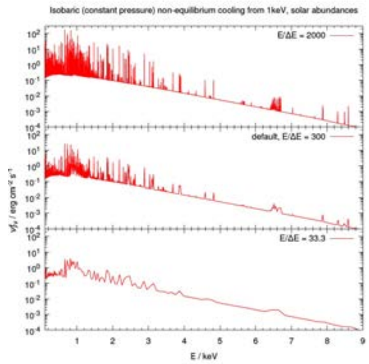
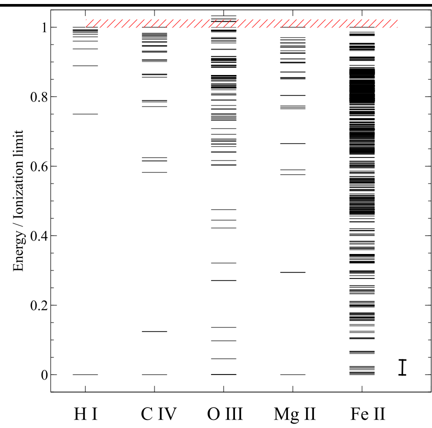
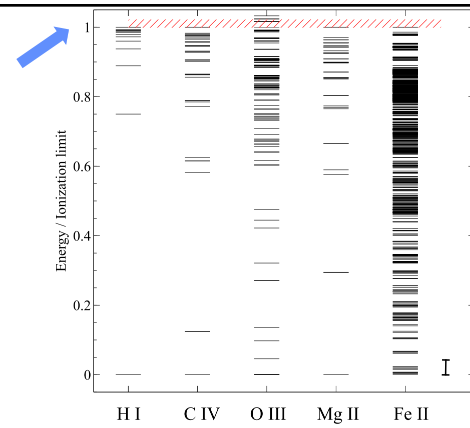
Vary blackbody temperature

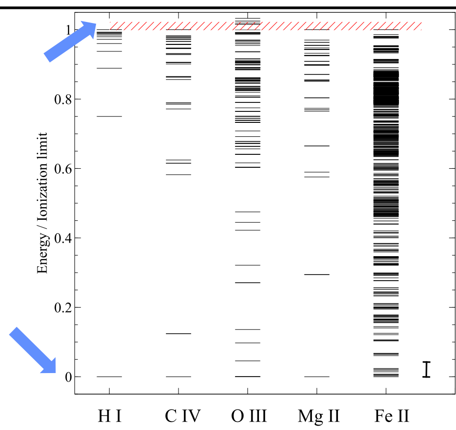
- Stoy or “energy balance” method of determining stellar temperatures
- AGN3 Section 5.10

- How to make sense of all these lines







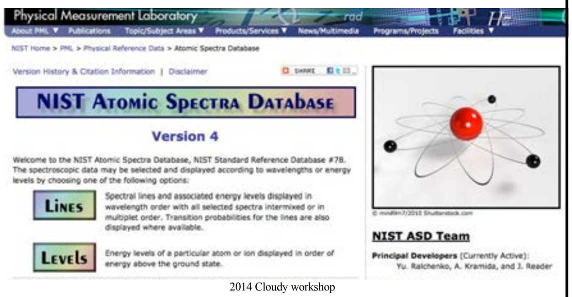


Peter’s atomic line list

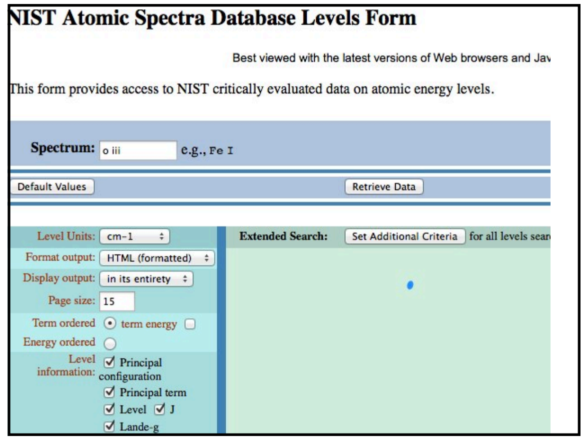
- http://www.pa.uky.edu/~peter/atomic/
- http://www.pa.uky.edu/~peter/newpage/
  - Beta version with new features
- Search wavelength range to find what lines are present

NIST

- http://www.nist.gov/pml/data/asd.cfm

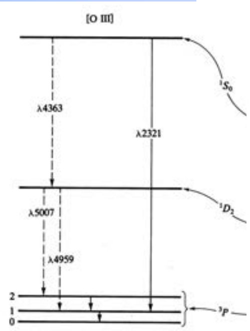


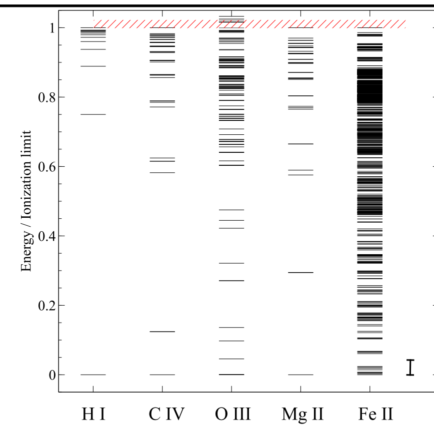
2014 Cloudy workshop



O III

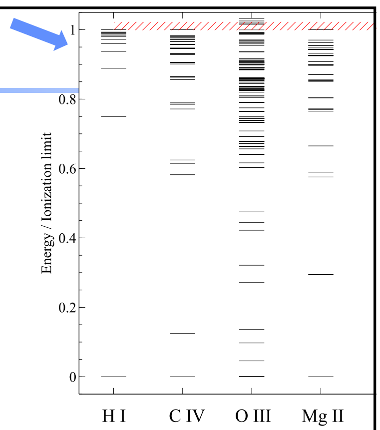
Configuration	Term	J	Level (cm^{-1})
$2s^2 2p^2$	^3P	0	0
		1	113.178
		2	306.174
$2s^2 2p^2$	^1D	2	20 273.27
$2s^2 2p^2$	^1S	0	43 185.74
$2s2p^3$	$^5S°$	2	60 324.79
$2s2p^3$	$^3D°$	3	120 025.2
		2	120 053.4
		1	120 058.2

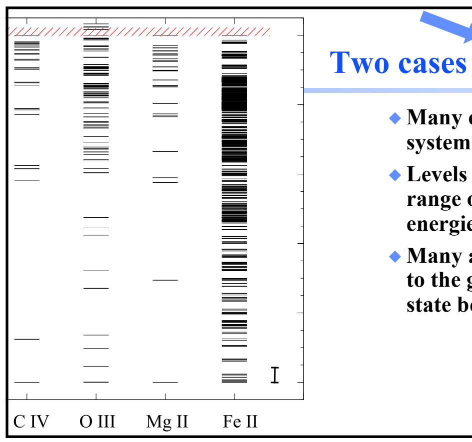




Two cases

- One and two electron systems
- Levels are closer to the continuum above than the ground state below





Two cases

- Many electron systems
- Levels have range of energies
- Many are close to the ground state below

Two types of lines

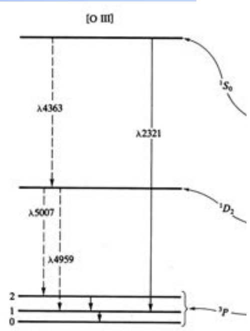
- **Recombination AGN3 sec 4.2**
  - e + p radiative recombination
  - Rate coefficient $q \sim 10^{-13}$ cm^3 s^{-1}
  - Mainly H, He
- **Collisionally excited AGN3 3.5**
  - Inelastic e + ion collision
  - $q \sim 10^{-9}$ cm^3 s^{-1}
  - Heavy elements

Selection rules for transitions

- **AGN3**
- **Appendix 4 Nebular quantum mechanics**
- **Appendix 6 Molecular quantum**

O III

Configuration	Term	J	Level (cm^{-1})
$2s^2 2p^2$	^3P	0	0
		1	113.178
		2	306.174
$2s^2 2p^2$	^1D	2	20 273.27
$2s^2 2p^2$	^1S	0	43 185.74
$2s2p^3$	$^5S^\circ$	2	60 324.79
$2s2p^3$	$^3D^\circ$	3	120 025.2
		2	120 053.4
		1	120 058.2



Species vs spectra

- **H^0, C^{3+}, O^{2+}, H_2, CO are baryons**
- **H I, C IV, O III, H_2, and CO are the spectra they emit / absorb**
- **O III is a permitted line produced by O^{2+}, while [O III] is a forbidden line**
- **C III] is a semi-forbidden line, often an intercombination line**

Species vs spectra

- **H I Lyα *emission* can be produced by**
  - Recombination of H^+
  - Impact excitation of H^0
- **H I absorption can only be produced by H^0**
- **H I is not the same as H^0**
  - Ambiguous for emission lines

Baryons and spectra

- **Hazy 1 Section 2.5**
- **SpeciesLabels.txt in docs**
- **Molecules are not ambiguous**
  - H2
  - CO
  - O2
  - H2+
  - C2+
  - Their spectra have the same notation as the baryon

Baryons and spectra

- Atomic spectra use number of spectra
  - H 1
  - C 4
- The baryon
  - "H"
  - "He+"
  - "C+2"
  - (C2+ is C_2^+ in our notation)

Lines in the main output

- Print lines column
- Print lines sort wavelength
- Print lines faint

Finding lines in Cloudy

- A line is identified by a spectral label & wavelength
- docs/LineLabels.txt has label, wavelength, comment about line
  - Generated with command "Save line labels"
- Pick lines from this file

Air vs vacuum wavelengths

- The rule in atomic physics has been to use vacuum wavelengths for $\lambda < 2000$Å and air for $\lambda > 2000$Å
- SDSS has used vacuum for all wavelengths
- Today's papers use a mix of both
- Vacuum is probably the future
- Print line vacuum
  - But you need to change your wavelengths

Some familiar lines

Species	λ(air)	λ(vacuum)
H 1	1215.67A	1215.67A
O 2	3726.03A	3727.09A
O 2	3728.81A	3729.88A
O. 3	4363.21A	4364.44A
H 1	4861.33A	4862.69A
O 3	5006.84A	5008.24A
H. 1	6562.81A	6564.62A

Other database reporting options

- See C17 review article, section 2
- Database print

Line blends

- Blnd 3727
- Blnd 2798
- Blnd 1549

- Two or more lines that appear as a single line in most spectra

Luminosity, relative intensity

- **Intensity or luminosity of line**
  - depending on case
- **Intensity relative to normalization line, default Hβ**
  - Change with *normalize* command

O	3	88.3323m	-5.577	1.5126
O	3	51.8004m	-5.106	4.4704
O	3	4931.23A	-8.339	0.0026
O	3	4958.91A	-4.876	7.5973
O	3	5006.84A	-4.401	22.6702
O	3	2320.95A	-7.193	0.0366
O	3	4363.21A	-6.593	0.1456
O	3	1660.81A	-7.187	0.0371
O	3	1666.15A	-6.720	0.1087

Why use the laser at all

- Cloudy has lots of lines and does many levels for many ions
- A single zone (which we do for speed) is optically thin
- So continuum fluorescent excitation can be important.
- But would not happen with a finite column density

- Show fig with energy levels for H, C IV etc and say continuum photons would excite to all upper levels

Two level atom AGN3 Sec 3.5

- **Excitation, deexcitation rates**
- **Transition probabilities**
- **Critical density**
- **Two limits**
  - Low densities, every excitation leads to emission of a photon
  - high densities, levels are n LTE, photon emission proportional to n_u A_{ul}

$$4\pi j = n_u A_{ul} h\nu$$
$$[\mathrm{erg\ cm^{-3}\ s^{-1}}]$$

$$n_l q_{lu} n_e = n_u [A_{ul} + q_{ul} n_e]$$

$$\frac{n_u}{n_l} = \frac{q_{lu} n_e}{A_{ul} + q_{ul} n_e}$$

$$n_u + n_l = n$$

critical density

$$A_{ul} = q_{ul} n_{crit}$$

LDL

$$n_e \ll n_{crit}$$
$$4\pi j = n_e n_l q_{lu} h\nu$$

HDL

$$n_e \gg n_{crit}$$
$$4\pi j = n_e \frac{q_{lu}}{q_{ul}} A_{ul} h\nu$$

Why we set the ionization

- If most O were O3+ the process
- O3+ + e -> O2+ + hn
- Would be fast, and would make O III recombination lines
- This can happen in nature, but it would confuse our homework problem

Vary density over extreme range

- Plot emissivity vs density over wide range to see how emissivity changes
- Recombination line, [O III] forbidden lines

Recombination lines

- $H^+ + e \rightarrow H^{0*} \rightarrow H^0$ + photons
- Critical densities of H I, He I, and He II optical lines are very high, $n > 1e15\ cm^{-3}$, so they are usually in LDL
- Emissivity goes as n^2 for $n < 10^{20}\ cm^{-3}$
- Case B predictions
- H I, He I, He II are the strongest in UV/ Opt/ IR
- Second row (C,N, O, Ne) & Fe in X-ray

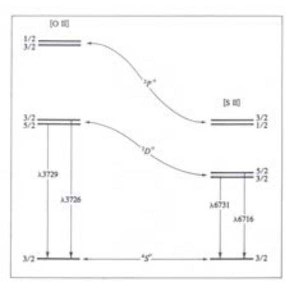
Forbidden lines

- [O III]
- $O^{++} + e \rightarrow O^{++*} + e \rightarrow O^{++} + e$ + photons
- Critical densities of many forbidden lines $n \sim 1e3\ cm^{-3}$, so they can be in LDL or HDL
- Emissivity goes as n^2 or n

Compute spectrum of clouds with two very different densities

- Hden = 4
- Hden = 14
  - How will emission from these cloud compare?
  - How can we “trick” the model into having roughly the same emission?

Density indicators



AGN3 Fig 5.7

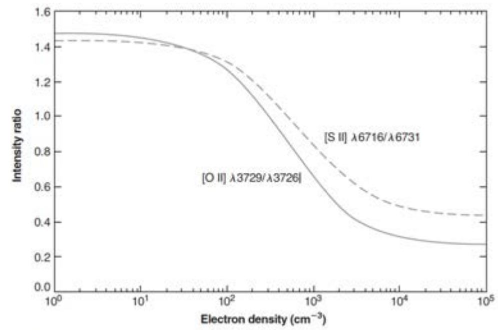
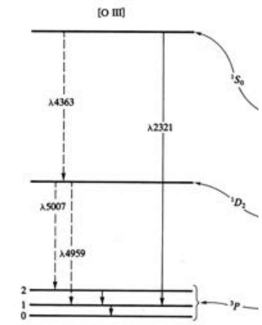


Figure 5.8

Calculated variation of [O II] (*solid line*) and [S II] (*dashed line*) intensity ratios as functions of n_e at T = 10,000 K. At other temperatures the plotted curves are very nearly correct if the horizontal scale is taken to be $n_e(10^4/T)^{1/2}$.

Temperature indicators



Temperature indicators

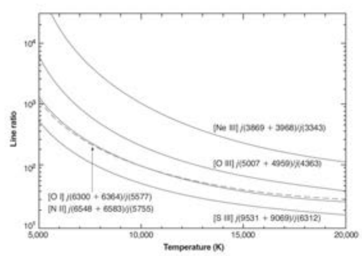


Figure 5.1

Four temperature sensitive forbidden line ratios are shown as a function of the electron temperature. The [O I] (solid line) and [N II] (dashed) ratios are nearly coincident, partially because of their similar excitation potentials. The ratios are shown in the low density limit (n_e = 1 cm^{-3}).