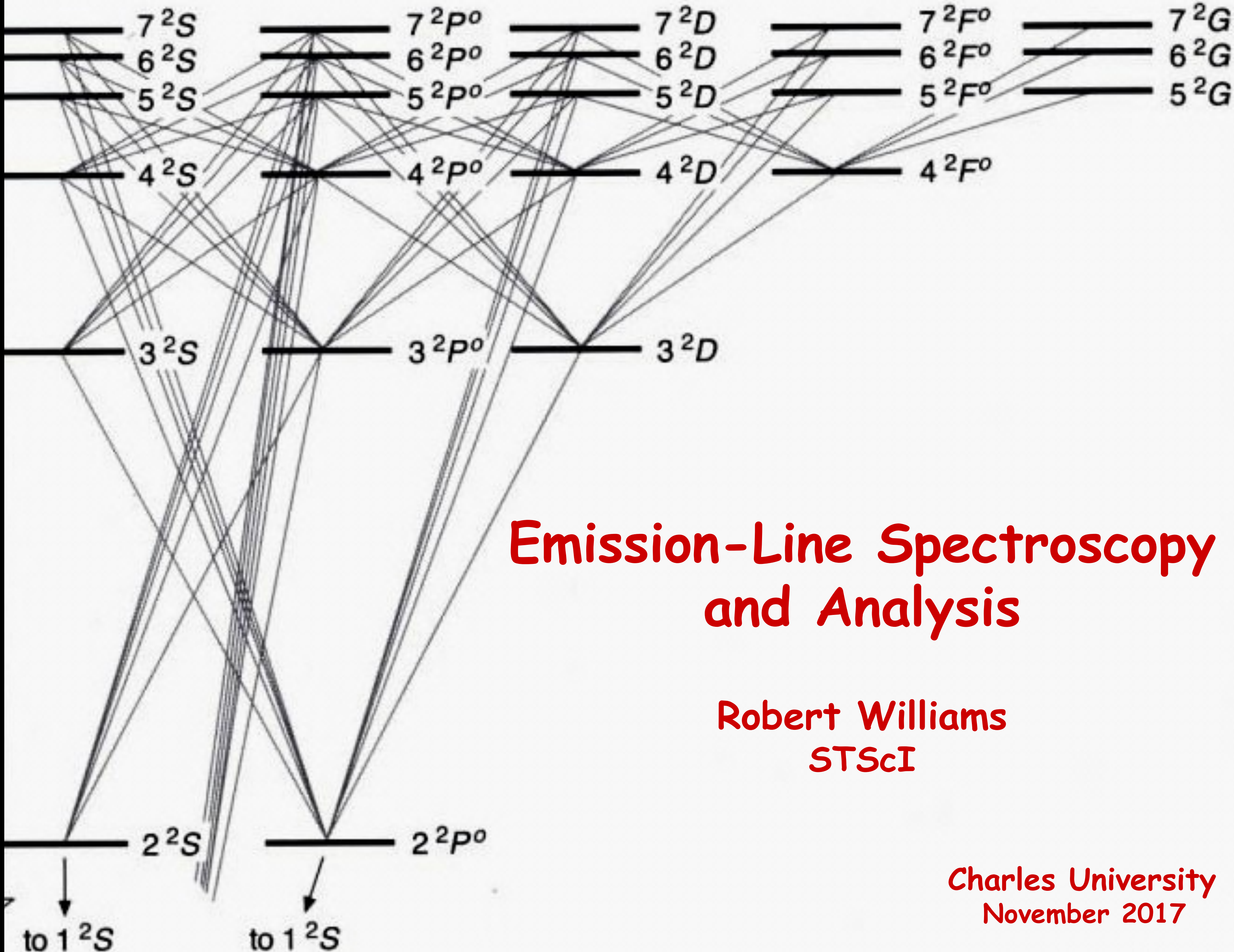

Emission-Line Spectroscopy and Analysis

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STScI

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Various topics to be addressed:

- Processes that govern ISM/nebular excitation and ionization
- Diagnostic information obtained from different kinds of transitions
- Why most ionized (nebular) regions have kinetic T_e~10^4 K
- The Balmer decrement (H recombination spectrum)
- Why forbidden lines are prominent in ionized gas regions
- e-databases useful for spectroscopy

Reference Books:

-Osterbrock, D. E. & Ferland, G. J. 2006, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei 2nd edn* (Sausalito: Univ. Sci. Books)

-Pradhan, A.K. & Nahar, S.N. 2011, *Atomic Astrophysics & Spectroscopy* (Cambridge: Cambridge Univ. Press)

-Bashkin, S. & Stoner, J. 1975, Atomic Energy Levels & Grotrian Diagrams (North-Holland: Amsterdam)

- v2.05 Atomic Line List website: http://www.pa.uky.edu/~peter/newpage/
- NIST Atomic Spectra Database website: https://www.nist.gov/pml/atomic-spectra-database

stanley bashkin and john o. stoner, jr

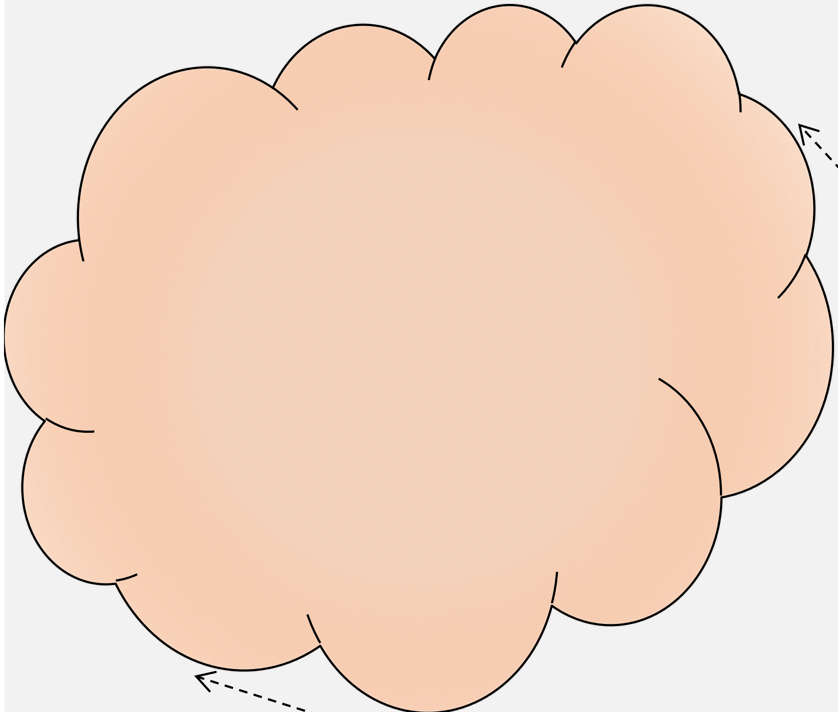
atomic energy levels & grotrian diagrams 1

hydrogen I – phosphorus XV

north-holland/american elsevier

Lecture 1

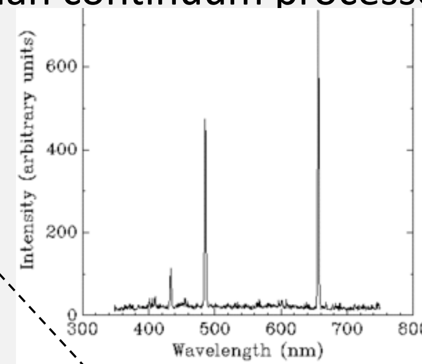
- Emission spectra
- Spectroscopic notation
- Atomic processes
- Interaction rates
- Cross sections



<u>Emission Spectrum</u>: produced in ***Statistical Equilibrium***:

-Mean free path of photons > size of object (***'opt thin'***)

-Due to bound-bound (line) transitions have larger cross sections than continuum processes for emission



Emission Spectrum

--Originate in low density objects

--(Photon) mean free path = $1/(n\sigma)$

(n α R^{-3} for constant mass) $\propto$ R^3

Therm Equilib: *applies whenever physical processes that determine thermodynamic properties of a gas (P, n, T) occur over distance scales less than distances over which n & T change. (Mean free path small -> isolation)*

<u>Continuous Spectrum</u>: produced whenever . . . .

-Mean free path of photons << size of object (***'opt thick'***)

-In high density, ***Thermodynamic Equilibrium*** applies:

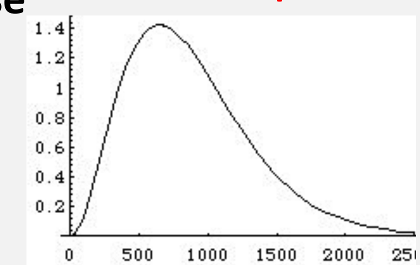
Isolation<->**'Detailed Balance'**<-> **reaction rates = their inverse**

> intensity, I_v = Planck fn $B_v(T)$

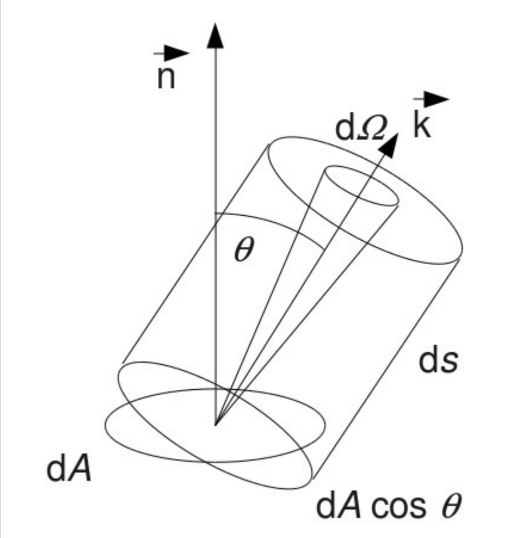
> velocity distribution, f(v) = Max-Boltzmann fn

> ionization & excitation = Saha and Boltzmann eqns

Continuous Spectrum



Emission Spectrum



Define:

Intensity, $\mathbf{I_\nu}$ = radiant energy crossing surface per unit (area•time•solid angle•freq) [erg/(cm^2 sec ster Hz)]

Flux, F_ν = radiant energy crossing surface *in all directions* per unit (area•time•freq) [erg/(cm^2 sec Hz)]

$$= \int \mathbf{I_\nu} \cos\Theta \, d\Omega$$

Equation of Radiative Transfer:

$$d\mathbf{I_\nu}/ds = j_\nu - \kappa_\nu \mathbf{I_\nu} \longrightarrow \mathbf{I_\nu} = \int j_\nu \, ds \quad \text{if no absorption}$$

(Volume) Emission coefficient, j_ν = energy emitted per unit (volume•time•solid angle) [erg/(cm^3 sec ster)] *for transition* i ➔j

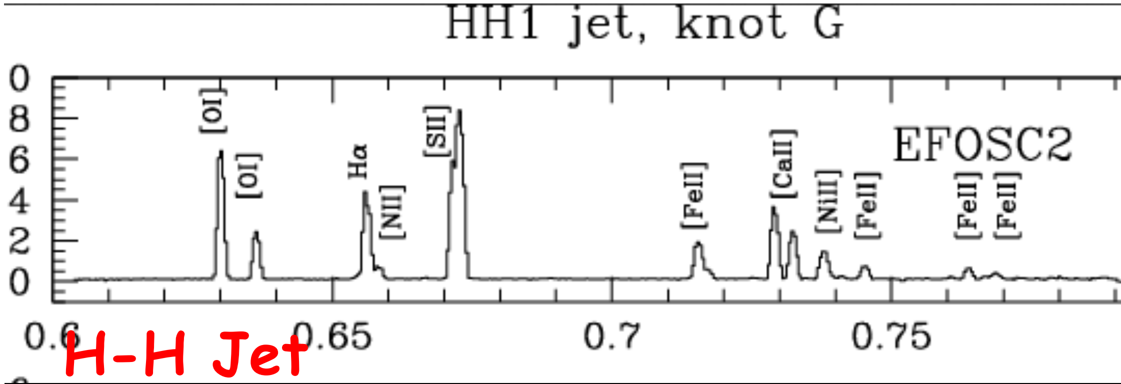
$$= n_i A_{ij} h\nu_{ij}/4\pi \quad \text{for emission } \textbf{\textit{line}} \text{ transitions } i \rightarrow j$$

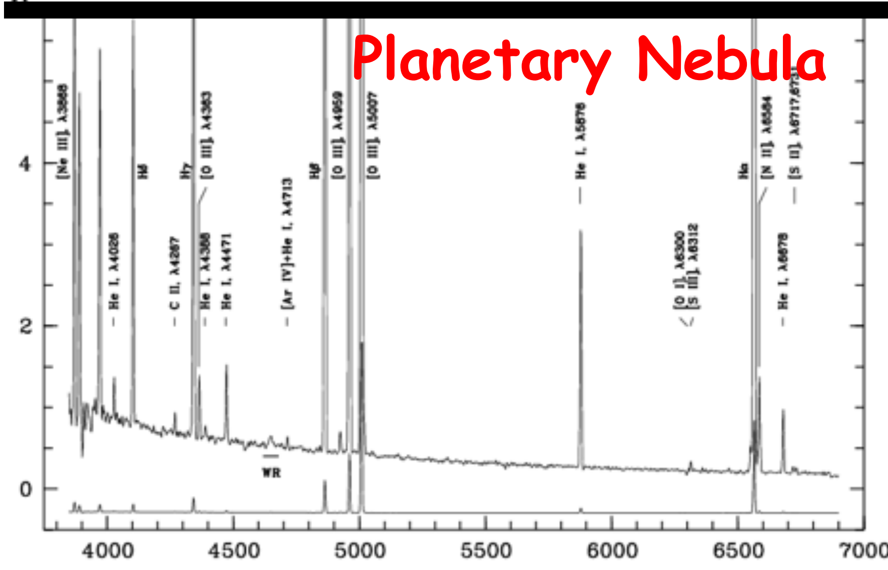
(Volume) Absorption coefficient, $\kappa_\nu = n\, a_\nu$ = 1/(mean free photon path) [cm^{-1}]

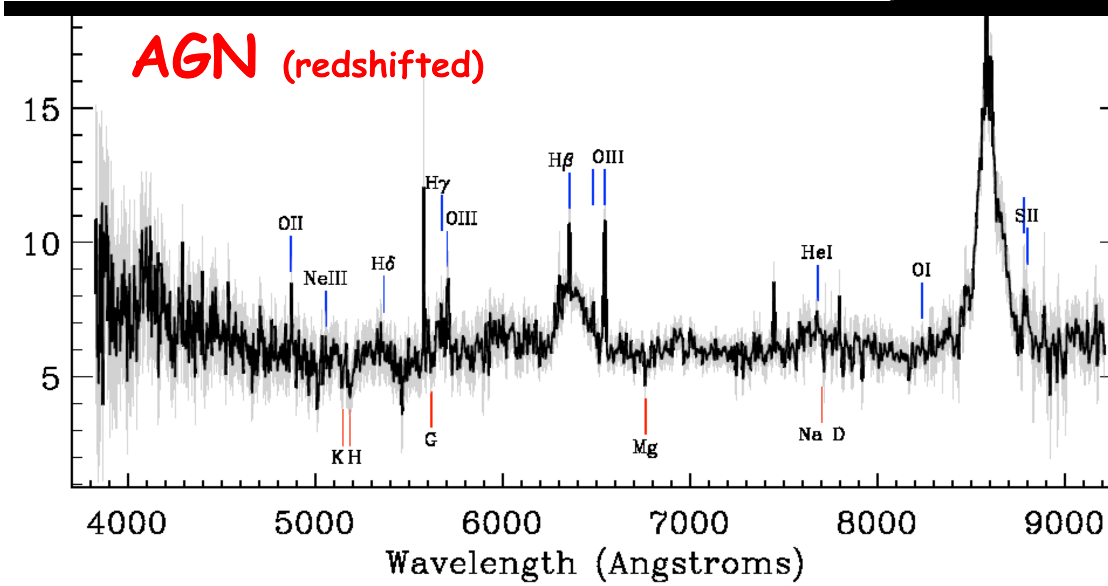
where n = density of absorbers [cm^{-3}]

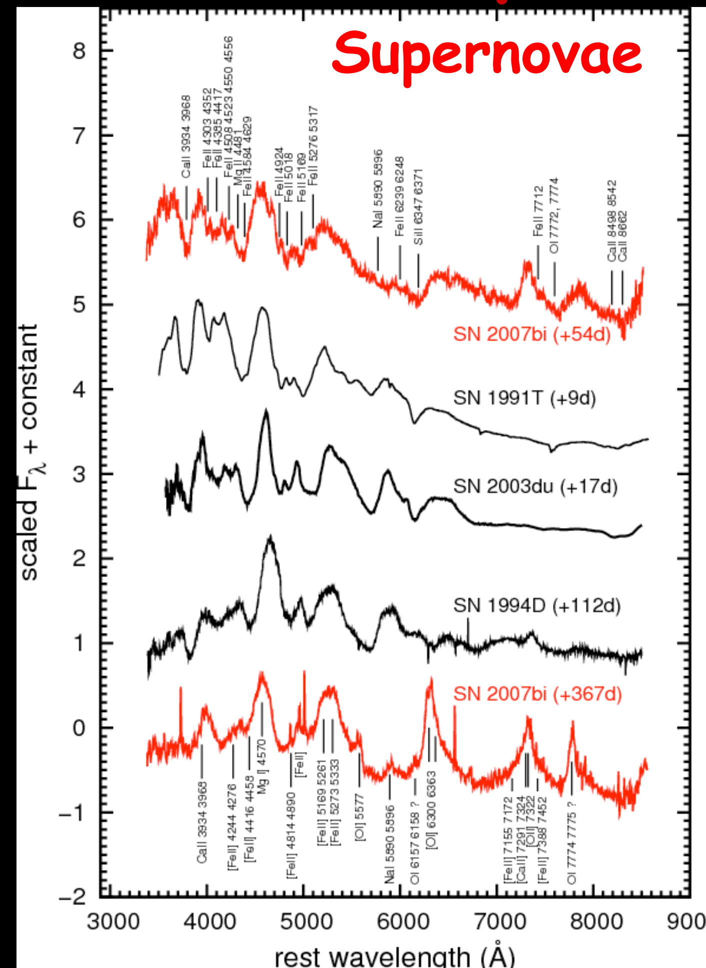
a_ν = absorption cross section [cm^2]

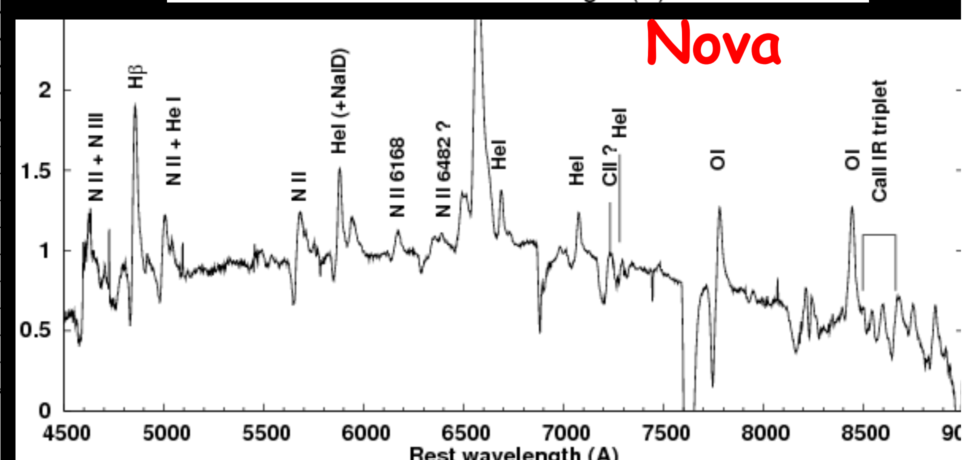
Emission-line Spectra



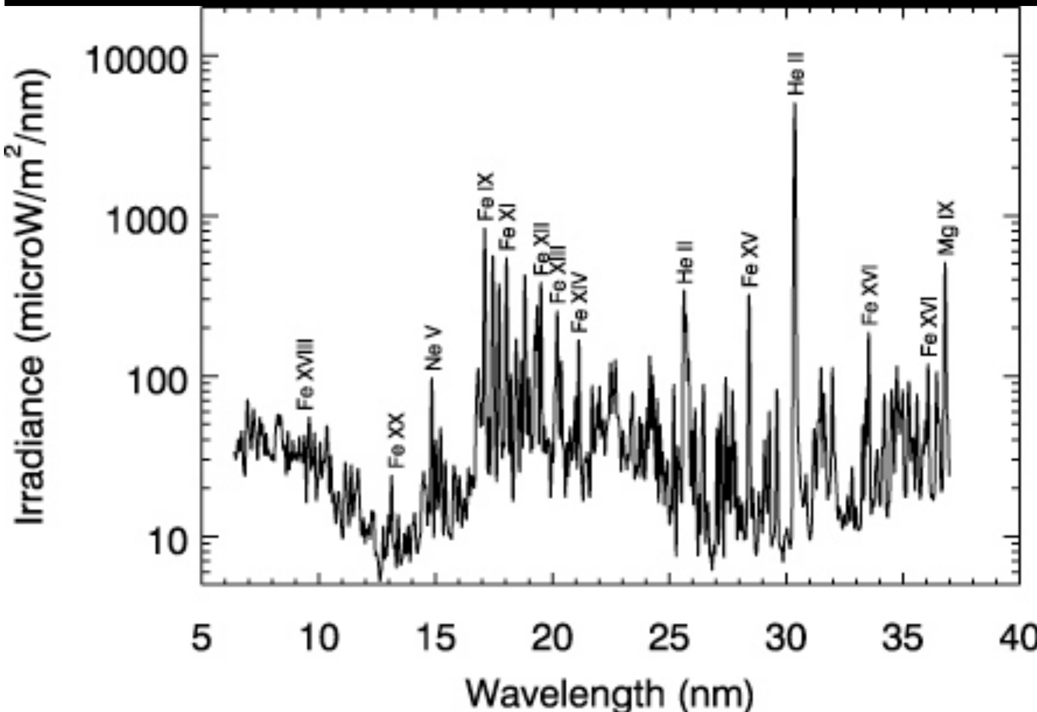




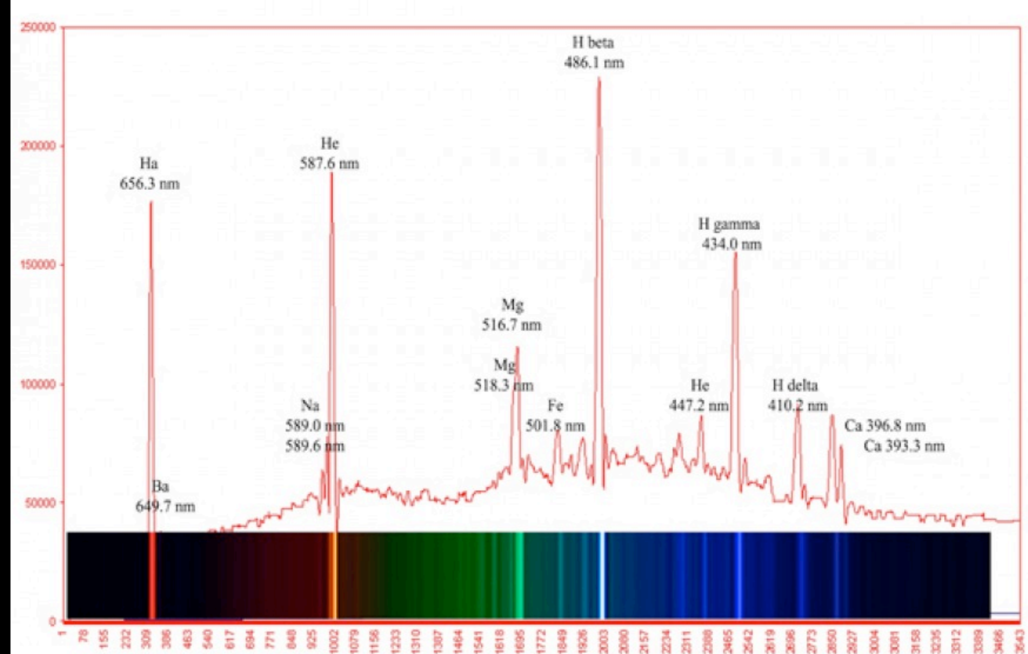


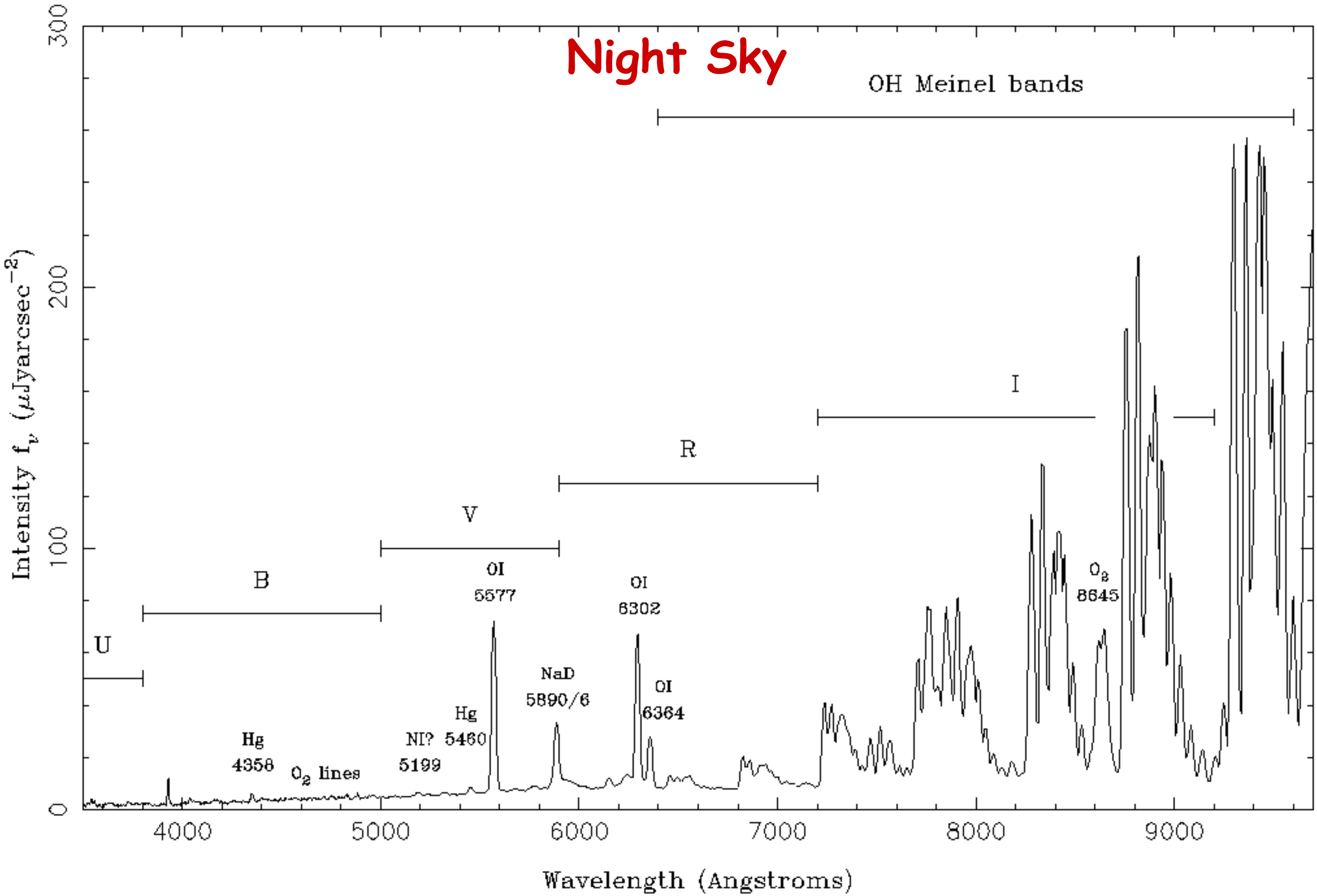


Solar Corona & Chromosphere



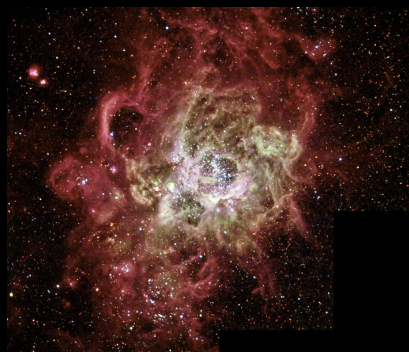
The Solar Chromosphere Spectrum (Flash Spectrum)

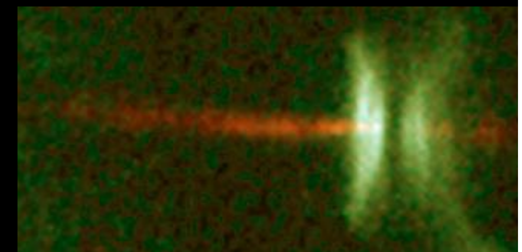




Night Sky
OH Meinel bands
U
B
V
R
I
Hg 4358
O2 lines
NI? 5199
Hg 5460
OI 5577
NaD 5890/6
OI 6302
OI 6364
O2 8645
Intensity f_ν (μJyarcsec^-2)
Wavelength (Angstroms)
0
100
200
300
4000
5000
6000
7000
8000
9000

Ionized ISM Constituents





	H II Regions	Planetary Nebulae	Nova & Supernova Remnants	Herbig-Haro Object Jet
Size	1-100 pc	0.2 pc	1 – 50 pc	1,000 au
Mass	$10^{4\text{-}6}\ M_\odot$	0.3 $M_\odot$	1-10 $M_\odot$	10^{-6} M
Lifetime	$10^{7\text{--}8}$ yr	2×10^4 yr	10^4 yr	10^6 yr
Abundances	Solar	CNO~2 Solar	>10 Solar	~Solar
Expansion velocities	5-10 km/s	20-30 km/s	$10^{2\text{-}3}$ km/s	100 km/s
Energy source	O Association hot stars	RG→WD hot central star	Explosion of SN + pulsar	Stellar grav Potential; mag field

Atomic Energy Levels

- Energy levels are determined by the **Schroedinger Eqn**

$$H\psi = E\psi$$

where H is the Hamiltonian of a charged particle with spin in an electric field:

$$H = p^2/2m - Ze^2/4\pi\varepsilon_o r + (\ )\, \underline{s}\bullet\underline{\ell} + (\ )\, \underline{s}\bullet\underline{s}$$

In quantum mechanics the momentum operator p can be replaced by $\hbar/i\ \partial/\partial x$.

For a spherically symmetric system $H\psi = E\psi \longrightarrow -\hbar^2/2m\ \nabla^2\psi - Ze^2/4\pi\varepsilon_o r = E\psi$

In spherical polar coordinates:

$$\boxed{-\hbar^2/2mr^2 \left[\partial/\partial r\,(r^2\partial\psi/\partial r) + 1/\sin\Theta\ \partial/\partial\Theta\,(\sin\Theta\ \partial\psi/\partial\Theta) + 1/\sin^2\Theta\,(\partial^2\psi/\partial\Phi^2\right] - Ze^2\psi/4\pi\varepsilon_o r = E\psi}$$

The solution of the Schroedinger eqn for the single e^- atom can be written generally in the form

$$\psi_{nlm} = A_{nlm}\, L_{nl}(r)\, P_{lm}(\cos\Theta)\, e^{im\phi}$$ with eigenstate energy: E_{nlms}

Laguerre & Legendre polynomials

Energy Levels & Spectroscopic Notation

- The energy levels of many-electron atoms/ions are specified by the quantum numbers of the electrons:

  $n_i \rightarrow$ orbit of each electron i
  $\ell_i \rightarrow$ orbital angular momentum of each electron, with $\ell_i < n_i$ (ℓ_i=0 [s], ℓ_i =1 [p])
  $L \rightarrow$ orbital angular momentum of the state $= \sum \ell_i$ (vector) (L=1 [S], L=2 [P])
  $S \rightarrow$ spin angular momentum of the state $= \sum s_i$ (vector) (where $s_i = \frac{1}{2}$)
  $J \rightarrow$ total angular momentum of the state $= \underline{L} + \underline{S}$ (vector)

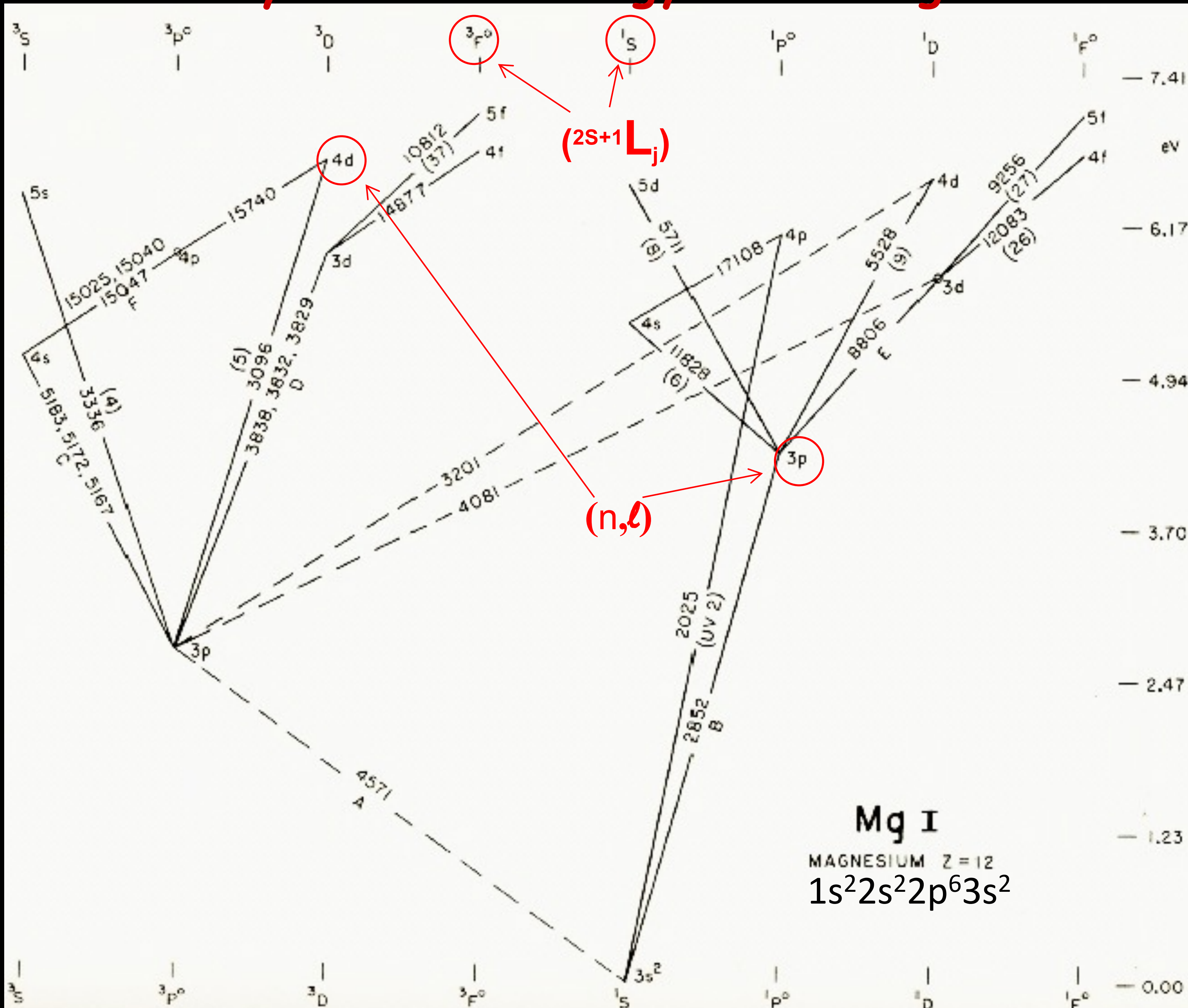
- Specification of these quantities represents a distinct state with a unique energy. For "L-S coupling", the *energy levels are most sensitive to the quantum numbers n_i - ℓ_i - L - S – J in that order.*

- The spectroscopic notation of different energy states uses the convention:

$$(n_i, \ell_i)\ ^{2S+1}L_J \qquad \text{for example: } [1s^2 2s^2 2p^6]\, 3s^2\ ^1S_0$$

For example, the configurations **$1s^2$** $^1S_0$ & **$1s2p$** $^3P_2$ represent two different energy states of helium, with the second state ($^3P_2$) having the higher energy because one electron is in a higher orbit.

Many-Electron Energy Level Diagram



Ionized ISM Physical Processes

	Process	Description	Comments
RADIATIVE	Photoionization	$A^i + h\nu \rightarrow A^{i+1} + e^-$	Energy threshold: $h\nu \geq \chi_I$. Main source of ISM ionization.
	Recombination	$A^{i+1} + e^- \rightarrow A^i_* + h\nu$	Source of bound-free continuum radiation. Inverse of photoionization
	Spontaneous Radiative Decay	$A^i_* \rightarrow A^i + h\nu_1$	No energy threshold. Most common form of de-excitation. Primary source of emission lines
	Photoexcitation/ Fluorescence Excitation	$A^i + h\nu \rightarrow A^i_*$	$h\nu = \Delta E$. Populates a few specific levels. Usually followed by spontaneous radiative decay
COLLISIONAL	Collisional: Ionization Excitation De-excitation	$A^i + e^- \rightarrow A^{i+1} + e^- + e^-$ (ionization) $\rightarrow A^i_* + e^-$ (excitation) $A^i_* + e^- \rightarrow A^i + e^-$ (de-excitation)	Threshold: $\frac{1}{2} m_e v^2 \geq \chi_I$ (i.e., $kT_e \geq \chi_I$) $\frac{1}{2} m_e v^2 \geq \chi_{exc}$ (e^- coolant) No energy threshold
	Dielectronic Recombination	$A^{i+1} + e^- \rightarrow A^i_{**}$	No radiation emitted. Large cross section, subject to condition: $\frac{1}{2} m_e v^2 = \chi^2_{exc} - \chi^1_{exc}$
	Autoionization	$A^i_{**} \rightarrow A_*^{i+1} + e^-$	Often follows dielectronic recombn if there is no stabilizing emission: $A^i_{**} \rightarrow A^i_* + h\nu$
	Charge Exchange	$A^i + H^o \leftrightarrow A^{i-1} + H^+ + \Delta E$	Large resonance ($\Delta E \sim 0$) cross section. Controls $O^0 \leftrightarrow O^+$ ionization

A^i_* = excited state of ion i; A^i_{**} = doubly excited state of ion i

General 'Interaction Rate' Equation

(from Transport Theory)

* Define $\sigma = \pi r_o^2$ as the cross section for interactions between particles of types A & B, so that if an A & B particle come within distance r_o the interaction occurs (statistically). For most interactions $\sigma(v) \propto v^{-n}$ ($n>0$) because higher velocity particles have greater self energy and spend less time influenced by the interaction field.

Let n_A , n_B = number density of particles A & B (cm^{-3})

$f(v)\,dv$ = particle speed distribution function (usually Maxwell-Boltzmann) $\propto v^2 \exp(-mv^2/2kT)$

$\sigma(v)$ = interaction cross section (cm^2) (typically $\sigma \sim 10^{-16}\ cm^2$ for particle interactions)

v_o = threshold velocity for interaction to occur (from energetics)

Then, the no. of interactions per unit volume and time is easily shown to be

$$\boxed{\text{Number of A-B interactions/(cm}^3\text{ sec)} = n_A\, n_B \langle \sigma(v)\, v \rangle} \quad cm^{-3}\ s^{-1}$$

$$\text{where} \quad \langle \sigma(v)\, v \rangle \equiv q(T) \equiv \int_{v_o}^{\infty} \sigma(v)\, v\, f(v)\, dv$$

'collision coefficient'

$$\propto T^{-1/2} \exp(-mv_o^2/2kT) \qquad [\text{for } \sigma(v) \propto v^{-2}]$$

* For radiation the photon density n_ν is related to the mean intensity of radiation J_ν by

$$n_\nu = 4\pi J_\nu/(ch\nu)$$

Thus, the rate of radiative interactions (absorption, ionization, etc.) for an ion i is

$$\text{Number of absorptions by ion i /(cm}^3\text{ sec)} = n_\nu\, n_i \langle \sigma_\nu\, c \rangle = \boxed{n_i \int_{\nu_i}^{\infty} 4\pi J_\nu \sigma_\nu / h\nu \; d\nu}$$

(typically $\sigma_\nu \sim 10^{-18}\ cm^2$ for continuum radiative interactions)

Cross Sections