ASTR 421

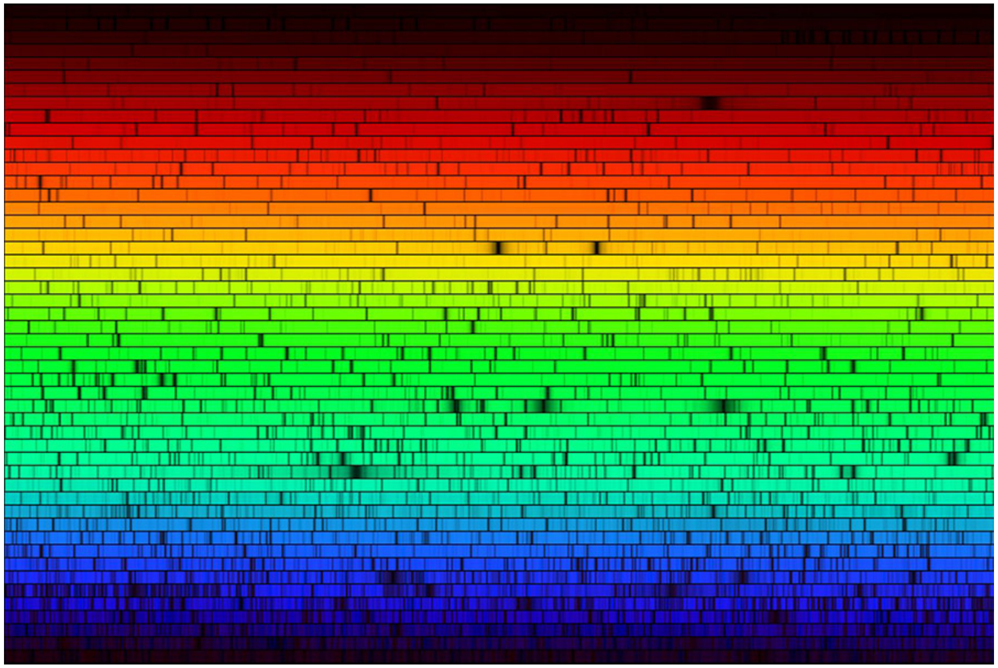
Stellar Observations and Theory

Lecture 03
Spectroscopy: I

Prof. James Davenport (UW)

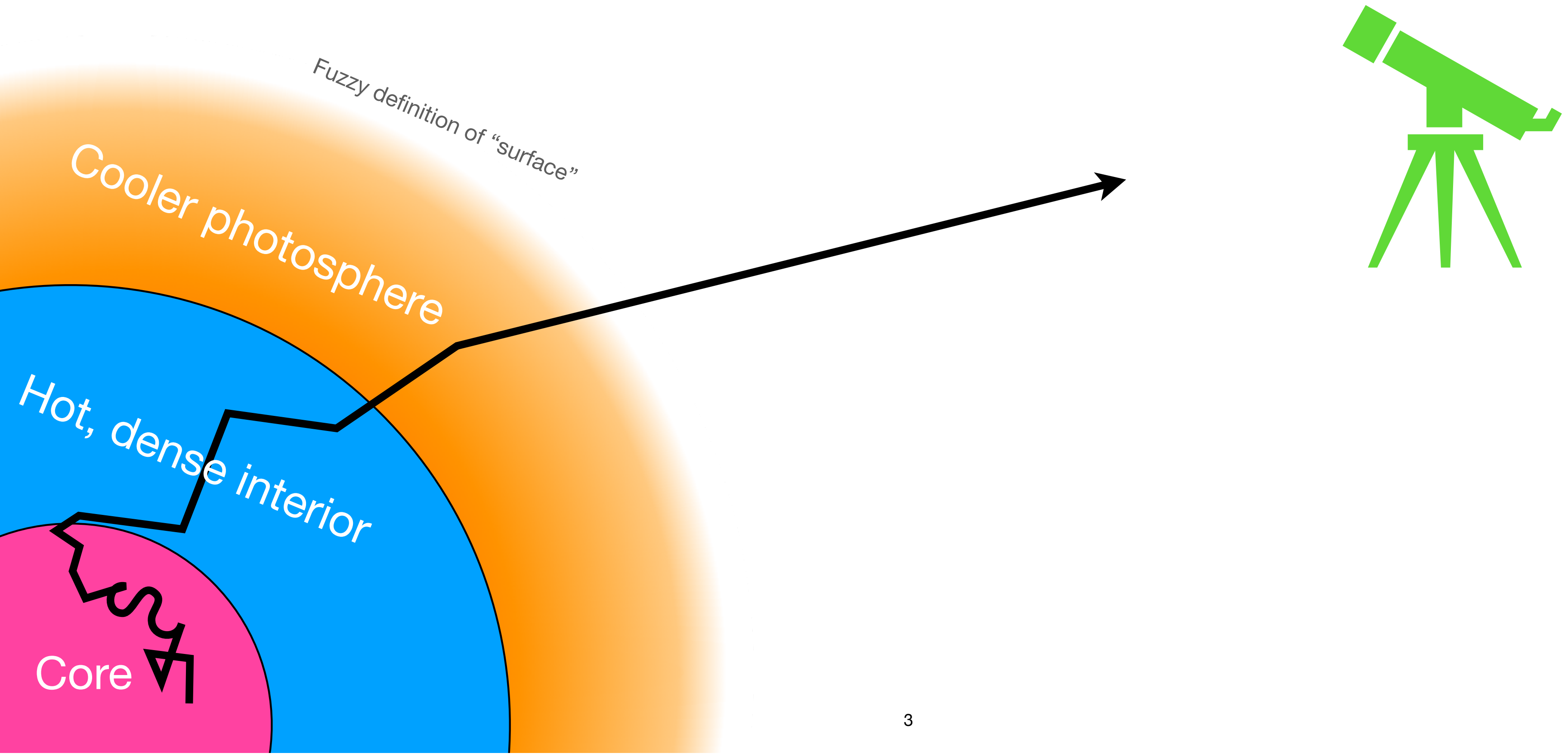
Today's Goal: Foundations of Spectroscopy

- Blackbody (thermal) spectra
- Atomic lines (emission & absorption)
- Boltzmann and Saha equations



https://scied.ucar.edu/image/sun-spectrum

Where do the photons come from?



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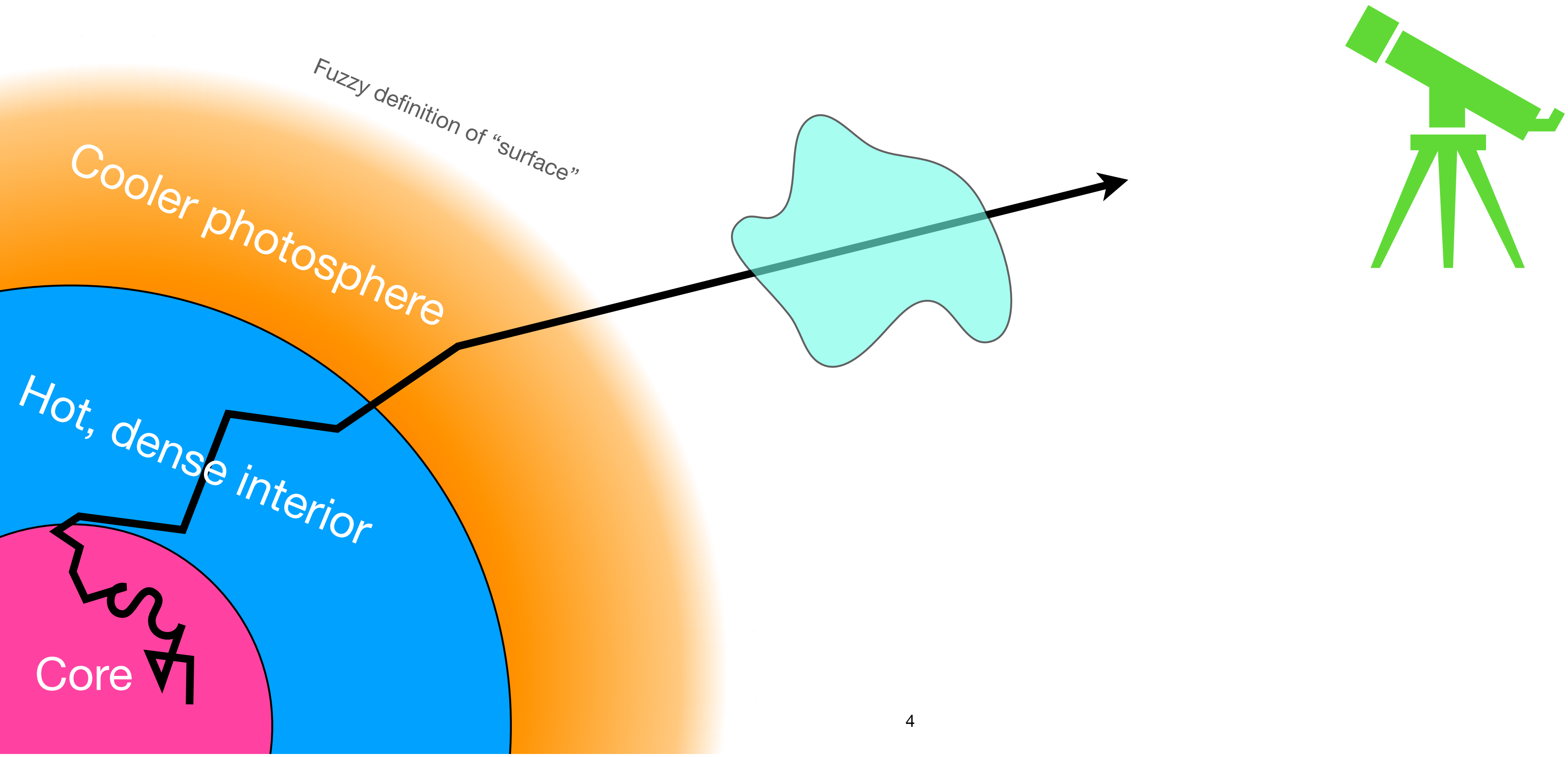


Blackbody Spectrum

- Very commonly used as a 1st order guess for many things in astronomy from stars/planets, disks (both hot and cool), flares…
- A "perfect radiator"…
- Requires Thermal Equilibrium, velocities of dense (ideal) gas follow a Maxwell-Boltzmann distribution
- **Nothing is a perfect BB**

$$\frac{1}{2}m\bar{v}^2 = \frac{3}{2}k_BT$$

$$n_v dv = n\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT}\, 4\pi v^2 dv \qquad (8.1)$$

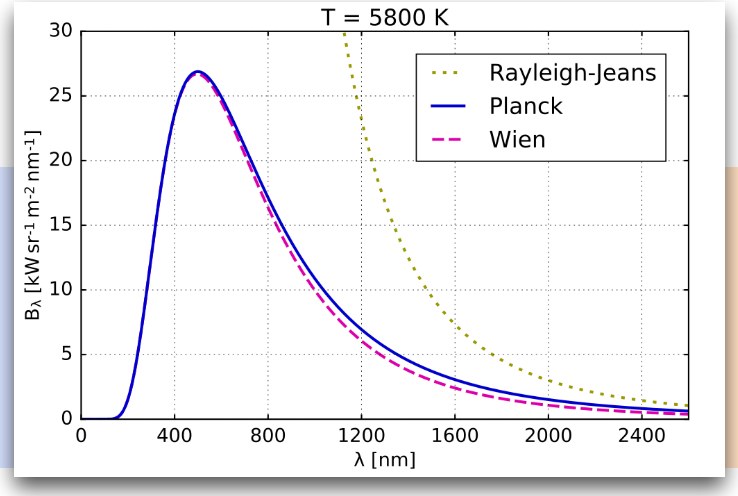
Blackbody Spectrum

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

- Defined using the Planck equation (law)

$$B_\nu(T) = \frac{8\pi\nu^2}{c^3} \frac{h\nu}{e^{h\nu/kT} - 1}$$

- 2 sides of the distribution:
  Wien approximation, and Rayleigh-Jean's "tail"



Temperature and T$_{eff}$

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

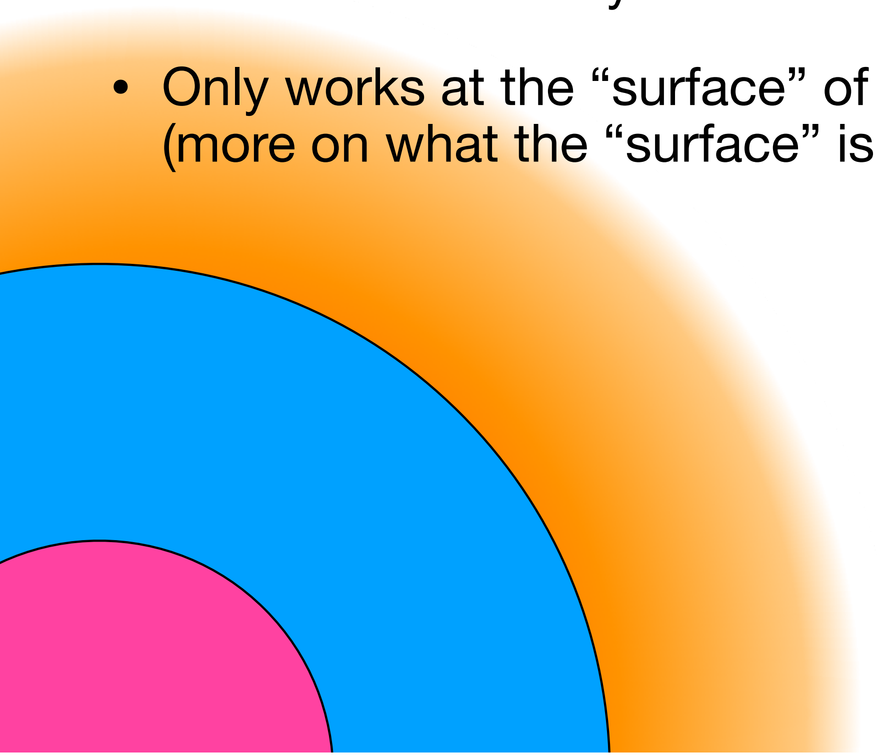
- The "effective temperature" is the Temp that a star would have if it were a perfect blackbody with the same luminosity

- Only works at the "surface" of the star (more on what the "surface" is next week!)

$$\frac{1}{2} m \bar{v}^2 = \frac{3}{2} k_B T$$

$$n_v dv = n \left(\frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} \, 4\pi v^2 dv$$

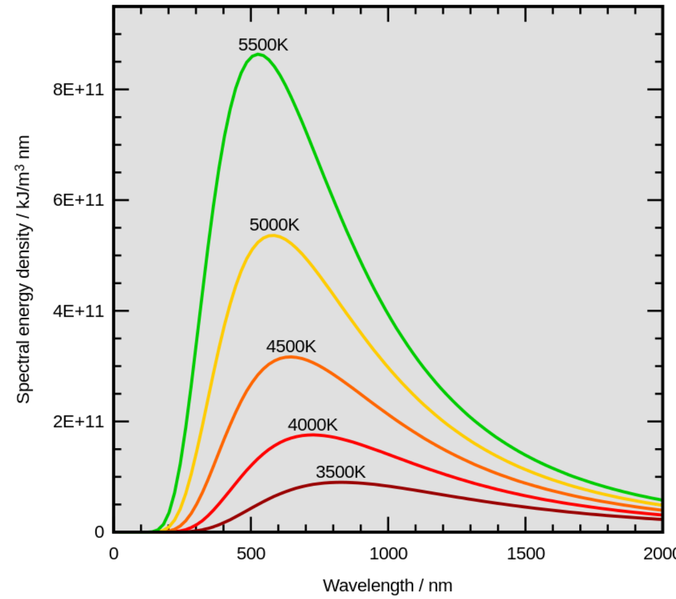
$$L = 4\pi R^2 \sigma_{SB} T^4$$

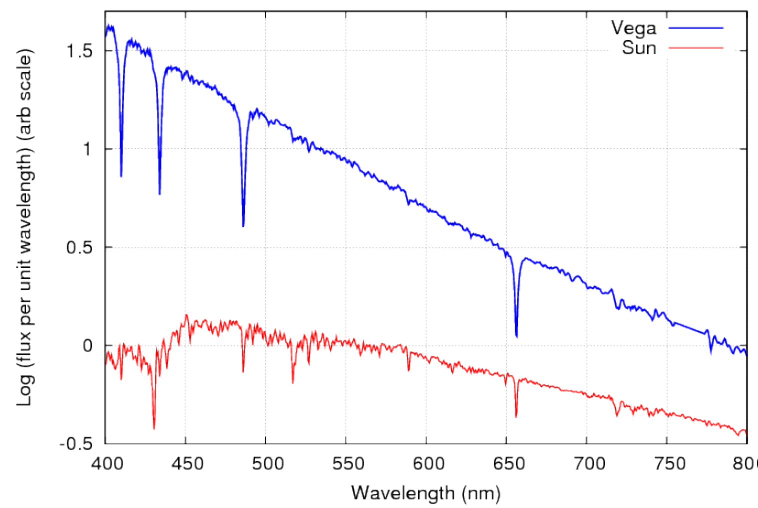


Wien’s Law

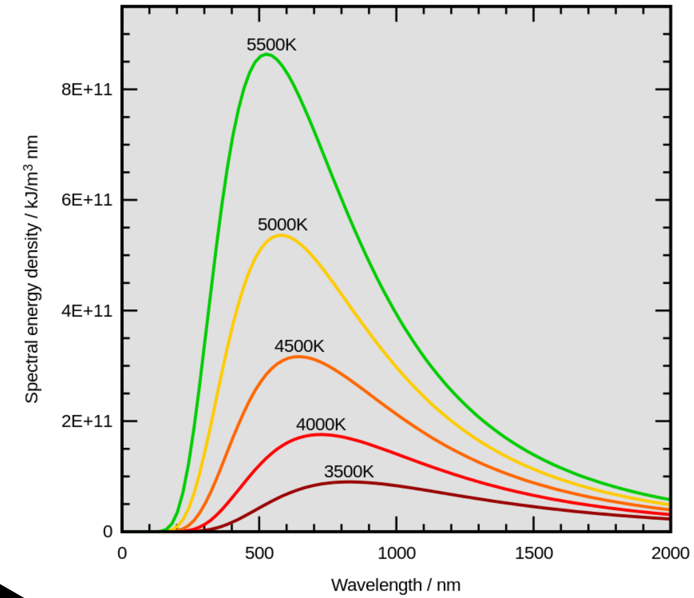
- Sometimes called “Wein’s displacement law”
- Basically just the derivative (peak) of the Wien Approximation
- OK approximation for ~hot stars
  bad for very hot or very cool stars

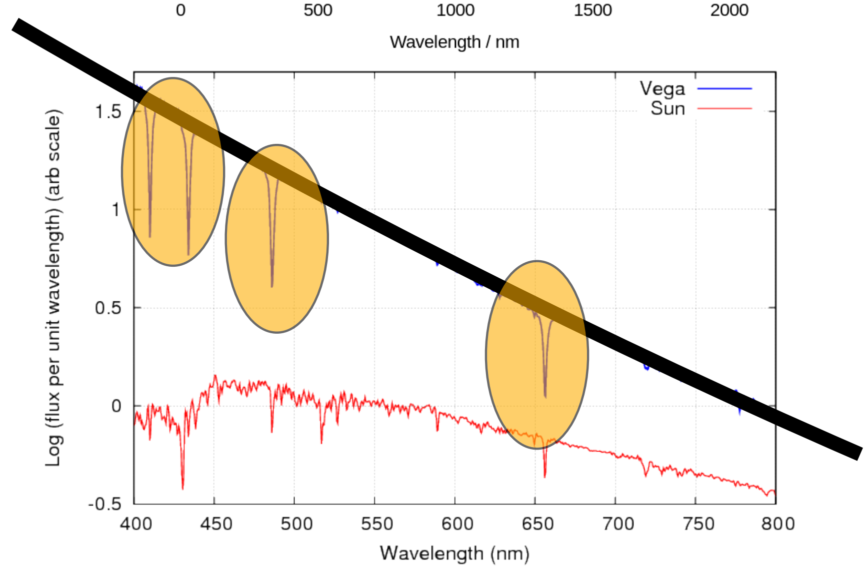
$$\lambda_{peak} = b/T$$
$$b = 2898\mu m$$





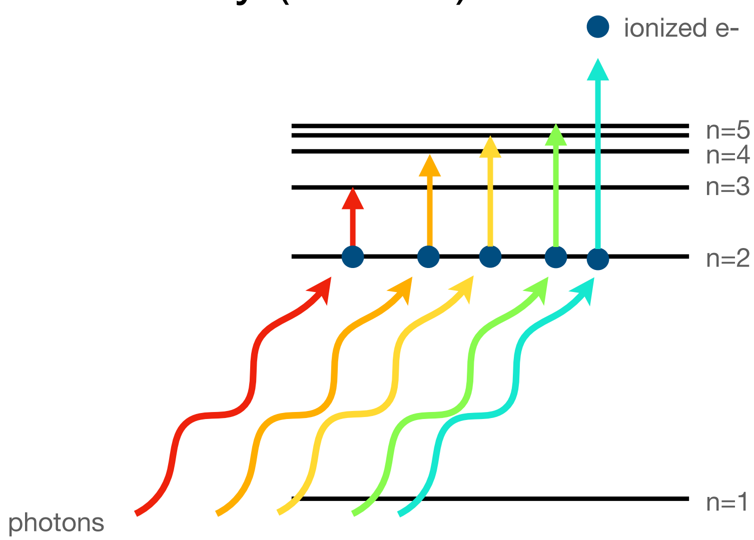
So that nicely explains the blackbody portion of stellar spectra… what about all this junk?!

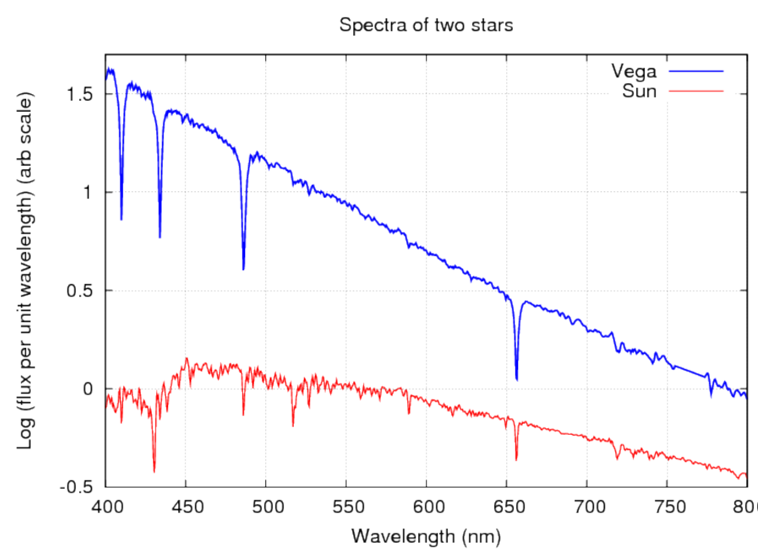




Absorption

- Absorption lines form when photons of the *right* energy (wavelength) hit an electron, causing it to “jump” to another energy or orbital state, or off the atom entirely (ionized)

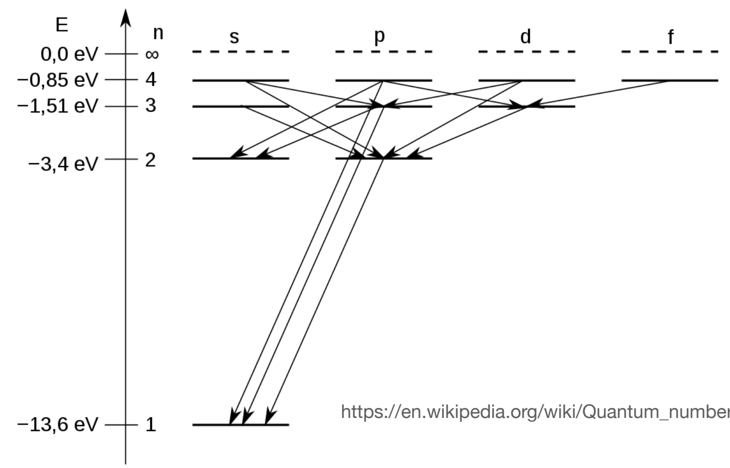




Energy Level (Grotrian) Diagram

BOB uses n, l, m_l, m_s

- Represents the Bohr model of an atom
- Includes info about *quantum states* for e-, and the "degeneracy" of each level
- Good to draw for H, He… gets messy quick for bigger atoms!
- The number of possible states for each energy level is called the "statistical weight", g
- For Hydrogen, $g_n = 2n^2$



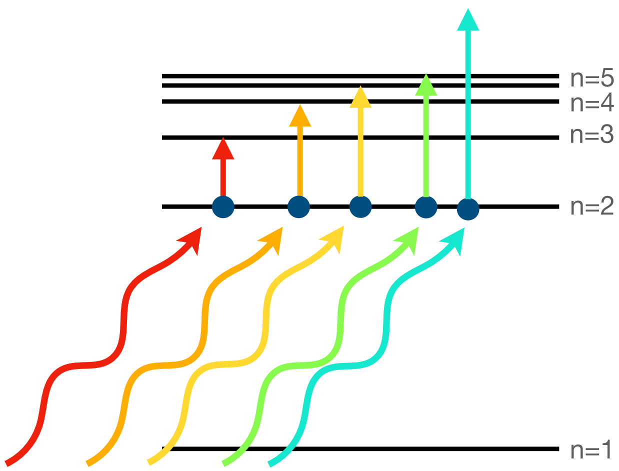
https://en.wikipedia.org/wiki/Quantum_number

Boltzmann Equation

- For a gas in TE, at a given temperature (*T*), what is the probability of finding an electron will be at a given energy state (n)?

$$n_v dv = n\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT}\, 4\pi v^2 dv$$

$$g_n = 2n^2$$



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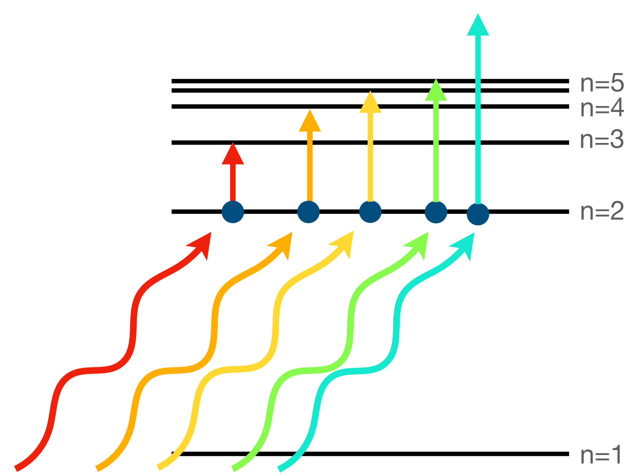
$$P(E_b) \sim g_b e^{-E_b/kT}$$



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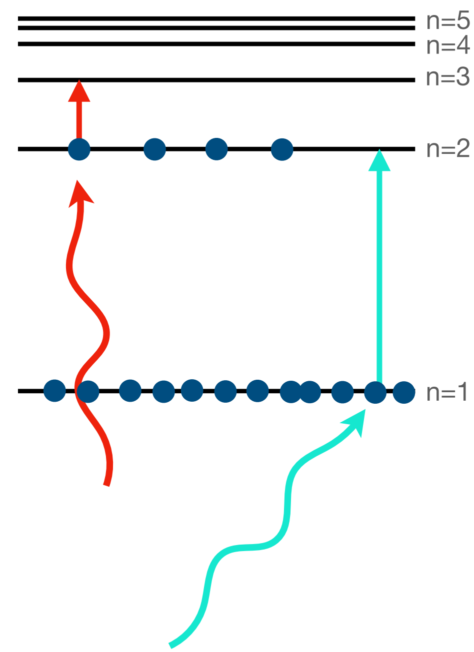
$$g_n = 2n^2$$

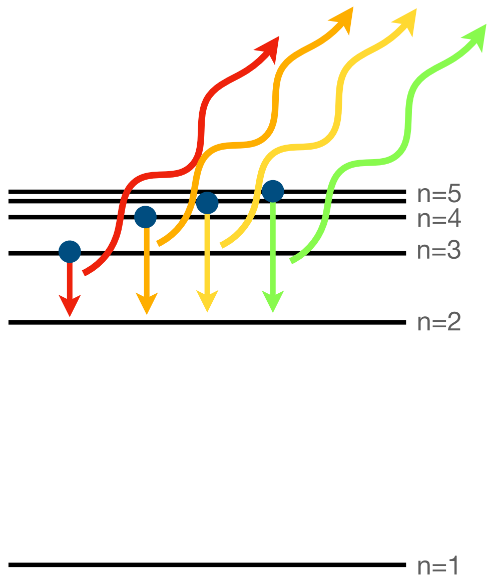
$$\frac{N_b}{N_a} = \frac{g_b}{g_a} e^{-(E_b - E_a)/kT}$$

a,b are energy level numbers (n=1,2,3…)



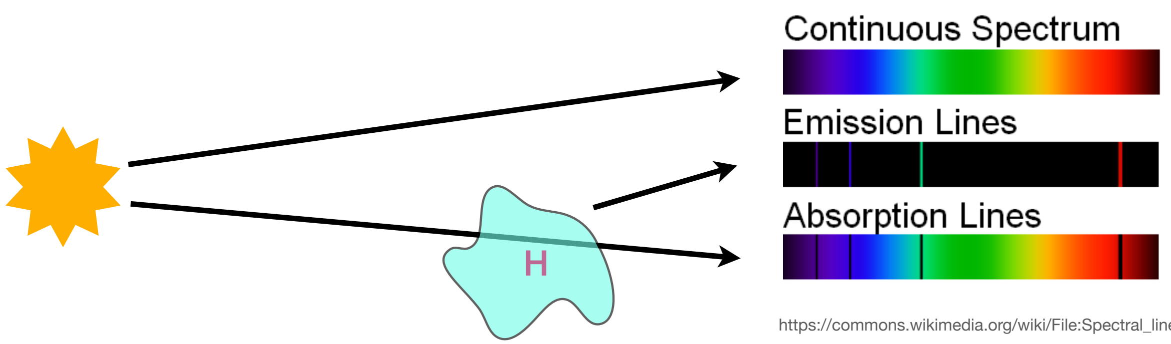
Emission

- Conceptually works opposite of absorption
- Need low density gas for photon to escape
    - Otherwise photon will just re-absorb! (hello, thermal equilibrium)



Kirchoff's Laws (of spectra)

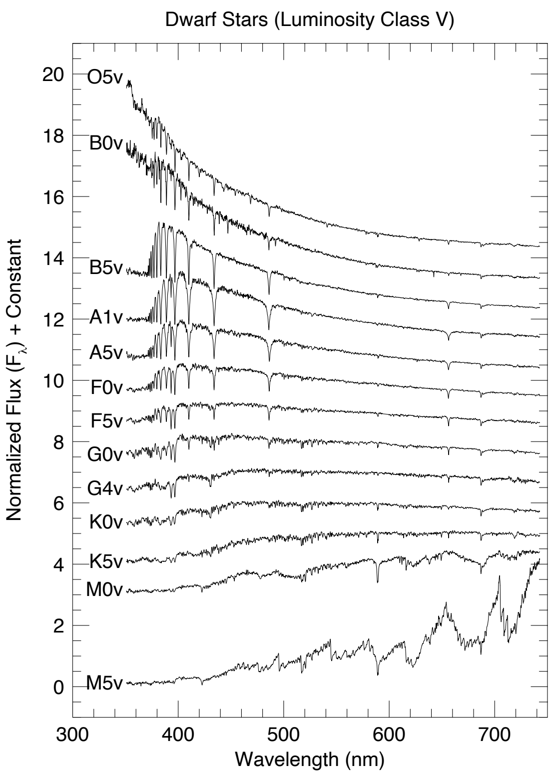
1. Dense gas emits a continuous (i.e. blackbody) spectrum
2. Hot, low density gas emits
3. Cool, low density gas absorbs

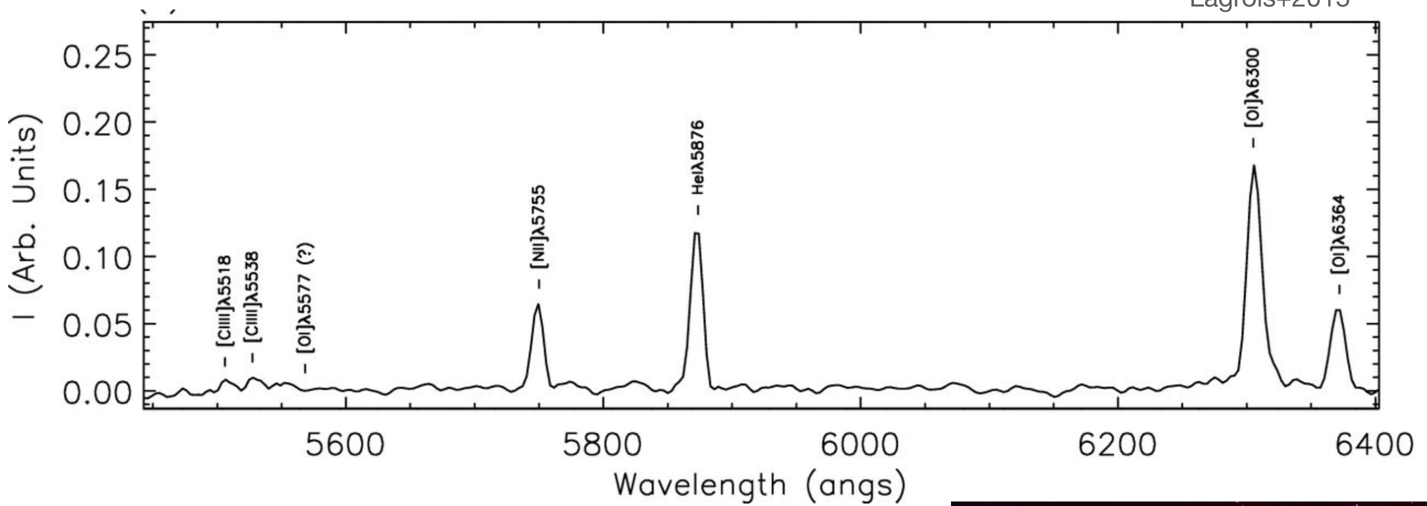


https://commons.wikimedia.org/wiki/File:Spectral_lines_en.PNG

Kirchoff's Laws - some real spectra!

Lagrois+2015





https://www.astronomy.ohio-state.edu/pogge.1/Ast162/Unit1/SpTypes/dwarfs.pdf

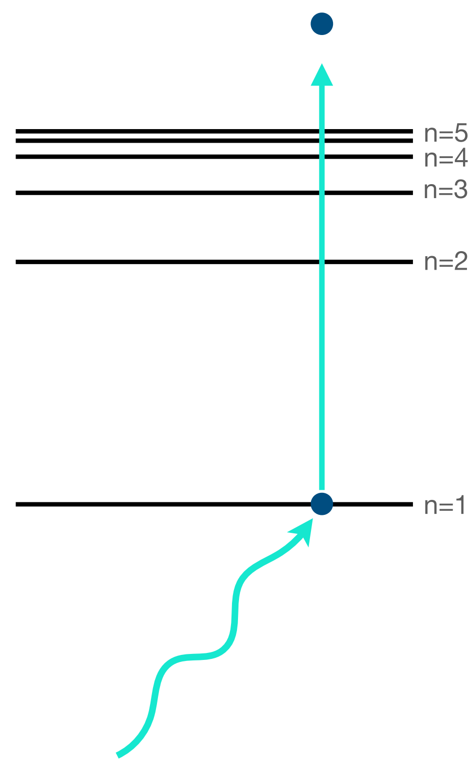
Ionization

- At higher temps, more likely to find electrons at higher energy levels (Boltzmann eqn)

- At very high temperatures, photons will ionize the electrons

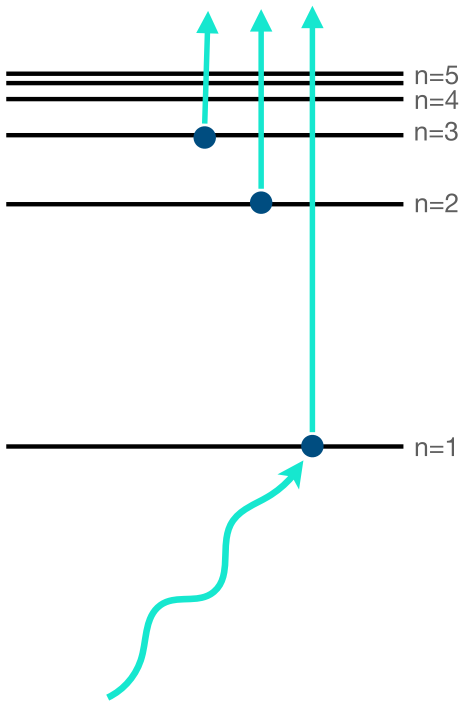
- Really *annoying* notation enters…
  HI is neutral hydrogen (i.e. has its e-, at any level *n*)
  HII is singly ionized hydrogen (i.e. has lost 1 e-)

- For H, a photon w/ energy ≥ 13.6 eV can ionize an e-. This often written as χ_I



Ionization

- So in a hot gas, what is the likelihood of finding ionized atoms?
-



Saha Equation

$$\frac{N_{i+1}}{N_i} = \frac{2kT}{P_e}\frac{g_{i+1}}{g_i}\frac{(2\pi m_e kT)^{3/2}}{h^3}\ e^{-\chi_i/kT}$$

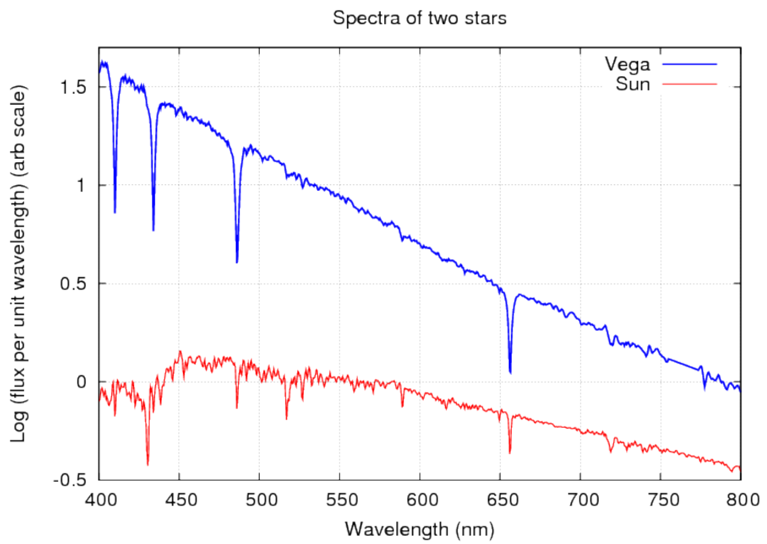
- Several forms of this (2 in BOB ch8, another in your homework!) substituting different variables, etc
  - i.e. $P_e = n_e kT$
- Use Saha to calculate e.g. $\frac{N_{II}}{N_I}$, the number of ionized to neutral atoms as a function of temperature
- The ratio of the statistical weights here is really the *Partition Function ratio*, which sums up the energies of degenerate states

Combine the Saha & Boltzmann… but don't *mix*

- In a given Temp gas, electrons in atoms will be at various levels (Boltzmann) N_2/N_1

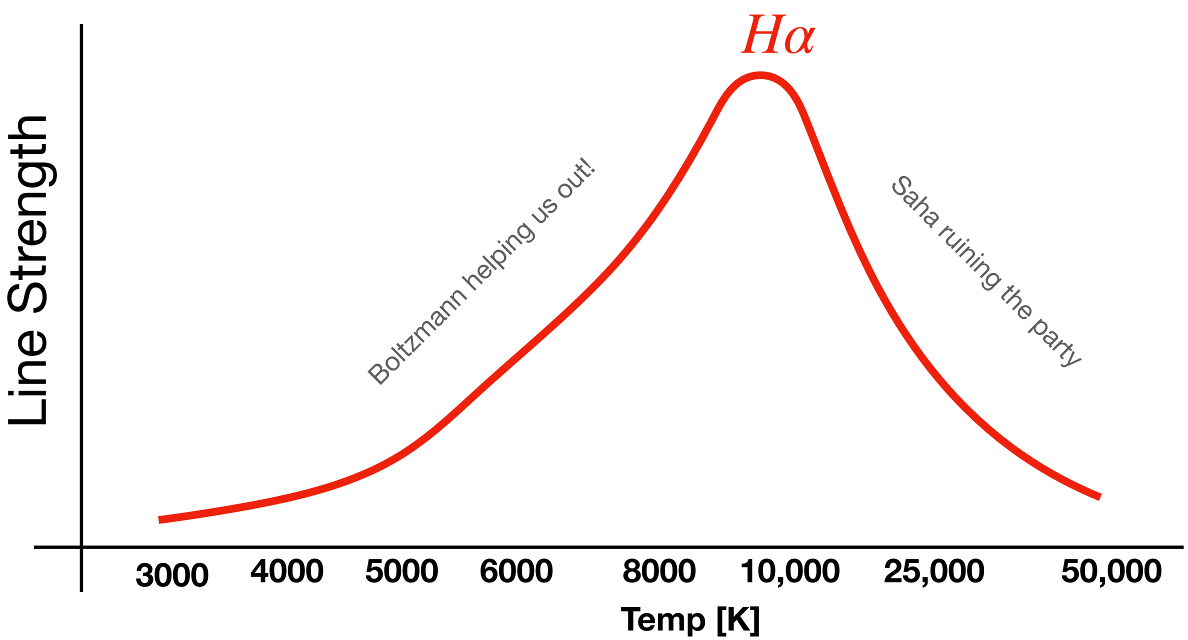
- In a given Temp gas, some fraction of atoms will be ionized, some will be neutral (Saha), N_{II}/N_I

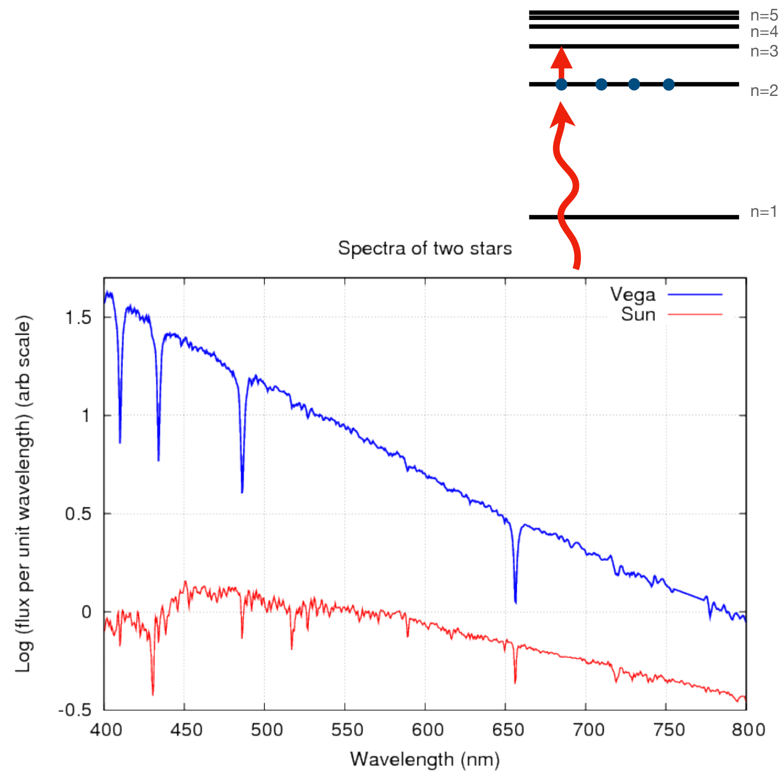
- Don't write things like N_{II}/N_2



Combine the Saha & Boltzmann… Homework 2

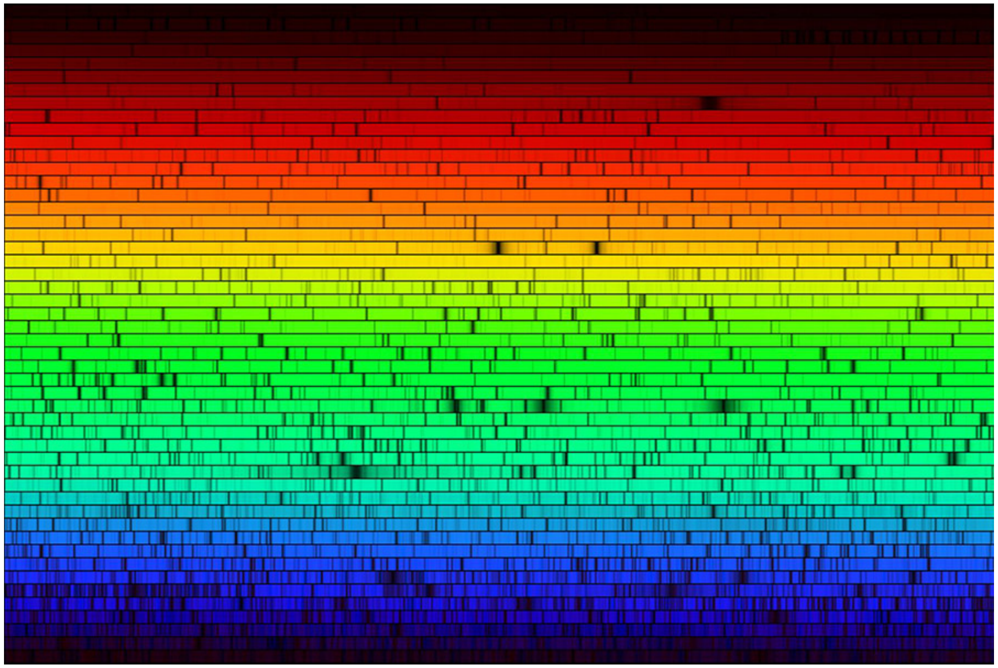
- Because even I find this a bit confusing at times… Homework 2 is designed to help reinforce THE important spectroscopic result of this week's lectures:





Next time:

- More on spectroscopy
  - Spectral Types
  - Metallicity, surface gravity
  - Observations



- Reading suggestion
  BOB: Ch 8 (The Classification of Stellar Spectra)
  LeBlanc: Ch 1 still