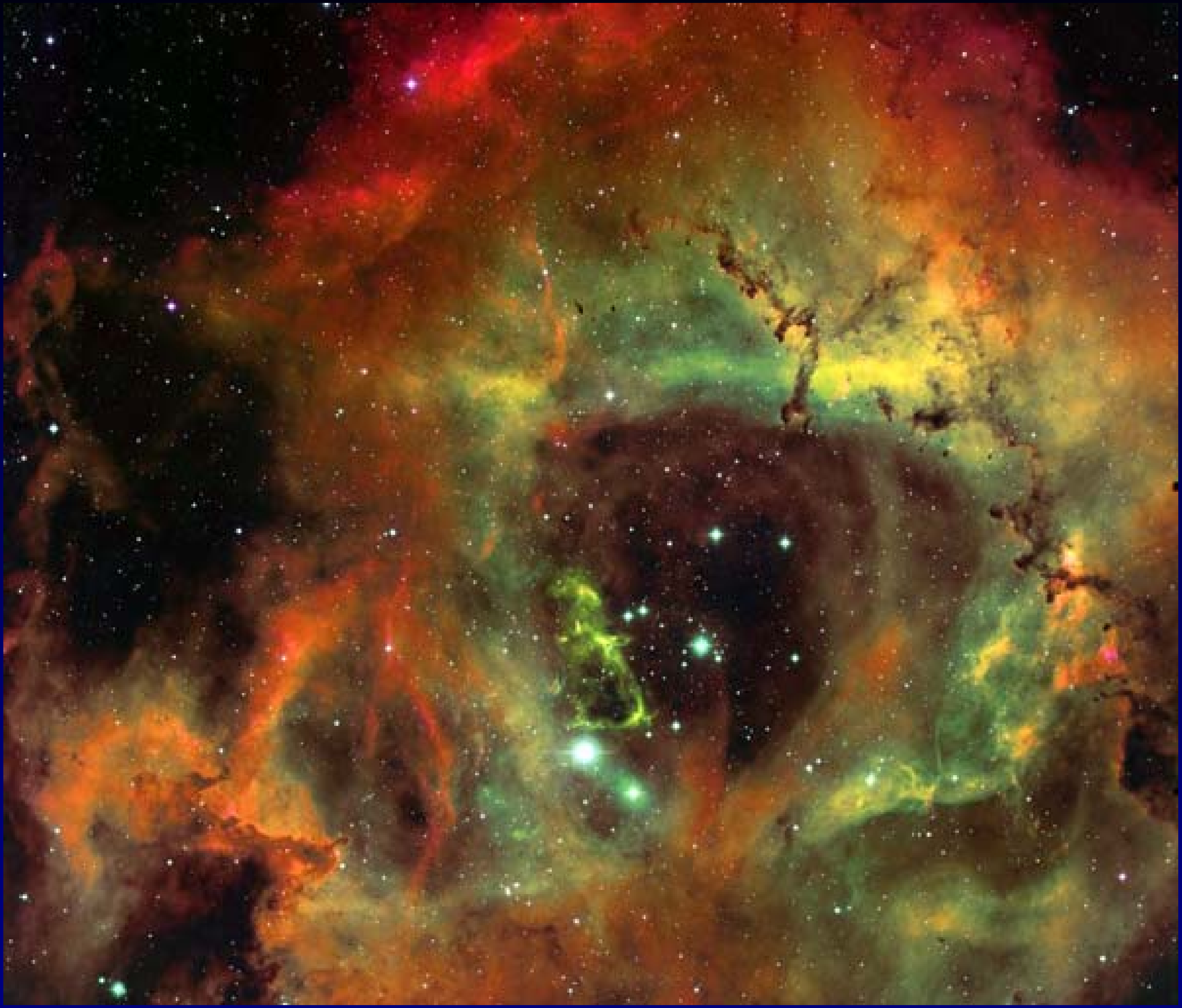
Fluorescent Lights

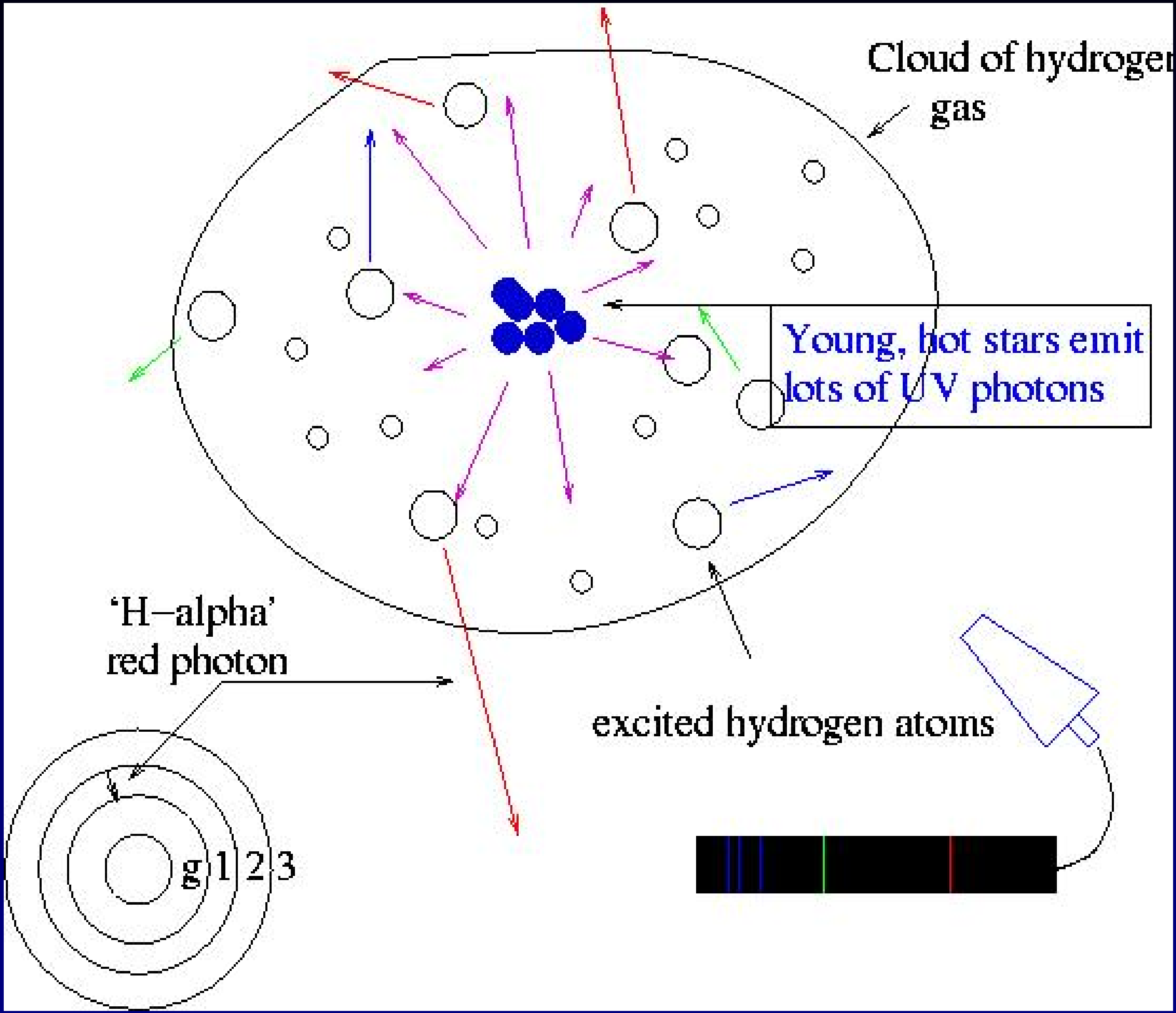
- Fluorescent lights are based on *collisional excitation* of atoms in the tube.
- Turn on the power, boil some e- off the filament and send them crashing back and forth through the bulb at 60Hz.

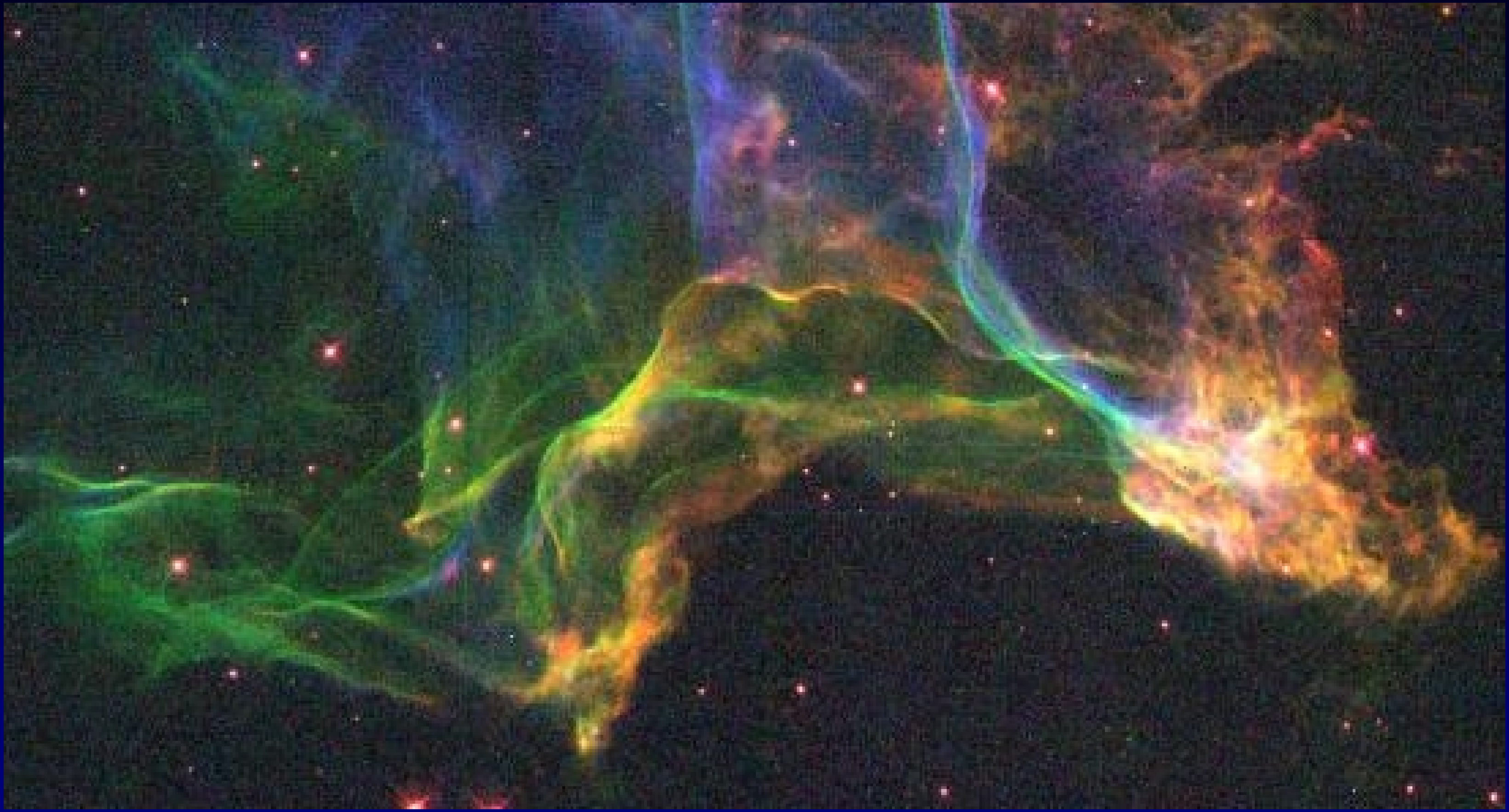


- The atoms in fluorescent bulbs typically produce UV photons on de-exciting. These are absorbed by a phosphor coating in the bulb and each UV photon is converted via a cascade to a number of visible-light photons with the same total energy as the original UV photon.
  - No emission in the IR (`cool’ and energy efficient
  - Do emit UV (clothes fade)
  - Good for plants (full spectrum ish)
  - Whiter-that-white detergents
  - Some phosphors has a long decay time -- glow-in-the-dark toothbrushes.
- With no phosphor, you get a `black light’’.

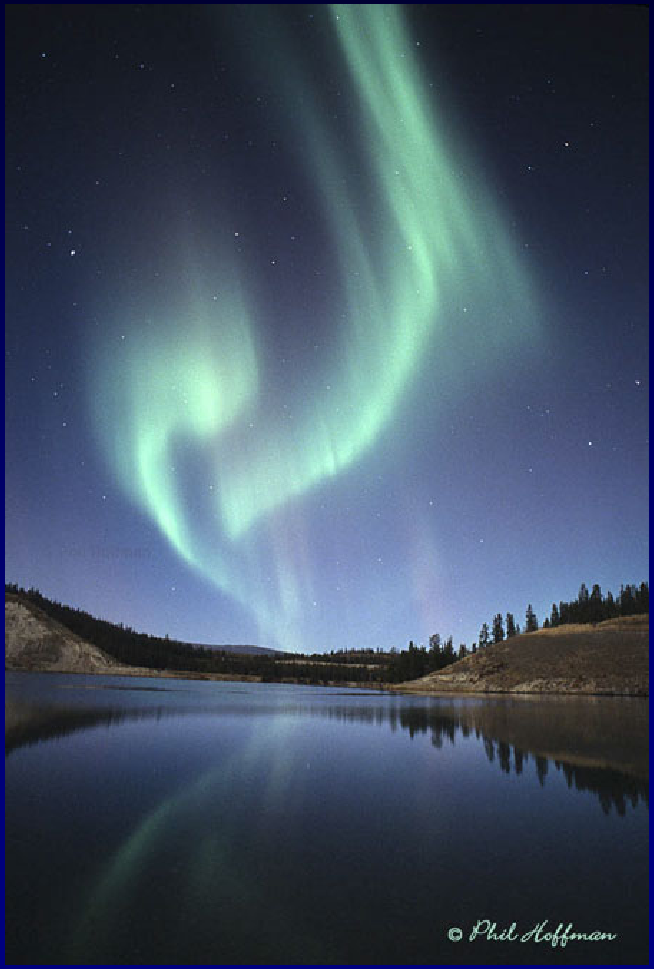
Fluorescence in Astronomy




Cloud of hydrogen
gas
Young, hot stars emit
lots of UV photons
'H−alpha'
red photon
excited hydrogen atoms
g 1 2 3



The Earth’s Aurora are due to the de-excitation of atoms in the atmosphere that were collisionally excited by particles streaming off the Sun

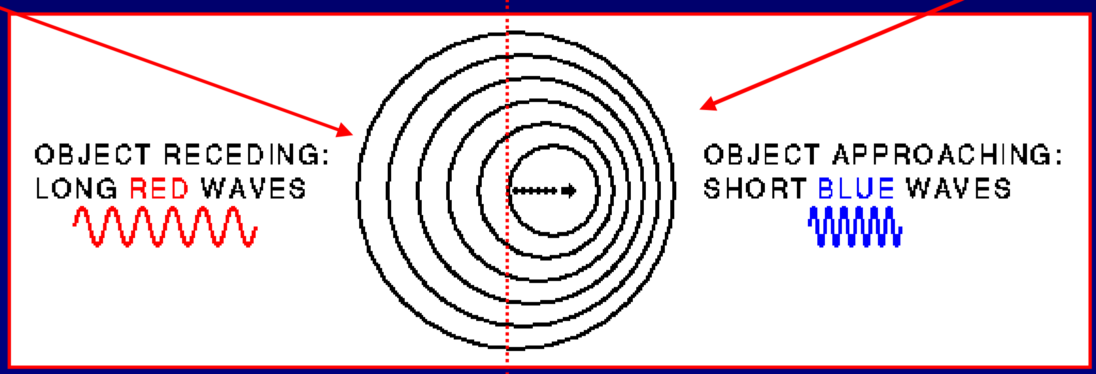


The Doppler Shift

- If a light source is moving toward or away from an observer (or visa versa) the speed of the light doesn’t change, but the frequency/wavelength does.

Waves spread out

Waves bunch up



Transverse motion doesn’t produce any shift

- The change in wavelength due to a relative radial motion is called the *Doppler Shift*.

$$\frac{\lambda_0 - \lambda_v}{\lambda_0} = \frac{v}{c}$$

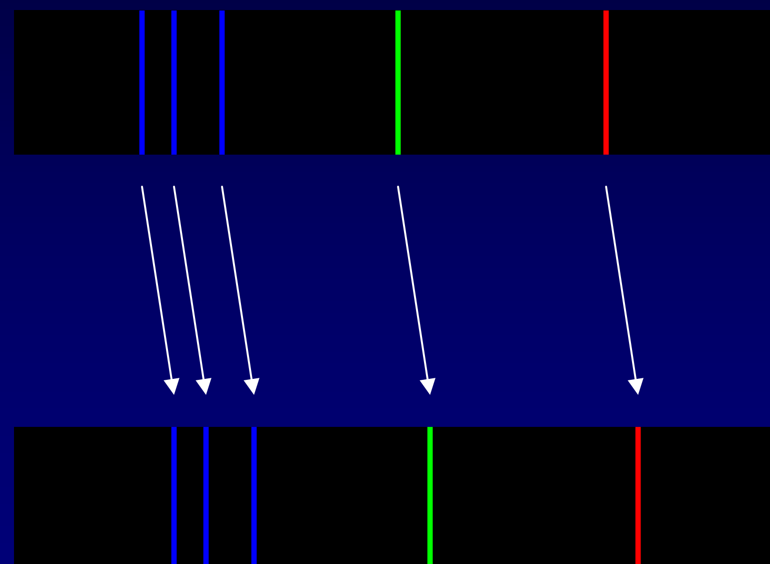
λ_0= \`rest' wavelength

λ_v= wavelength at speed \`v'

v = speed toward or away from observer

c = speed light

Hydrogen Balmer series



Doppler Shift Example

- You are busy talking on your cell phone and drive through a red light. You claim that because you were approaching the traffic light, it was Doppler shifted and looked green. How fast would you have to have been going?

$$\frac{\lambda_0 - \lambda_v}{\lambda_0} = \frac{v}{c}$$

$$\frac{\lambda_0 - \lambda_v}{\lambda_0} \times c = v$$

$$\frac{600nm - 500nm}{600nm} \times 3x10^5 km/\sec = v = 110{,}000{,}000 miles/hr$$

600nm = rest wavelength of red light

500nm = wavelength of green light

$3x10^5$ km/sec = speed of light

V > speed limit