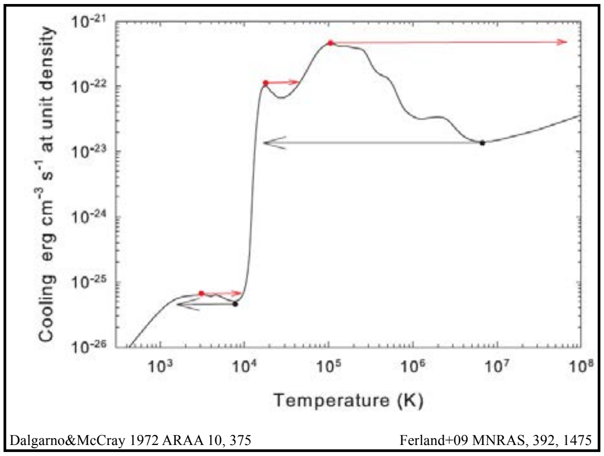
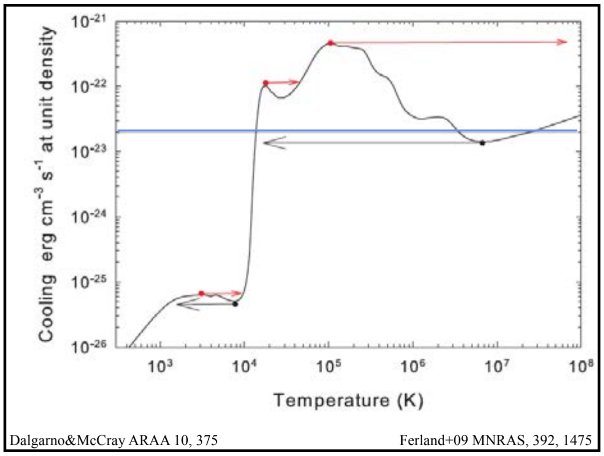


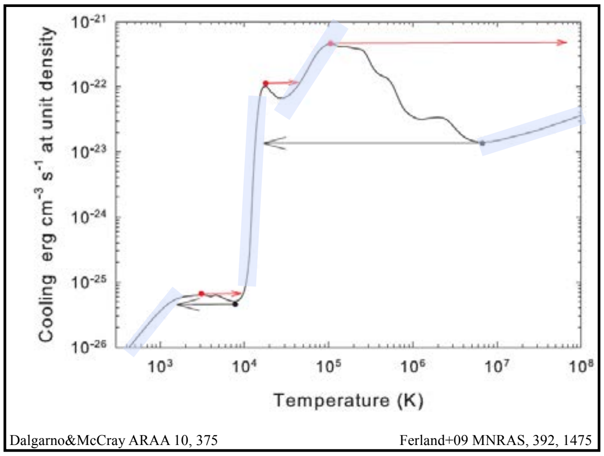
Dalgarno&McCray 1972 ARAA 10, 375

Ferland+09 MNRAS, 392, 1475



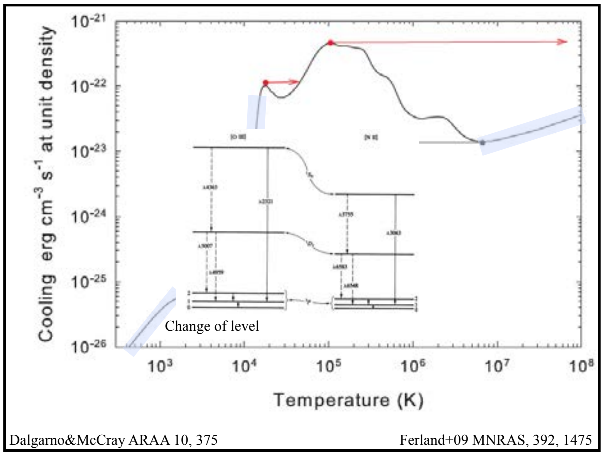
Dalgarno&McCray ARAA 10, 375

Ferland+09 MNRAS, 392, 1475



Dalgarno&McCray ARAA 10, 375

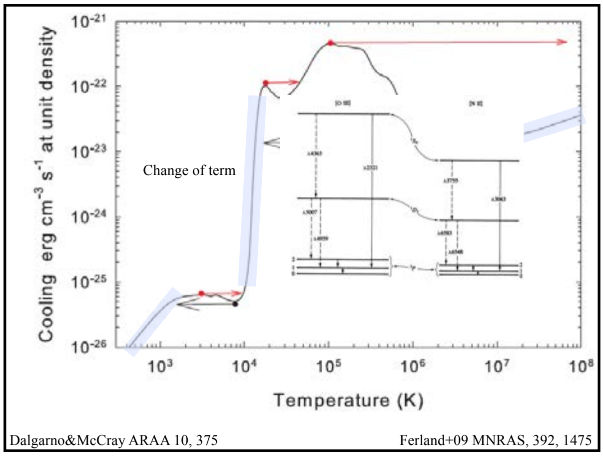
Ferland+09 MNRAS, 392, 1475



Change of level

Dalgarno&McCray ARAA 10, 375

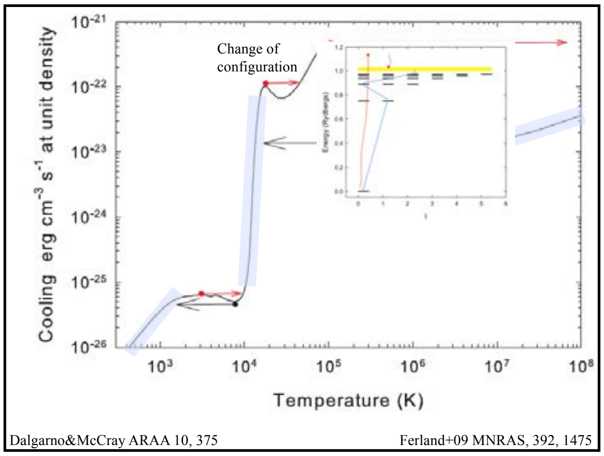
Ferland+09 MNRAS, 392, 1475



Change of term

Dalgarno&McCray ARAA 10, 375

Ferland+09 MNRAS, 392, 1475

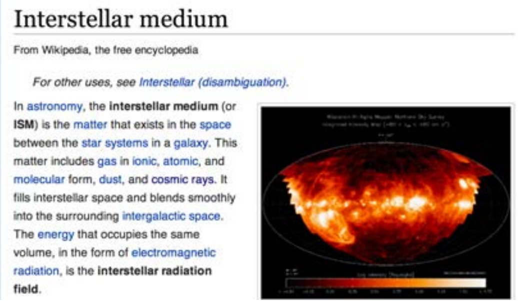


Change of configuration

Dalgarno&McCray ARAA 10, 375

Ferland+09 MNRAS, 392, 1475

http://en.wikipedia.org/wiki/Interstellar_medium



Interstellar medium

From Wikipedia, the free encyclopedia

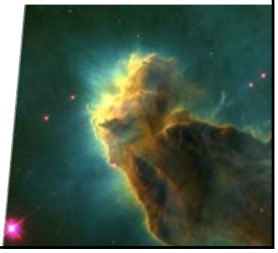
For other uses, see Interstellar (disambiguation).

In astronomy, the **interstellar medium** (or **ISM**) is the matter that exists in the space between the star systems in a galaxy. This matter includes gas in ionic, atomic, and molecular form, dust, and cosmic rays. It fills interstellar space and blends smoothly into the surrounding intergalactic space. The energy that occupies the same volume, in the form of electromagnetic radiation, is the **interstellar radiation field**.

California Nebula APOD
Xi Persei

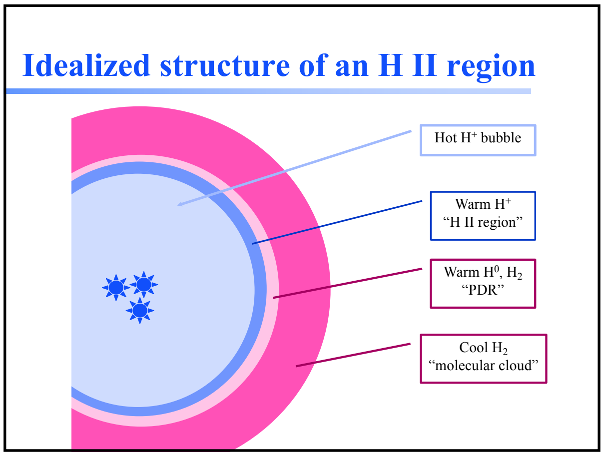
Star forming H II regions

- Hot young stars very close to the molecular cloud that formed it
- Ionizing radiation and stellar winds strike nearby molecular cloud



ESO

NASA/CXC/PSU/L.Townsley et al.; Infrared: NASA/JPL



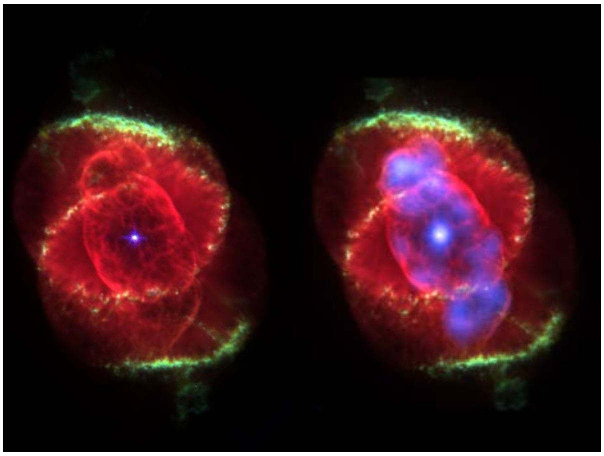
Idealized structure of an H II region

Hot H^+ bubble

Warm H^+
"H II region"

Warm H^0, H_2
"PDR"

Cool H_2
"molecular cloud"



Three-phase pressure stability

- tsuite / auto / ism_grid

Heating – cooling balance

- Both heating and cooling depend on square of density
- So no density dependence
- Try it! compare temperatures at two densities

Vary Metals –temperature balance

- **Then energy balance**
  - varyZ

Thermostat effect AN3 S9.5

- **Vary metals with temperature balance**
  - varyZ.in
- **Look at line ratios, temperature vs Z**
- **Cooling and heating vs Z**
- **Thermostat effect – line spectrum does not change dramatically when Z changes**
  - Heating and cooling are equal
  - Cooling is mainly O III lines
  - So they are constant when they are the main coolant

Vary blackbody temperature

- **Stoy or "energy balance" method of determining stellar temperatures**
- **AGN3 Section 5.10**

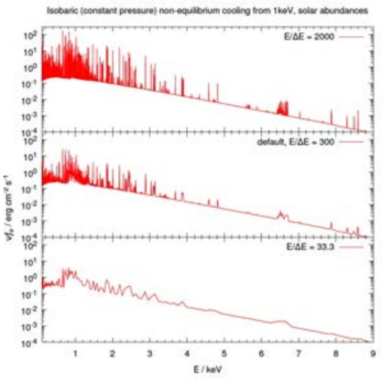
Three cases

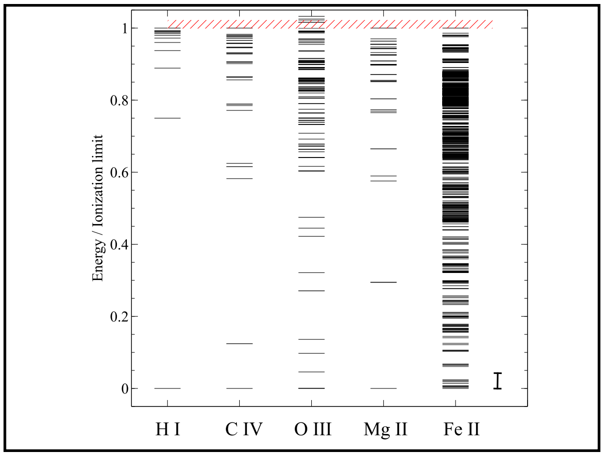
- **HII.in – set radiation field, properties of cloud determined self consistently**
  - This is how we usually use Cloudy
- **coronal.in – no radiation, but gas kinetic temperature set by external physics. Ionization and emission set by gas kinetic temperature**
- **constant temperature models – may include radiation but kinetic temperature set by external physics. Ionization determined by both radiation field and gas temperature**
  - Hazy1 Chap 11

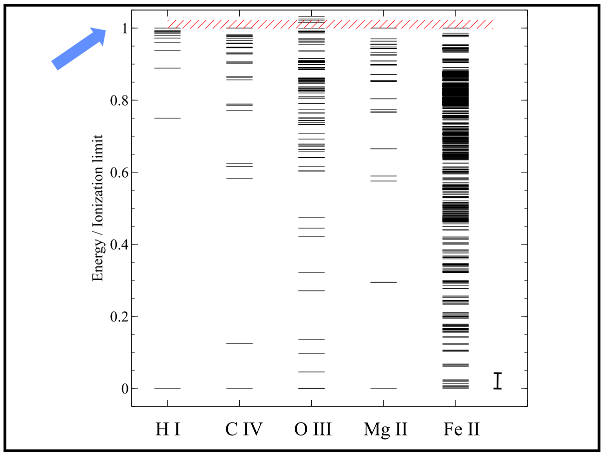
Vary blackbody temperature

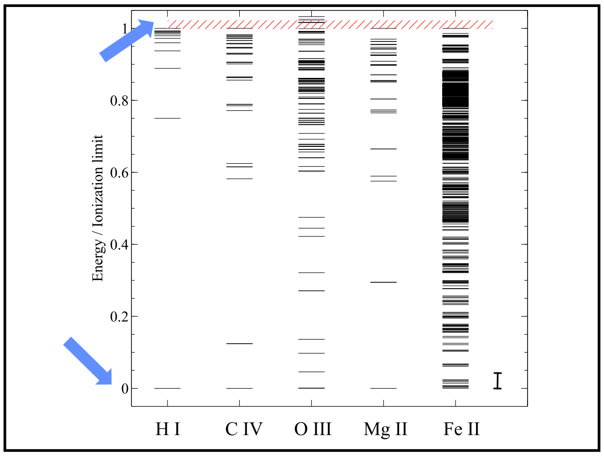
- **Stoy or “energy balance” method of determining stellar temperatures**
- **AGN3 Section 5.10**

- **How to make sense of all these lines**




Energy / Ionization limit
1
0.8
0.6
0.4
0.2
0
H I
C IV
O III
Mg II
Fe II


Energy / Ionization limit
1
0.8
0.6
0.4
0.2
0
H I
C IV
O III
Mg II
Fe II

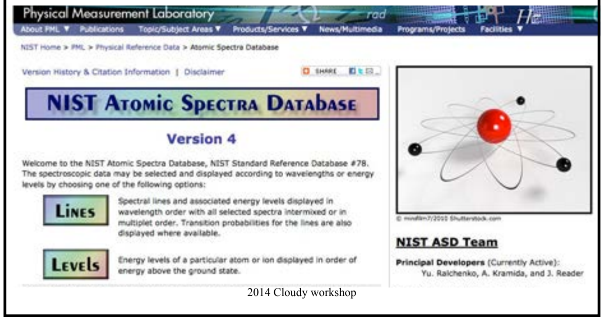

Energy / Ionization limit
1
0.8
0.6
0.4
0.2
0
H I
C IV
O III
Mg II
Fe II

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



NIST ATOMIC SPECTRA DATABASE

Version 4

Welcome to the NIST Atomic Spectra Database, NIST Standard Reference Database #78. The spectroscopic data may be selected and displayed according to wavelengths or energy levels by choosing one of the following options:

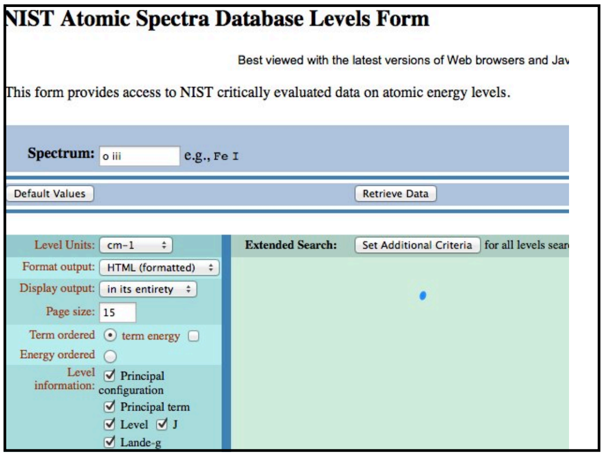
LINES Spectral lines and associated energy levels displayed in wavelength order with all selected spectra intermixed or in multiplet order. Transition probabilities for the lines are also displayed where available.

LEVELS Energy levels of a particular atom or ion displayed in order of energy above the ground state.

NIST ASD Team

Principal Developers (Currently Active):
Yu. Ralchenko, A. Kramida, and J. Reader

2014 Cloudy workshop



NIST Atomic Spectra Database Levels Form

Best viewed with the latest versions of Web browsers and Jav

This form provides access to NIST critically evaluated data on atomic energy levels.

Spectrum: o iii e.g., Fe I

Level Units: cm-1

Format output: HTML (formatted)

Display output: in its entirety

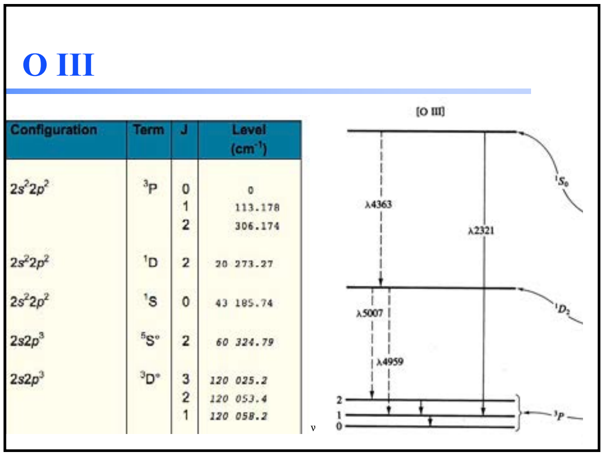
Page size: 15

Term ordered ● term energy ☐

Energy ordered ○

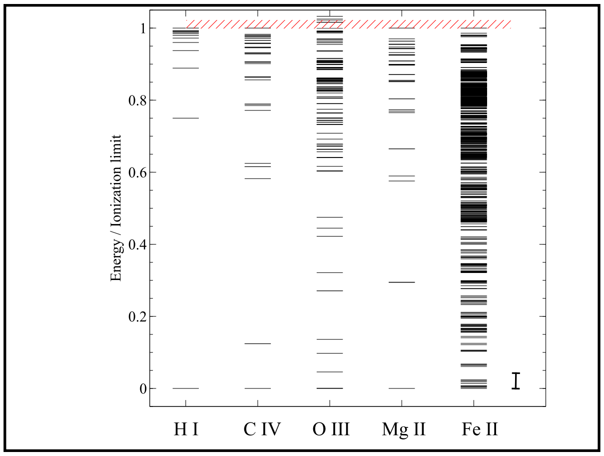
Level information: ☑ Principal configuration
☑ Principal term
☑ Level ☑ J
☑ Lande-g

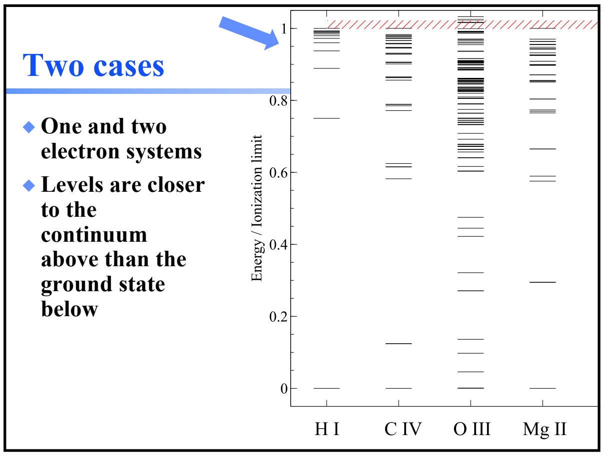
Extended Search: Set Additional Criteria for all levels sear



O III

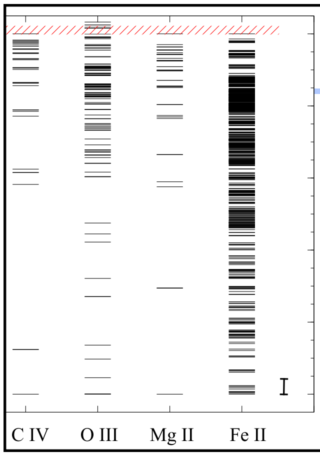
Configuration	Term	J	Level (cm^{-1})
$2s^22p^2$	^{3}P	0 1 2	0 113.178 306.174
$2s^22p^2$	^{1}D	2	20 273.27
$2s^22p^2$	^{1}S	0	43 185.74
$2s2p^3$	^{5}S°	2	60 324.79
$2s2p^3$	^{3}D°	3 2 1	120 025.2 120 053.4 120 058.2





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

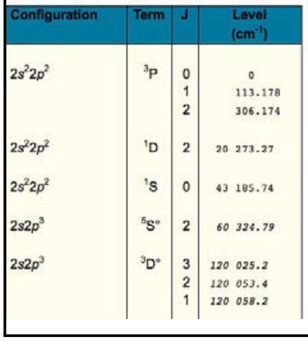
Two types of lines

- **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

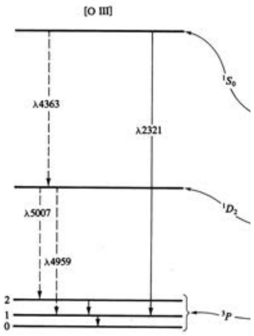
- AGN3
- Appendix 4 Nebular quantum mechanics
- Appendix 6 Molecular quantum

O III



Configuration	Term	J	Level (cm^{-1})
$2s^22p^2$	^{3}P	0	0
		1	113.178
		2	306.174
$2s^22p^2$	^{1}D	2	20 273.27
$2s^22p^2$	^{1}S	0	43 185.74
$2s2p^3$	^{5}S°	2	60 324.79
$2s2p^3$	^{3}D°	3	120 025.2
		2	120 053.4
		1	120 058.2

v



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

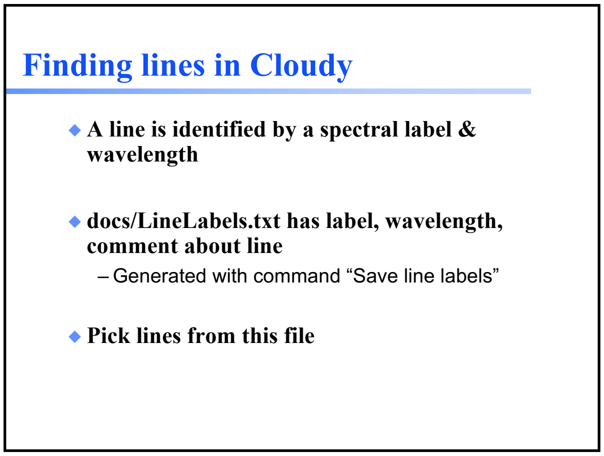
- **Hazy 1 Section 2.5**
- **SpeciesLabels.txt in docs**
- **Molecules are not ambiguous**
  - H2
  - CO
  - O2
  - H2+
  - C2+
  - Their spectra have the same notation as the baryon

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)

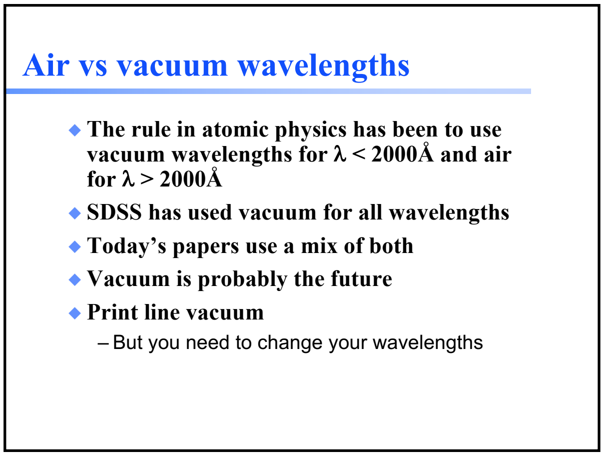
Lines in the main output

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



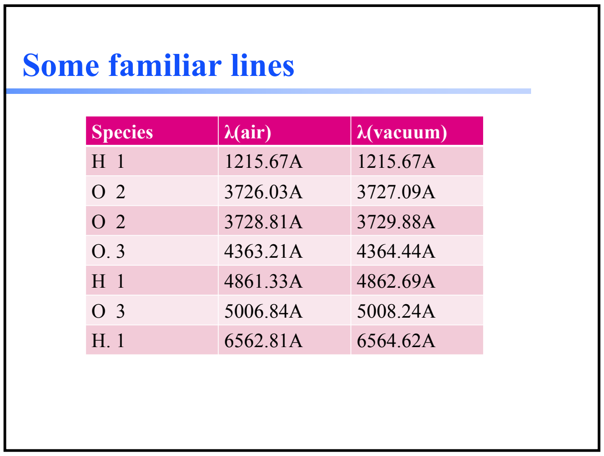
Finding lines in Cloudy

- 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
```

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 dencity

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

$$n_e \ll n_{crit}$$

LDL

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

$$n_e \gg n_{crit}$$

HDL

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

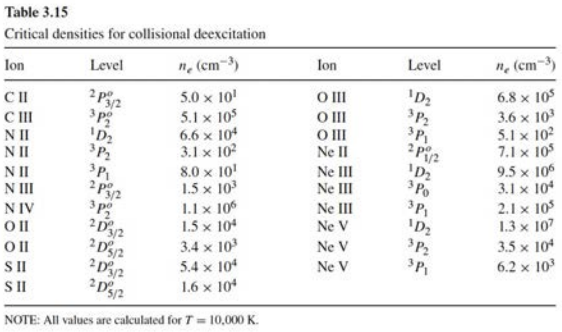


Table 3.15

Critical densities for collisional deexcitation

Ion	Level	n_e (cm^{-3})	Ion	Level	n_e (cm^{-3})
C II	$^2P^o_{3/2}$	5.0×10^1	O III	$^1D_2$	6.8×10^5
C III	$^3P^o_2$	5.1×10^5	O III	$^3P_2$	3.6×10^3
N II	$^1D_2$	6.6×10^4	O III	$^3P_1$	5.1×10^2
N II	$^3P_2$	3.1×10^2	Ne II	$^2P^o_{1/2}$	7.1×10^5
N II	$^3P_1$	8.0×10^1	Ne III	$^1D_2$	9.5×10^6
N III	$^2P^o_{3/2}$	1.5×10^3	Ne III	$^3P_0$	3.1×10^4
N IV	$^3P^o_2$	1.1×10^6	Ne III	$^3P_1$	2.1×10^5
O II	$^2D^o_{3/2}$	1.5×10^4	Ne V	$^1D_2$	1.3×10^7
O II	$^2D^o_{5/2}$	3.4×10^3	Ne V	$^3P_2$	3.5×10^4
S II	$^2D^o_{3/2}$	5.4×10^4	Ne V	$^3P_1$	6.2×10^3
S II	$^2D^o_{5/2}$	1.6×10^4			

NOTE: All values are calculated for $T = 10{,}000$ K.

Vary density over extreme range

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

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

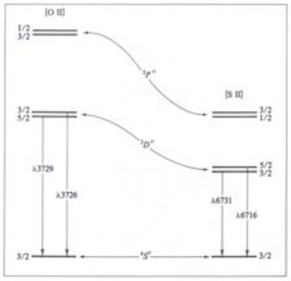
Forbidden lines

- [O III]
- $O^{++} + e \rightarrow O^{++*} + e \rightarrow O^{++} + e$ + photons
  - $n_e\, n(O^{++})\, q_{ul}$
- Critical densities of many forbidden lines $n \sim$ 1e3 - 1e5 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

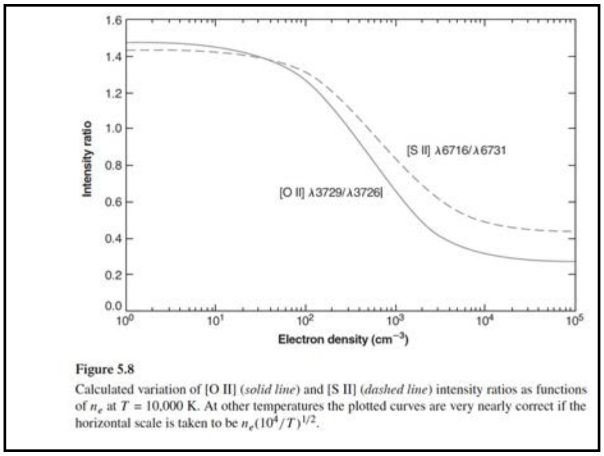
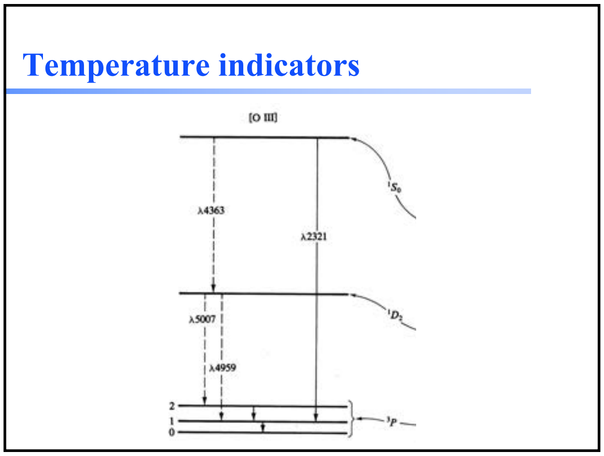


Figure 5.8

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

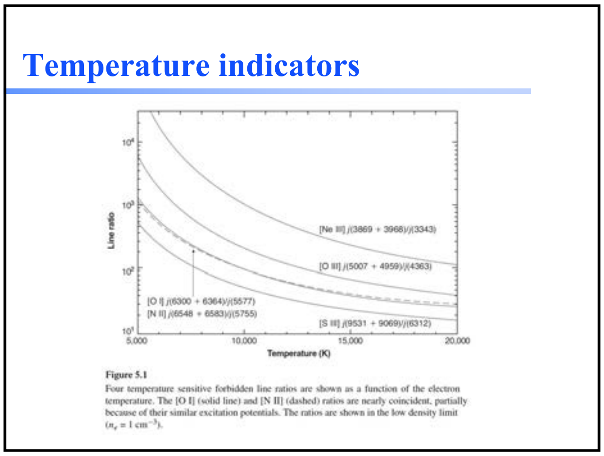


Figure 5.1

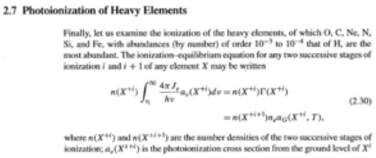
Four temperature sensitive forbidden line ratios are shown as a function of the electron temperature. The [O I] (solid line) and [N II] (dashed) ratios are nearly coincident, partially because of their similar excitation potentials. The ratios are shown in the low density limit ($n_e = 1$ cm^{-3}).

Radiative recombination edges

- Hrec3, hrec4.in in sims
- Hrec spreadsheet in sims
- Maybe do in x-rays instead? More common application

The ionization parameter

- U, the ratio of ionizing photon to hydrogen densities
- See Davidson & Netzer 1979



2.7 Photoionization of Heavy Elements

Finally, let us examine the ionization of the heavy elements, of which O, C, Ne, N, Si, and Fe, with abundances (by number) of order 10^{-3} to 10^{-4} that of H, are the most abundant. The ionization-equilibrium equation for any two successive stages of ionization i and $i+1$ of any element X may be written

$$n(X^{+i})\int_{\nu_i}^{\infty}\frac{4\pi J_\nu}{h\nu}a_\nu(X^{+i})d\nu = n(X^{+i})\Gamma(X^{+i}) = n(X^{+i+1})n_e\alpha_G(X^{+i},T), \quad (2.30)$$

where $n(X^{+i})$ and $n(X^{+i+1})$ are the number densities of the two successive stages of ionization; $a_\nu(X^{+i})$ is the photoionization cross section from the ground level of X^i

U and T(star) determine ionization

- No matter how intense the radiation field, how large the U, ions with ionization potentials higher than the highest energy in the SED cannot be produced