Spectroscopy Lecture.

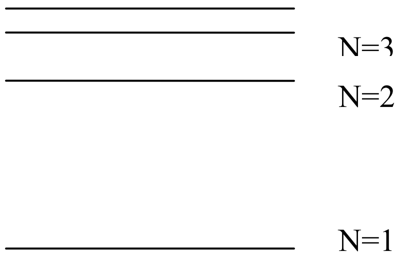
1) In observing the Sun and getting the observations needed that yield our views of the magnetic fields (T, ρ, and v) we use spectral analysis.
2) What is the underlying physics of spectral analysis? * can someone give me the three most basic parts of this?

[redacted]

3) Markus covers these topics in chapter 2 of his book to tell you what is impotant. I'd like to give you a little deeper understanding of how we get what he talked about.
    a. I think it's important that you study some of these things on your own, to increase your depth of knowledge, if you haven't already had them in other courses.
    b. You should understand what causes absorption lines, and how they are formed. * ? question
    c. How about emission lines, what is the difference? * ? question

A Atomic Structure:

1) Conceptual model is the Bohr atom – <u>visualization based on data</u>.
    d. Balmer showed that emission lines in H could be described by
        1. $\nu=R(1/2^2 - 1/n^2)$ for the Balmer series
        2. for other series just change the 2 squared.
    e. Bohr postulated that electron went around the nucleus at distance a with frequency omega in orbits without emitting radiation. When they jumped from one orbit to another, they emitted radiation.
    f. Postulated that the integral of the angular momentum around an orbit was an integer multiple of h. $2\pi m a \omega^2=nh$ a is radius ω is angular vel.
    g. Balance acceleration of electron in orbit with electrostatic energy gives $m a \omega^2=Ze^2/a^2$
    h. Working with kinetic energy and potential energy gives total energy $W_n=-2\pi^2 m Z^2 e^4/(n^2h^2)$
    i. This gives the simple energy level diagram for H



j.

k. This can all be done rigorously in QM, but this model gives a vizualization. – Think about how these guys got there from where they were.

l. Next step is angular momentum and multi-electron
    i. Orbit can be elliptical. Angular momentum is vector **L**=m**RxV** where L is the angular momentum vector perpendicular to R and V. See diagram 2.4 on pg 41 of Aller.
    ii. Angular momentum given by quantum number l where l=k-1 and angular momentum is l(h/2π). k goes from 1 to n so for n=1 l=0, n=2 l=0 and l=1 etc. l=0->s l=1->p ,,d,f,etc show diagram on pg 42. fig 2-5 l=0 most tightly bound, least angular momentum, least circular. Note: observed that delta l can only be 1 for allowed transitions.
    iii. This rotation yields an internal magnetic field, or magnetic moment of the atom. The electron also has a spin and is observed to only allow +_1/2.

m. Vector model j=l+s or j=l-s spin is + or – vector model developed for prediction capability
    i. He example, 2 electrons. Ground state is 1^1s, n=1, l=0, and the 2 s electrons must have opposite spin, so s=0 or superscript 1 for singlets
    ii. For second level, the 2 spins can either be opposite again, singlets 2^1s , l can now be 0 or 1 s or p, 2^1p. Or, you can now have triplets, where the net spin is 1, either +1 or -1. 2^3s, 2^3po and 2^3p1,2. the numbers after the p are for j, how l and s add. In He for example energy different from 2^3S to 2^3P_0 and $2^3P_{1,2}$ They yield the two IR lines of He at 10829.1 and 10830.3.
    iii. This all starts on pg. 47 of Aller. It is referred to as LS coupling. It is helpful in understanding the spectroscopic notation of spectral lines. You can see from the magnetic moments how some lines might be more affected by magnetic fields than others. Our understanding of atomic structure allows us to measure the solar **B** field.

2) Quantum Mechanics gives much more complete quantitative characteristics of the atom.

B) Gas

1) The basic observed equation is P=NkT, $N=\rho/uM_H$
    a. This is important: if you know two, you know the third.
    b. Can make observations that yield T, and ρ so you can get P.

2) Temperature and mean velocity

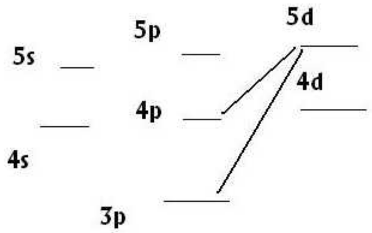
   a. Perfect box with perfect collisions: collision momentum with wall is $2mv_x$
   b. Number of collisions $v_x/2L$ L is size of box
   c. Total of all momentum is $\Sigma Mv_x^2/L$
   d. Momentum is pressure so $P=ML^{-3}\Sigma v_x^2$
   e. Define mean $v_x^2=n^{-1}\Sigma v_x^2$
   f. $v_x^2=v_y^2=v_z^2=1/3v^2$
   g. $P=n/3L^3(Mv^2)=1/3(NMv^2)$
   h. So average energy $½\ Mv^2=3/2\ kT$ This is important because it relates energy, velocity, to temperature.

3) Maxwellian Velocity Distribution
   a. If we can relate T to the velocity distribution of the gas, not just the mean velocity, we can learn a lot about the physics of the gas from remote observations.
   b. The whole idea involves visualization of the problem:
      i. Work in phase space with momentum and space
      ii. Determine a statistical weight as being proportional to the area, need quantum statistical weights
      iii. Put n particles in a series of phase space boxes; can have all in 1 box to 1 in each box and everything in between.
      iv. Probability of distribution in phase, velocity space. The objective is to know what the particle velocity distribution will be in a gas.
   c. After much manipulation you get: $f(v,T)= (M/2\pi kT)^{3/2}e^{-(Mv2/2kT)}$
   d. Draw the curve:
      i. Velocity profile of gas
      ii. Optically thin gas $I_\nu=\varepsilon f(\nu,T)\ \sim e^{-c2(\lambda-\lambda o)/\alpha 2\lambda o2}$ a Gaussian line profile.
      iii. What would you measure in a spectrum to get the T? What measurement would you make?
      iv. High energy tail for solar wind.
      v. In outer corona, heliosphere, is Maxwellian velocity distribution valid? Why(not)?

4) Boltzmann equation
   a. $N_i/N=g_i/ue^{-\varepsilon/kT}$ $\varepsilon=h\nu$
   b. Can use the ratio for 2 energy levels to get relative populations between two energy levels.
   c. Measure two lines from same atom to get T
   d. $N_i/N_j=g_i/g_je^{-}\delta\varepsilon/kT$

5) Saha equation
   a. equation
   $N_i/N_j(N_e)=(2\pi mkT)^{3/2}/h^3(2(u_i(T)/u_j(T))e^{-\varepsilon/kT}$
   b. Used to determine gas temperature

6) Applications



a. Sample atom

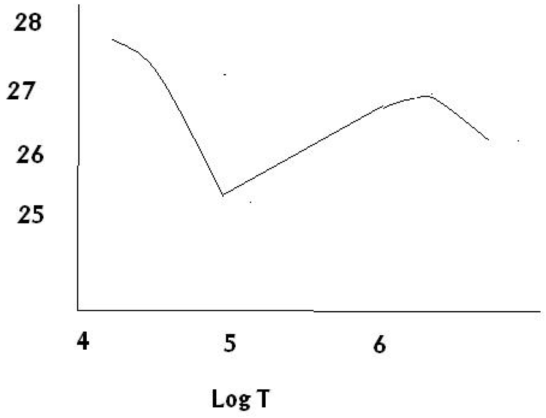
b. Two transitions shown. Both from the same level so upper population known. Significantly different λ so we can get the ratio of sensitivity in region 1 compared with region 2. Used to help calibrate detector.

c. Absolute calibration for any line based on A value and collisional temperature. NIST in Fredrick MD, Berlin, Orsay in Paris.

d. Compare 4s-3p with 5s-3p. Relative population of 4 vs 5 is dependent on T based on Boltzmann equation.

e. Compare emission of ion species to get T, Saha equation.

f. Differential Emission measure, basically how much material is at temperature T.



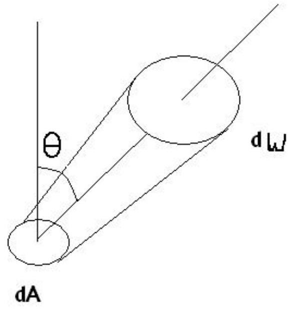
Integral $n_e^2 dh$

g. See Mariska's book pg 74

h. Magnetic fields – splitting of atomic levels. Discuss this.

i. What quantities determine the characteristics of an emission line? ([redacted]

7) Emission and Absorption of radiation



a.
b. $dE_\nu = I_\nu \cos\theta \, dA \, d\nu \, d\omega$

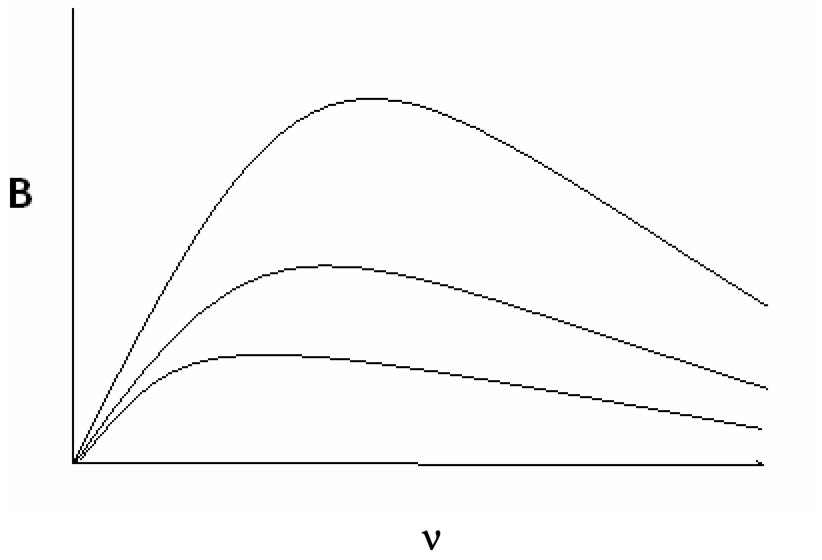
c. Mean intensity is average $J_\nu = 1/4\pi \int I_\nu d\omega$

d. Flux is energy passing through a cm^2 $F_\nu = \int I_\nu \cos\theta d\omega$ We use flux in and Flux out, net Flux= Fout-Fin

e. Isotropic, net flux is 0.

f. Black body radiation is net flux = 0 , surface of the Sun is not black body – technically. Particles at surface see ½ hot atmosphere, ½ black space.

   i. Black body curve



    - ii. Derivation of Planck's law is based on the number of degrees of freedom of e&m waves in a box with temperature T. Each degree of freedom is related to an energy ½ kT .

  - g. Emission and absorption
    - i. $dE_\nu=j_\nu dv d\nu$ here v is volume
    - ii. $dI_\nu=-\kappa_\nu I_\nu \rho dx$ $I_\nu=Io_\nu e^{-\kappa\nu\rho x}$ If you have a cloud over the atmosphere, like a prominence (depends on what line you are talking about).
    - iii. Line profiles:
      - 1. Natural width –QM – uncertainty principle.
      - 2. Doppler width –T, and bulk velocity
      - 3. Stark Broadening – electric field, electrons
      - 4. Zeeman splitting, B field
    - iv. Effect of T on emission or absorption (Planck function, line profile).
    - v. Effect of ϕ_ν on how deep you are looking.
    - vi. EIT emission lines.
    - vii. CDS emission lines
    - viii. Visible spectrum absorption lines.
    - ix. Non-LTE What does it mean. $T_e \neq T_r$, the temperature related to J_ν is not the same as that related to C_{ij}.
- 8) Scattering
  - a. Rayleigh scattering $\nu_o >> \nu$ ν_o is the resonance frequency of the atoms or molecules in the system – air
  - b. Thomson scattering $\nu_o << \nu$ electrons in the corona
- 9) Transition probabilities
  - a. A values, probability of decay. Electron falls from n+1 to n, or n+2 to n.
  - b. nA is energy emitted if no stimulated emission. $A \sim 10^8$ for resonance lines. For high level lines $A \sim 10^3$
  - c. For up transitions it is a function of IB where B is related to A.
  - d. Also have collisions. Usually collisions up and emission down.
  - e. Collision rates related to A values N_e and T_e
- 10) Continuous absorption and emission
  - a. $1/\nu^3$ or $1/\nu^2$ we use this to analyze spectra.

If there is time, talk about some of the work I have done:

1. Prominence absorption in EUV
2. Prominence absorption – cloud model
3. Temperature in prominence due strictly to radiation from photosphere, chromosphere, and corona.

Homework:

1) Derive the relation for the relative numbers of atoms in the nth energy level in the qth stage of ionization to the number in the n'th energy level in the q'th stage of ionization
   $N_{nq}/N_{n'q'}=$

2) Derive the combined Boltzmann and ionization equation for hydrogen for the population of level n. $N_n=f(N_i,N_e,T,Z,n)$ where Z is the atomic number for H=1.