How is E-M Radiation Produced?

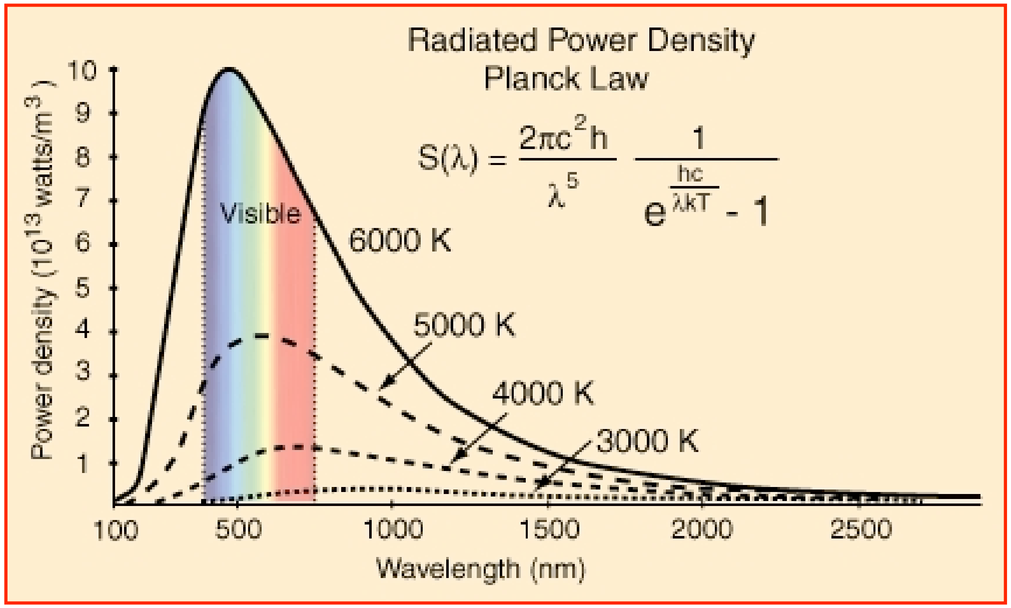
1. Accelerate charged particle back and forth like they do at the radio station.
2. All solids or liquids with temperature above *Absolute Zero* emit E-M radiation.
   - Absolute zero is the temperature at which all motion (on an atomic level) ceases.
   - $0K = -459^{o}F = -273^{o}C$

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

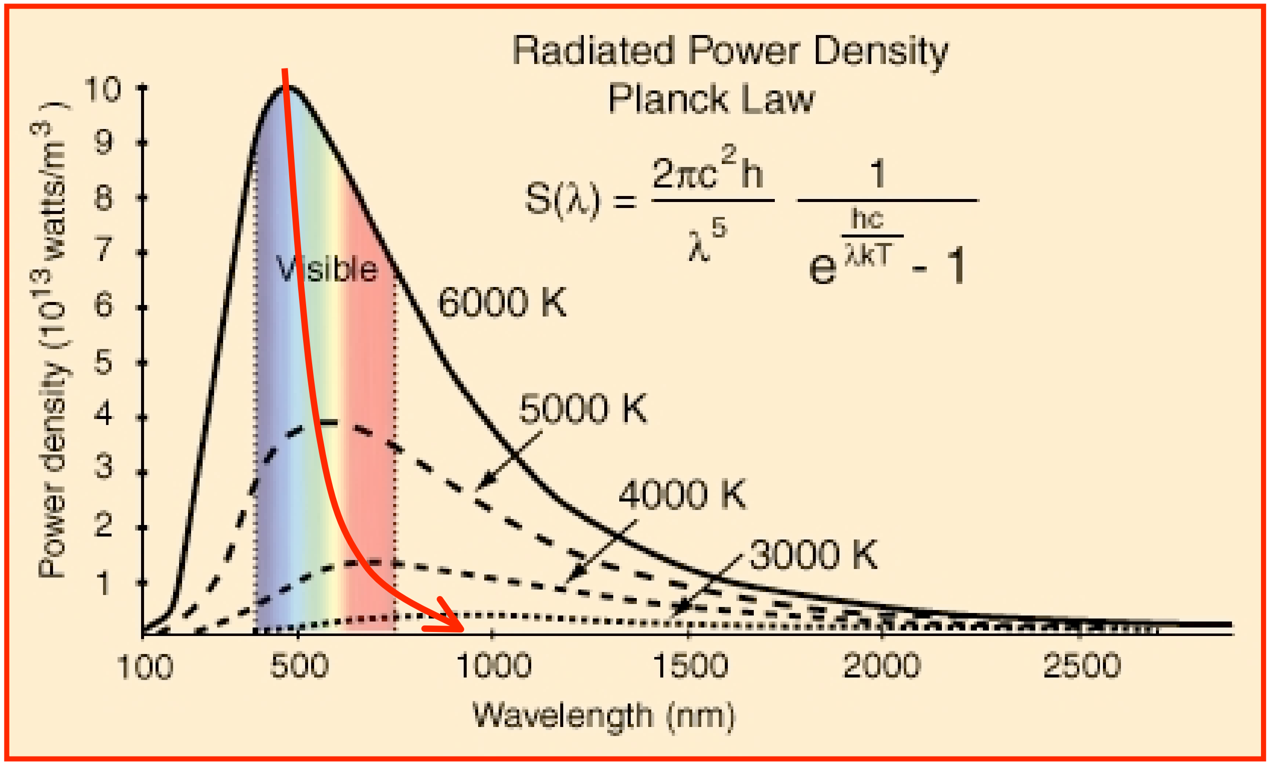
Wavelength

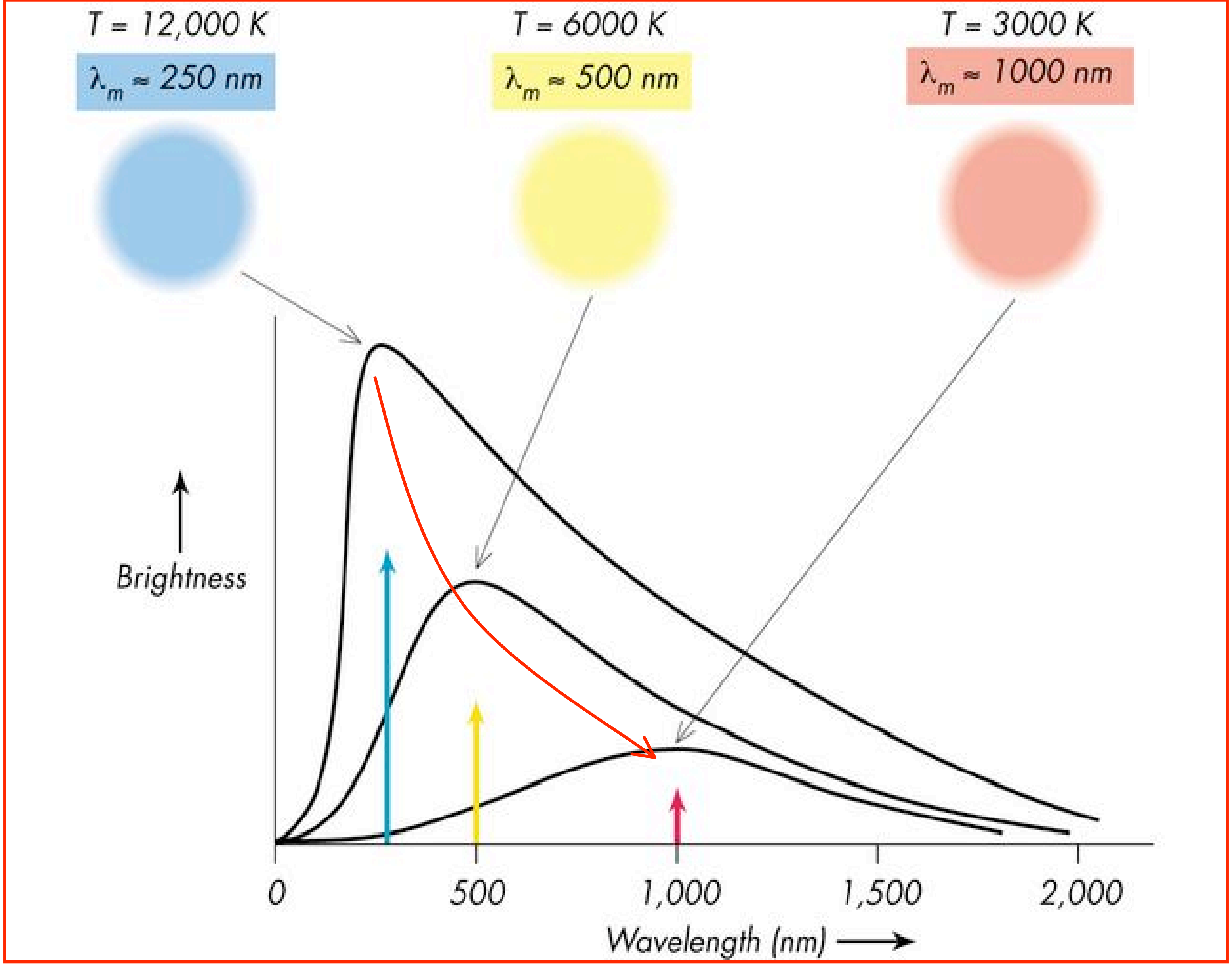
Continuous Spectra

- 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
$\lambda_m \approx 250$ nm
T = 6000 K
$\lambda_m \approx 500$ nm
T = 3000 K
$\lambda_m \approx 1000$ 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*.

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

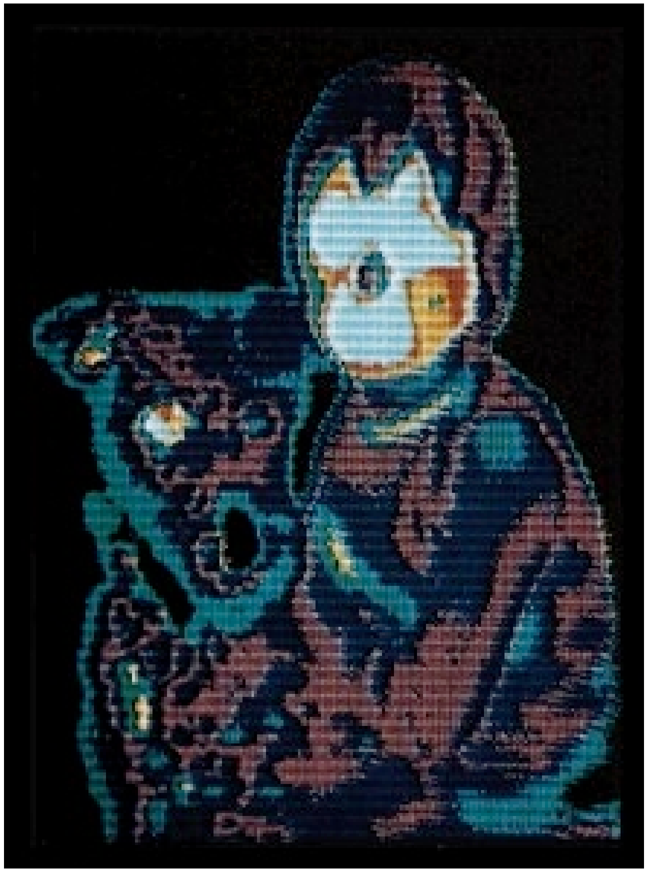
- This is very powerful!

Wien’s Law

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

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

Radiation from Humans

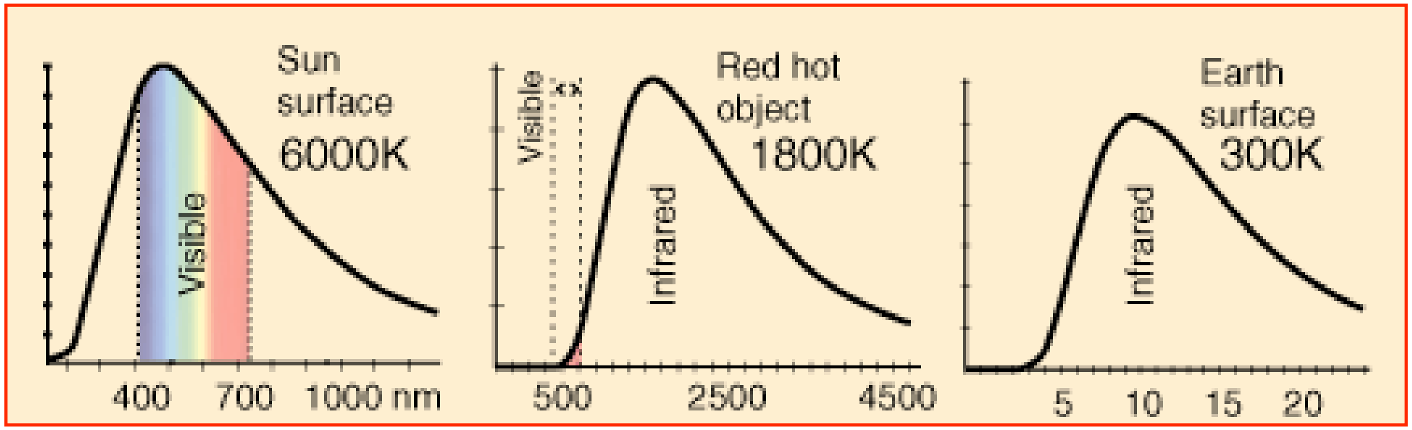


- Note that the radiation we are using to see one another is *reflected* from the lights in the room.
- Human temperature is about 300K, so the peak radiation is:

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

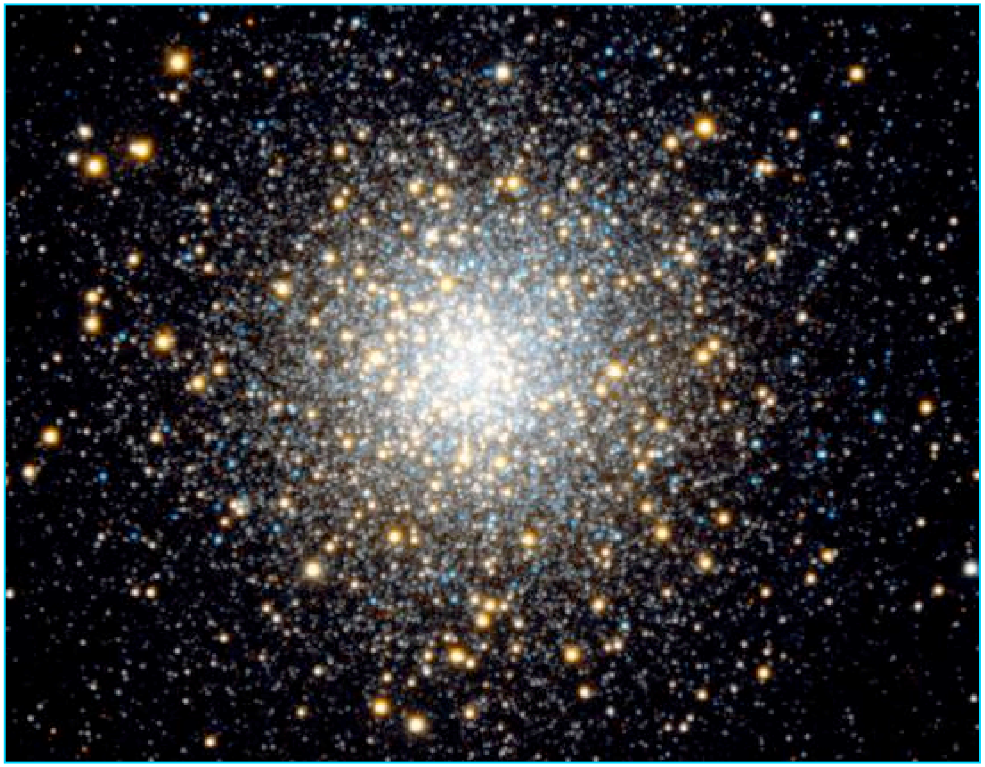
- This is in the infrared.

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



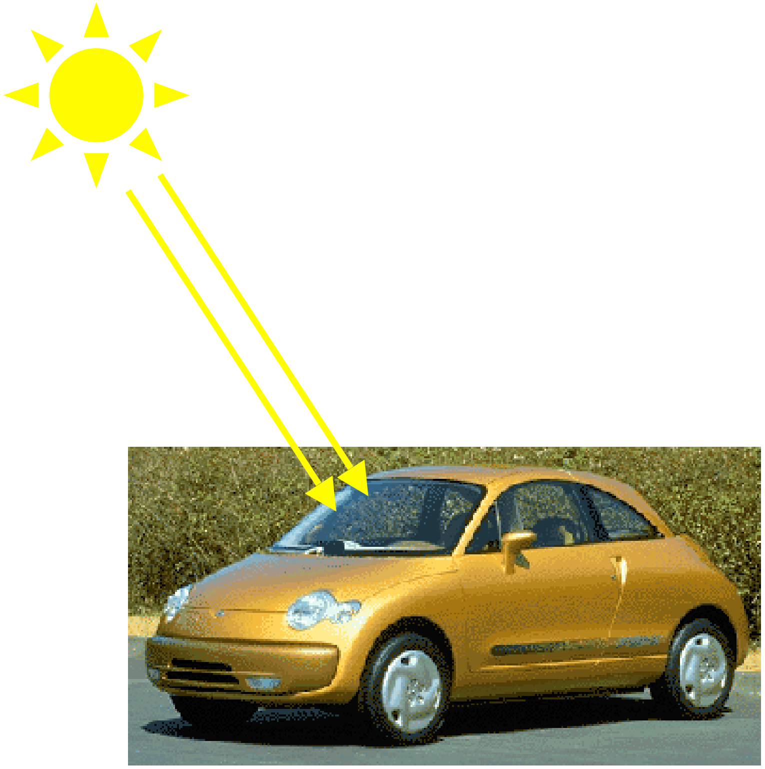
- Think about the stove element. When its temperature is <800K, it emits IR radiation.
- By ~1300K, it emits more IR radiation and is emitting enough radiation at shorter wavelengths to just start to glow red.

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

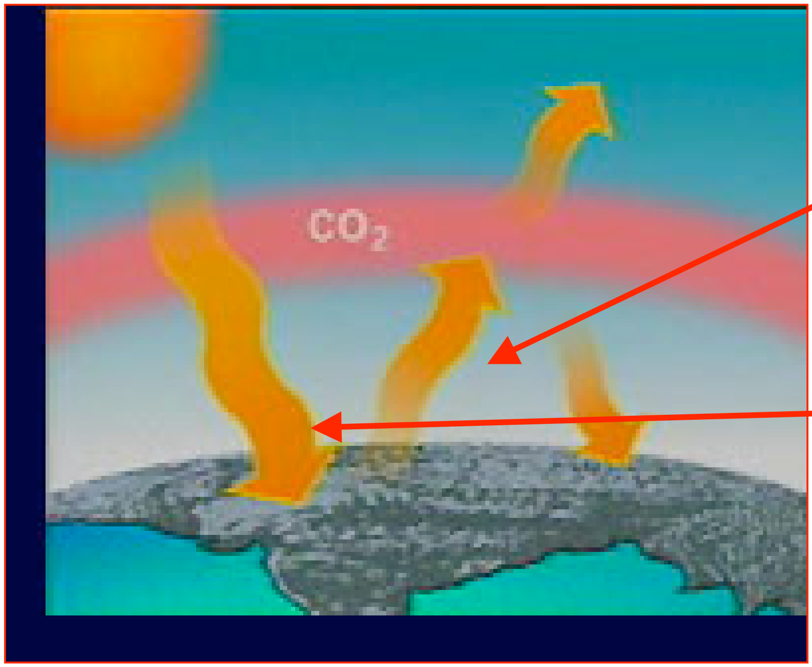
- The seats heat up to say 350K and radiate E-M radiation in what part of the spectrum?

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.

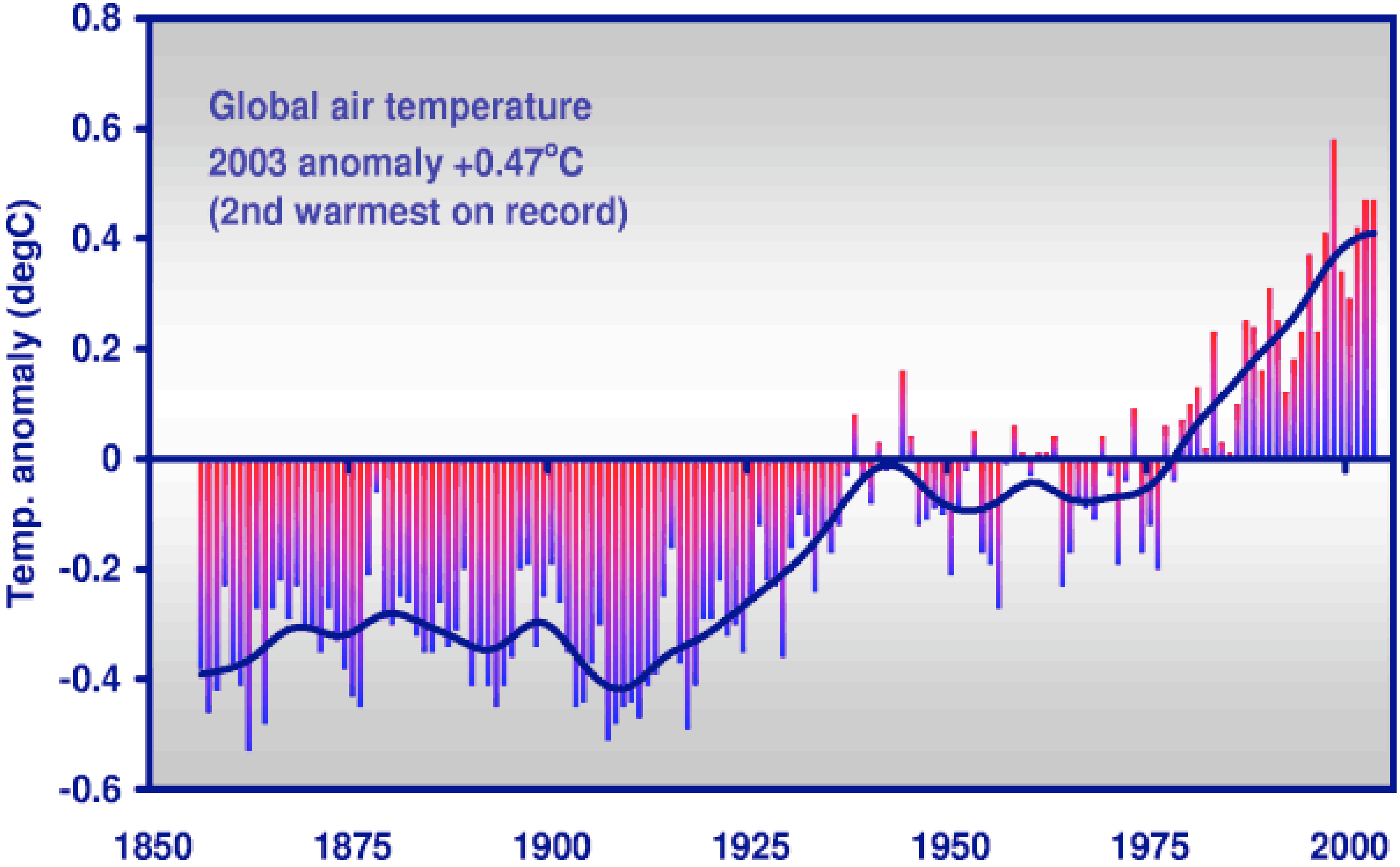


- Bad graphic that sort of shows the effect.

IR radiation

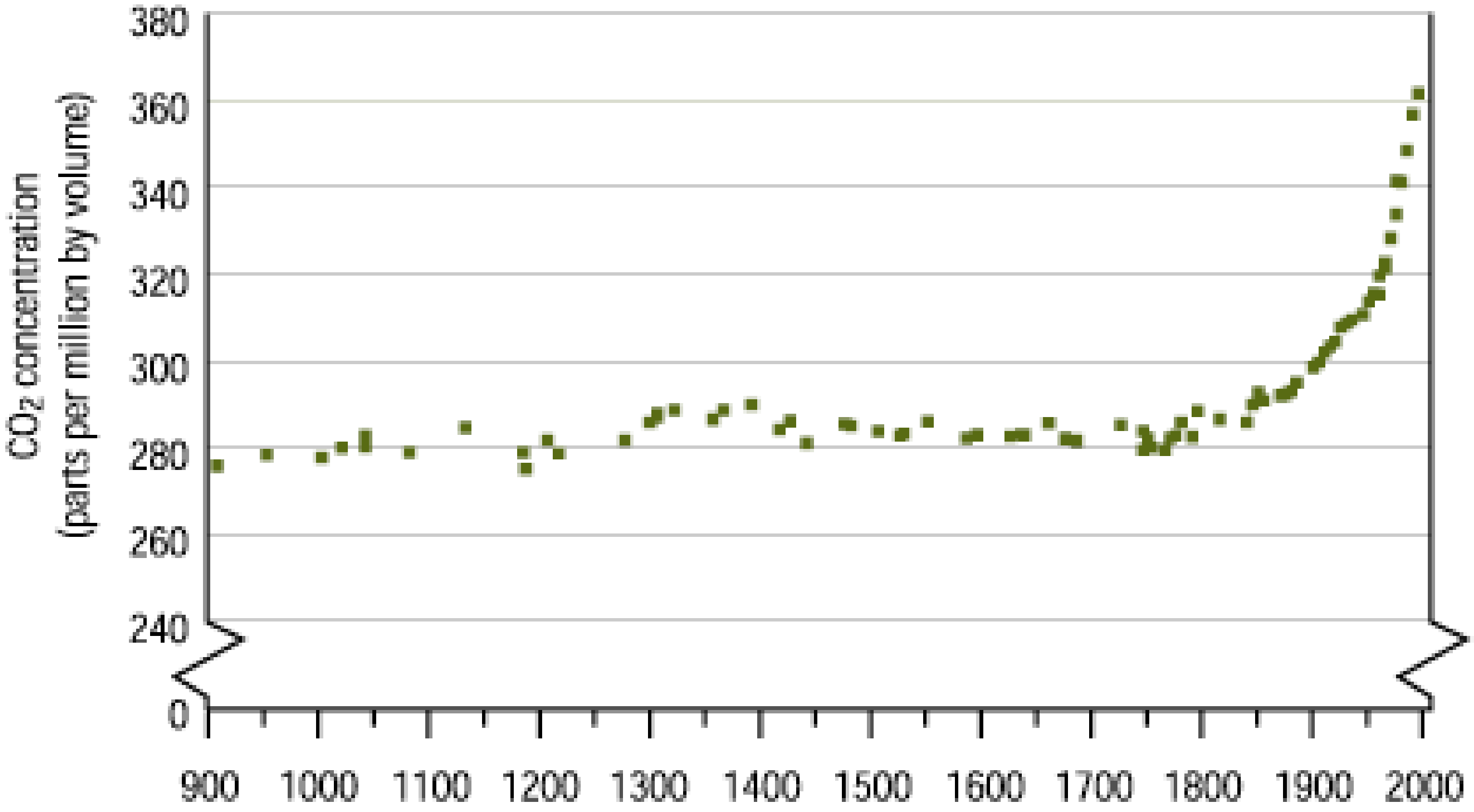
Visible radiation

- 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

Trends in global carbon dioxide (CO_2) concentrations based on data from atmospheric monitoring stations and ice cores from Antarctica and Greenland, 900 –1995

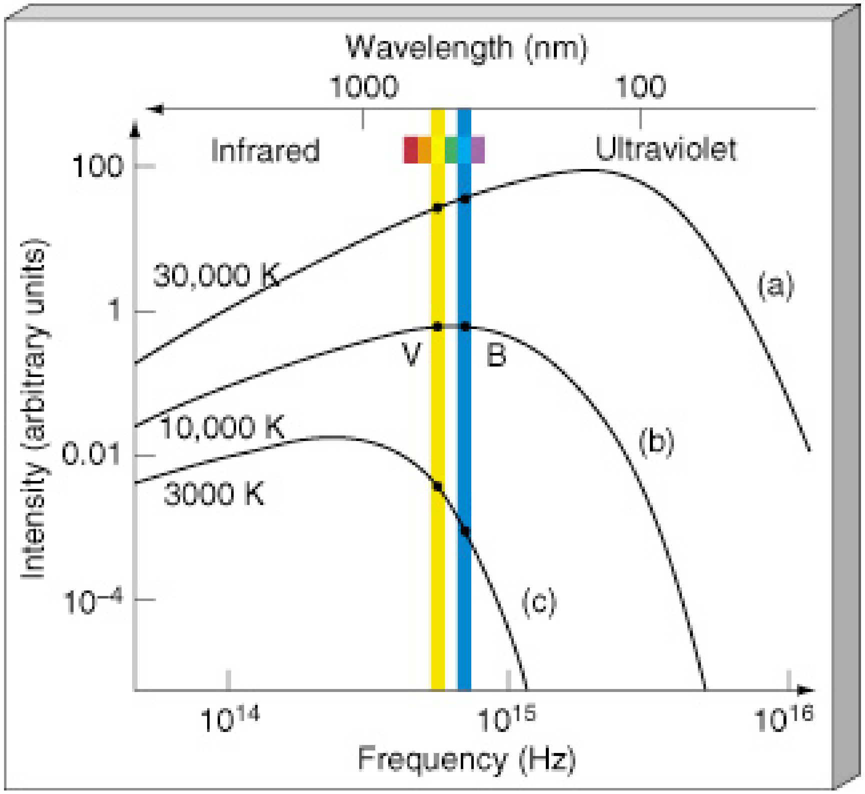


Source: Meteorological Service of Canada.

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

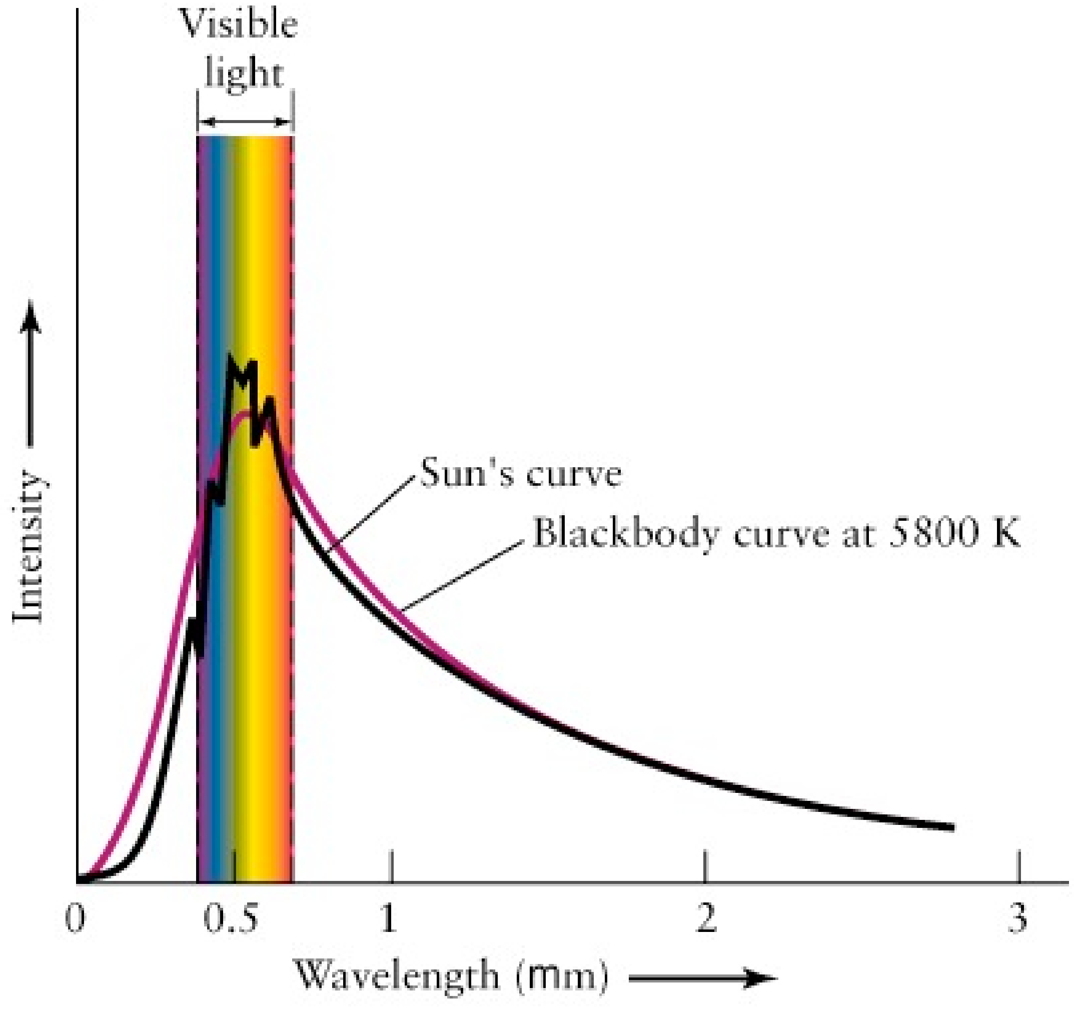


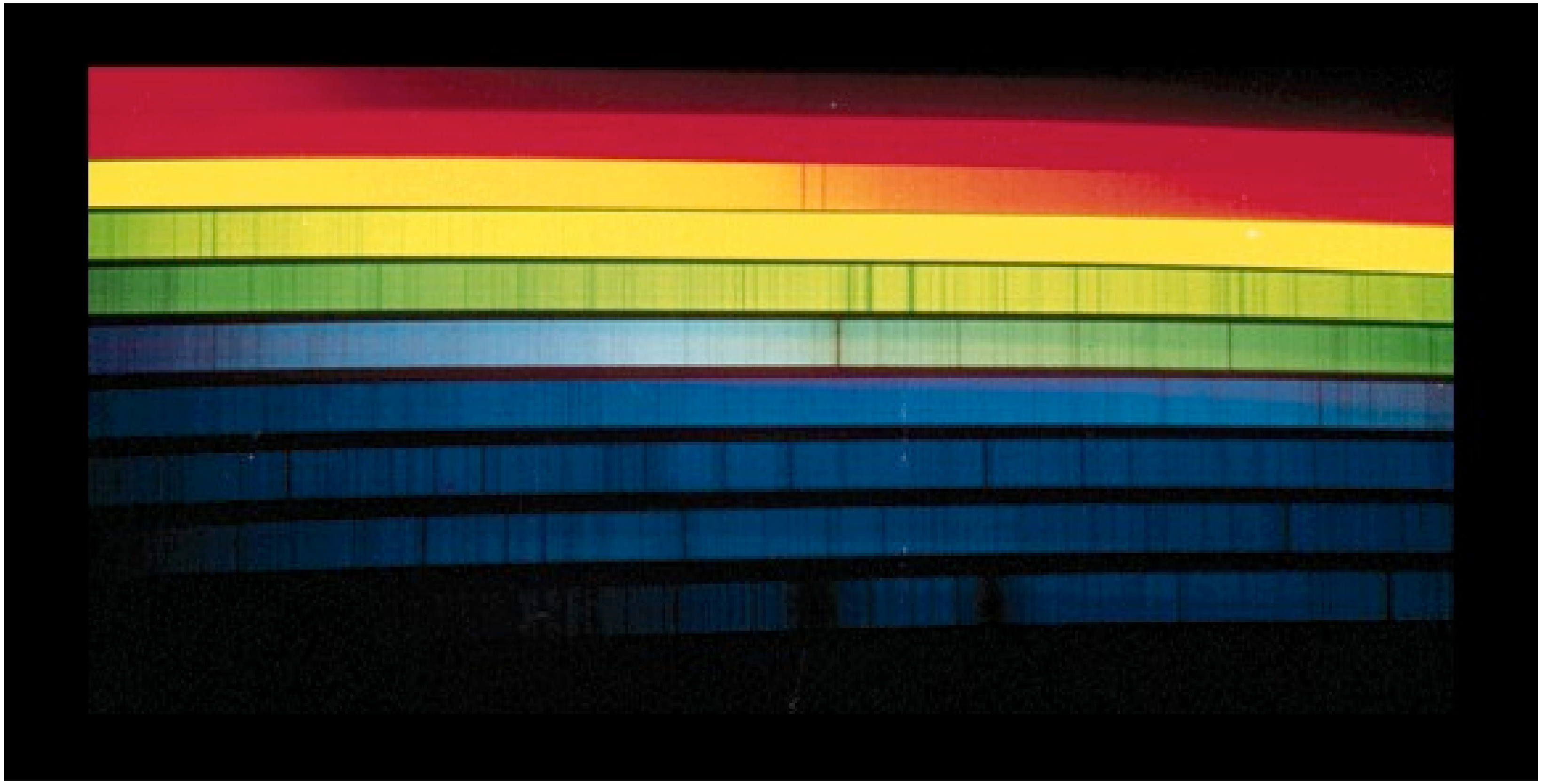
- For Planck spectra the ratio of the light in two different color filters unambiguously give the temperature of the radiating object.

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



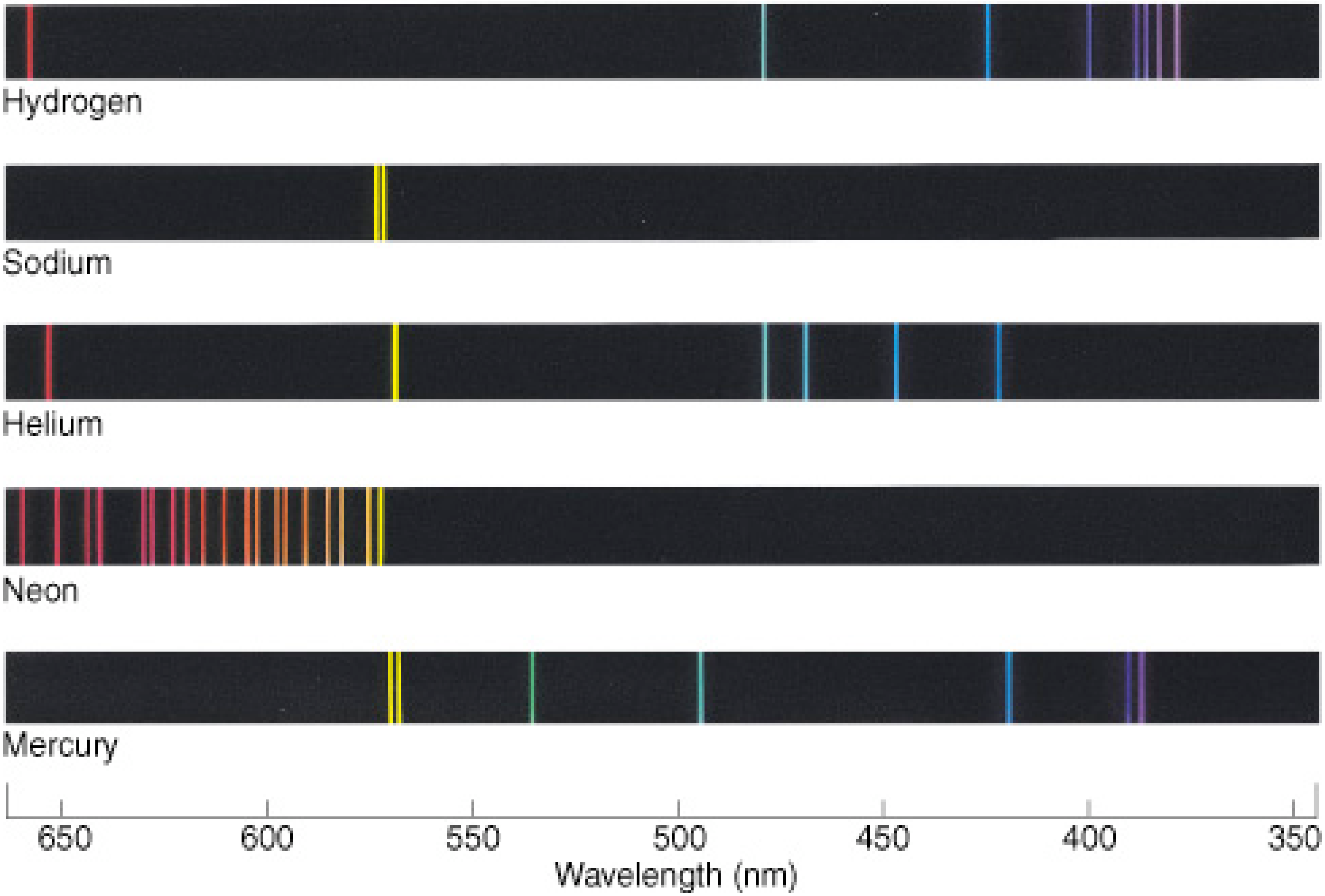


- Because the spectra of stars are pretty close to being Planck Curves, stellar colors can be used to measure stellar temperatures. The process is:

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

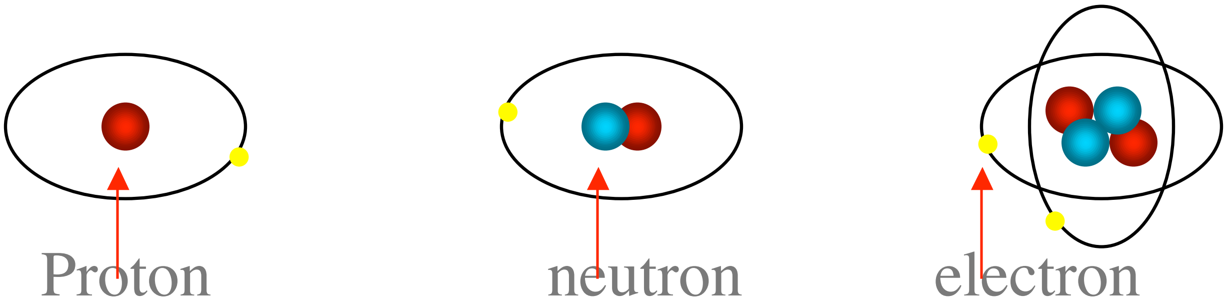
- The wavelengths with missing light in stellar spectra turned out to be very interesting and important.
- When chemists heated gases to the point where they (the gases) began to glow, the resulting spectra were not continuous, but had light at discrete wavelengths that matched the wavelengths of missing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

Hydrogen



Helium

Proton

neutron

electron

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

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

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

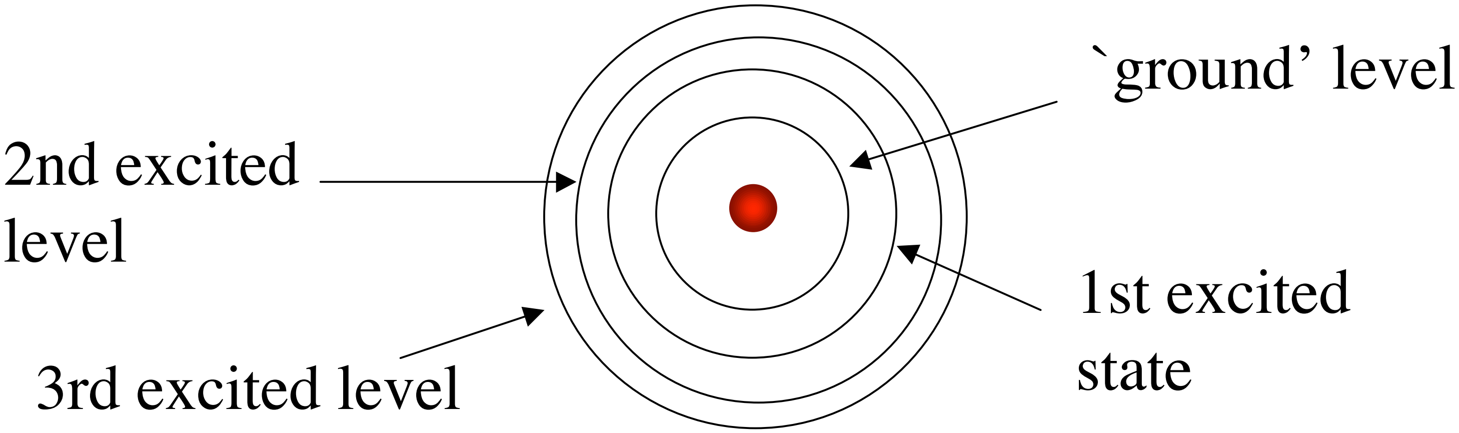
Atoms and Spectra

- 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*.



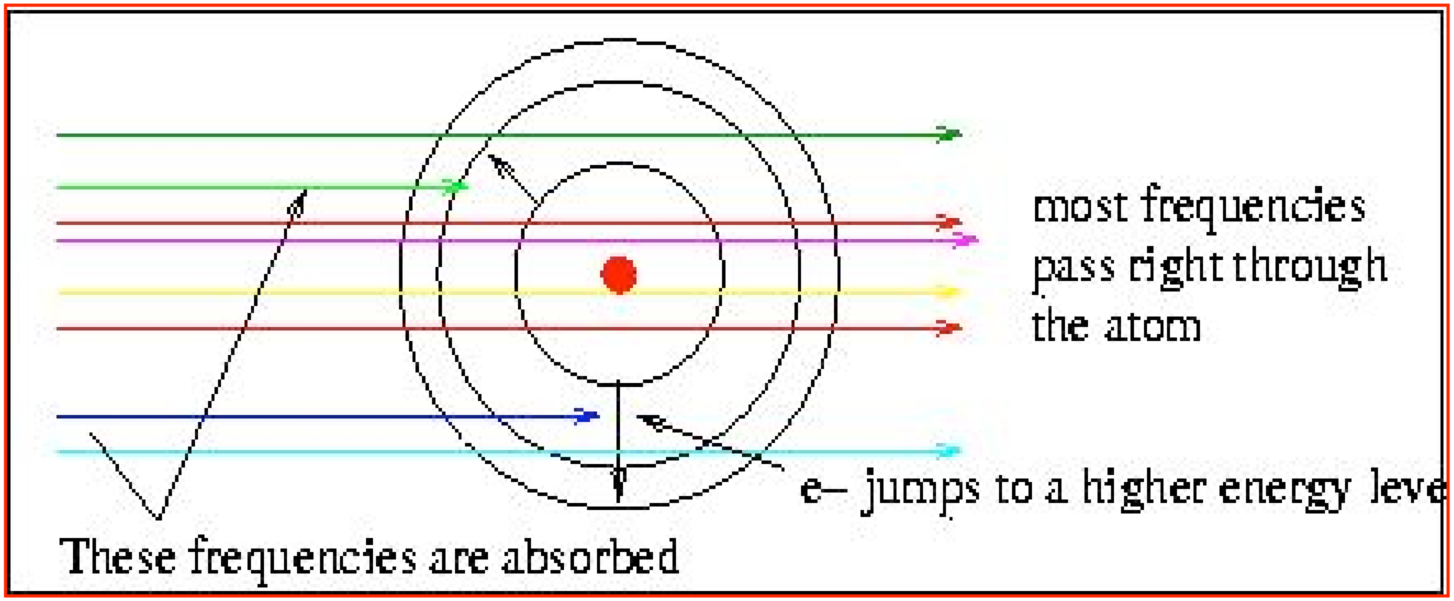
`ground’ level

2nd excited level

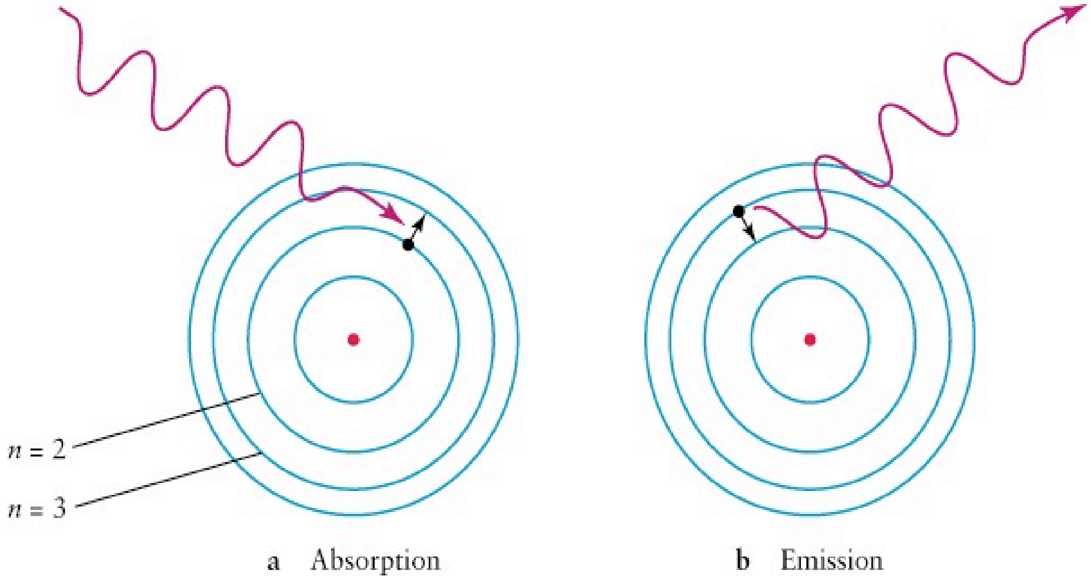
1st excited state

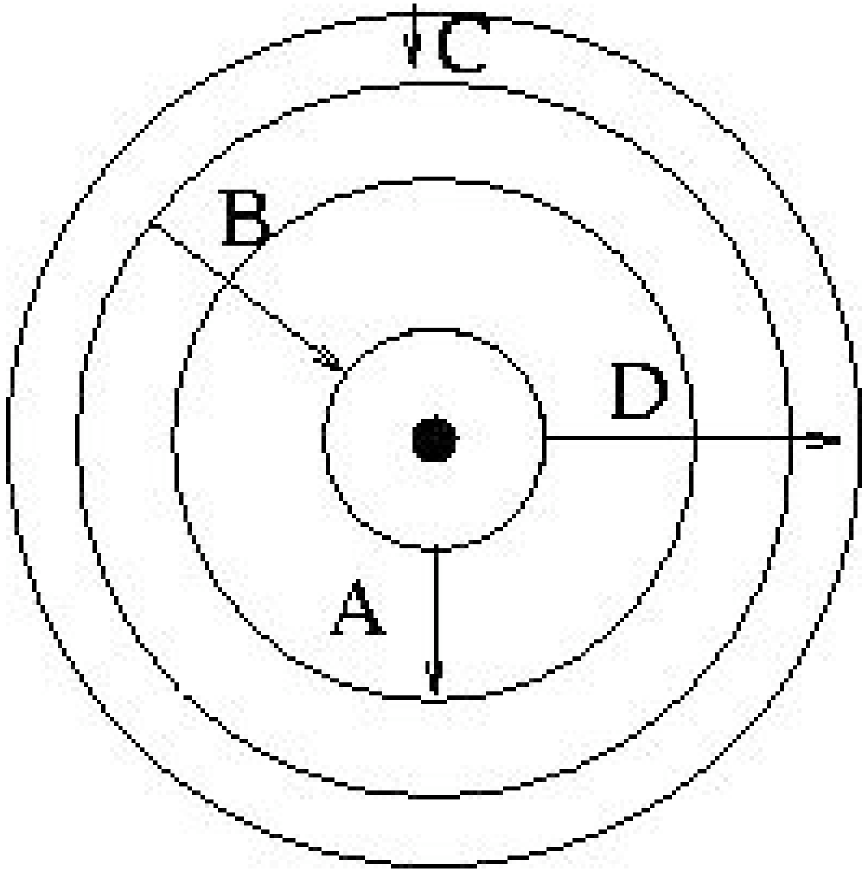
3rd excited level

- 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.*


most frequencies pass right through the atom
e– jumps to a higher energy leve
These frequencies are absorbed

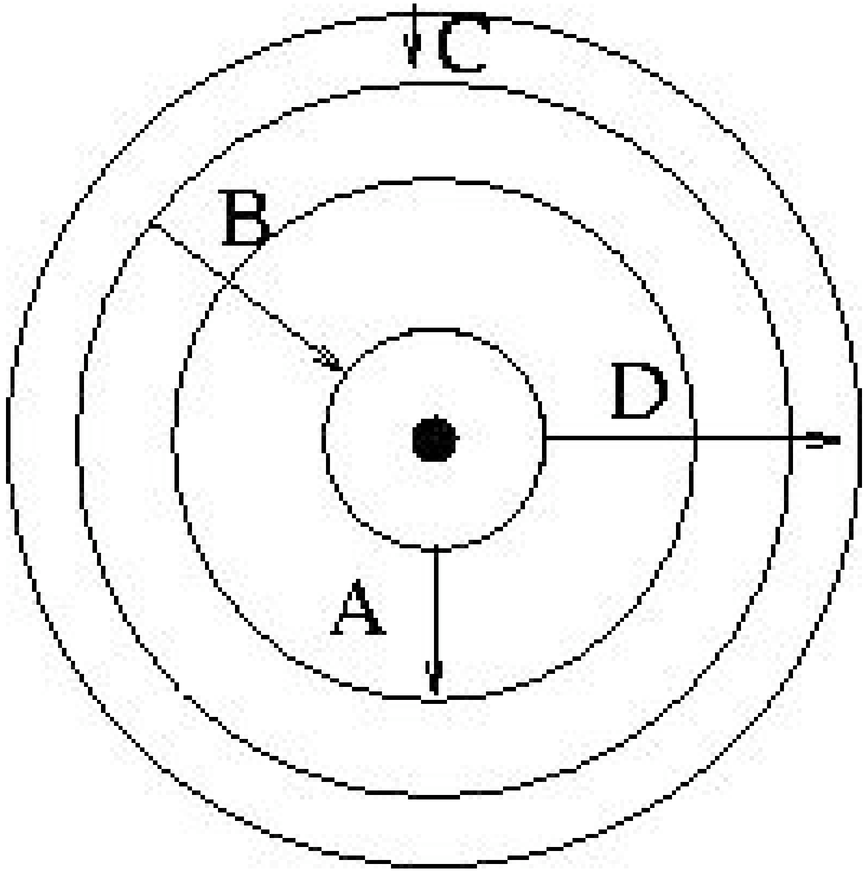
- Now, one of Nature's favorite rules is that systems always seek the lowest available energy state.
- This means that atoms with electrons in excited levels will rapidly `de-excite' and spit out a photon to conserve energy.


n = 2
n = 3
a Absorption
b Emission



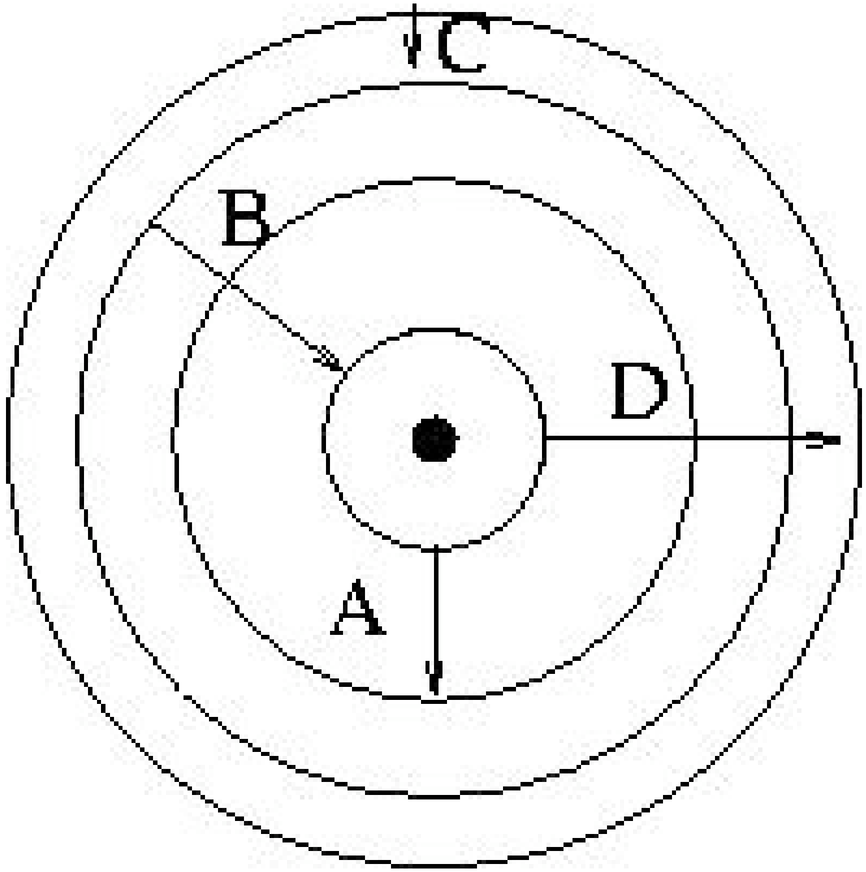
Q. Which transition(s) correspond to ABSORPTIONS of photons?

A, D

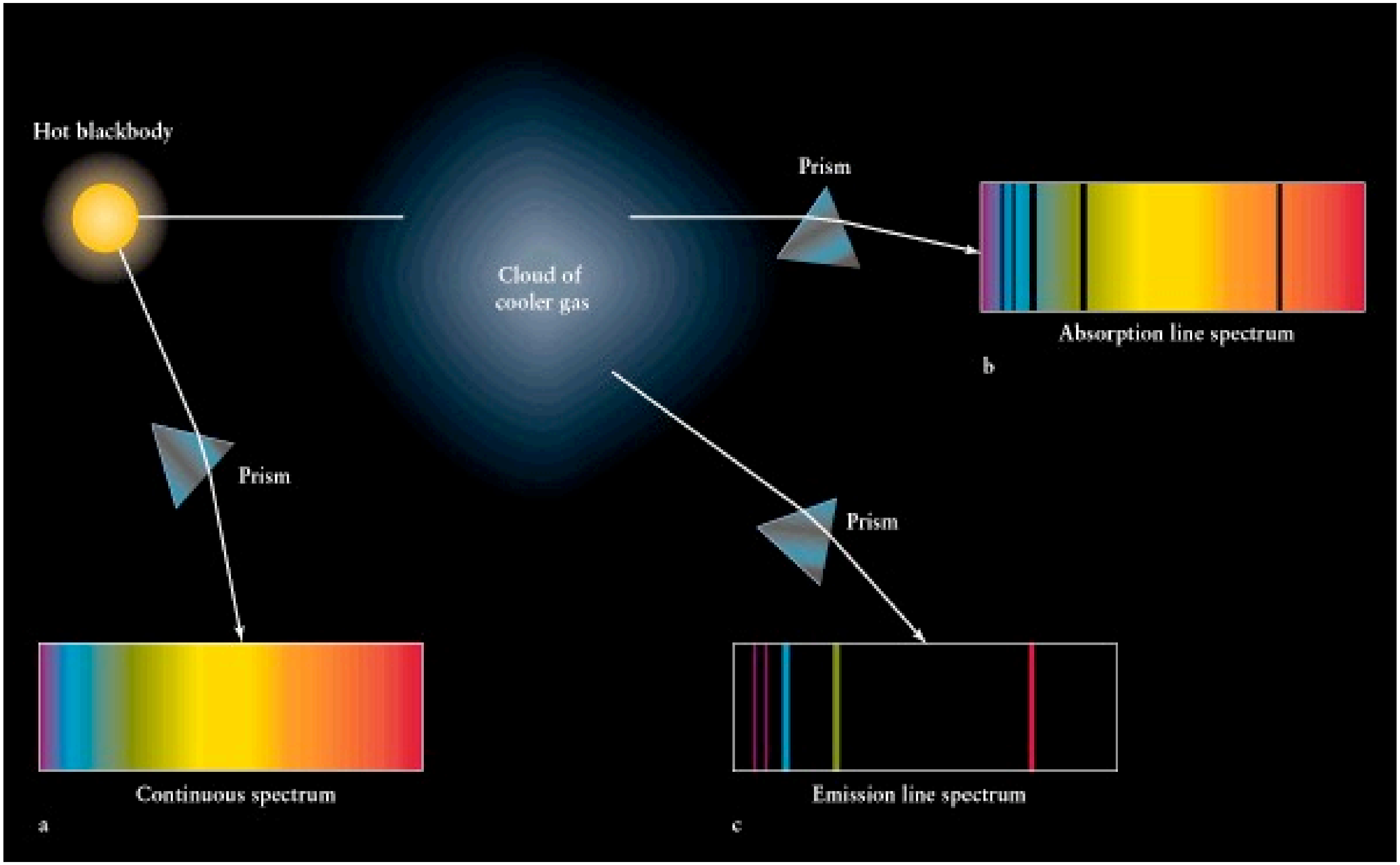


Q. Which transition(s) correspond to the highest energy photon EMITTED?

B



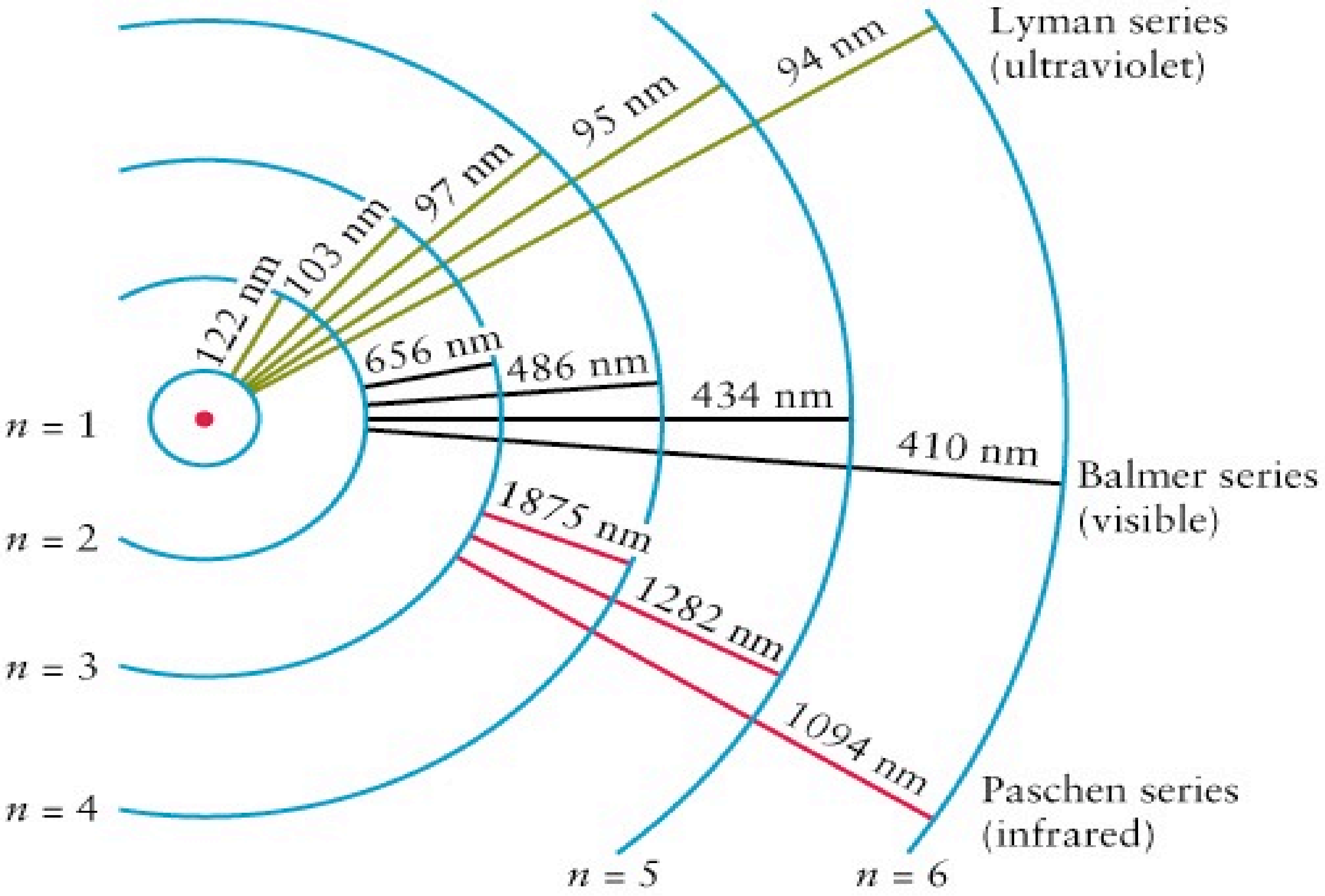
Q. Which transition corresponds to the longest wavelength photon emitted? C


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


Lyman series
(ultraviolet)
94 nm
95 nm
97 nm
103 nm
122 nm
656 nm
486 nm
434 nm
410 nm
Balmer series
(visible)
1875 nm
1282 nm
1094 nm
Paschen series
(infrared)
$n = 1$
$n = 2$
$n = 3$
$n = 4$
$n = 5$
$n = 6$

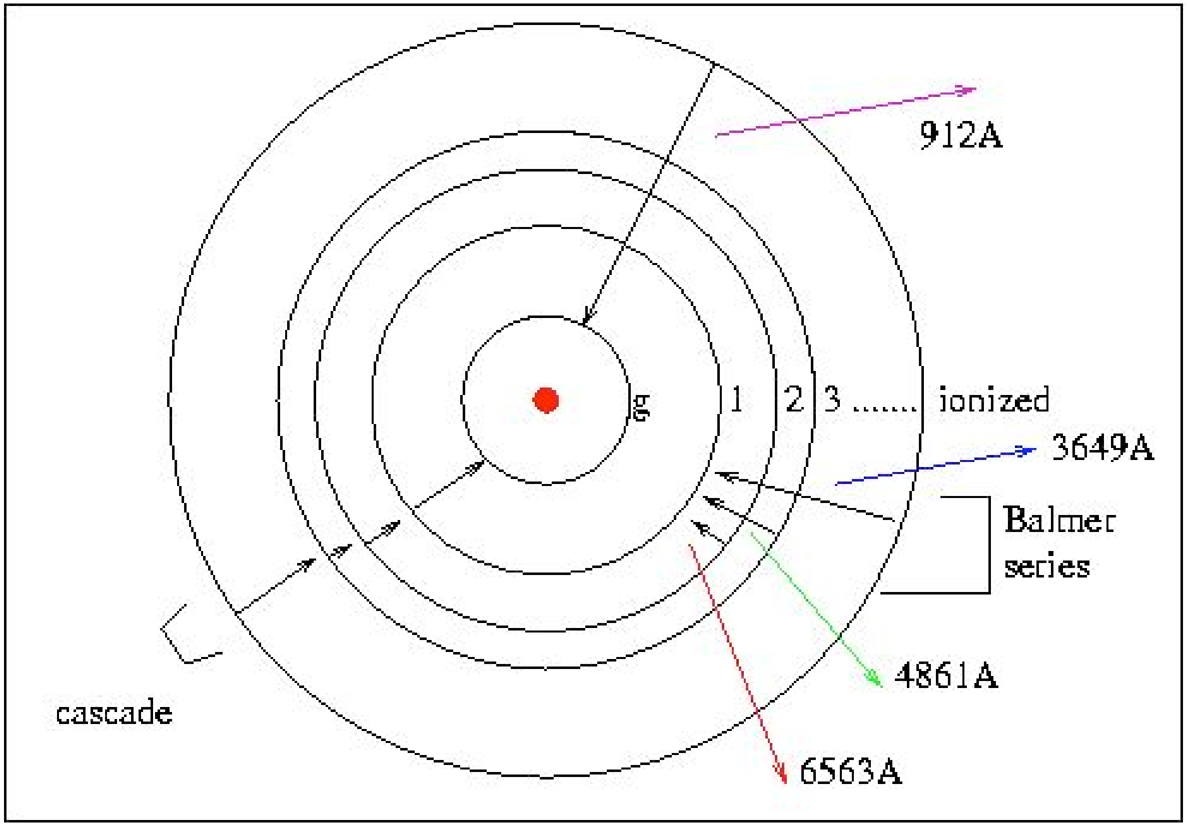
Emission from Gas Clouds

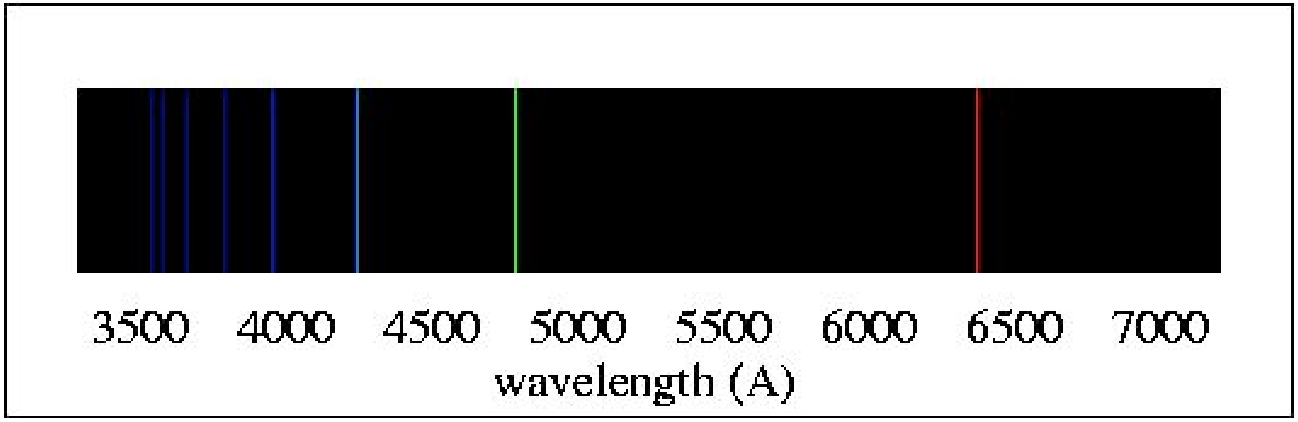
- Atoms in a gas cloud can be `collisionally’ excited. Imagine atoms flying around in a gas cloud, bumping into one another. Sometimes part of the energy of the collision will bump an electron into an excited level. On de-excitation, a photon is emitted (cooling the gas).

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


912A
g
1
2
3 ....
ionized
3649A
Balmer series
cascade
4861A
6563A



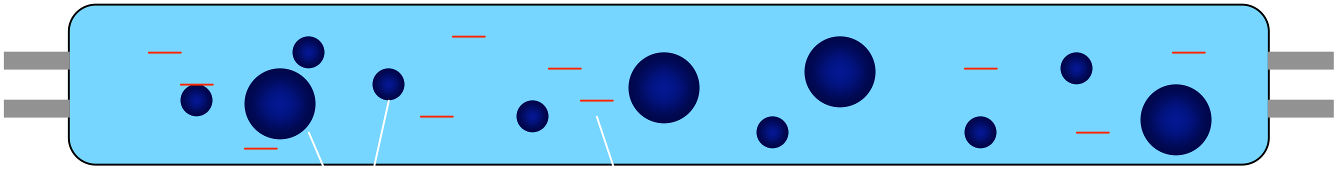
Lights around the House

- 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

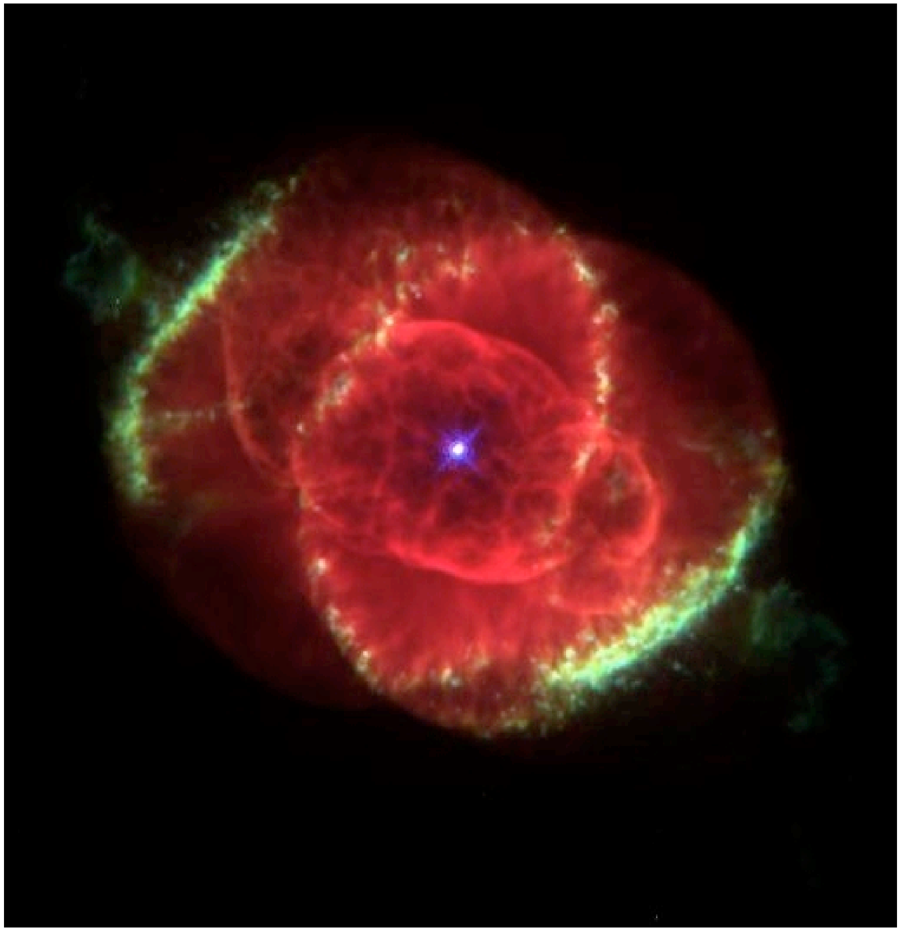
Fluorescent Lights

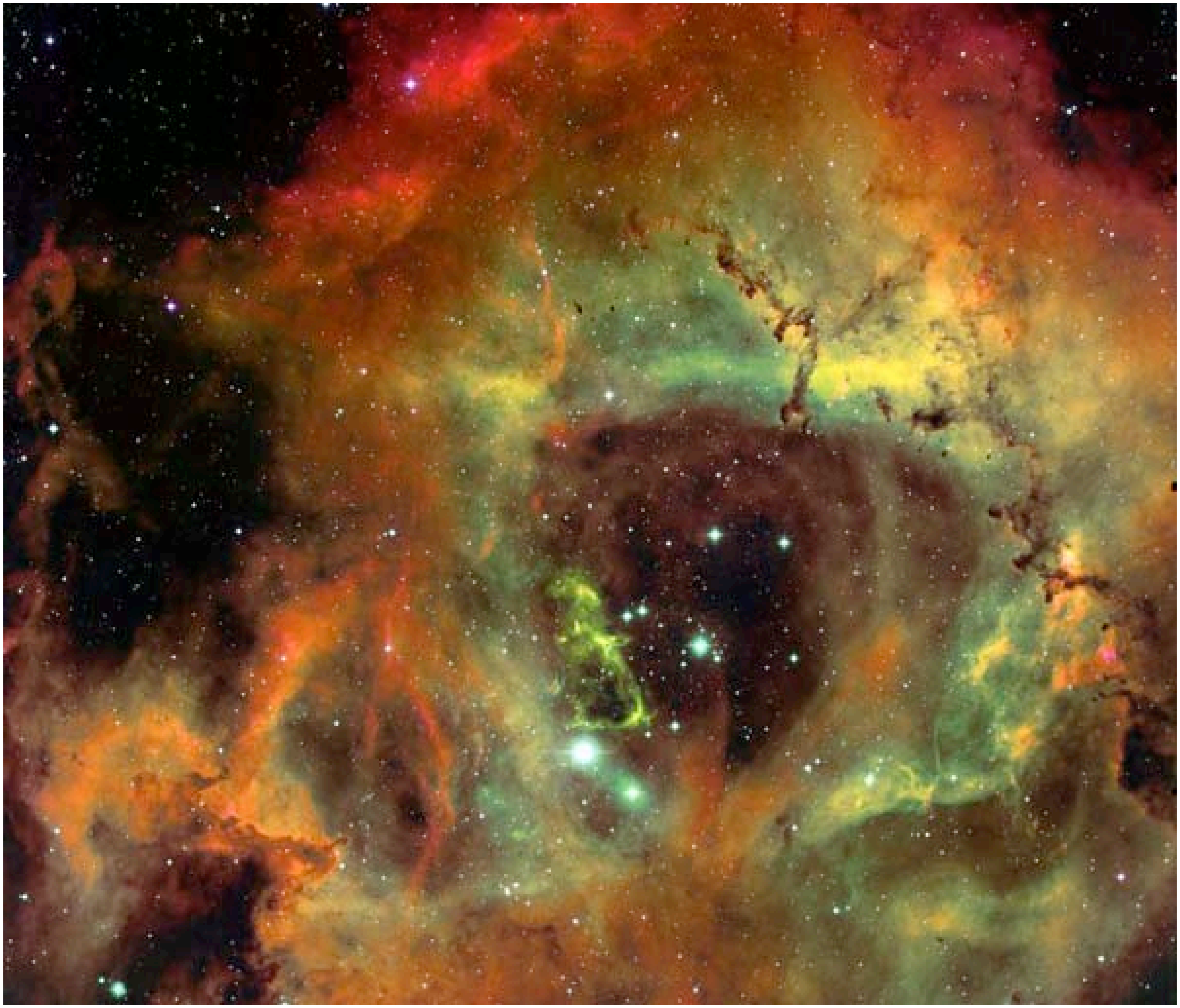
- Fluorescent lights are based on *collisional excitation* of atoms in the tube.
- Turn on the power, boil some e- off the filament and send them crashing back and forth through the bulb at 60Hz.

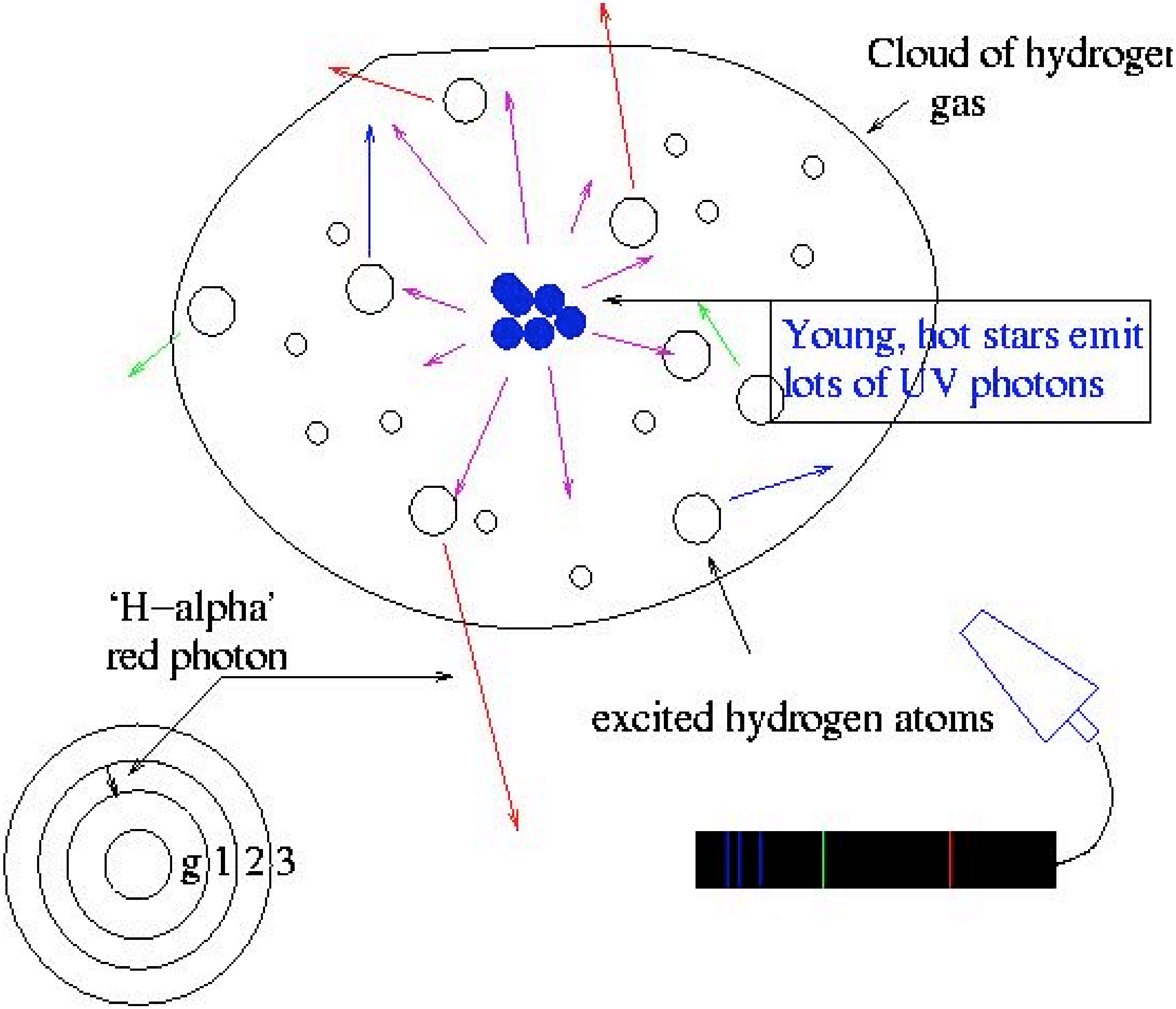


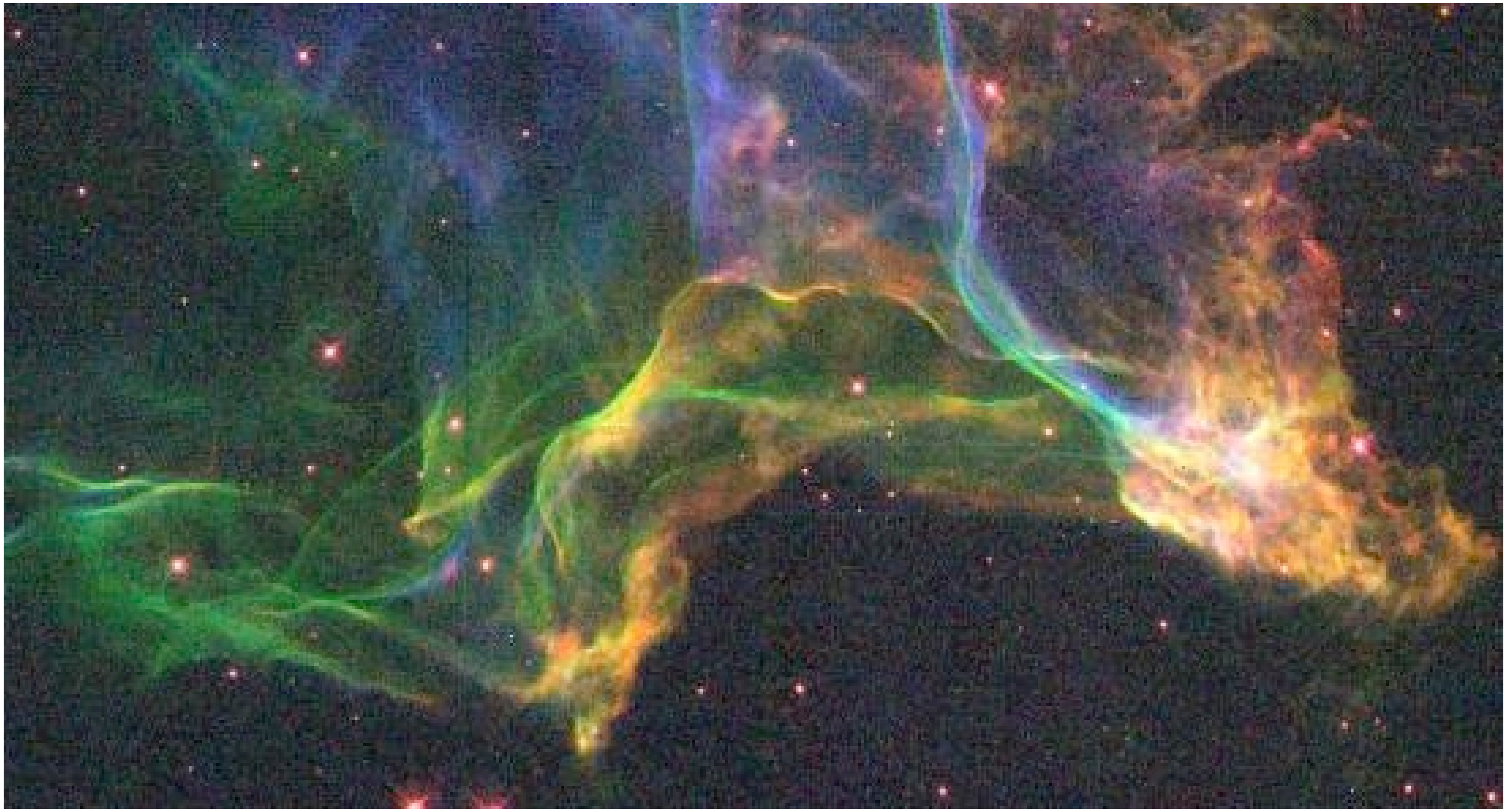
- The atoms in fluorescent bulbs typically produce UV photons on de-exciting. These are absorbed by a phosphor coating in the bulb and each UV photon is converted via a cascade to a number of visible-light photons with the same total energy as the original UV photon.
- With no phosphor, you get a `black light''.
  - 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.

Fluorescence in Astronomy



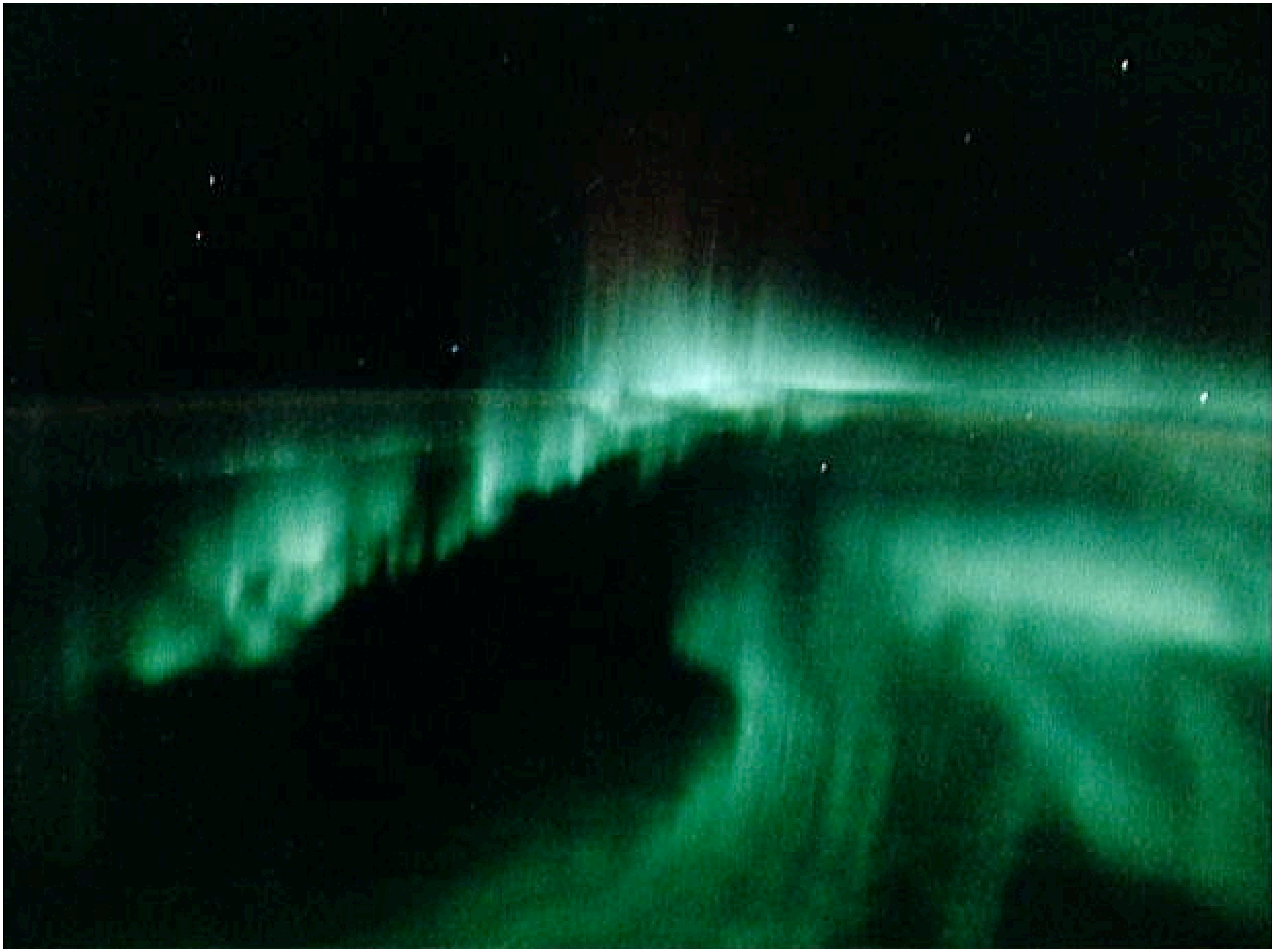



Cloud of hydrogen
gas
Young, hot stars emit
lots of UV photons
'H–alpha'
red photon
excited hydrogen atoms
g
1
2
3



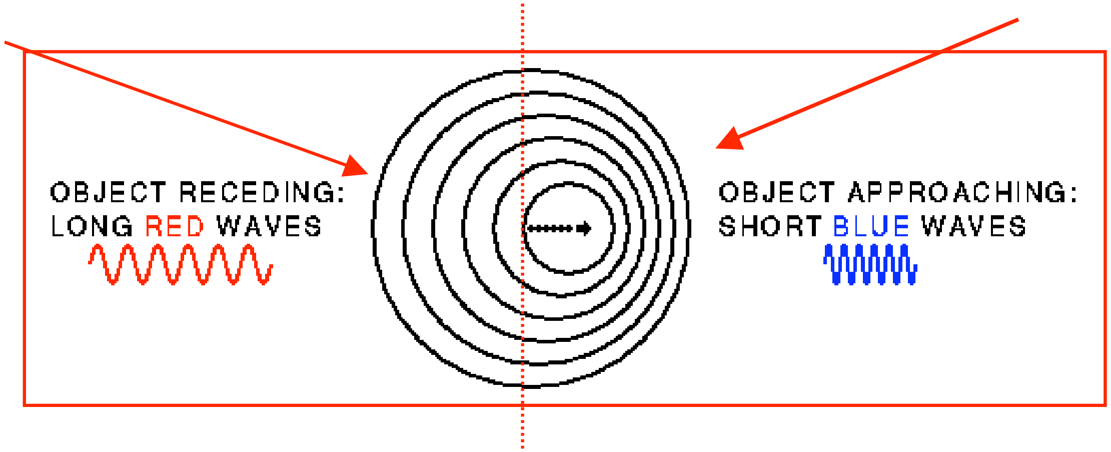
The Earth's Aurora are due to the de-excitation of atoms in the atmosphere that were collisionally excited by particles streaming off the Sun

© Phil Hoffman



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.


OBJECT RECEDING:
LONG RED WAVES
OBJECT APPROACHING:
SHORT BLUE WAVES

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

$$\lambda_0 - \lambda_v \qquad\qquad v$$

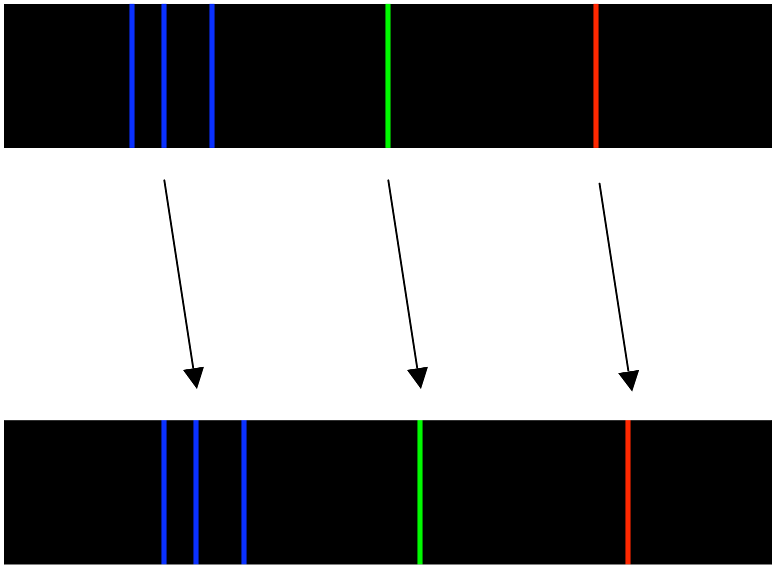
$$\lambda_0 \qquad\qquad c$$

λ_0= `rest' wavelength

λ_v= wavelength at speed `v'

v = speed toward or away from observer

c = speed light



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?

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

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

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