[10] Spectroscopy (9/28/17)

Upcoming Items

1. Homework #5 due on Tuesday
2. Midterm #1 October 10
3. Read Ch. 6.2 & 6.3 by next class (skim the rest of Ch. 6). Do the self-study quizzes

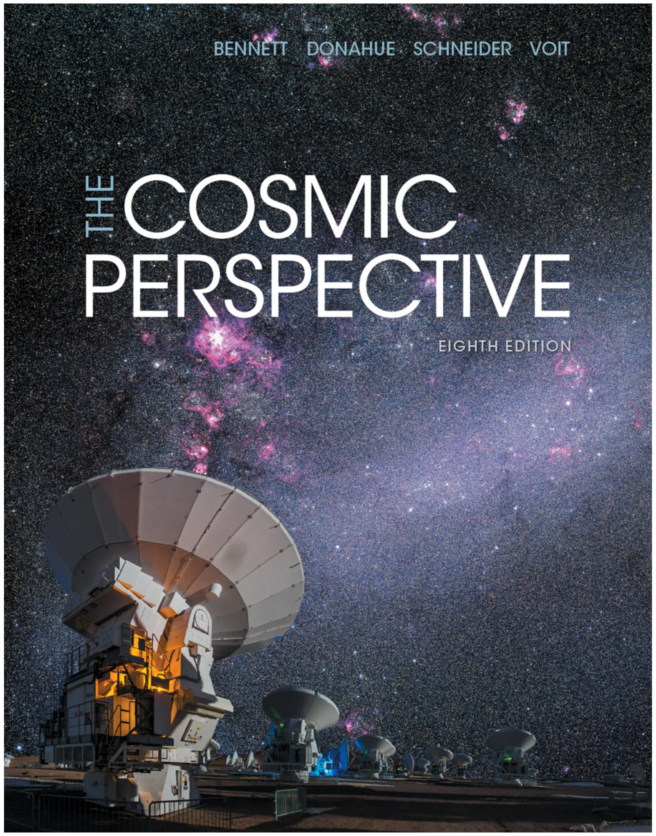
APOD 9/28/16

LEARNING GOALS

Chapter 5.4

For this class, you should be able to…

- … *relate continuum, absorption, and emission spectra to electron energy level transitions*
- … *infer the relative temperatures and sizes of objects based on their thermal radiation spectra and luminosities, using Wien's law and/or the Stefan-Boltzmann law and the relationship between flux, luminosity, and size.*



Any astro questions?

In-class Quiz!

Assume all stars radiate as blackbodies

1. Star 1 has luminosity L_1 and radius R_1, while Star 2 has luminosity L_2 and radius R_2. If $L_1 < L_2$ and $R_1 > R_2$, what can be inferred about the temperatures of the stars, T_1 and T_2?

A. $T_1 < T_2$.

B. $T_1 > T_2$.

C. $T_1 = T_2$.

D. There is not enough information.

2. A star of radius R, luminosity L, and temperature T doubles in radius while keeping its luminosity constant. How does the final temperature T_f relate to the initial temperature T_i?

A. $T_f = T_i / \sqrt{2}$.

B. $T_f = T_i / 2$.

C. $T_f = T_i / (2\sqrt{2})$.

D. $T_f = T_i / 4$.

E. $T_f = T_i / 16$.

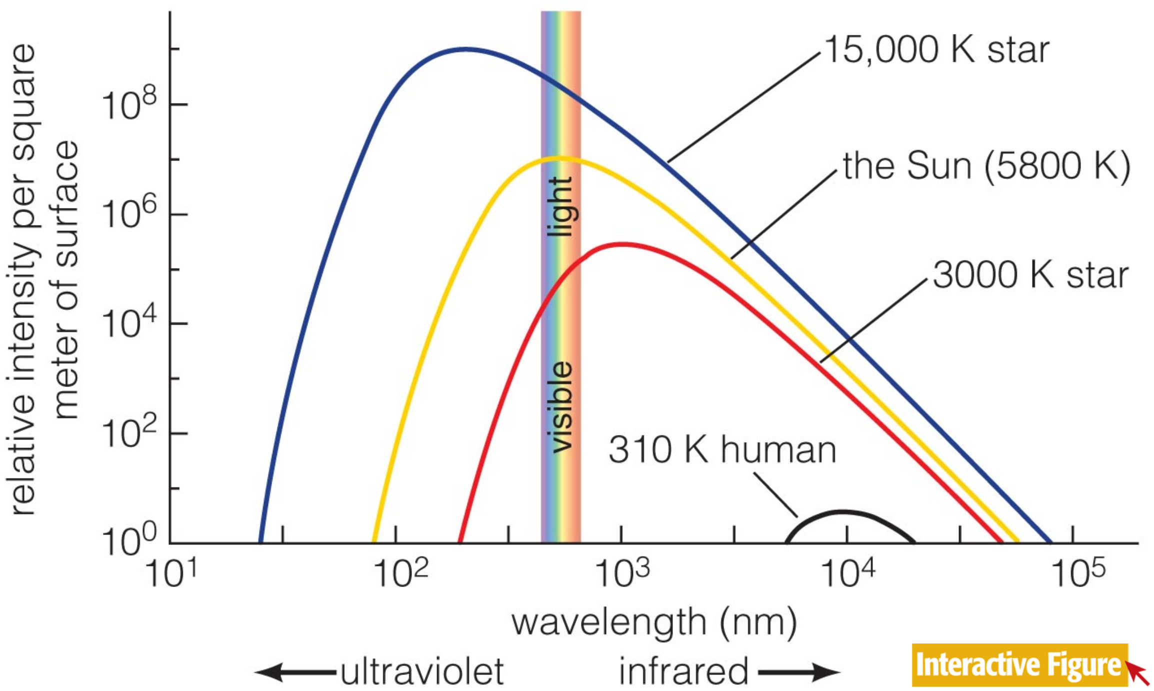
Upcoming dinner and lecture

- Thanks to Cameron Moye for the heads-up!
- Philosophical Society of Washington
- “Searching for Signs of Habitability and Life on Other Ocean Worlds”
- James B. Garvin, Chief Scientist, NASA’s Goddard Space Flight Center; Co-chair, Europa Lander Science Definition Team
- Friday, October 6, 8:00-10:30 PM
- Held at the Cosmos Club: 2121 Mass Ave NW, DC

Reminders: Blackbody Radiation

- Hotter objects emit more light at ***all*** frequencies *per unit area*.
- Hotter objects emit photons with a *higher average energy*.
- Peak energy of a blackbody spectrum is proportional to kT
- Total integrated flux (energy/area/time) proportional to T^4

Notice log scale…



Flux and Luminosity

- The Stefan-Boltzmann law gives the total ***flux*** from a blackbody at temperature T, $F_{\mathrm{emit}} = \sigma T^4$.
  - Units: [power] / [area] = $\mathrm{W/m^2}$ = ([energy] / [time]) / [area] = $\mathrm{J/s/m^2}$.
  - $\sigma = 5.67\mathrm{x}10^{-8}\ \mathrm{W\ m^{-2}\ K^{-4}}$ Stefan-Boltzmann constant
- The ***luminosity*** of an object is the total power emitted from its surface. For a sphere of radius R, $L = 4\pi R^2 \sigma T^4$.
  - Units: [power] = W = [energy] / [time] = $\mathrm{J/s}$.
- Examples:
  1. Sun ($T = 5800$ K, $R = 7.0\times10^5$ km):

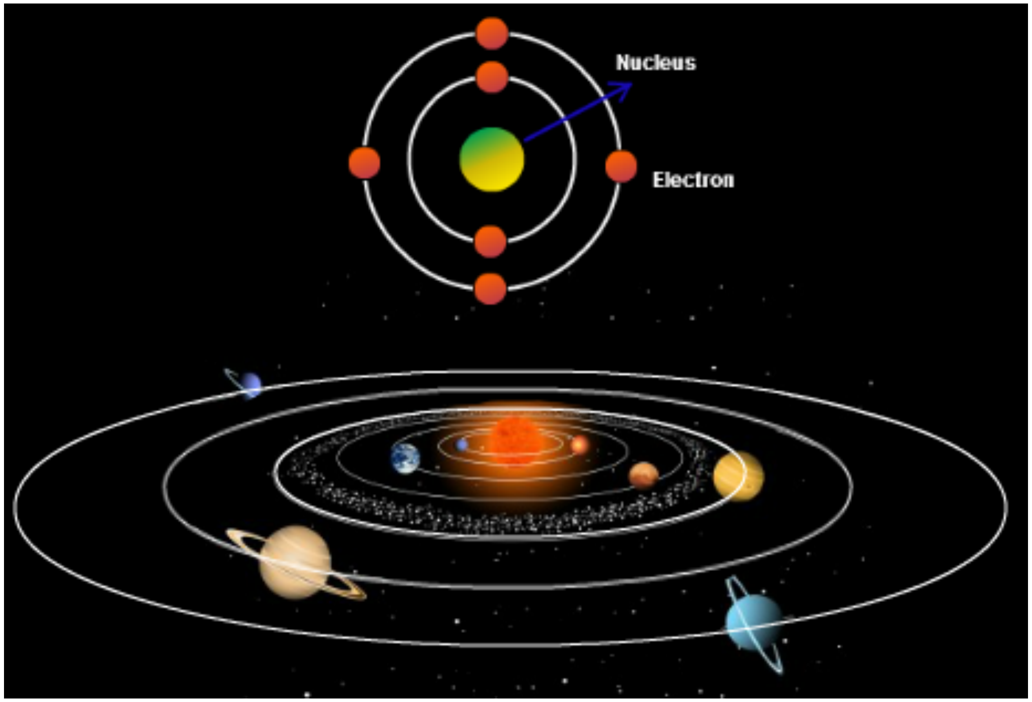
     $F_{\mathrm{emit}} = 6.4\times10^7\ \mathrm{W/m^2}$, $L \sim 4.0\times10^{26}$ W.

The Nature of Matter

- Now, finally, we'll get to some details about how light interacts with matter, and thus how we can use the specifics of the spectrum of an astronomical object to learn about that object.
- This is actually pretty amazing! Auguste Comte, 1842: *Of all objects, the planets are those which appear to us under the least varied aspect. We see how we may determine their forms, their distances, their bulk, and their motions, but we can never known anything of their chemical or mineralogical structure*
- ...and he thought we could know even less of stars!
- So how *can* we learn about such distant things?

Solar System Model of the Atom

- Early 1900s, people discovered that atoms have parts
  Positively charged nucleus, negatively charged electrons
- Popular way to display: the "Solar System" model, in which electrons orbit the nucleus
- But there is a huge problem with this model...



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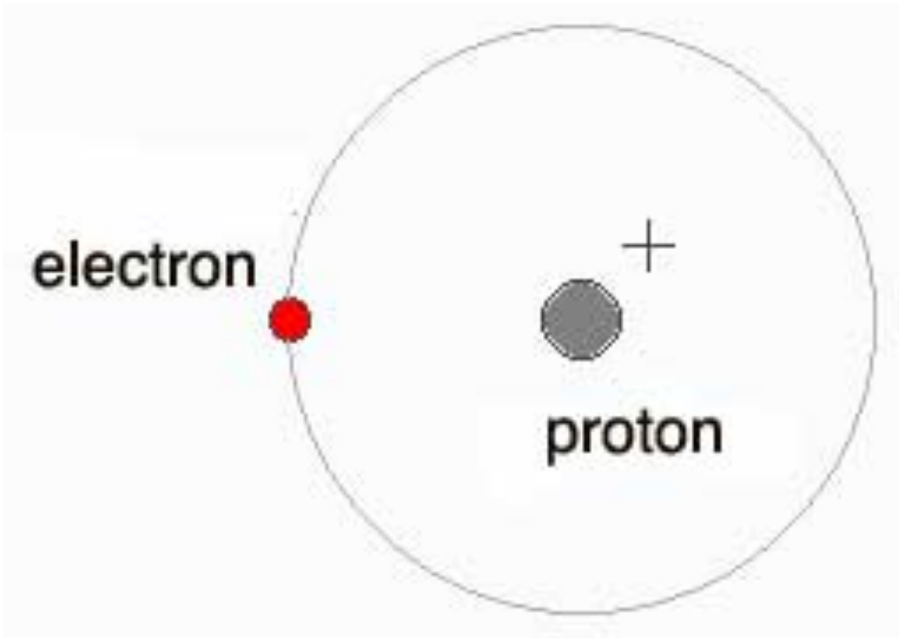
Radiation Catastrophe!

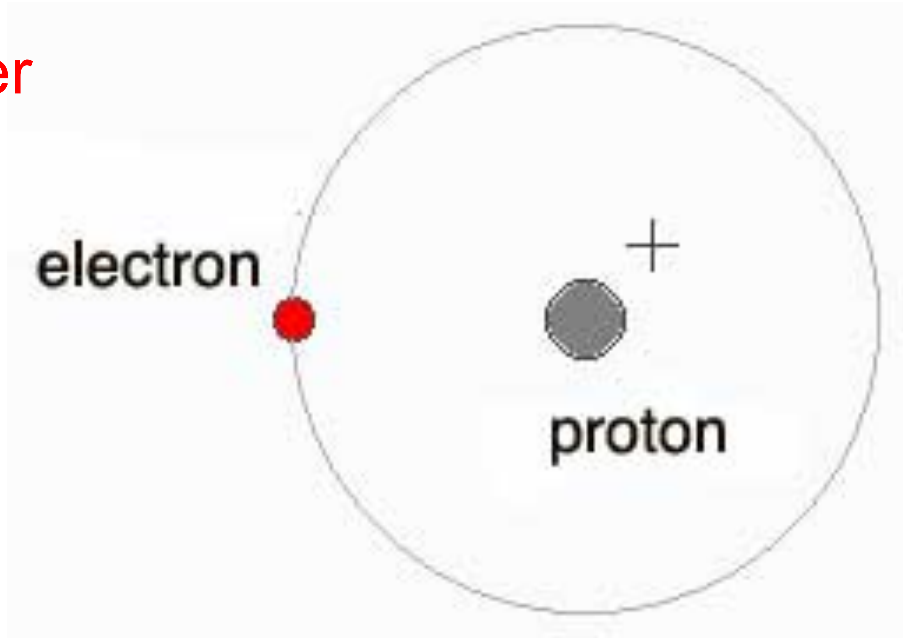
- Let's pretend the system is just like the Solar System
- Remember that for a circular orbit, the speed is $v=(GM/r)^{1/2}$. The total energy is always $E_{tot}=(1/2)mv^2-GMm/r$, or $-GMm/(2r)$ for circular orbit
- Same with electrical forces, but different constants (and depends on electric charge rather than mass)
- Do you see the problem yet?



http://quatr.us/chemistry/atoms/pictures/hydrogen.jpg

Radiation Catastrophe!

- The problem is twofold:
  1. If the total energy is proportional to -1/r, then smaller r decreases the energy indefinitely
  2. As was known by then, an accelerated electric charge radiates, so it will go to the lowest possible energy
- So the "orbiting" electron will radiate an infinite energy(!)
- And calculations showed that this would take ~10^{-8} s for H!!!



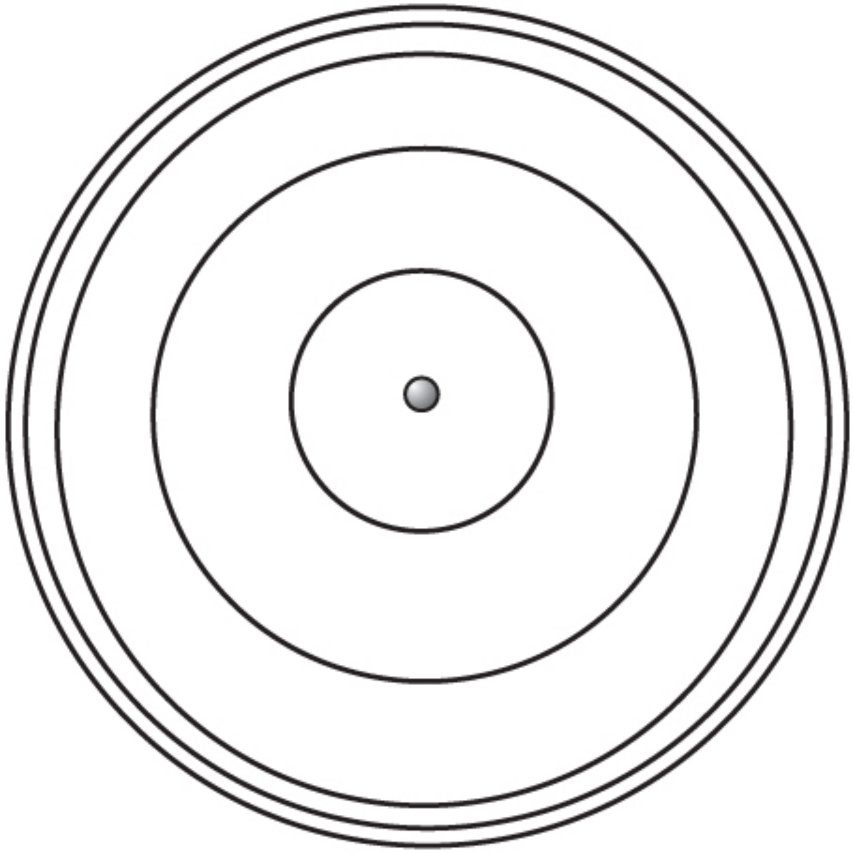
http://quatr.us/chemistry/atoms/pictures/hydrogen.jpg

Why don't electrons radiate as they orbit?

- Wrong to think of electrons as classical particles on Newtonian orbits.
- In quantum mechanics, classical particles are replaced by wavefunctions (probability distributions).
- But in discussion tomorrow you will get a semiclassical idea of part of the solution: the uncertainty principle establishes a minimum energy. Not –infinity!
- In addition, a remarkable conclusion emerged from quantum mechanics: not all energy levels are allowed! Atomic energy levels are discrete, or "quantized"
- This is the basis of all atomic structure, and because energy levels are different for different atoms, it allows us to identify different atoms (and molecules) from spectra

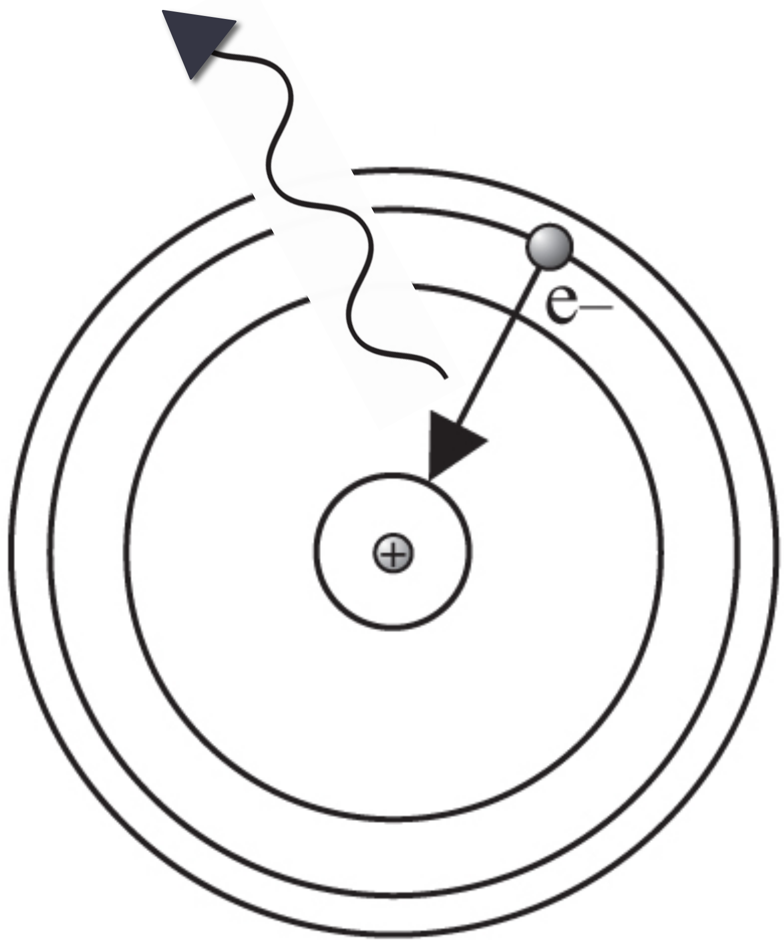
Electron Transitions

- Each transition between energy levels corresponds to a photon with a specific energy.



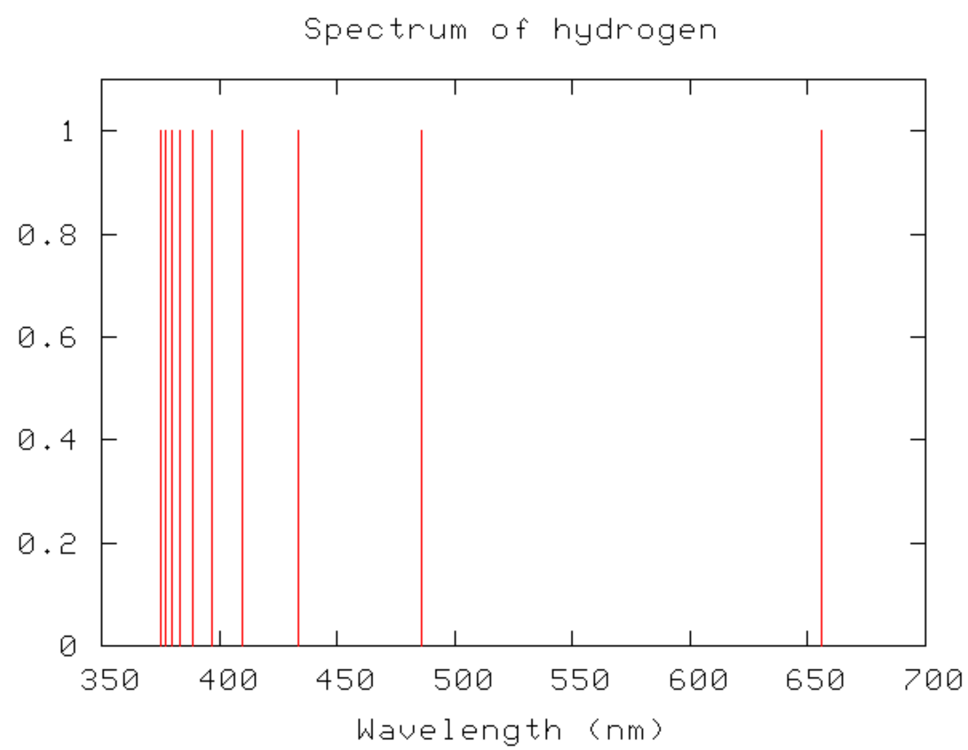
Electron Transitions: Emission

- Electrons give off a specific amount of energy when they move to lower levels.
- Energy is *emitted* in the form of a photon.
- *Spontaneous* emission is random; happens for isolated atom, no perturbation needed
- For *stimulated* emission, a photon of that energy prods the atom and produces an identical photon
  This is the basis of lasers!



Emission spectrum

- From the atom itself, the line energies are very well-defined
- This is the basis of the “signature” of atoms
- But what about other effects?
- Group questions: what would happen to the spectrum on the right if (1) the whole thing were moving away, (2) the whole thing were moving toward us, (3) the system were hot, so some atoms move toward us and some move away?



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Chemical Fingerprints

- Each type of atom has a unique spectral fingerprint.

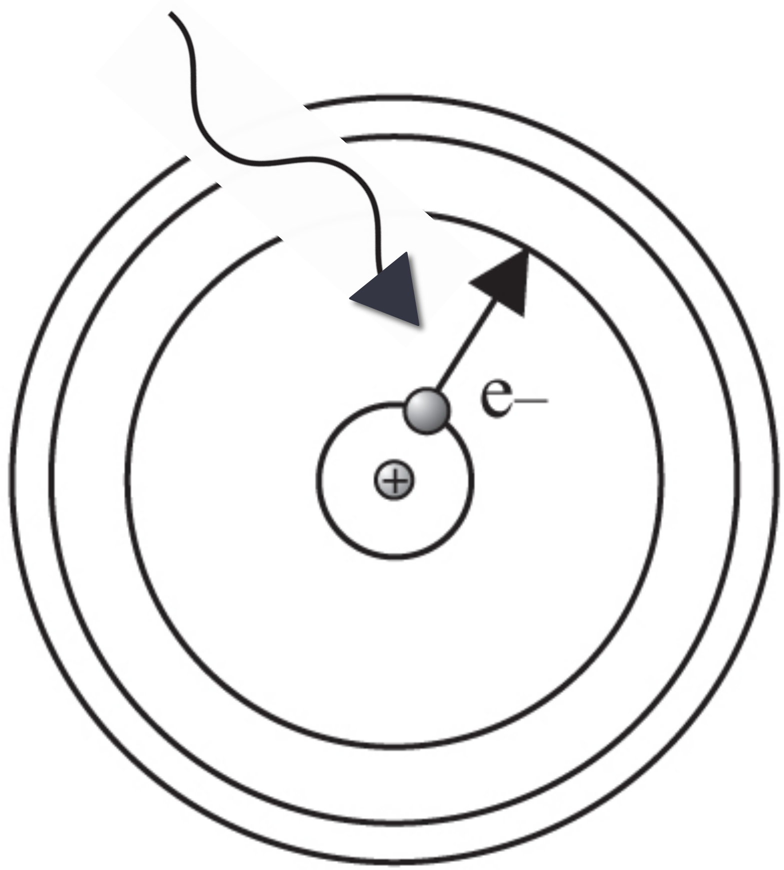
Energy Levels of Molecules

Molecular hydrogen (H_2)

- Molecules are more complex than atoms (for example, with multiple atoms they can vibrate, rotate, twist, ...) so the spectra of molecules can be very complicated.
- Many of these transitions are in the infrared or the radio.

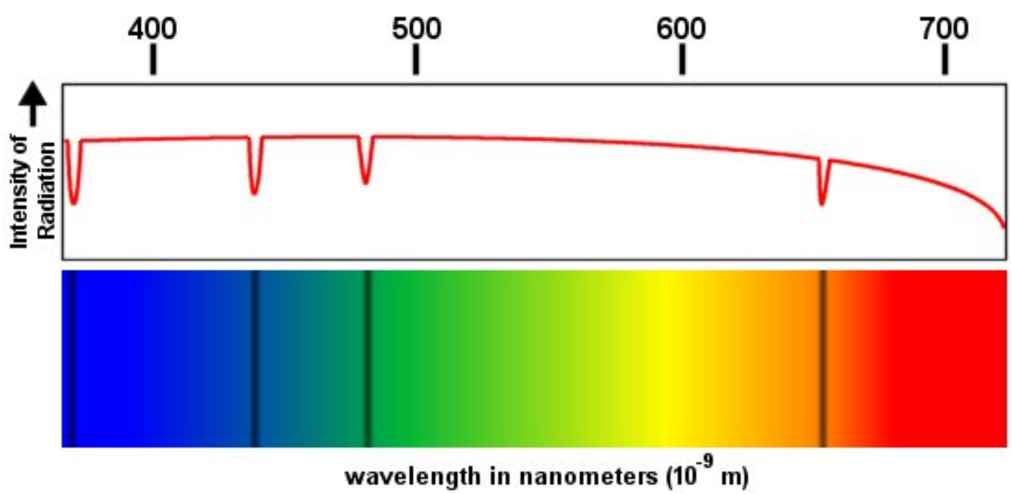
Electron Transitions: Absorption

- Electrons require a specific amount of energy to move to higher levels.
- Energy in the form of a photon is *absorbed*.
  - E.g., the energy difference between the 1st and 2nd levels of hydrogen is $10.2\ \mathrm{eV}$, which is the same as a photon of frequency $f = (10.2\ \mathrm{eV}) / h = 2{,}470\ \mathrm{THz}$ or $122\ \mathrm{nm}$.
- This is called a "bound-bound" transition; going from one bound state to another



Bound-bound absorption spectrum

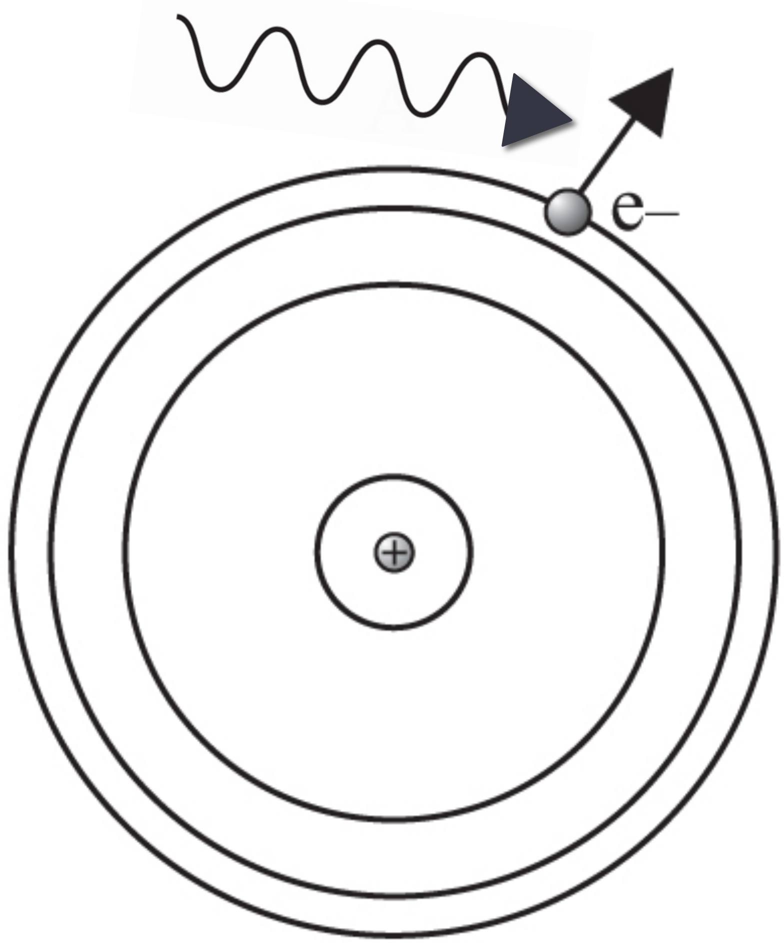
- Absorption *lowers* the flux around the absorption energies
  This is the inverse process to emission
  Very narrow range of energies; bound states are precise!
- Why? Light with energies below or above transition energies doesn't interact as much, but at those energies, light can be absorbed and then re-radiated at different energy or in different direction



http://www.astro.princeton.edu/~dns/teachersguide/spectrum3.jpg

Electron Transitions: Absorption

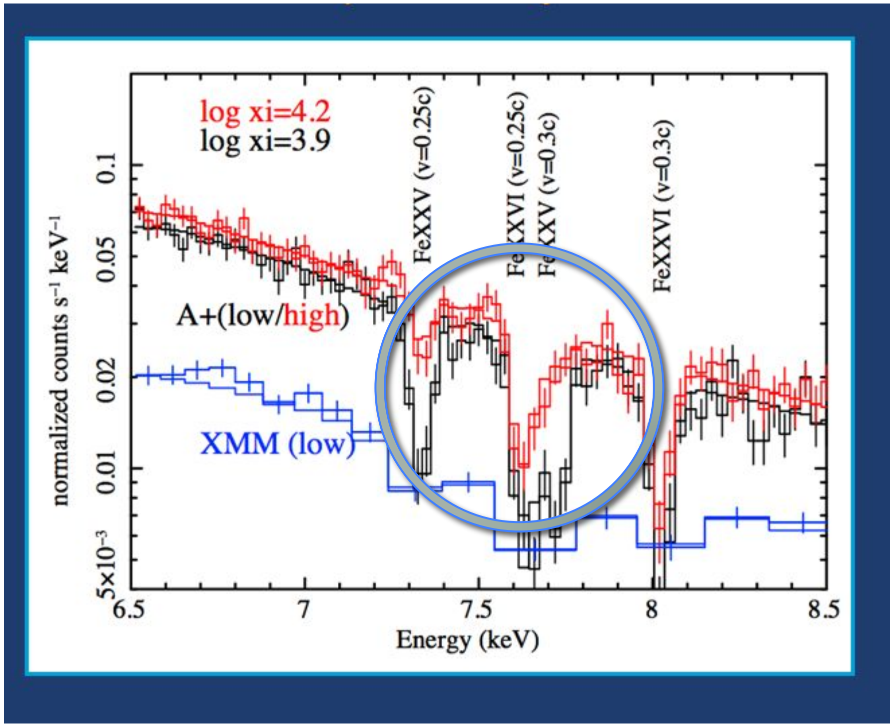
- If an incoming photon has enough energy, an atom can be *ionized*: the electron leaves the atom.
  - In hydrogen, 13.6 eV is needed to ionize an electron from the ground state.
- An ionization is also called a bound-free absorption From a bound state, to an unbound (or "free") state



Ionization (bound-free) Spectrum

- To move an electron from one energy level to another, need a *specific* energy
- But to kick out an electron, need a *minimum* energy
- Thus ionization (bound-free) transitions are much broader than bound-bound transitions
- Leads to wedge-like features in spectra

Spectrum of an active galactic nucleus



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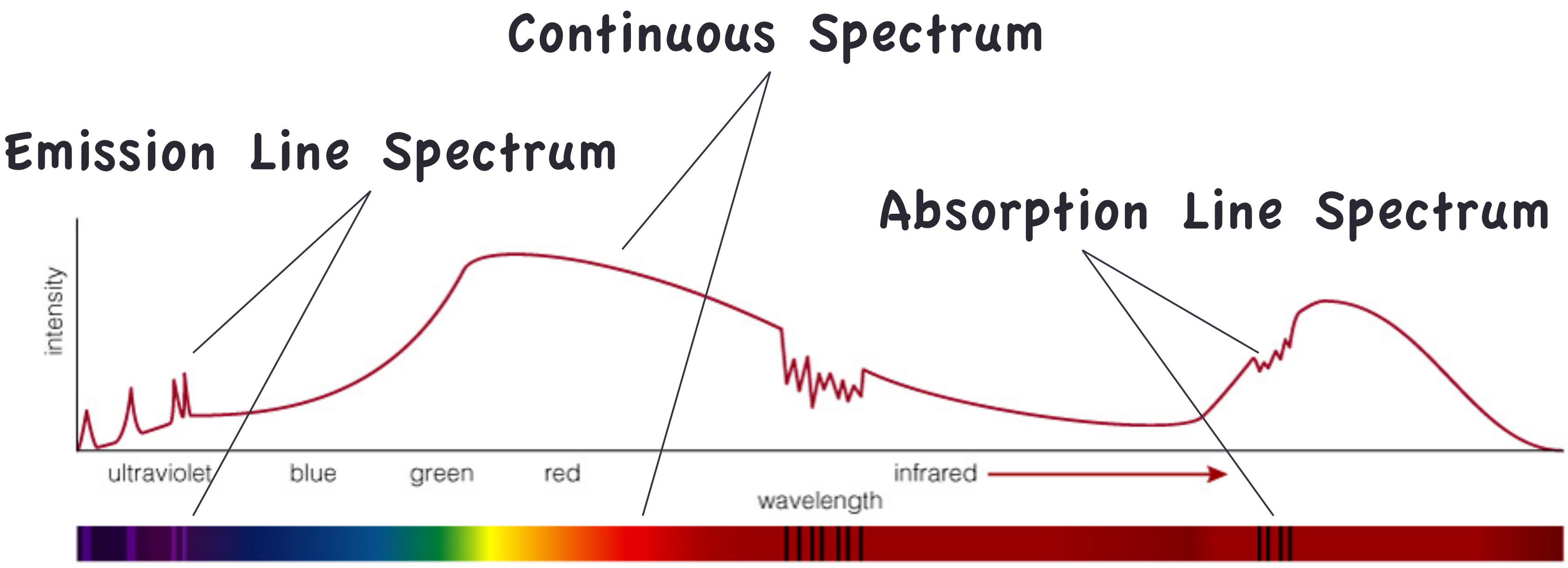
Putting a Spectrum Together

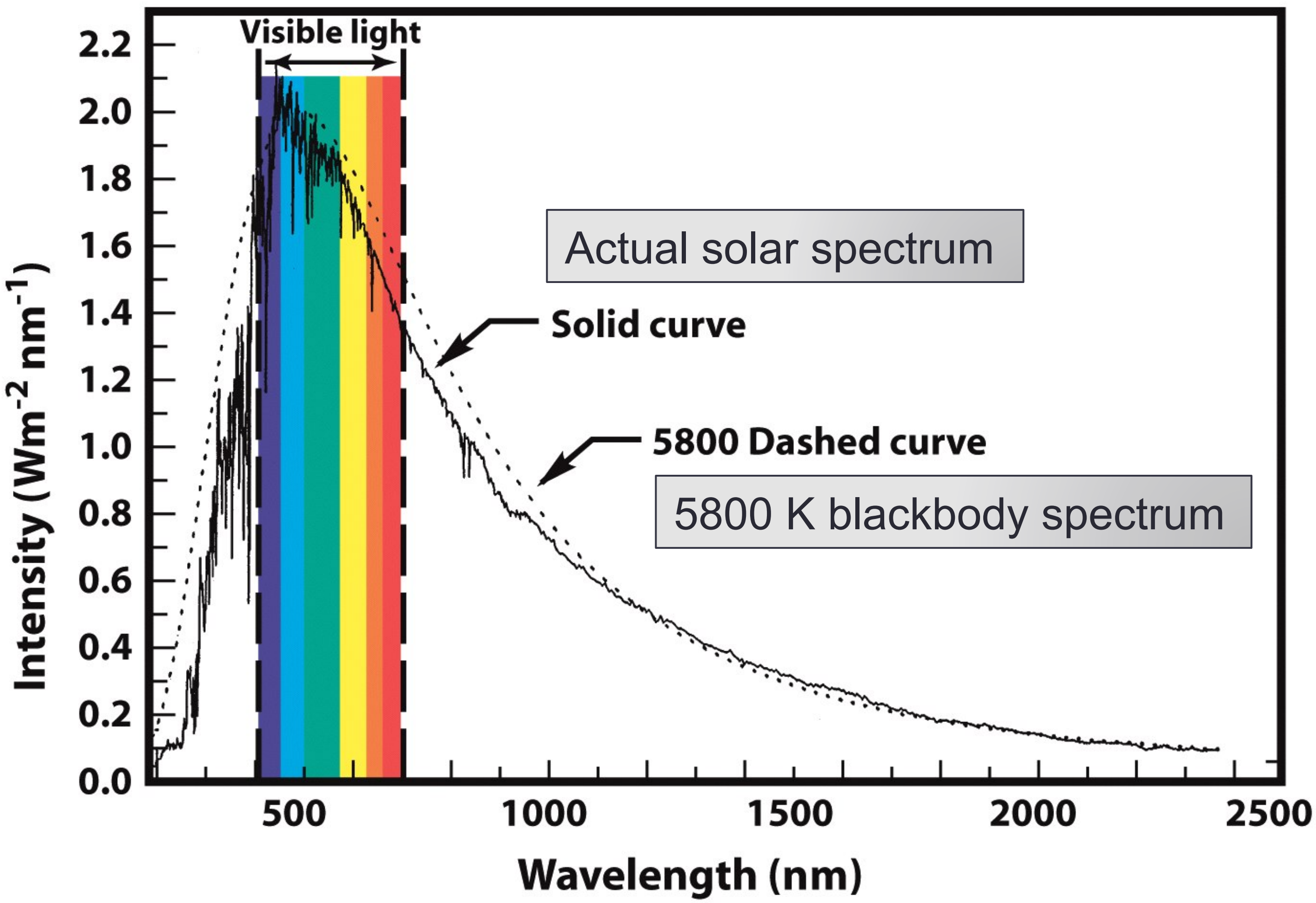
- An astronomical object will usually have multiple components to its spectrum
- First, you often have a smooth ***continuum***, which spans a wide range of photon energies
  Blackbody spectra are continuum spectra
- Then, you sometimes have ***emission lines*** on top of that spectrum
- Finally, you sometimes have ***absorption lines*** or other absorption features on top
- All can be broadened or moved by relative motion and other physical effects
- We can learn from all of these features!

Three Basic Types of Spectra



- Spectra of astrophysical objects are usually combinations of these three basic types (sometimes plus the bound-free wedges)

Example: the Sun!



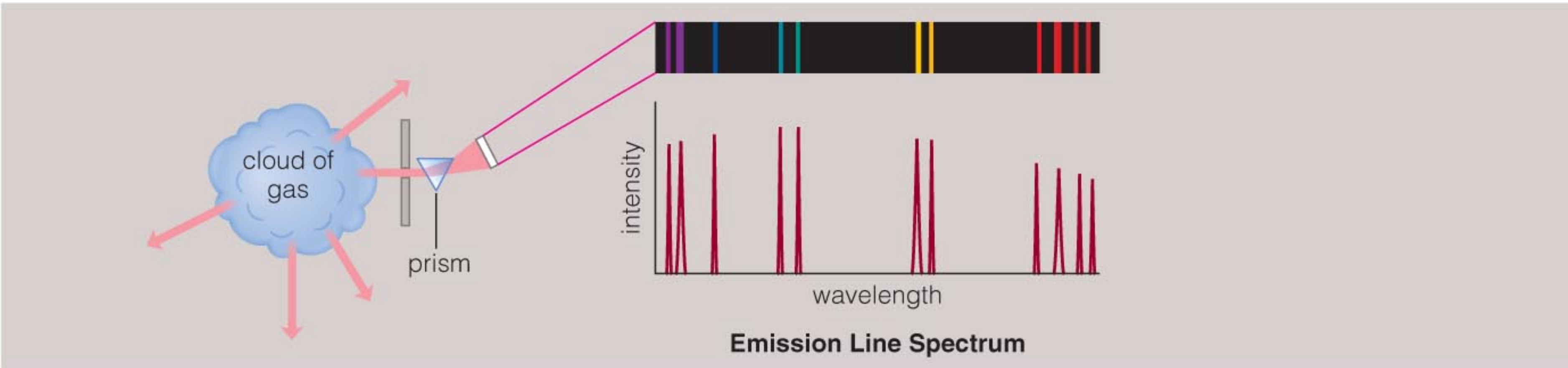
Actual spectrum of the Sun compared to a blackbody.

What color is the Sun? Where do the absorption lines come from?

When do we get each type of spect?

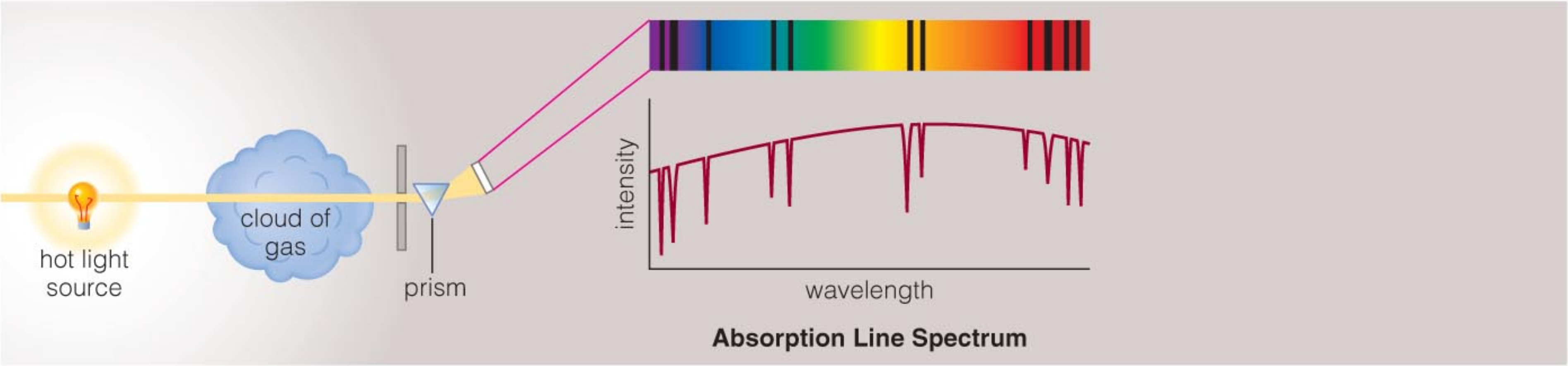
- Remember that emission lines are at the same energies as the corresponding absorption lines
- Group question: When would we expect to see emission lines and when would we expect to see absorption lines? Hint: optical depth has something to do with it
- Note: I'm asking you to think about this, even without complete information, because the resulting discussion will therefore be deeper and more meaningful

Emission Line Spectrum



- A thin or low-density cloud of gas emits light only at specific wavelengths that depend on its composition and temperature, producing a spectrum with bright emission lines.
- Why "thin"? Here we mean "optically thin at the wavelength of the transition". If not, light gets re-absorbed

Aborption Line Spectrum



- A gas cloud between us and a light bulb can absorb light of specific wavelengths, leaving dark absorption lines in the spectrum.
- This works if the cloud is optically *thick* in the line, but optically *thin* away from the line; this can happen, because the mean free path is much smaller near the wavelengths of the line
- Also works near the surface of something (Sun!); why is that?

Kirchhoff's Laws

1. A solid, liquid, or dense gas produces a continuous (blackbody or thermal) spectrum.
2. A tenuous gas seen against a hot glowing background produces an absorption-line spectrum.
3. A tenuous gas seen against a cool dark background produces an emission-line spectrum.