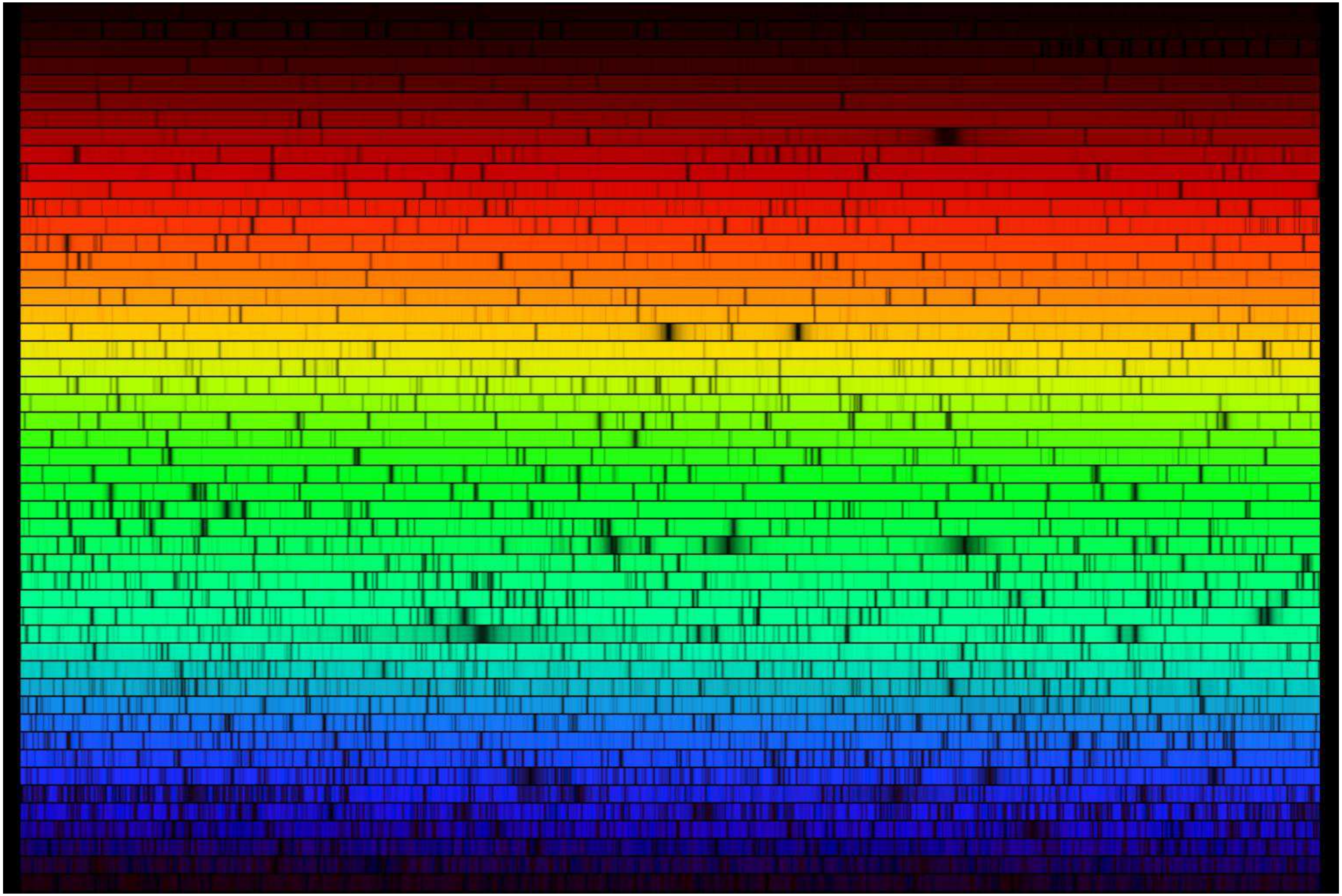
Atomic Spectra in Astrophysics



Potsdam University : Wi 2016-17 : Dr. Lidia Oskinova

lida@astro.physik.uni-potsdam.de

Types of Astronomical Spectra: Emission and absorption spectrum

- Absorption: cooler material in front of hotter material emitting light in suitable wavelength range
- Emission: requires atoms or ions in an excited state
- Stars, emission nebulae, galaxies, quasars

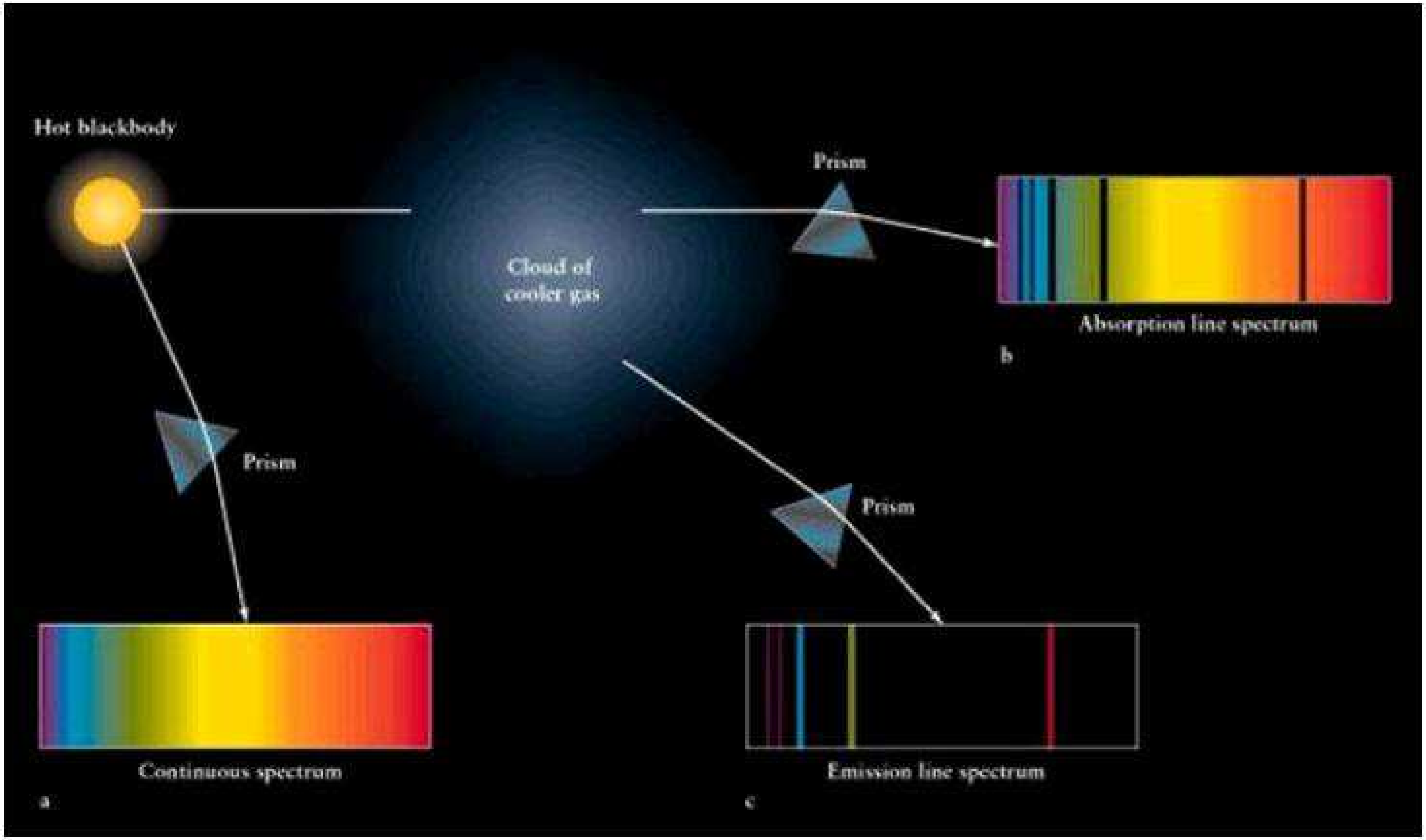
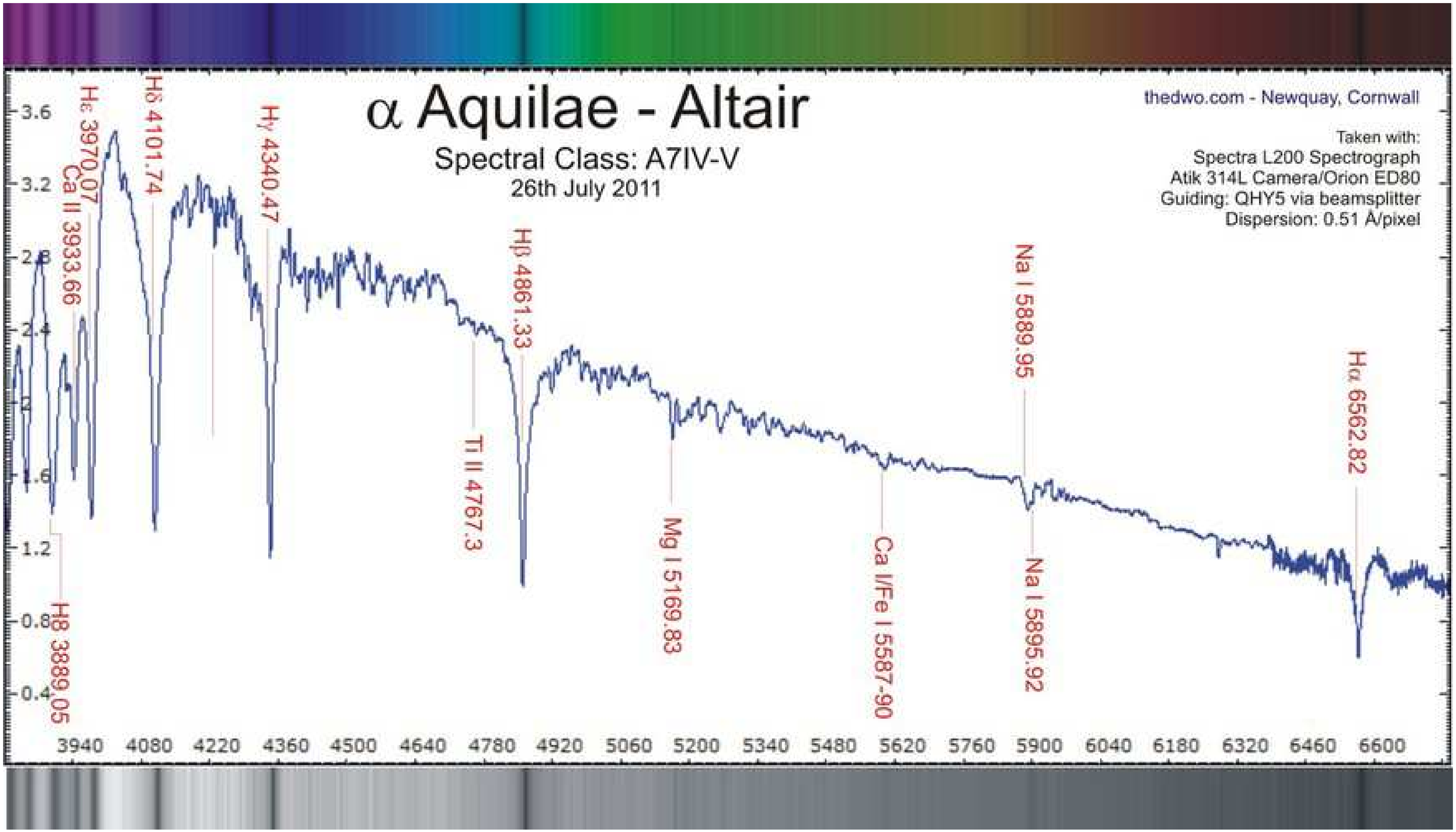


Fig: Emission & Absorption spectrum

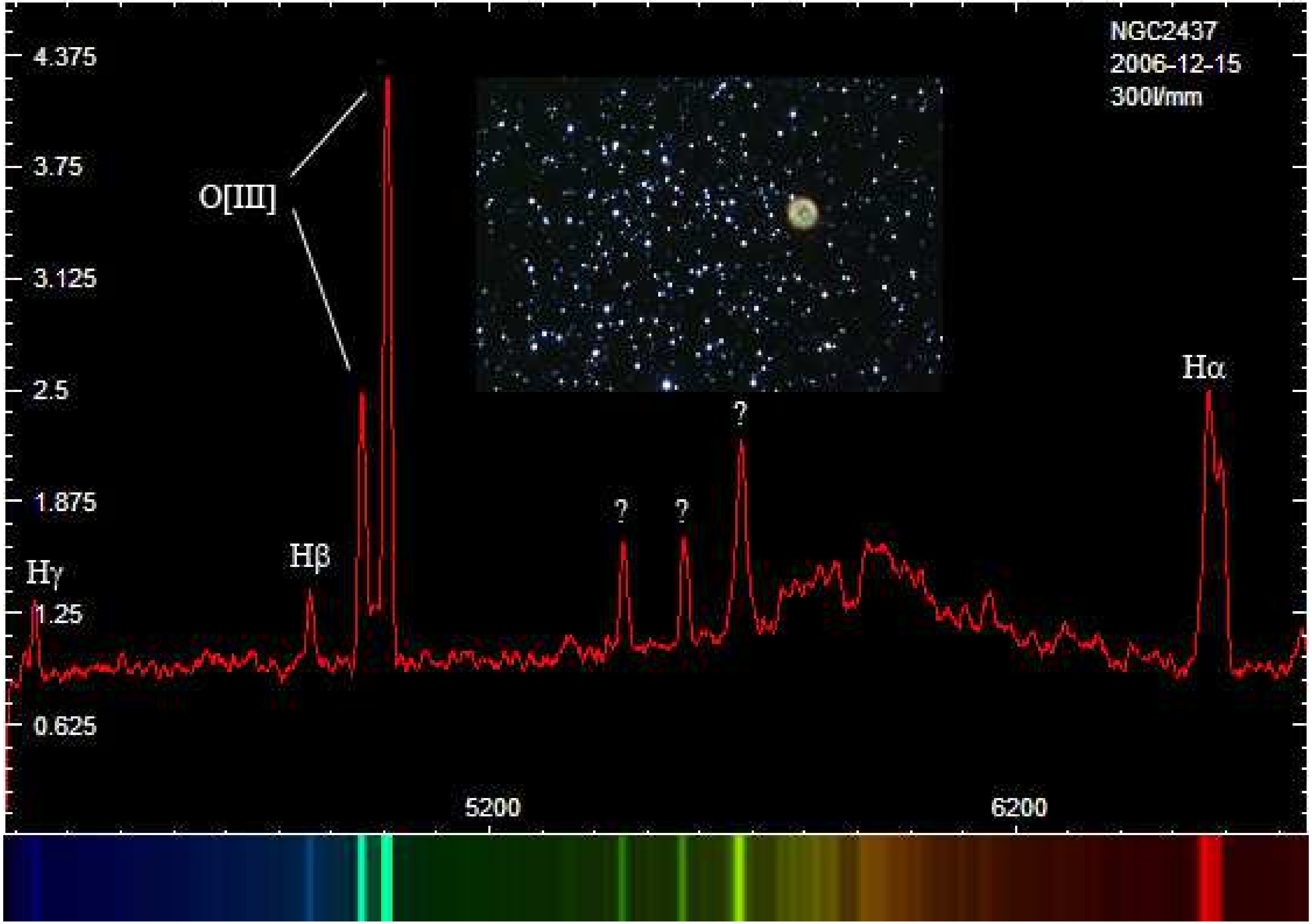
Stars

Stellar photosphere is blackbody with T_{eff}. Absorption lines formed in cooler atmosphere.



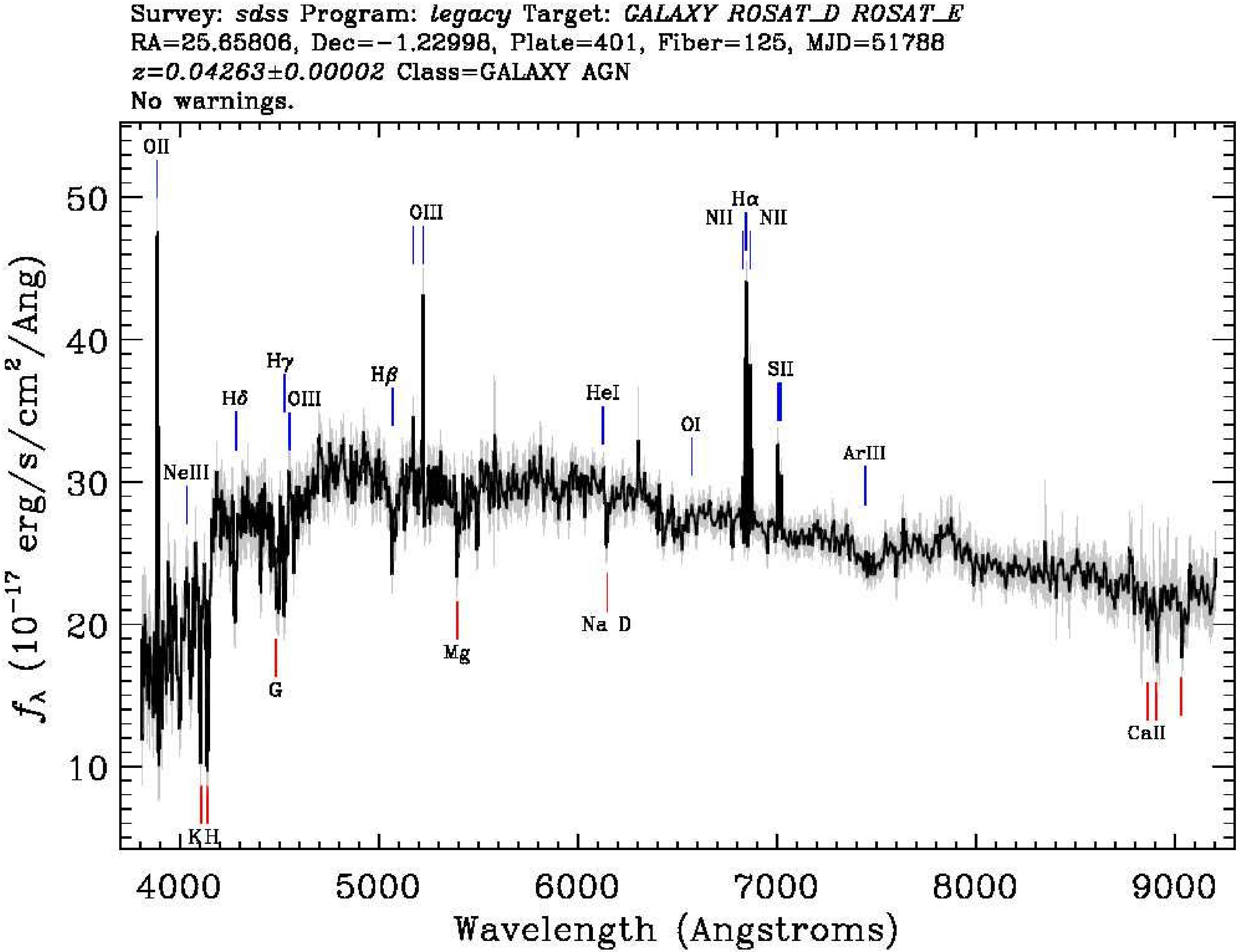
Emission nebulae

Emission is formed in optically thin nebular gas. There is no source of cintinous radiation (like bb) behind the nebular

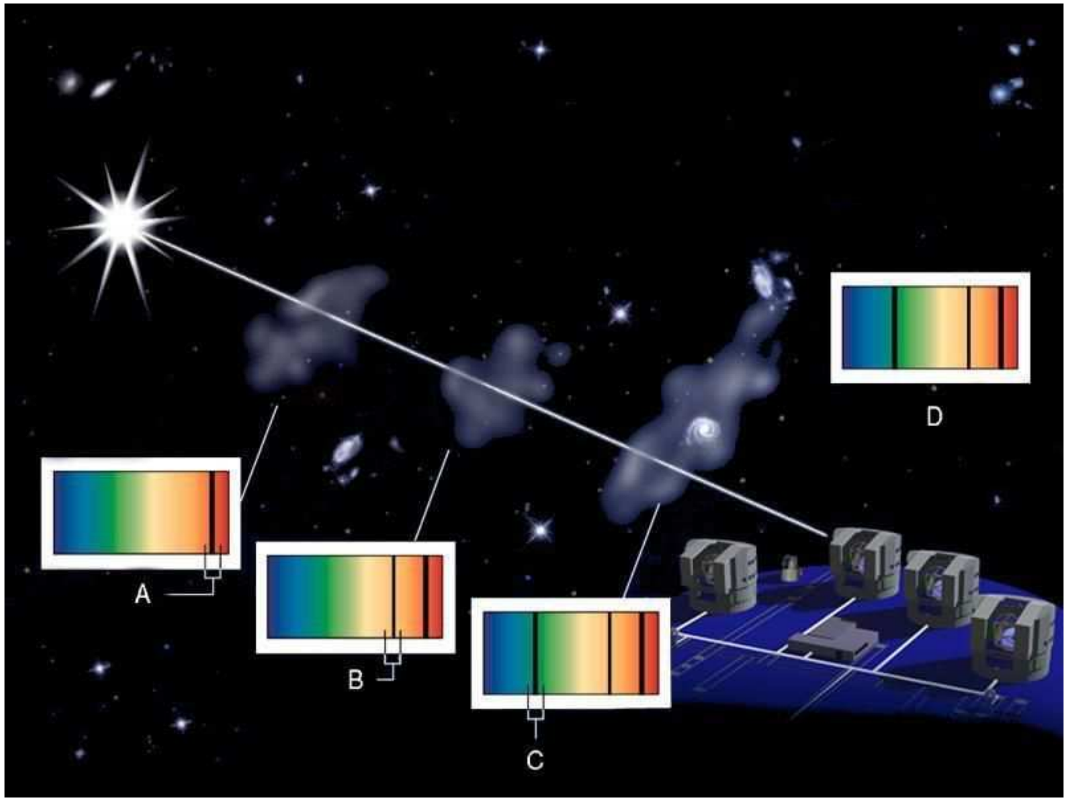


Galaxies

Composite spectrum of billions of stars and nebulae



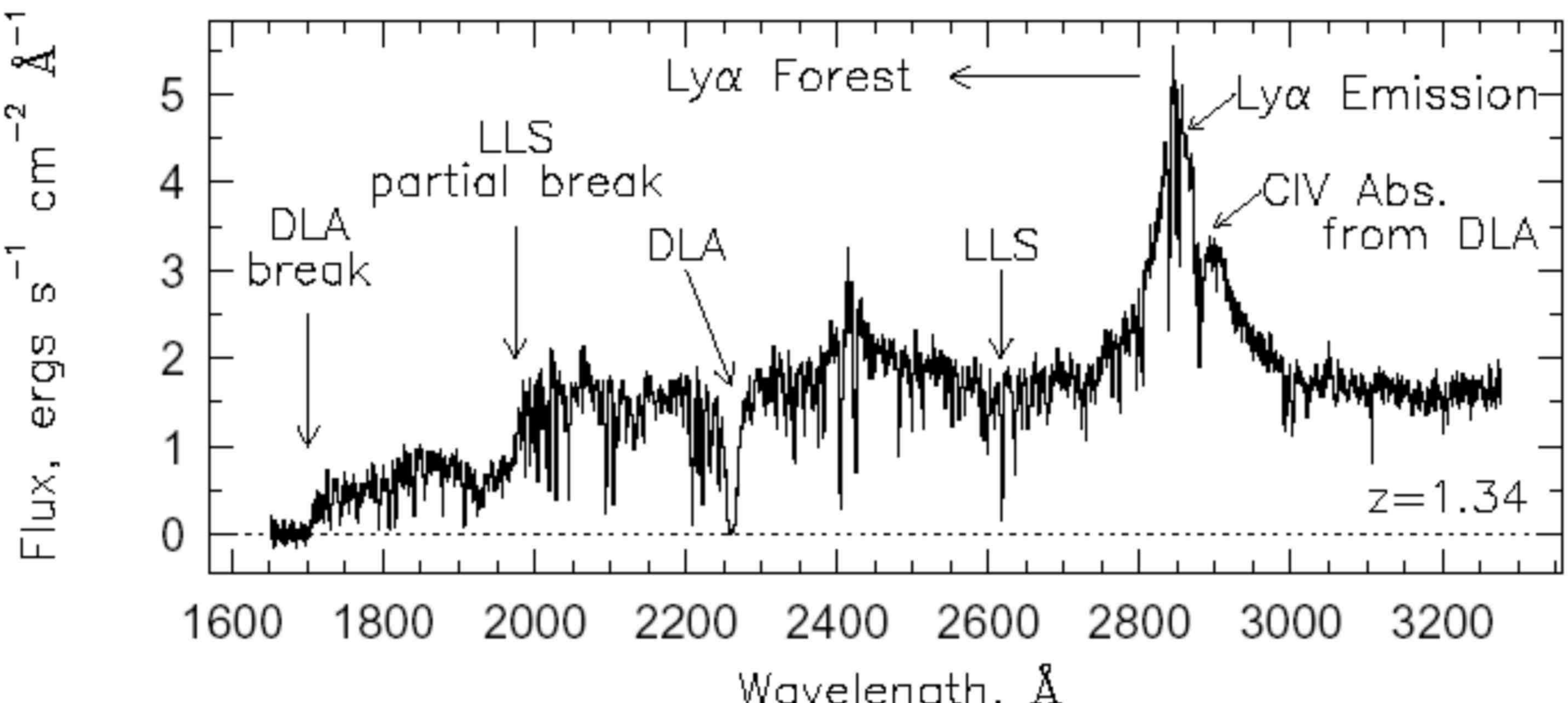
Quasars



- Lα-line is redshifted

$1+z=\lambda_{observed}/\lambda_{lab}$

- QSO provides background light source
- Absoption lines on different z_i from foregraound nebulae and galaxies



Information potential of spectroscopy

- **Composition.** each chemical element leaves own “fingerprint”
- **Temperature.** fom the degree of exitation of atoms and ions
- **Abundances.** from line strength
- **Motion.** Doppler shift & Rotation : line profiles

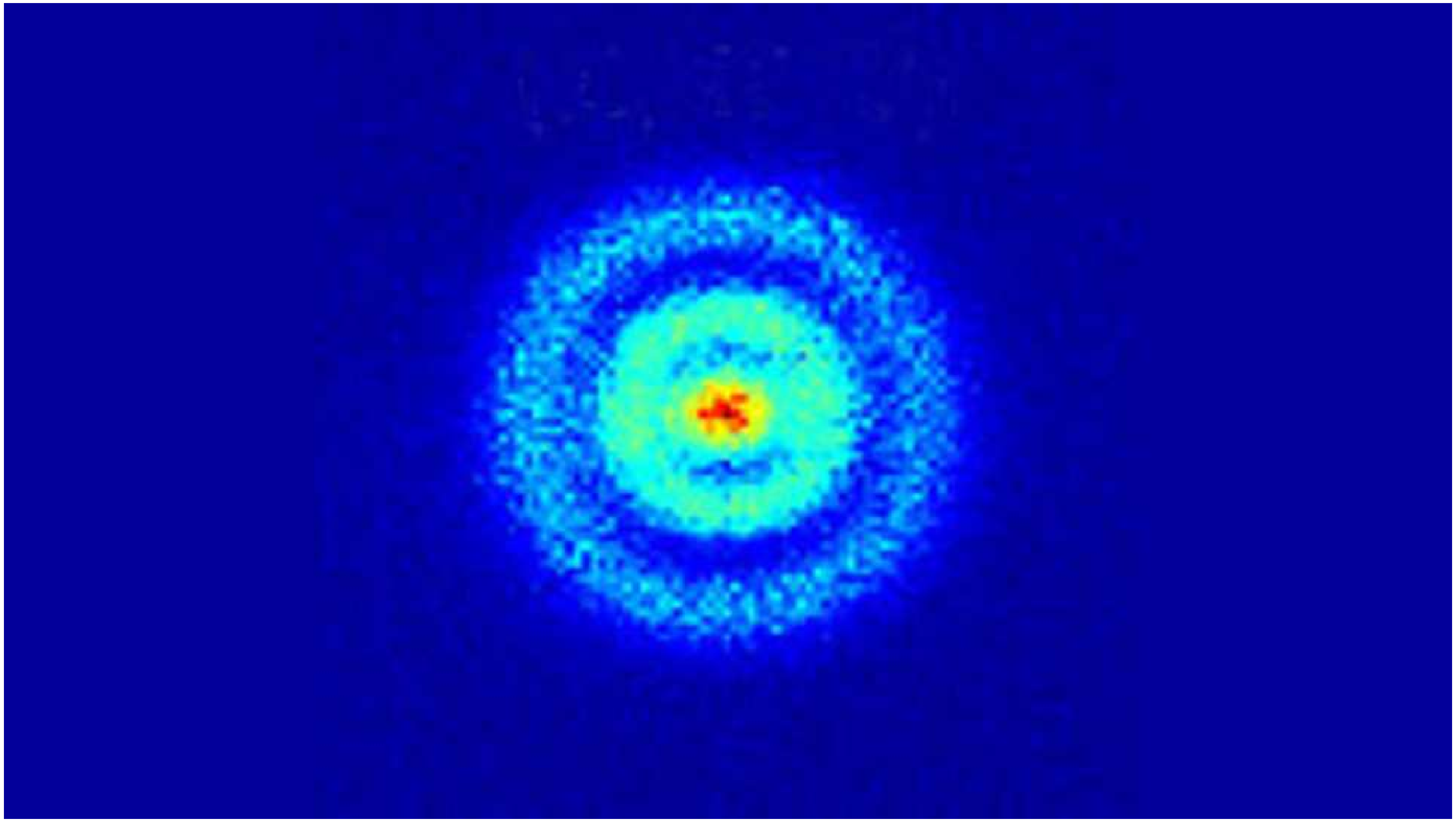
$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda}$$

- **Pressure.** Line broadening
- **Magnetic field.** Line splitting

For each atop or ion one needs to know:

- Spectral lines (often used are Grotrian diagrams)
- Its energy level structure
- Intrinsic line strength
- The rest wavelengths

Hydrogen Atom



Direct observation of H electron orbital (Stodolna et al. 2013, Phys. Rev. Lett. 110, 213001)

The Schrödinger Equation for a H-like atom

- The Hamiltonian operator of H-like system

$$\hat{H} = \frac{-\hbar^2}{2\mu}\nabla^2 - \frac{Ze^2}{4\pi\epsilon_0 r}$$

Atomic Units

- Electron mass, m_e=1.66 10^{-27} kg
- Electron charge, e=1.6 10^{-19} C
- Bohr radius, $a_0 = \frac{4\pi\epsilon_0\hbar^2}{me^2}$ = 5.29 10^{-11} m
- Dirack constant, h/2π = 1 a.u.

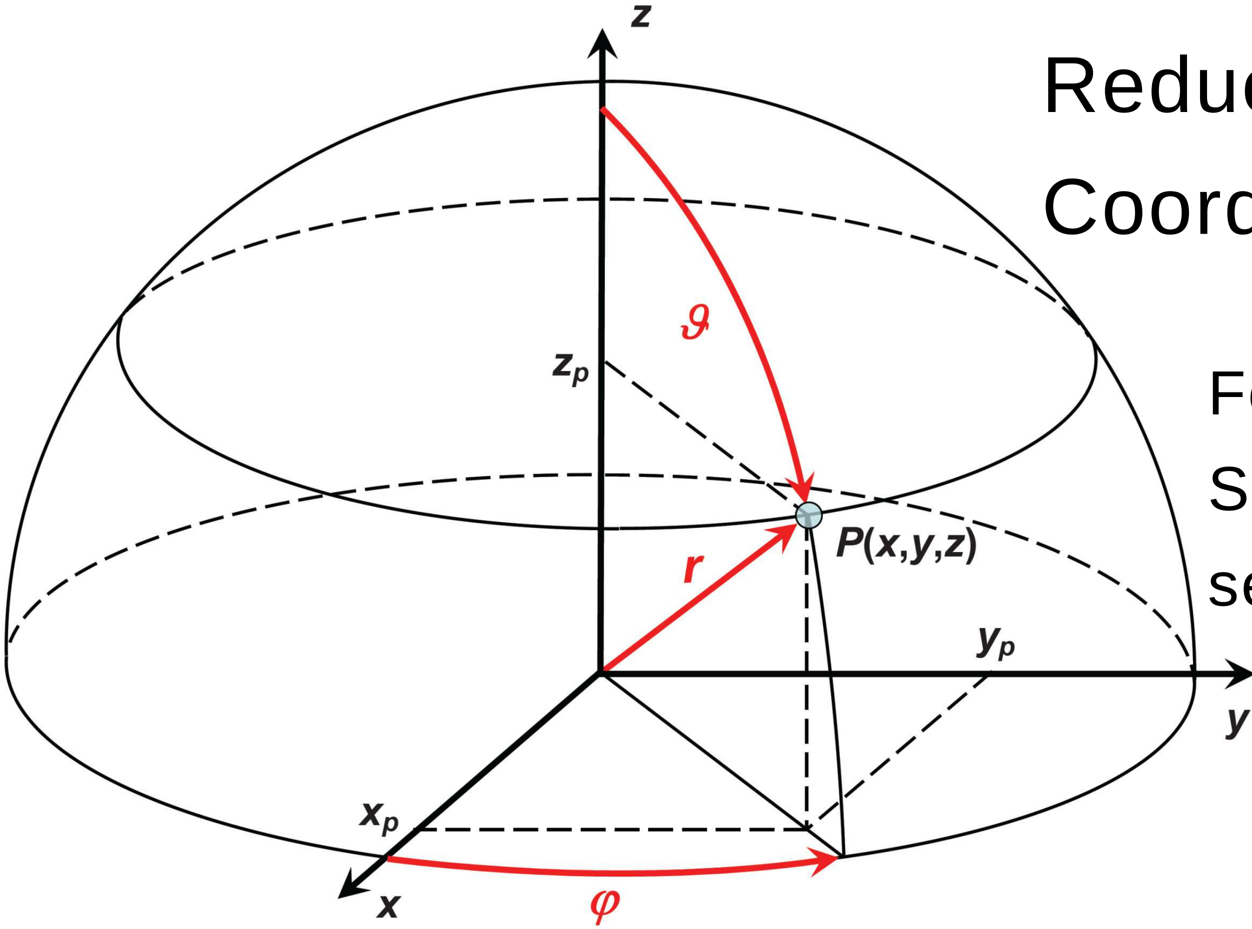
$$\hat{H} = -\frac{1}{2\mu}\nabla^2 - \frac{Z}{r}$$

For a system with energy E and wavefunction ψ: $\hat{H}\psi = E\psi$

For H-like atom

$$\left[-\frac{1}{2\mu}\nabla^2 - \frac{Z}{r} - E\right]\psi(\vec{r}) = 0$$

Wavefunctions and separating the variables



Reduced mass: $\mu = \frac{m_1 m_2}{m_1 + m_2}$

Coordinates $\vec{r} = (r, \theta, \phi)$

For H-like atoms one can solve Schrödinger eq. analytically by separating the variables.

Radial solutions -
Laguerre polinomials

Angular solutions -
spherical harmonics

$$\psi(r, \theta, \phi) = R_{nl}(r) Y_{lm}(\theta, \phi)$$

R(r)→ solutions exists only if main quantum number n=1,2,…, ∞

Y(τ,ψ): → orbital quantum number l = 0,1,2,…, n-1

and → magnetic quantum number m_l=-l, -l+1,..l-1, l (2l+1 values)

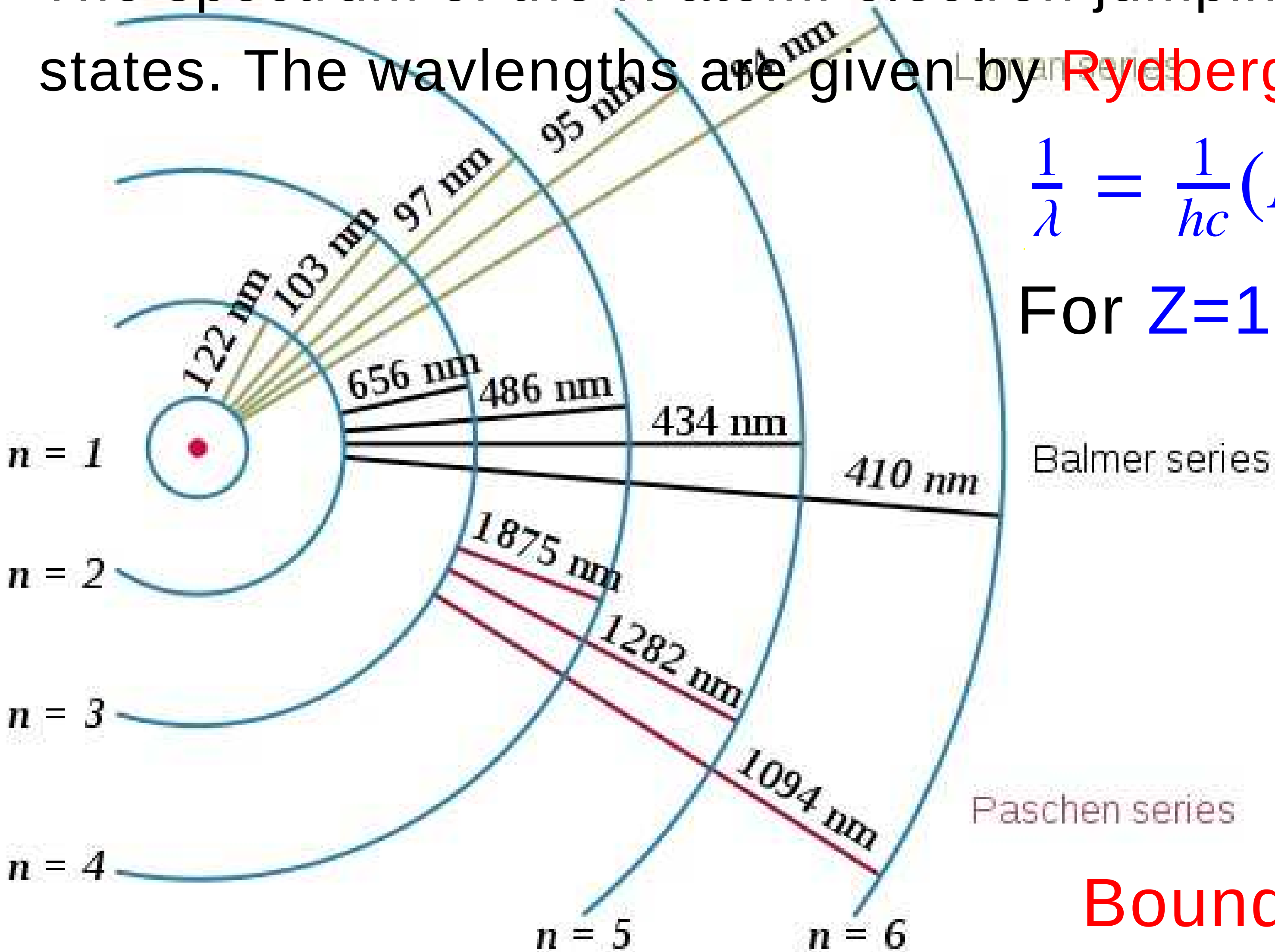
and → spin quantum number m_s=+1/2,-1/2

Energy levels and Hydrogen spectrum

For bound states the solution of Schrödinger equation

$$E_n = -R\frac{Z^2}{n^2}$$

The spectrum of the H atom: electron jumping between different states. The wavlengths are given by Rydberg formula:



$$\frac{1}{\lambda} = \frac{1}{hc}(E_{n1} - E_{n2})$$

For Z=1 $\frac{1}{\lambda} = R_H(\frac{1}{n_1^2} - \frac{1}{n_2^2})$

$$R_H = 109677.581\,\text{cm}^{-1}$$

$$R_H = \frac{\mu}{m_e}R_\infty$$

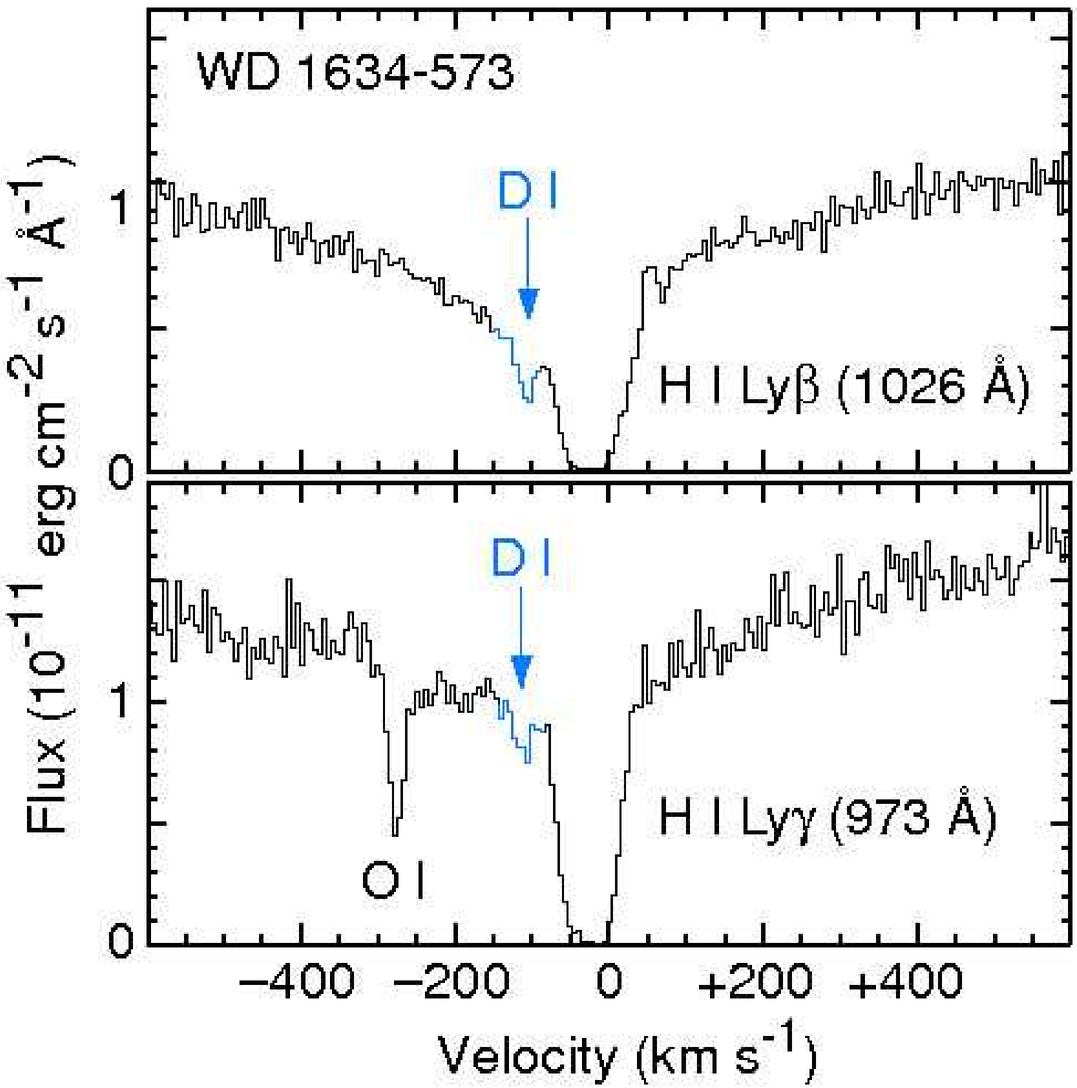
$$R_\infty = 109737.31\,\text{cm}^{-1}.$$

Bound-bound transitions

Deuterium ^{2}H

Nucleus contains one proton and one neutron

Nearly all ^{2}H was produced in the Big Bang. The ratio ^{1}H to ^{2}H → 26 atoms of deuterium per million hydrogen atoms



What is the wavelengths of Dα?

Hα → $15237\text{cm}^{-1} = R_H(\frac{1}{4} - \frac{1}{9})$

$$R_D = \frac{\mu_D}{\mu_H} R_H$$

$$\frac{\mu_H}{\mu_D} = \frac{(M_H + m_e)M_D}{(M_D + m_e)M_H} = 1.00027$$

Dα is at 15233 cm^{-1} (λ 6564.6Å), Hα is at λ 6562.9Å

and spectrographs resolution?

$R=\lambda/\Delta\lambda=\lambda_H/(\lambda_H-\lambda_D)=1/(1-R_H/R_D)$

R=3700 (ESO HARPS R=120000)

Angular momentum coupling in the Hydrogen atom

Sources of angular momentum:

- electron orbital angular momentum l
- electron spin angular momentum s
- nuclear spin angular momentum i - determined by spin coupling of the various nucleons: protons and neutrons have spin 1/2.

Only the total angular momentum is conserved. Individual momenta must be combined. This is done using a coupling scheme. Different schemes are possible, but ususally the strongest couplings are considered first.

Hydrogen the usual coupling scheme: $\vec{l} + \vec{s} = \vec{j}$

Next, combine electron and nuclear spin: $\vec{j} + \vec{i} = \vec{f}$

Rules for vector addition: $|a - b| \leq c \leq a + b$

In quantum mechanics the result is quantized with a unity step.

Example $l_1 = 2, l_2 = 3, \;\; \vec{L} = \vec{l_1} + \vec{l_2} \;\; \rightarrow \;\; L =$

The fine structure of hydrogen

Fine structure in the energy split according to the value of j.
For Hydrogen s=1/2. Lets take l=0,1,2,3.

$$^{(2S+1)}L_J$$

Configuration	l	s	j	H atom	Term	Level
ns	0	1/2	1/2	$ns_{1/2}$	n^2S	$n^2S_{1/2}$
np	1	1/2	1/2, 3/2	$np_{1/2}$, $np_{3/2}$	n^2P^o	$n^2P^o_{1/2}$, $n^2P^o_{3/2}$
nd	2	1/2	3/2, 5/2	$nd_{3/2}$, $nd_{5/2}$	n^2D	$n^2D_{3/2}$, $n^2D_{5/2}$
nf	3	1/2	5/2, 7/2	$nf_{5/2}$, $nf_{7/2}$	n^2F^o	$n^2F^o_{5/2}$, $n^2F^o_{7/2}$

E.g. n=2 give rise to three fine strucutre levels

Which line is formed by spontaneus transitions from this level?

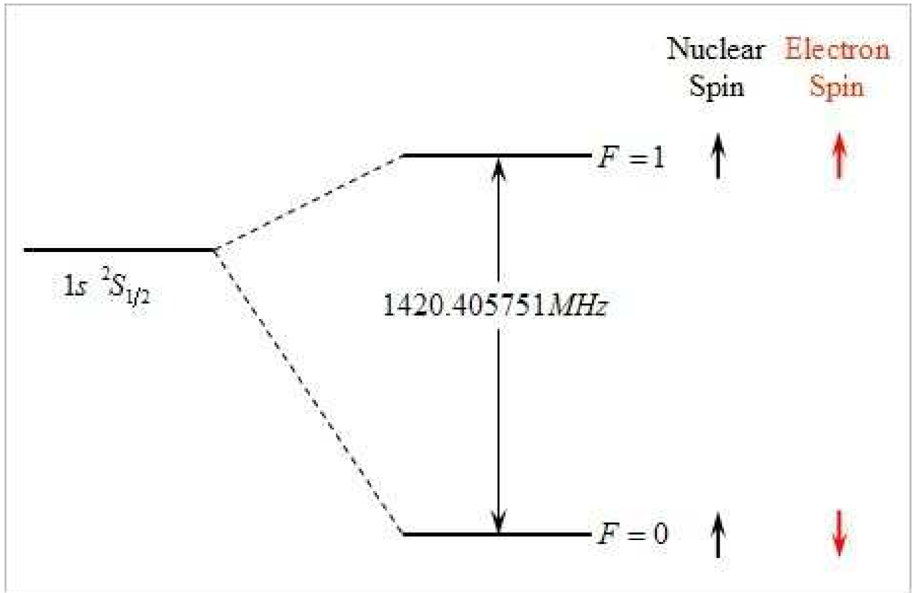
$$2^2S_{1/2}, 2^2P^o_{1/2}, 2^2P^o_{3/2}$$

Hyperfine structure of the H atom

Coupling between between total electron angular momentum j,and i=1/2 (for H) gives total angular momentum f.

$$f = j \pm 1/2$$

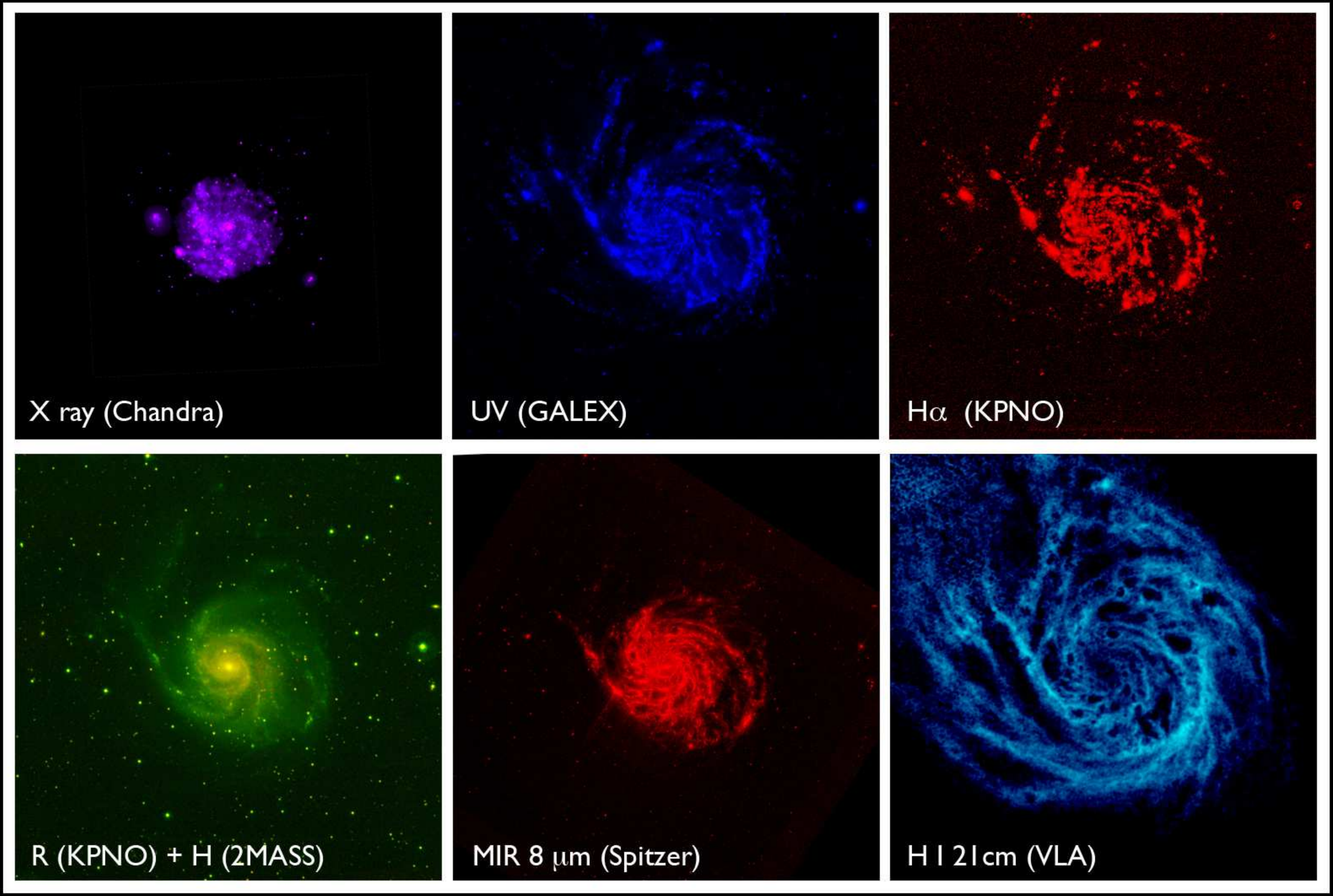
- The ground state of H is $^2S_{1/2}$ → it has j=1/2. Nuclear spin can split this level in f=0 and f=1 (f=1 is a triplet)
- Radiation with wavelength λ=21 cm is emitted. Most important line in astrophysics.
- Einstein cofficient $A=2.9\ 10^{-15}\ s^{-1}$, life time 10^7 yr → optically thin



λ21 cm

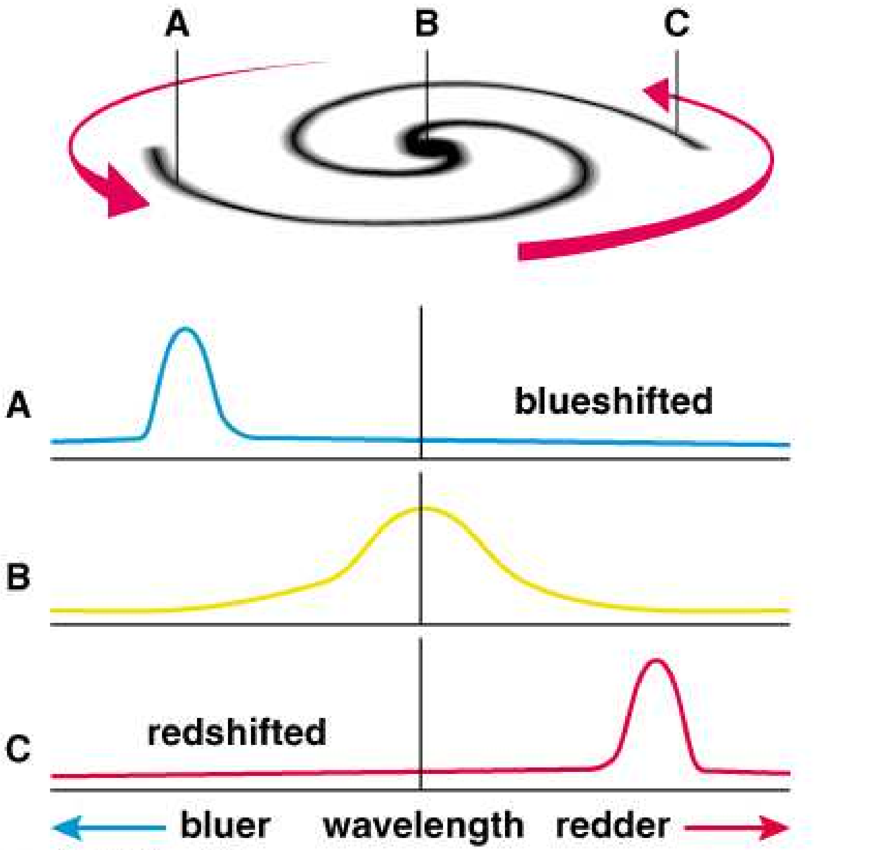
- Line of sign velocities
- Density directly from intensity
- Gas temperature
- Zeeman spitting → magnetic field

Multiwavelength data of the Spiral Galaxy M 101

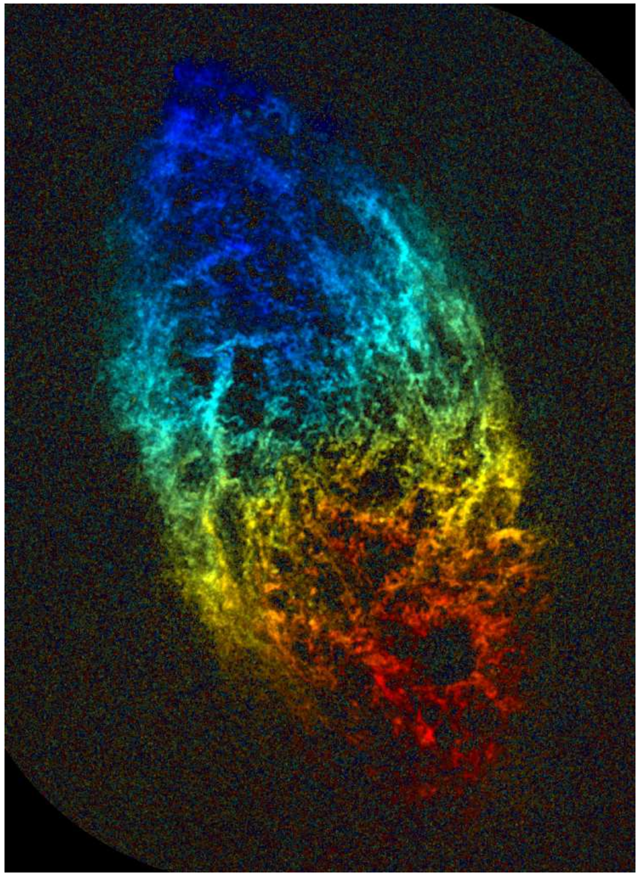


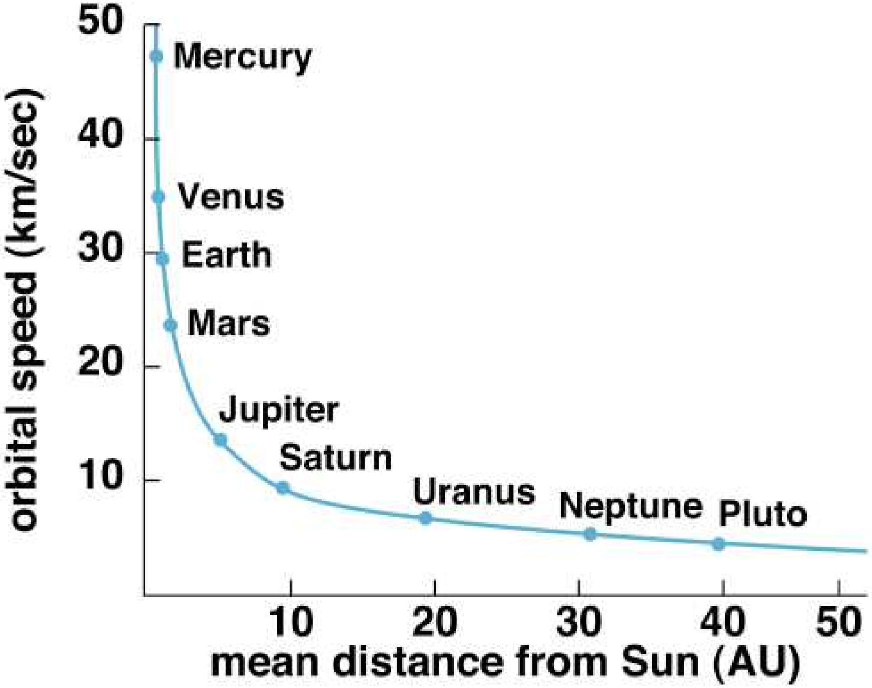
Credit of the images: Chandra X ray data: NASA/CXC/JHU/K.Kuntz et al,; GALEX data: Gil de Paz et al. 2007, ApJS, 173, 185; R & Hα data: Hoopes et al. 2001, ApJ, 559, 878; 2MASS data: Jarrett et al. 2003, AJ, 125, 525; Spitzer 8 μm data: Dale et al. 2009, ApJ, 703, 517; VLA HI 21 cm : Walter et al. 2008, AJ, 136, 2563, *"The H I Nearby Galaxy Survey"*.

Credit of the composition: **Ángel R. López-Sánchez** (Australian Astronomical Observatory / Macquarie University).



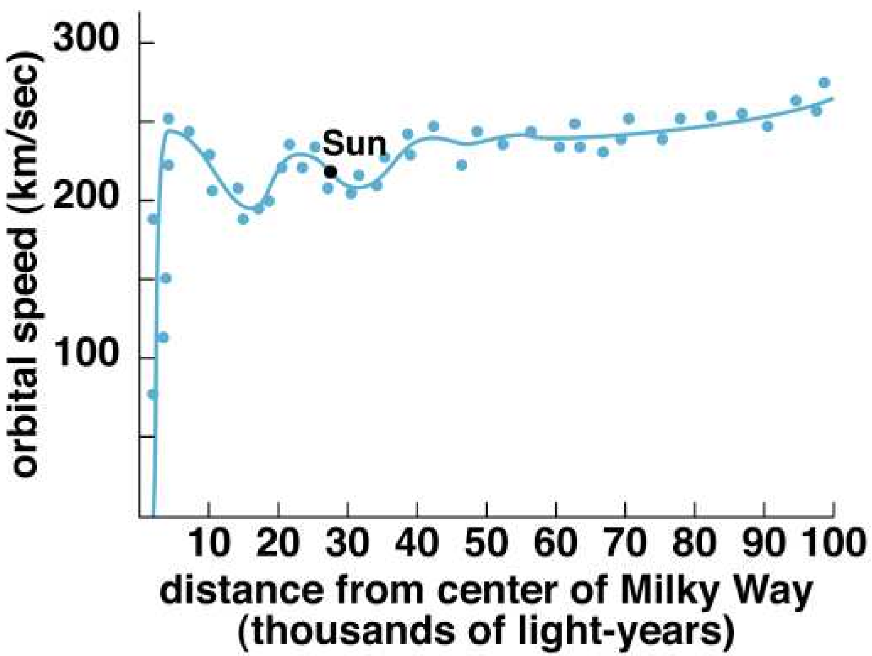
A
B
C
A
blueshifted
B
C
redshifted
bluer
wavelength
redder





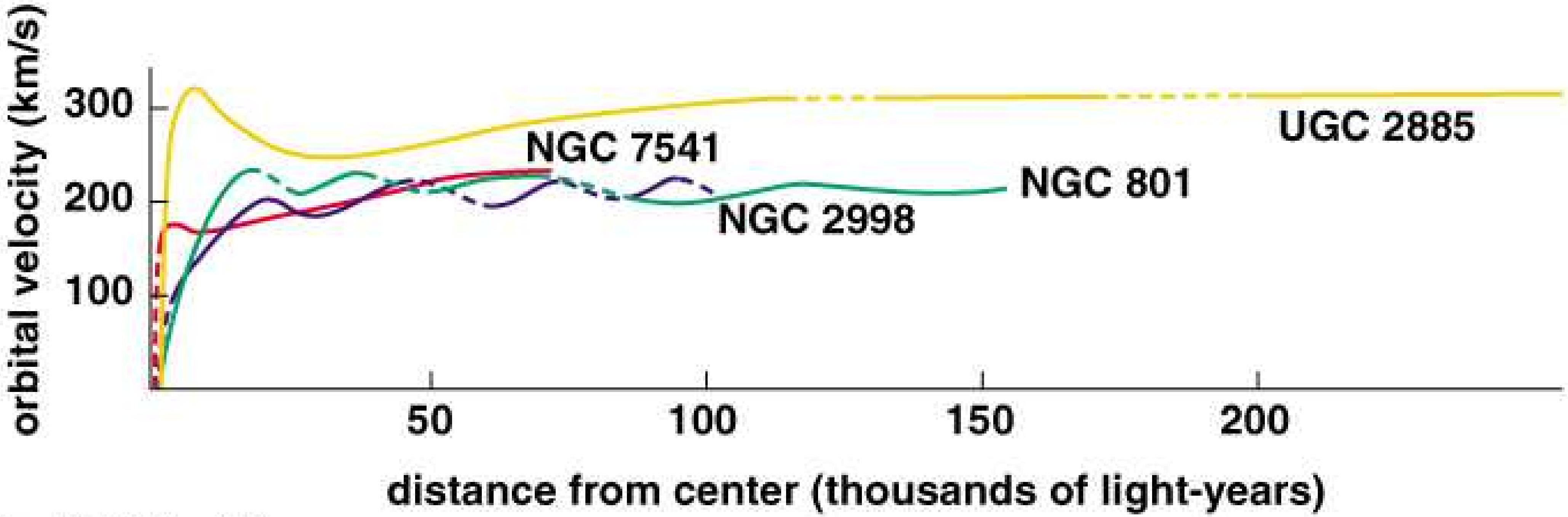
orbital speed (km/sec)
50
40
30
20
10
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
10
20
30
40
50
mean distance from Sun (AU)

(b)

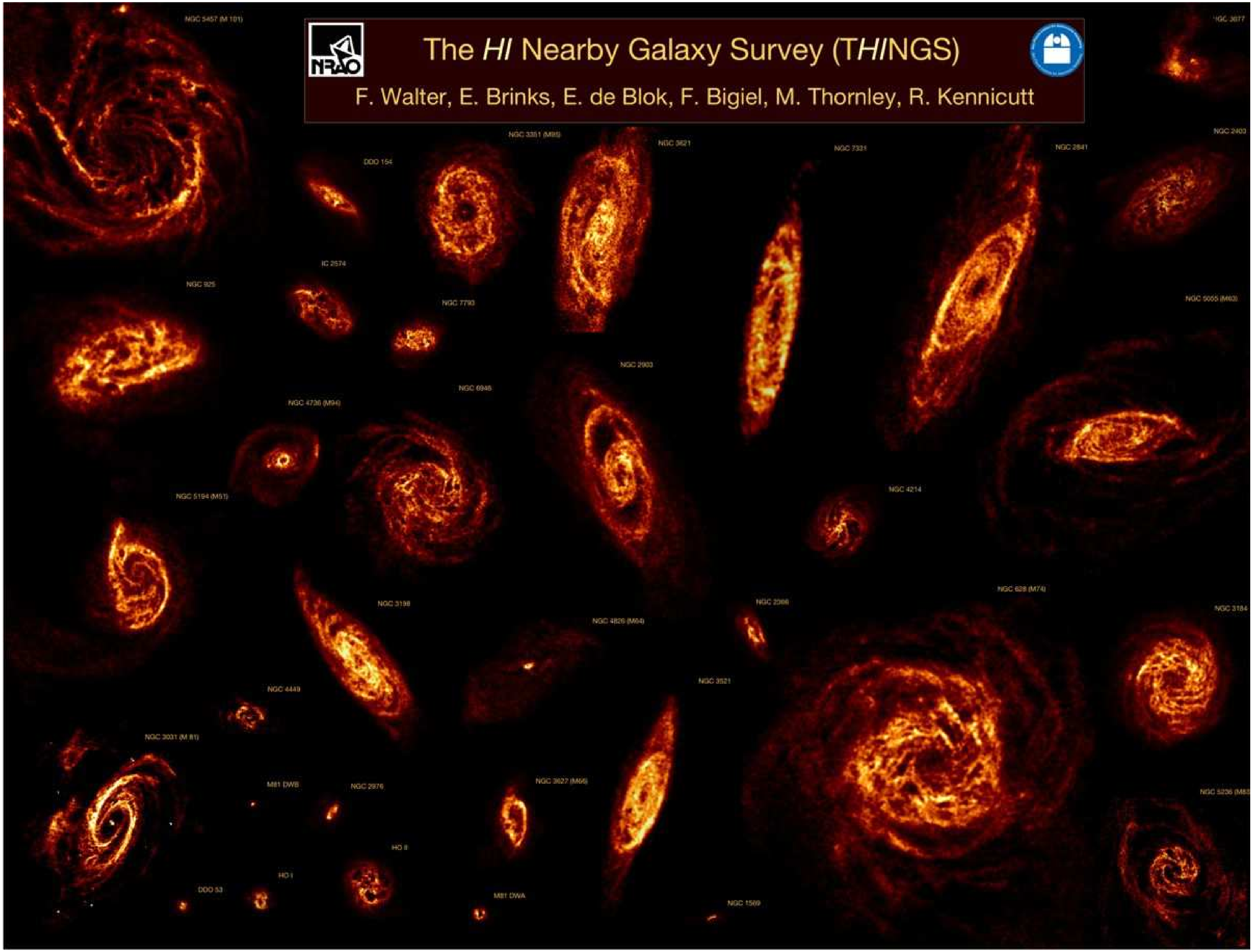


orbital speed (km/sec)
300
200
100
Sun
10 20 30 40 50 60 70 80 90 100
distance from center of Milky Way
(thousands of light-years)

(c)



Rotation curves for several galaxies Like the Milky Way, virtually all galaxies have flat rotation curves to well beyond where they have many stars, i ndicating that they are all surrounded by large halos of dark matter.


The HI Nearby Galaxy Survey (THINGS)
F. Walter, E. Brinks, E. de Blok, F. Bigiel, M. Thornley, R. Kennicutt
NRAO
NGC 5457 (M 101)
NGC 3351 (M95)
NGC 3621
NGC 7331
NGC 2841
NGC 2403
DDO 154
IC 2574
NGC 925
NGC 7793
NGC 5055 (M63)
NGC 2903
NGC 6946
NGC 4736 (M94)
NGC 4214
NGC 5194 (M51)
NGC 628 (M74)
NGC 3198
NGC 2366
NGC 4826 (M64)
NGC 3184
NGC 3521
NGC 4449
NGC 3031 (M 81)
M81 DWB
NGC 2976
NGC 3627 (M66)
HO II
HO I
DDO 53
M81 DWA
NGC 1569

Selectrion Rules

Selection rules are derived rigorously using quintum mechanics.

• Strong transitions are driven by electric dipoles. Weaker transitions could also be driven by quadrupoles.

• For electric dipole transitions in hydrogen

- Δn any
- Δl = +-1
- Δs = 0 (for H is always satisfied as s=1/2)
- Δj = 0, +-1
- Δm_j = 0, +-1

Lets consider Hα.: n=2-3, Δl = +-1 → 2s-3p, 2p-3s, 2p-3d are allowed, 2s-3s, 2p-3p, 2s-3d are not allowed.

Considering fine structure, further constrains are put by Δj = 0, +-1 rule

H-Atom Continuum spectra

So far we considered transitions between discrete levels.

- The continuum of a proton and electron is not quantized.

Therefore, 1s state of can be ionized by any photon with $\lambda<912$Å. This is the process of photoionization.

$$H(1s) + h\nu \rightarrow H^{+} + e$$

Similarly, The Balmer continuum is observed for $\lambda<3646$Å

- The reverse process is radiative photorecombination, free-boind transition

$$H^{+} + e \rightarrow H(nl) + h\nu$$

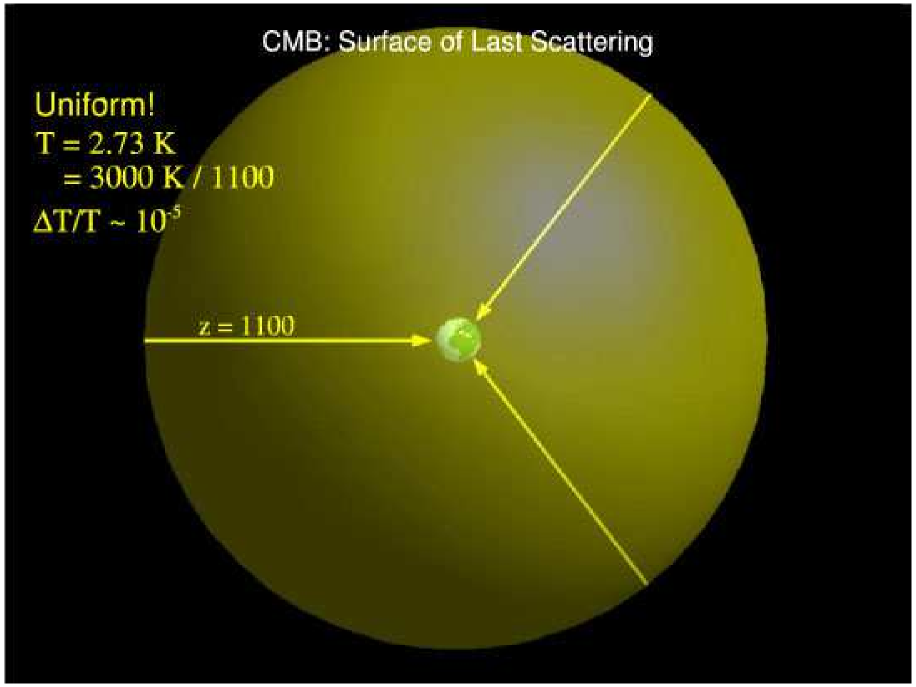
Consider heating and cooling. How photoionization and radiative recombination affect thermal balance?

Brief history of the Universe

- Paradigm of expanding, cooling universe predicts the cosmic microwave background (CMB). A rough history of the universe → a time line of increasing time and decreasing temperature.
  - $T \sim 10^{15}$ K, $t \sim 10^{-12}$ s: Primordial soup of fundamental particles
  - $T \sim 10^{13}$ K, $t \sim 10^{-6}$ s: Protons and neutrons form
  - $T \sim 10^{10}$ K, t~3 m: Nucleosynthesis: nuclei form
  - T ~ 3000K, t~300000 yr: Atoms form Recombination followed by Dark Ages
  - T ~ 10K, $t \sim 10^{9}$ yr: Stars form Re-ionization
  - T ~ 3K, $t \sim 10^{10}$ yr: Today
- Before recombination the mean free path of a photon was smaller than the horizon size of the universe. After recombination the mean free path of a photon is larger that the universe.
- The universe is full of a background of freely propagating photons with a blackbody distribution of frequencies at T~3000 K.
- As the universe expands the photons redshift, temperature drops These photons today are observed as CMB with T ~ 2.73 K.

Brief history of the Universe

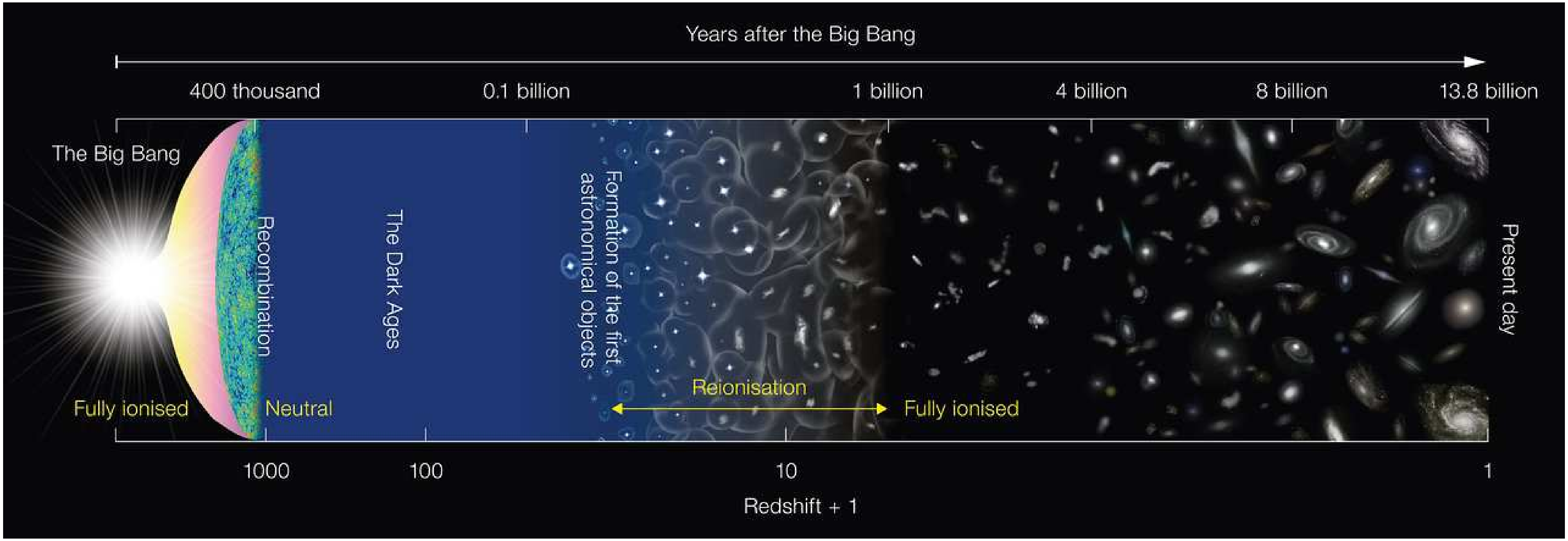
- The redshift of the last scattering surface $1+Z_R=T_R/T_0=1100$



The Universe is neutral. Dark Ages. Can you suggest which processed could emit light during this time?

Which sources emit light today? Today, the Universe is ionized. Which objects could have re-ionized the Universe?

Brief history of the Universe



Ioniztion of hydrogen and Saha equaiton

- Ionization stages: Saha law for hydrogen

$$\frac{n_e n_p}{n_H} = \frac{(2\pi m_e kT)^{3/2}}{h^3} e^{-\frac{h\nu_{1c}}{kT}}$$

- Lets define the ionization fraction as

$$x = \frac{n_e}{n_p + n_H}$$

- Using $n_p = n_e$ and $n_p + n_H = n$ (number of nuclei) one can re-write the Saha equation

$$\frac{x^2}{1-x} \propto \frac{1}{n_p + n_H} T^{3/2} e^{-\frac{13.6eV}{kT}}$$

- In cgs units $\frac{x^2}{1-x} = \frac{4\times10^{-9}}{\rho} T^{3/2} e^{-\frac{1.6\times10^5}{T}}$

Ionization fraction is determined by two parameters:

which ones?

Ioniztion of hydrogen and Saha equaiton

- Ionization stages: Saha law for hydrogen

$$\frac{n_e n_p}{n_H} = \frac{(2\pi m_e kT)^{3/2}}{h^3} e^{-\frac{h\nu_{1c}}{kT}}$$

- Lets define the ionization fraction as

$$x = \frac{n_e}{n_p + n_H}$$

- Using $n_p = n_e$ and $n_p + n_H = n$ one can re-write the Saha equation

$$\frac{x^2}{1-x} \propto \frac{1}{n_p + n_H} T^{3/2} e^{-\frac{13.6eV}{kT}}$$

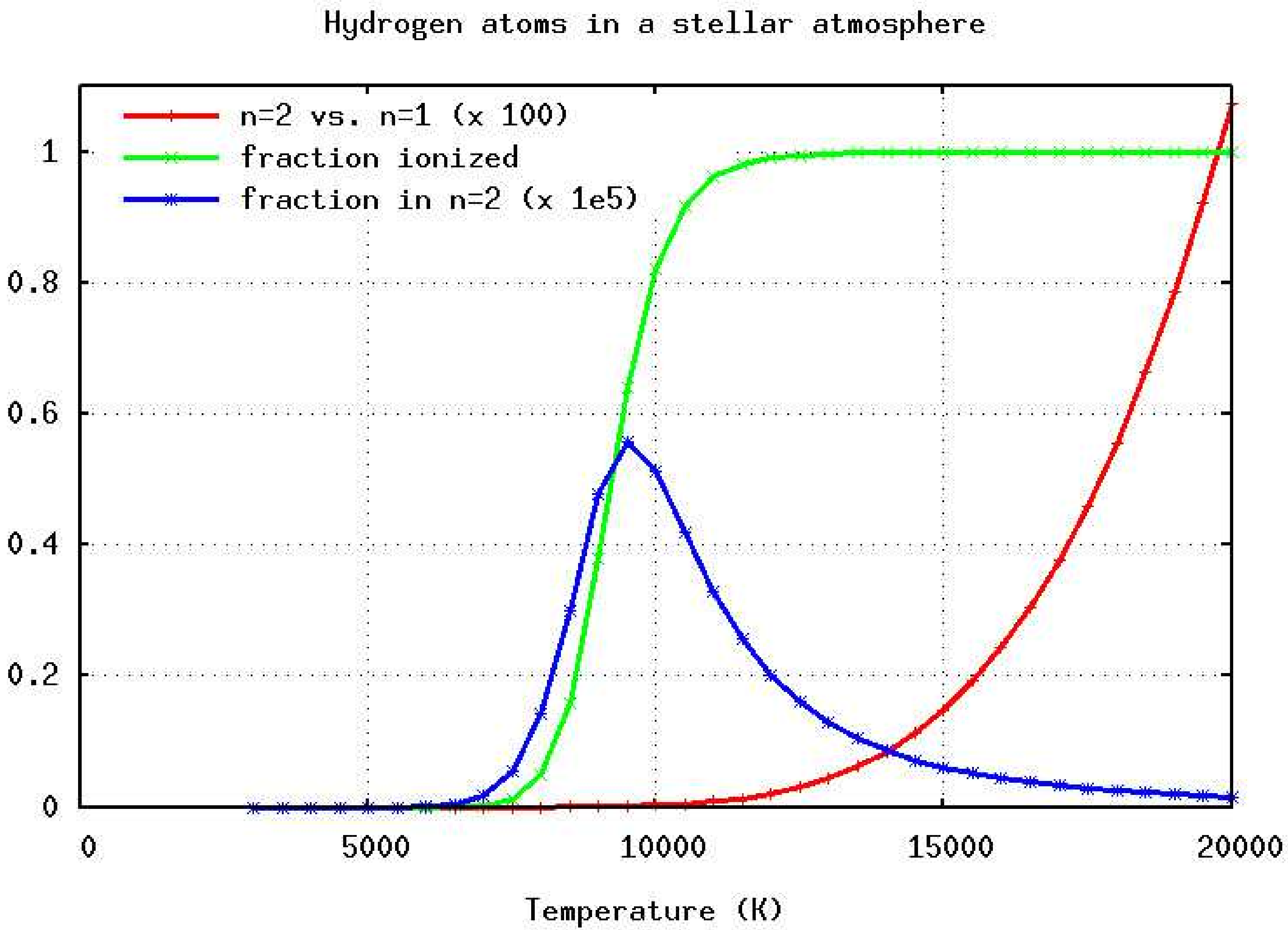
- Ionization fraction is determined by two parameters: temperature and density
- Temperature of the Universe $T(z)=2.728(1+z)$
- Density $(n_p+n_H)(z)=1.6(1+z)^3$ m^{-3}

T=4000K x=0.6

T=3800K x=0.29

T=3000K x=0.00017

Hydrogen ionization in stars



Average density in stars $n=10^{20}$ m^{-3}

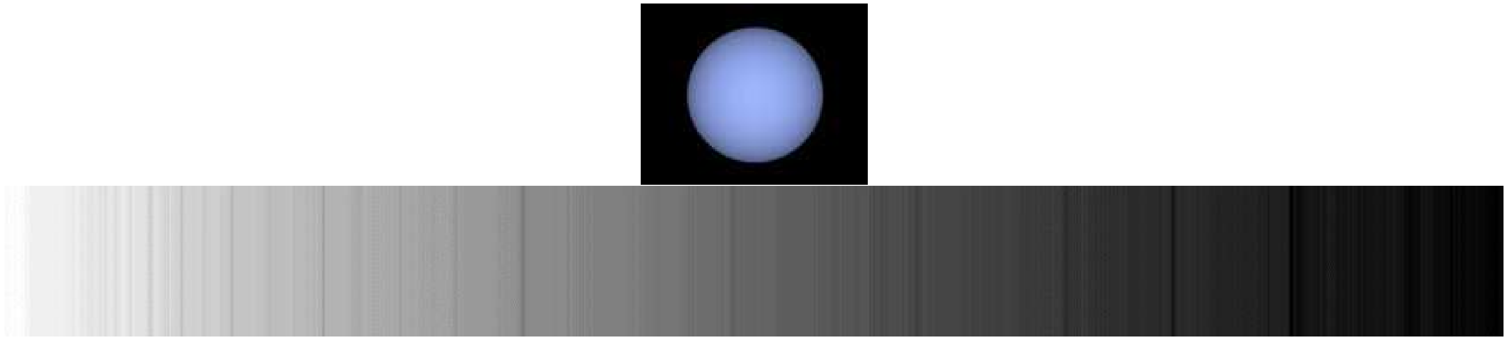
Edward Pickering (director, Harvard Observatory, 1877 to 1919)

Hired women as “computers” to systematically look at stellar spectra

‘Harvard computers’ incl. Williamina Fleming, Annie Jump Cannon, Henrietta Swan Leavitt and Antonia Maury

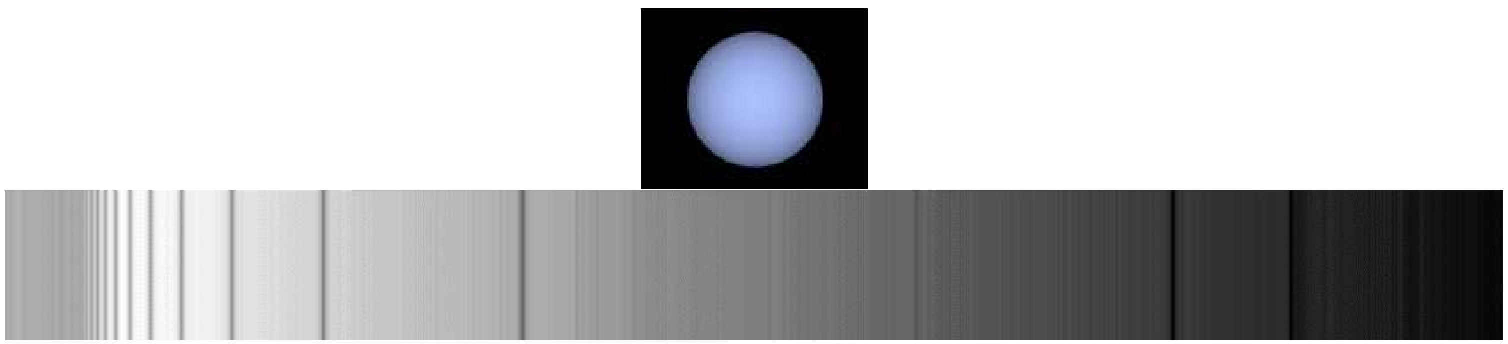
O stars

T>30 000 K; He+, O++, N++, Si++



B stars

T = 11,000 - 30,000 K, He, H, O+, C+, N+, Si+

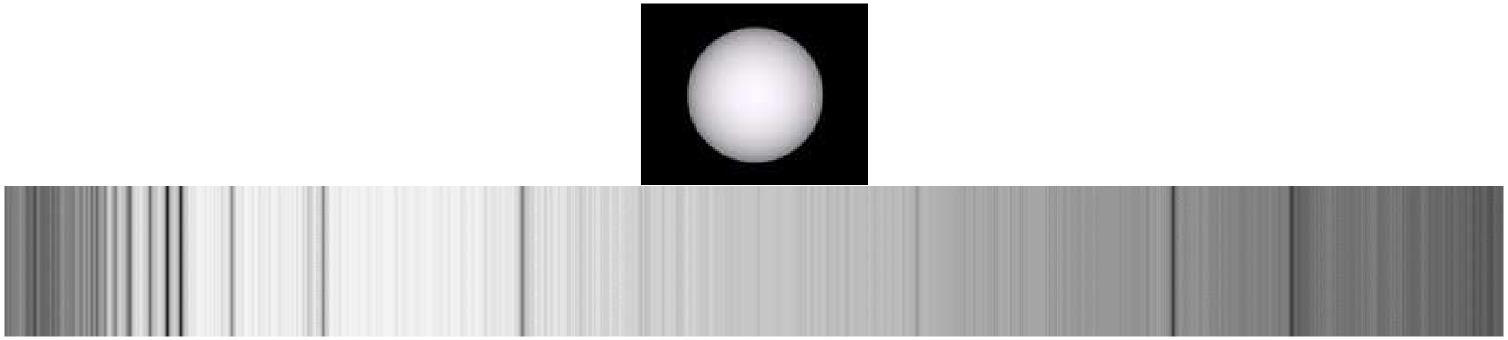


A stars

T = 7500 - 11,000 K, H(strongest), Ca+, Mg+, Fe+

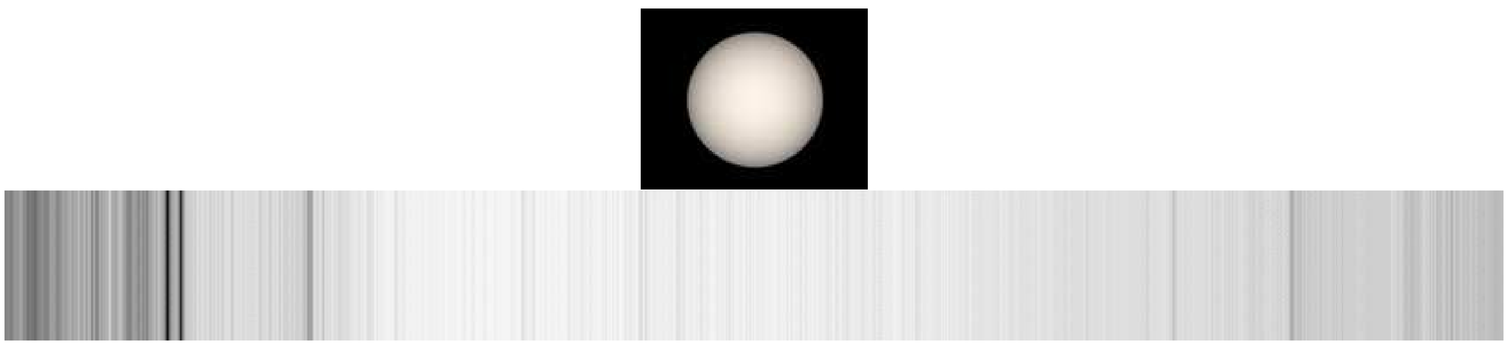
F stars

T = 5900 - 7500 K; H(weaker), Ca+, ionized metals



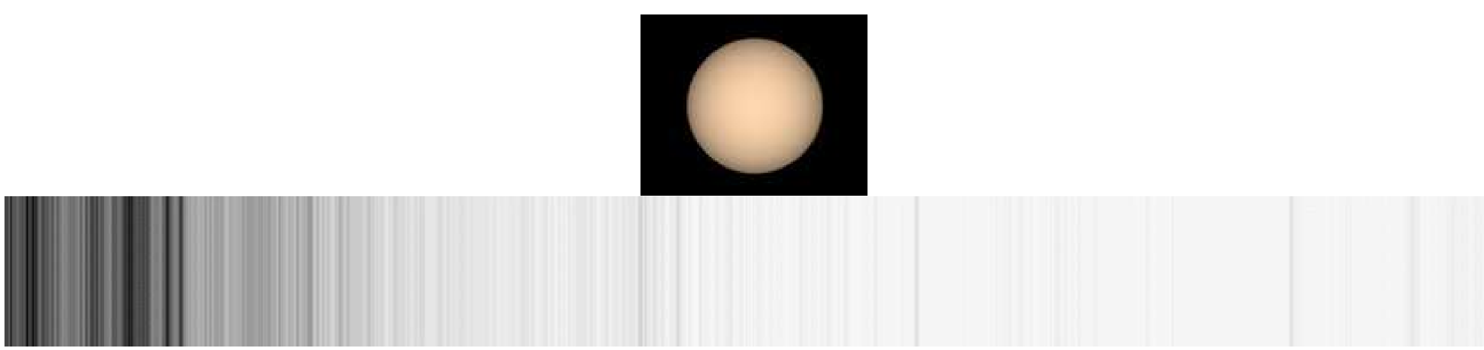
G stars

T = 5200 - 5900 K; Strong Ca+, Fe+ and other metals dominate



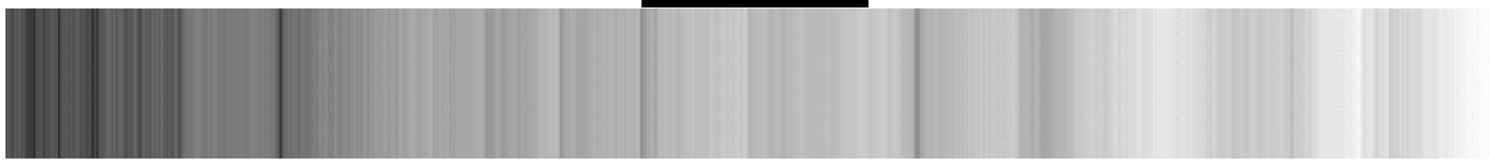
K stars

T = 3900 - 5200 K; Ca+(strongest), neutral metals, H(weak), CH & CN



M stars

T = 2500 - 3900 K Strong neutral metals, TiO, VO, no H



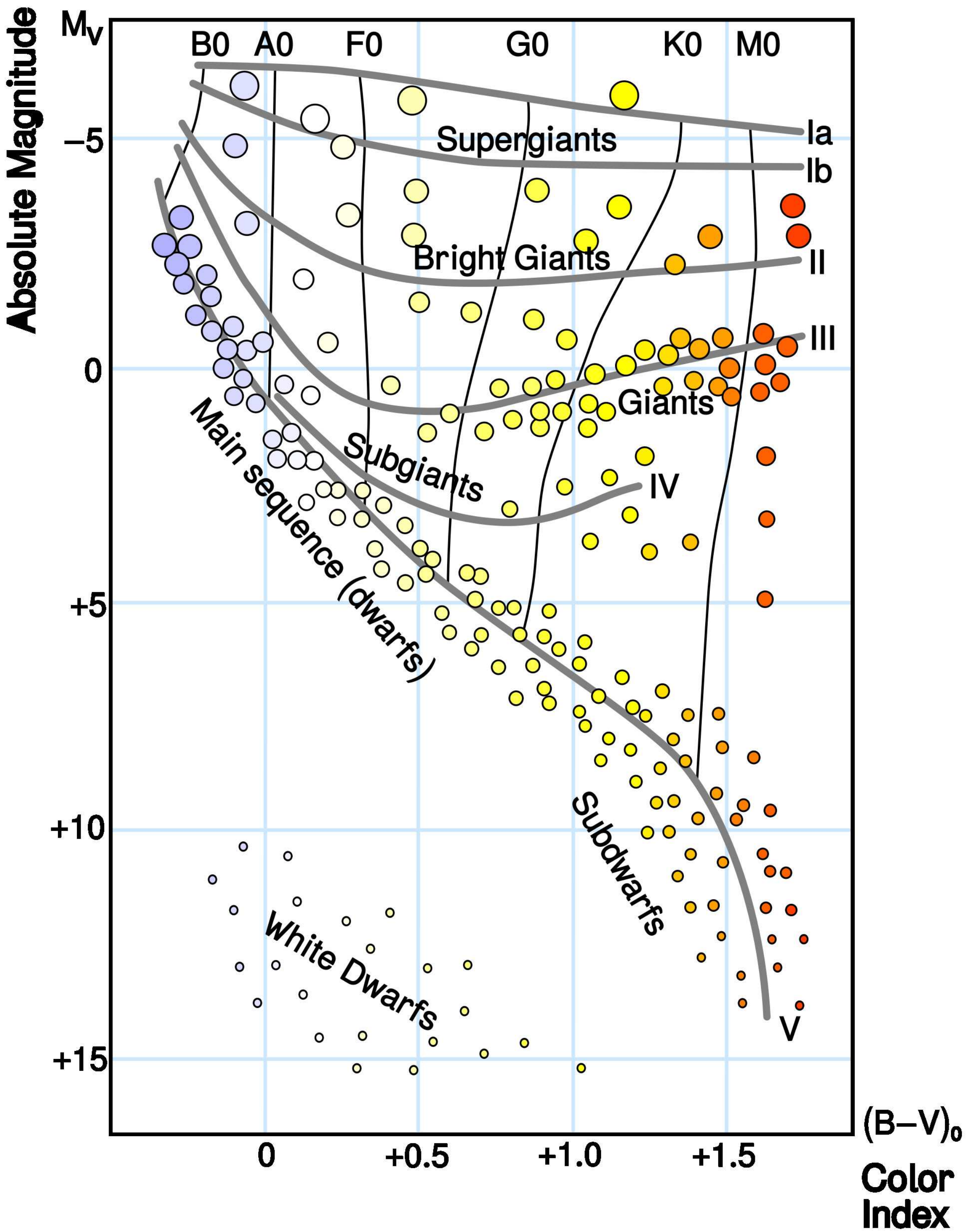
L stars

T = 1300 - 2500 K; strong molecular absorption bands particularly of metal hydrides and neutral metals like sodium, potassium, cesium, and rubidium. No TiO and VO bands. No spectra yet.

T dwarfs / Brown Dwarfs

T < 1300 K; very low-mass objects, not technically stars anymore because they are below the Hydrogen fusion limit (so-called "Brown Dwarfs"). T dwarfs have cool Jupiter-like atmospheres with strong absorption from methane (CH4), water (H2O), and neutral potassium. No spectra yet.

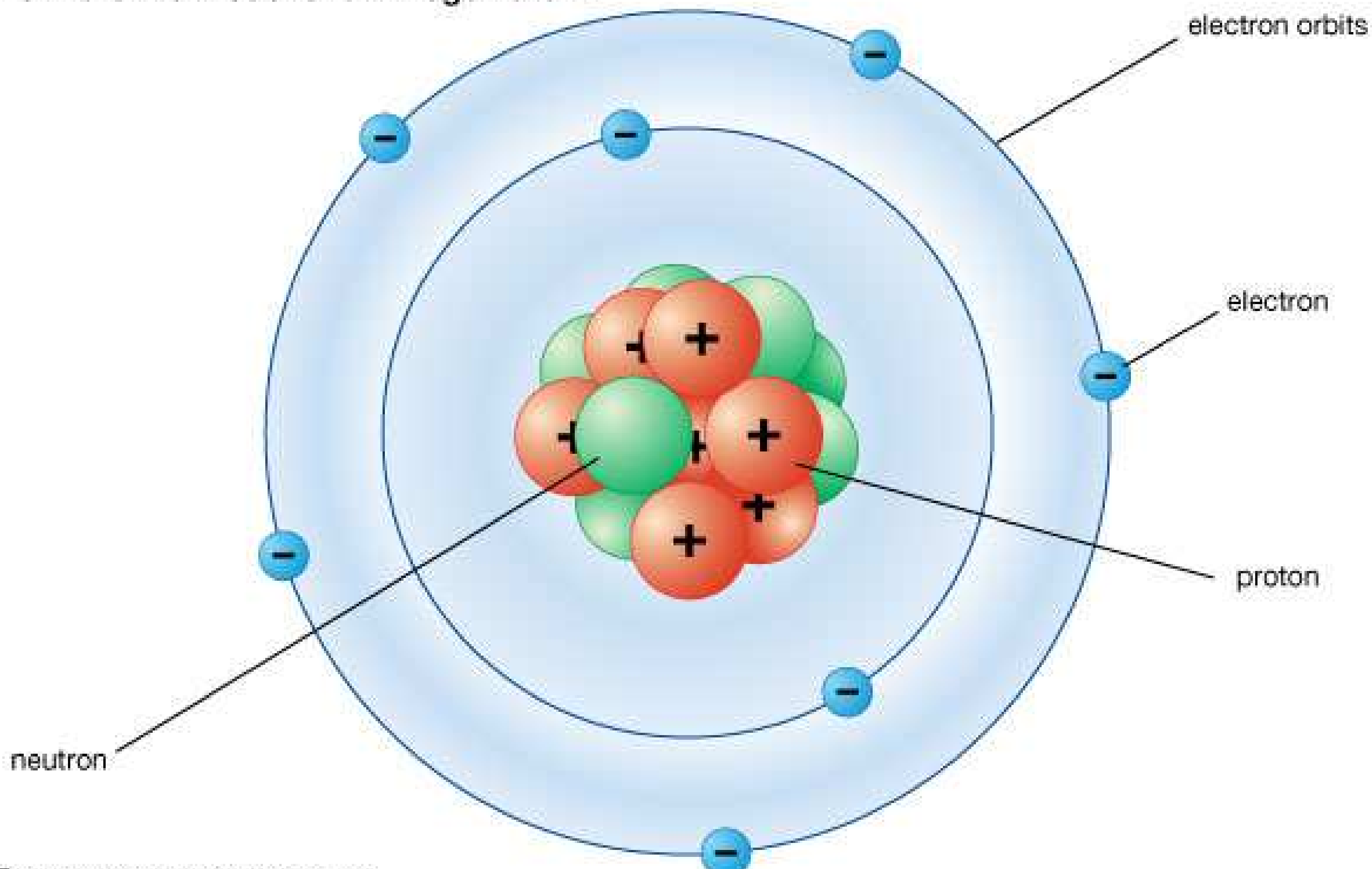
Modern MK classification: 2-dimentional



- "Phenomenology of spectral lines, blends, and bands, based on general progression of color index (abscissa) and luminosity (ordinate)."

Complex Atoms

Bohr atomic model of a nitrogen atom



Non-relativistic Schrödinger Equation

$$\left[\sum_{i=1}^{N}\left(\frac{-\hbar^2}{2m_e}\nabla_i^2 - \frac{Ze^2}{4\pi\epsilon_0 r_i}\right) + \sum_{i=1}^{N-1}\sum_{j=1+1}^{N}\frac{e^2}{4\pi\epsilon_0|\vec{r_i}-\vec{r_j}|} - E\right]\times\psi(\vec{r_1},..,\vec{r_N}) = 0$$

The first sum is a kinetic energy operator for the motion of each electron and the Coulomb attraction between this electron and the nucleus.

The second term: electron-electron repulsion term. Because of this term the equation cannot be solved analytically even for N=2.

Therefore, to understand such systems it is necessary to introduce approximations

Central Field model

The easiest approximation → reduce the problem to a single particle situation. I.e. a potential does not depend on the angular position of electrons around the nucleus. **Central field potential** - the force acting on each electron only depends on its distance from the nucleus. The Schrödinger eq. can be written for ith electron

$$\left[\left(\frac{-\hbar^2}{2m_e}\nabla_i^2 + V_i(r_i)\right]\phi_i(r_i) = E_i\phi_i(r_i)$$

where $V_i(r_i)$ is the angle-independent cental potential of each electron.

The total energy of the system is then $E = \sum_i E_i$

- The solutions, $\phi_i(r_i)$, are called **orbitals. Importnant to remember that this is an approximation.**

Indistinguishable Particles

Consider a system with two identical particles. If the wavefunction of these particles is $\Psi(1,2)$, and the particles are indistinguishable, what property their wavefunction must have?

Physically observable is $|\Psi|^2$. Then, if particles are indistinguishable $|\Psi(1,2)|^2 = |\Psi(2,1)|^2$.

Symmetric solution $\Psi(1,2)| = +\Psi(2,1)$, antisymmetric $\Psi(1,2)| = -\Psi(2,1)$. Pauli Principle:

Wavefunctions are antisymmetric with respect to interchange of identical Fermions

Fermions - any particles with half-integer spin (electrons, protons, neutrons).

A two-electron wavefunction which obeys the Pauli Principle can be written as

$$\Psi(1,2) = \frac{1}{\sqrt{2}}[\Phi_a(1)\Phi_b(2) - \Phi_a(2)\Phi_b(1)] = -\Psi(2,1)$$

where $\frac{1}{\sqrt{2}}$ is to preserve normalization.

The Pauli exclusion principle

Consider a two- electron wavefunction. If the two spin- orbitals, $\Phi_a = \Phi_b$, then $\Psi(1,2) = 0$. This solution is not allowed.

Hence solutions which have the two particle occupying the same spin-orbital are ecluded. The Pauli exclusion principle:

No two electrons can occupy the same spin-orbital

This exclusion is the key to atomic structure.

It also provides the degeneracy pressure which holds up the gravitational collaps of white dwarfs and neutron stars.

Angular Momentum in Complex Atoms

Complex atoms have more than one electron, hence several sources of angular momentum.Ignoring nuclear spin, the total conserved angular momentum, J is the sum of spin plus orbital momenta of all electrons.

There are two coupling schemes of summing the individual electron angular momenta.

L-S or Russell-Saunders coupling

The total orbital angular momentum $\vec{L} = \sum_i \vec{l}_i$ and the total electron angular momentum $\vec{S} = \sum_i \vec{s}_i$

These are then added to give $\vec{J} = \vec{L} + \vec{S}$

Pauli Principle → closed shells and sub-shells (e.g. $1s^2$ or $2p^6$), have both L=0 and S=0. Hence, it is necessary to consider only electrons in open or partly-filled shells.

Consider OIII with the configuration $1s^2 2s^2 2p3d$

For the 2p electron: $l_1=1$ and $s_1=1/2$.
For the 3d electron: $l_2=2$ and $s_2=1/2$.

$$\vec{L} = \vec{l_1} + \vec{l_2} \rightarrow L = 1, 2, 3;$$
$$\vec{S} = \vec{s_1} + \vec{s_2} \rightarrow S = 0, 1;$$

$^{(2S+1)}L_J$

$$\vec{J} = \vec{L} + \vec{S}$$

L	S	J	Level
1	0	1	$^1P^o_1$
1	1	0, 1, 2	$^3P^o_0, {}^3P^o_1, {}^3P^o_2$
2	0	2	$^1D^o_2$
2	1	1, 2, 3	$^3D^o_1, {}^3D^o_2, {}^3D^o_3$
3	0	3	$^1F^o_3$
3	1	2, 3, 4	$^3F^o_2, {}^3F^o_3, {}^3F^o_4$

Twelve levels arise from $1s^2 2s^2 2p3d$ configuration of OIII.

Specroscopic Notations

The standard notation is called *spectroscopic notation* and works with L-S coupling

A *term* is a state of a configuration with a specific value of L and S:

$$^{(2S+1)}L^{(o)}$$

A state with S=0 is a *singlet* (2S+1=1); a state with S=1/2 is a *doublet;* a state with S=1 is a *triplet.*

o means *odd parity*. When parity is even, no superscript. A *level* is a term with a specific value of J:

$$^{(2S+1)}L_J^{(o)}$$

Each term can be split on 2J+1 sub-leveles called *states* which are designated by the total magnetic quantum number M_J = -J, -J+1, ..., J-1, J. These states are degenerate in the absence of an eternal field.

The splitting of levels into states in a magnetic field *Zeeman effect*.

Hund's rules

(1) For a given configuration, the term with maximum spin multiplicity has lowest energy.

(2) For a given configuration and spin multiplicity, the term with the largest value of L lies lowest in energy.

(3) For atoms with less than half-filled shells, the levels with the lowest value of J lies lowest in energy.

(4) For atoms with more than half-filled shells, the levels with the highest value of J lies lowest in energy.

Hund's rules are only applicable within L-S coupling. Furthermore, they are rigorous only for ground states.

Selection rules for Complex Atoms

Strong transitions are driven by electric dipoles. Electric dipole selection rules are two types: rigorous rules - must always be obeyed; propensity rules - lead to weaker transitions.

Rigorous selection rules

(1) ΔJ must be 0 or +/- 1 with J = 0 - 0 forbidden

(2) ΔM_J = 0, +/- 1

(3) Laporte rule: parity must change

Propensity selection rules

Additional set of rules which is not rigorously satisfied by complex atoms.

(4) The spin multiplicity is unchanged, $\Delta S=0$

(5) Only one electron jumps: the configuration of the two states must differ by only the movement of a single electron - Δn any, $\Delta l=+/-1$.

- Is $2s^2$ - $2s2p$ allowed? Is $2s^2$ - $2s3d$ allowed? Is $2s^2$ - $3p^2$ allowed?

Configuration interaction weakens this rule: e.g. ground state of Be $1s^2 2s^2$ is in fact mixed with 5% contribution from $1s^2 2p^2$

Propensity selection rules

(4) The spin multiplicity is unchanged, $\Delta S=0$

(5) Only one electron jumps: the configuration of the two states must differ by only the movement of a single electron - Δn any, $\Delta l=+/-1$.

(6) $\Delta L=0, +/- 1$, $L=0$ 0 - 0 is forbidden.

- Is ^1S - $^1P^o$ allowed? And is ^3D - $^3P^o$ allowed? What about ^1S - $^1S^o$ allowed? And ^3S - $^3D^o$?

Full set of rules can be found in the literature.

Allowed transitions satisfy all rules. Einstein coefficients are $>10^6\ s^{-1}$

Intercombination lines

Photons do not change spin → usual rule $\Delta S=0$. However, relativistic effects mix spin states, specially for high Z ions. Weak spin changing transitions → *intercombination lines*. Example: CIII] $2s^2\ ^1S$ - $2s2p\ ^3P^o$ at λ 1908.7Å

C^{2+} $2s2p\ ^3P^o$ state is *metastable* - no allowed radiative decay. Useful information about density. One of the filters in Hubble Space telescope is centered on this line -- F185W filter on WFPC2 camera

Propensity selection rules

(5) Only one electron jumps: the configuration of the two states must differ by only the movement of a single electron - Δn any, Δl=+/-1.

(6) ΔL=0, +/- 1, L=0 0 - 0 is forbidden.

Electric dipole transitions which violete rules 5 and 6 - *forbidden transitions*.

1906.7 Å C[III] $2s^2\ {}^1S_0$ - $2s2p\ {}^3P^o_2$ (magnetic transition)

322.57 Å C[III] $2s^2\ {}^1S_0$ - $2p3s\ {}^1P^o_1$

Forbidden lines are, generally, weaker than intercombination lines.

Grotrian Diagrams

Walter Grotrian (1890-1954) - war erst Privat-Dozent an der Universität Potsdam. 1928 “Graphische Darstellung der Spektren”

(1) The vertical scale is energy. It starts from the ground state at zero, and extends to the first ionization limit. Sometime the binding energy, expressed relative to the first ionization limit, is given at the right side.

(2) Terms (levels) are represented by horisontal lines

(3) States with the same term (or level if fine structure effects are large), are stacked veritically and labeled by n of the outer electron.

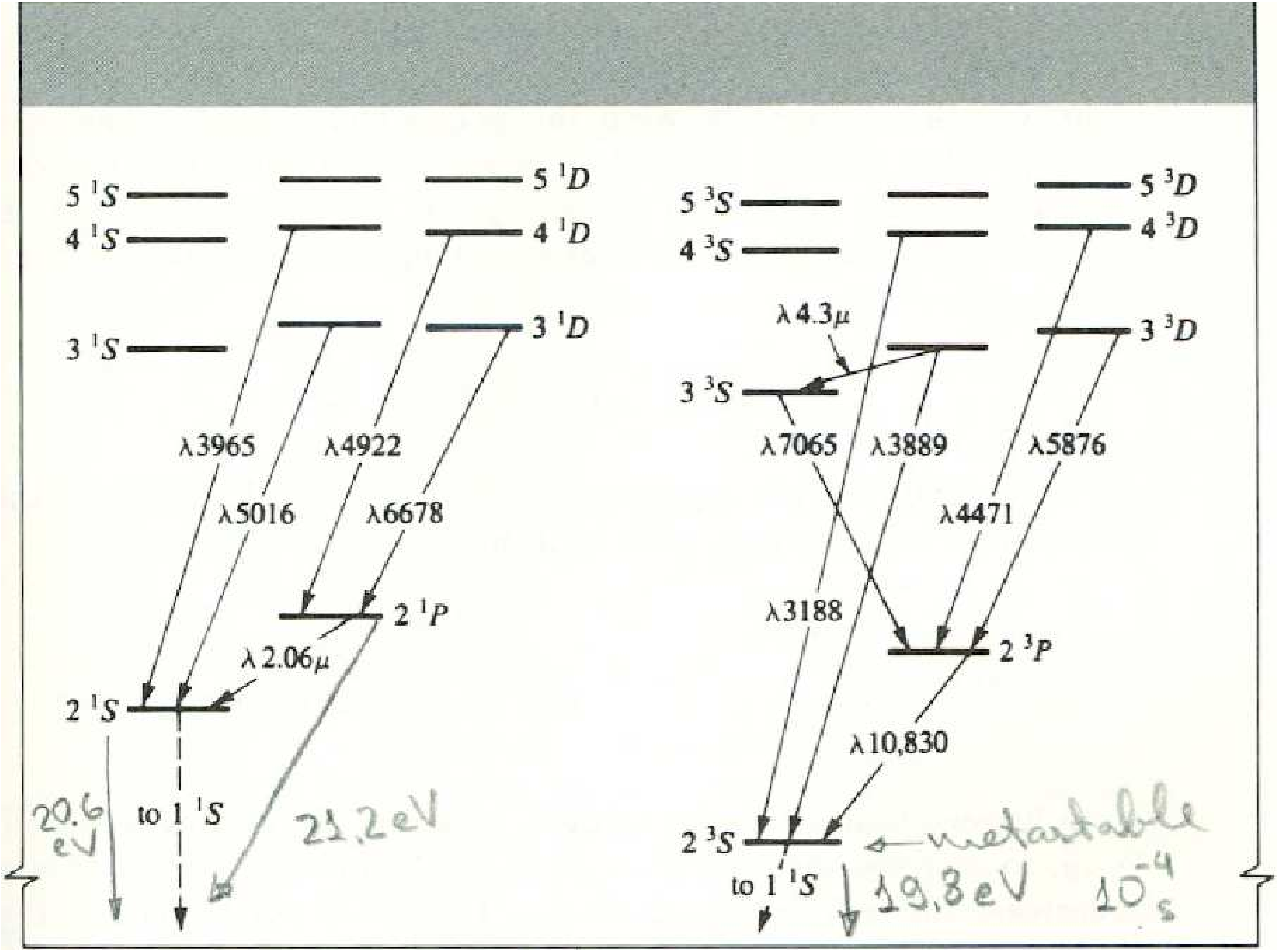
(4) Terms are grouped by spin multiplicity.

(4) Terms are grouped by spin multiplicity.

(5) States are linked by observed transitions with numbersw giving the wavelengths of the transition in Å. Thicker lines denote stronger transitions. Forbidden lines are given by dashed lines.

Lets construct Grotrian Diagram for HeI

Partial energy diagram of He I, showing strongest optical lines



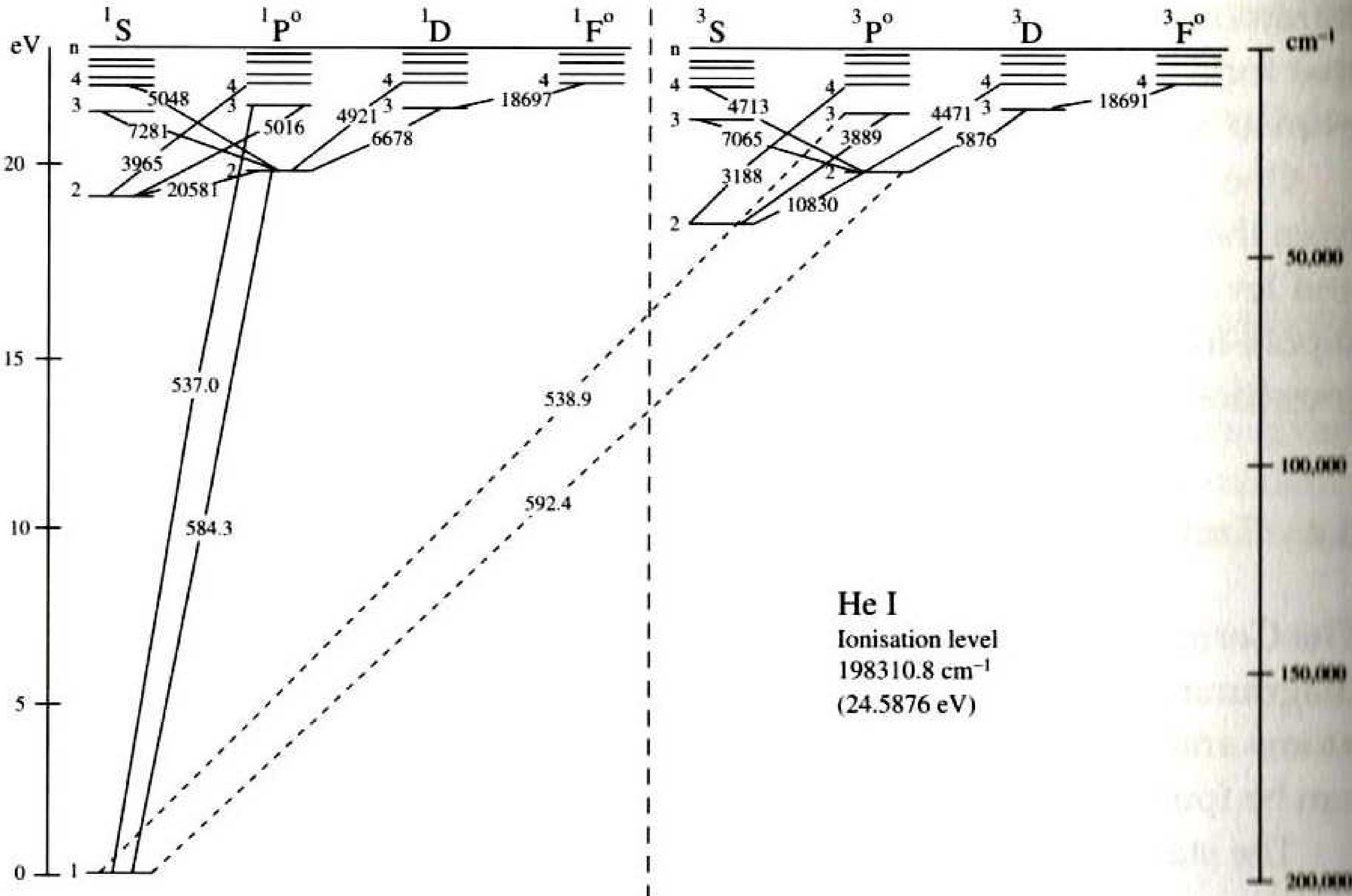
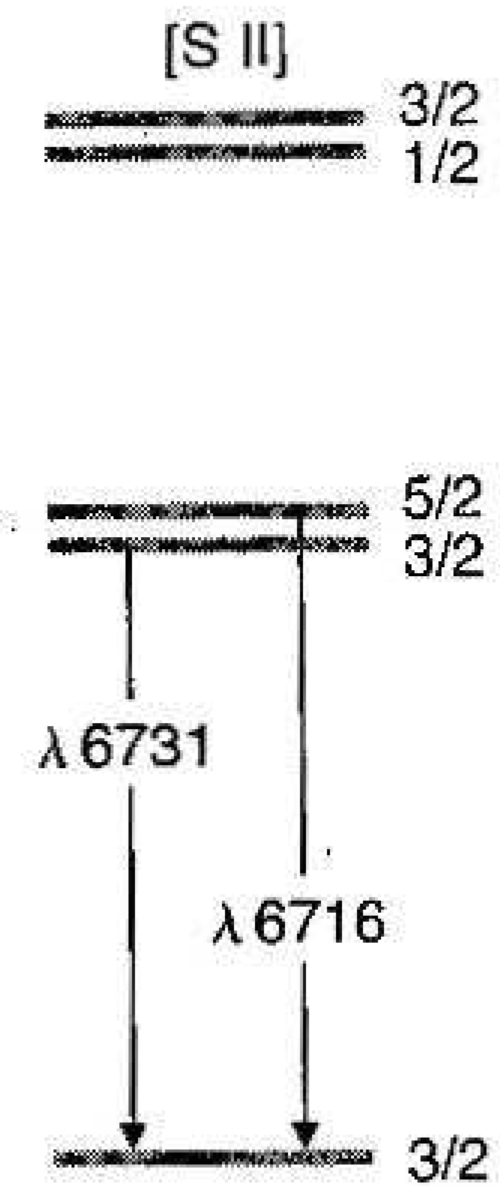


Fig. 5.2 Grotrian diagram for He I. The running numbers denote the principal quantum number of the active electron. The left-hand side of the figure is for 'para' singlet helium and the right-hand side is for 'ortho' triplet helium.

Basic Physical Ideas: Forbidden Lines



Osterbrock & Ferland, 2005

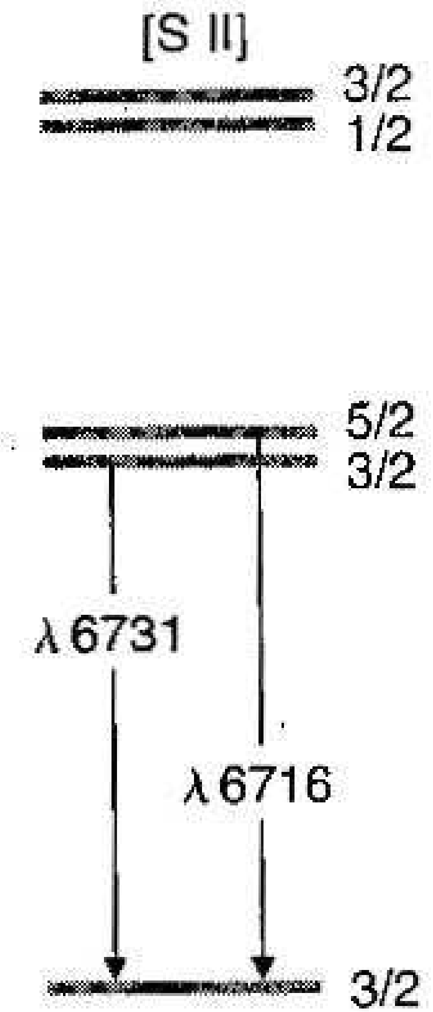
- Electron is excited to a higher level within the ground state.
- Singly ionized sulfur, S+, has 3 valence electrons. $1s^2 2s^2 2p^6 3s^2 3p^3$.
- Radiative transition are allowed when

$$\Delta l = \pm 1, \Delta m = 0, \pm 1$$

- If selection rules for dipole radiation are not fulfilled - dipole radiation is not possible
- Quadropole or magneto-dipole radiation may occure: But the probability of such transaction is 10^5 times smaller
- Metastable states - excited states which have a relatively long lifetime due to slow radiative and non-radiative decay
- Forbidden transitions: upper-state lifetimes of ms or even hr. Allowed transitions: upper-state lifetimes are a few nanos.
- The lifetime: the 5/2 and 3/2 levels are 3846s and 1136s.

Exercise: Determiming the Gas Density

The Sulfur Lines



lowest ground-state levels of p electrons

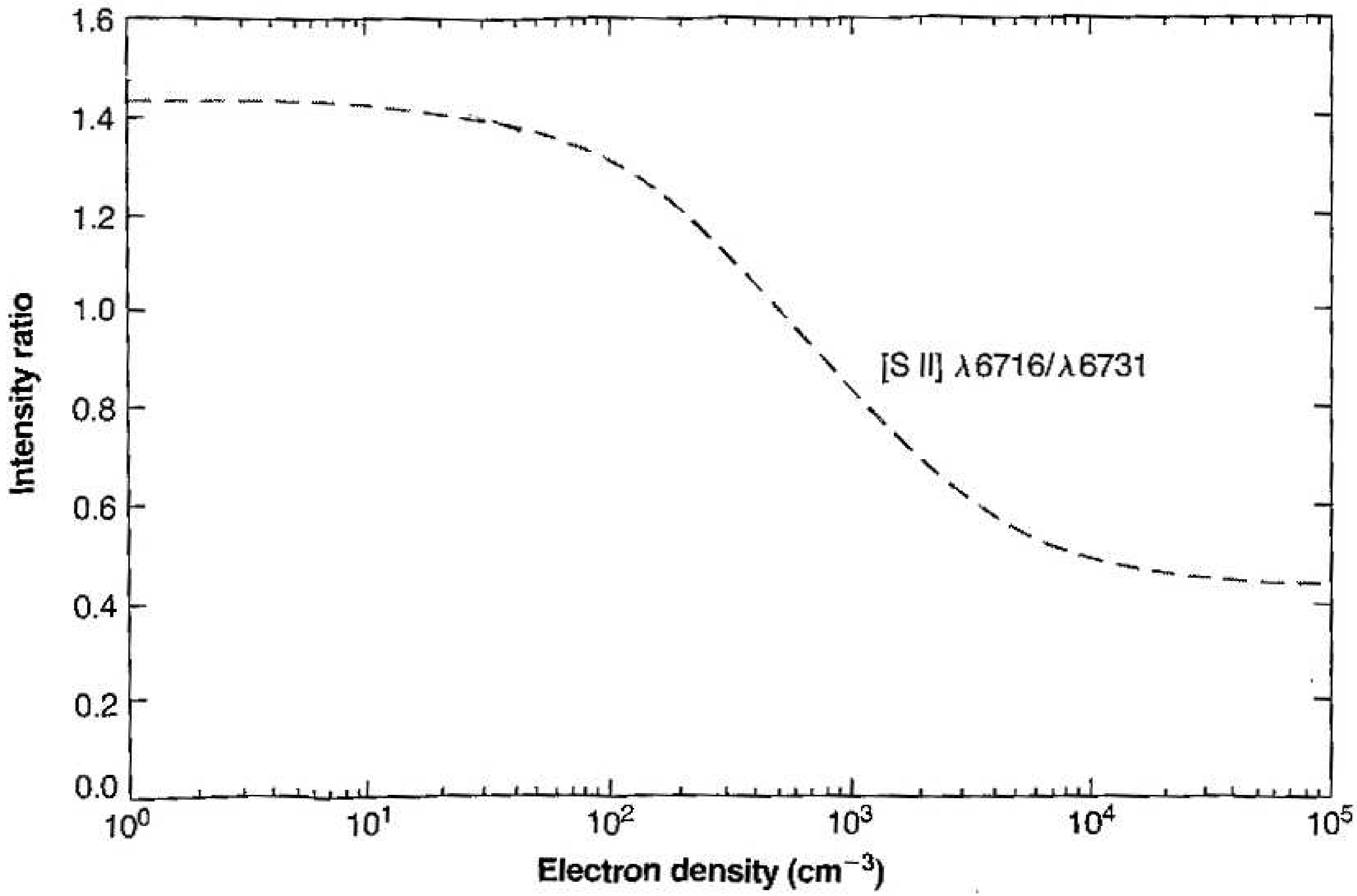
- Singly ionized sulfur S^+, $1s^2 2s^2 2p^6 3s^2 3p^3$ → 3 valence e
- All upper levels are metastable
- They can be populated **only** by collisions
- The lines of interest have very close wavelength
- Nearly all collisions which can exite level 3/2, can excite 5/2

- But! $g_{5/2}=6$, $g_{3/2}=4$ Why?
- What is the meaning of statistical weight?
- Life-time 5/2 is 3846 sec, 3/2 is 1136 sec
- Collisions can excite **and** deexcite
- Which line is more likely to be deexcited by collisions?

- For low densities (<100 cm^{-3}): deexcitation by ph emision
- Ratio of λ6716 to λ6731 is equal to the ratio of What?
- For high densities (>10000 cm^{-3}): deexcitation by collisions
- Ratio of λ6716 to λ6731 is equal to the ratio of What?
- Short lived level can emit more photons
- What is air density?

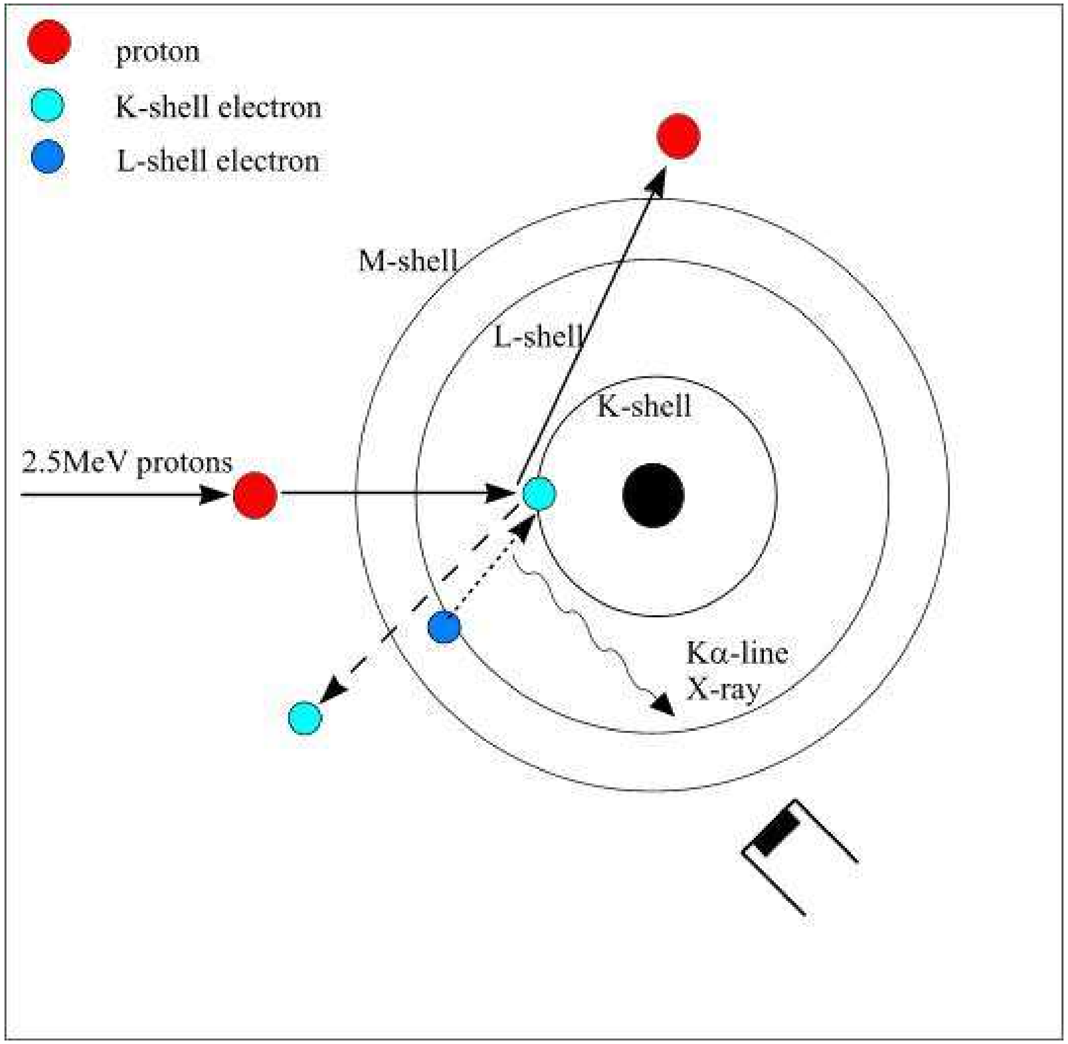
Exercise: Determiming the Gas Density

Follow www.williams.edu/Astronomy/research/PN/nebulae



Variation of λ6716/λ6731 ratio with density

Inner Shell Processes



X-ray fluorescence An electron can be removed from inner K-shell (how many electornes are there?)

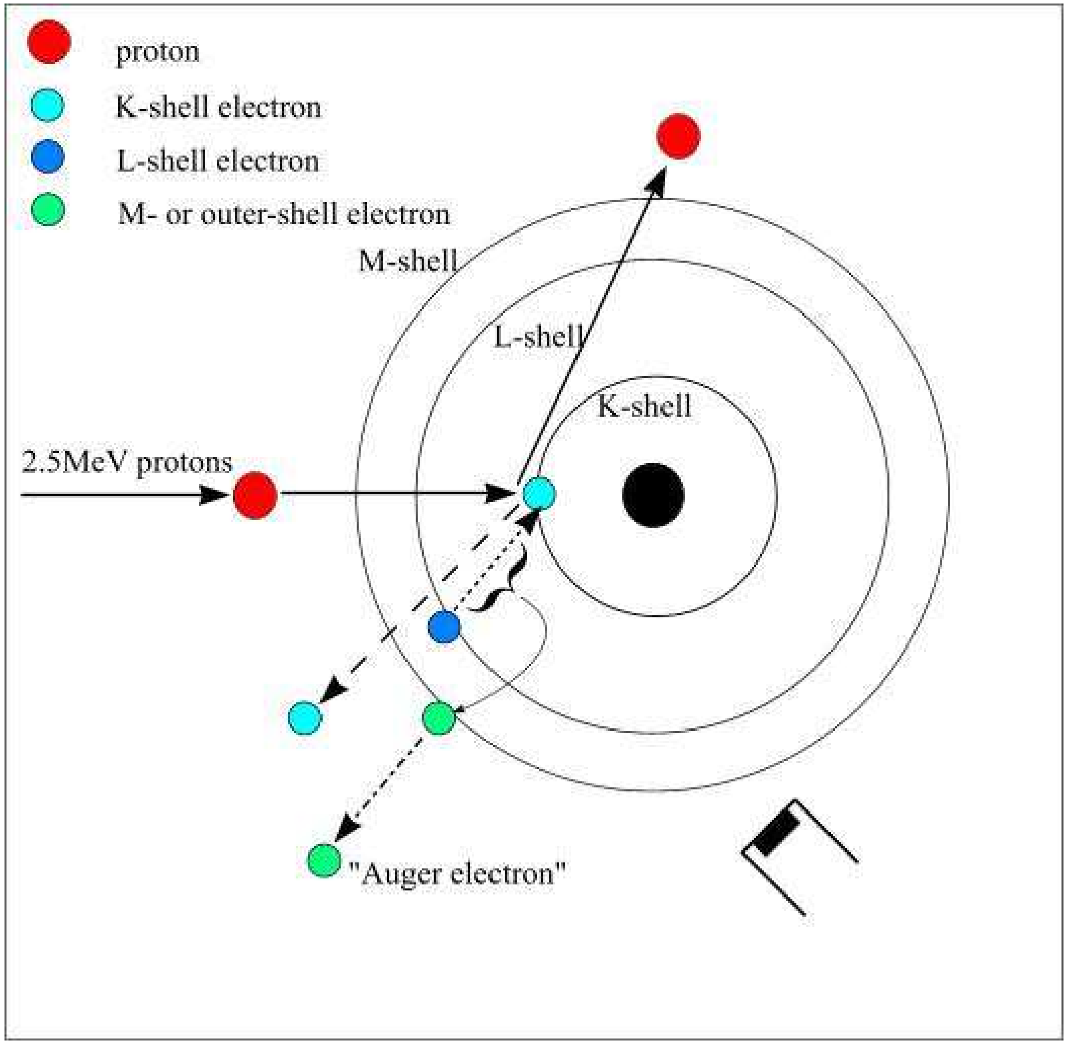
The vacancy is filled by a L-shell electron Kα-line. If the vacancy is filled by M-shell electron Kβ-line.

Iron is abundnat element with relatively large cross-section for K-shell ionization: Kα line at 6.4 keV is commonly observed from astrophysical objects

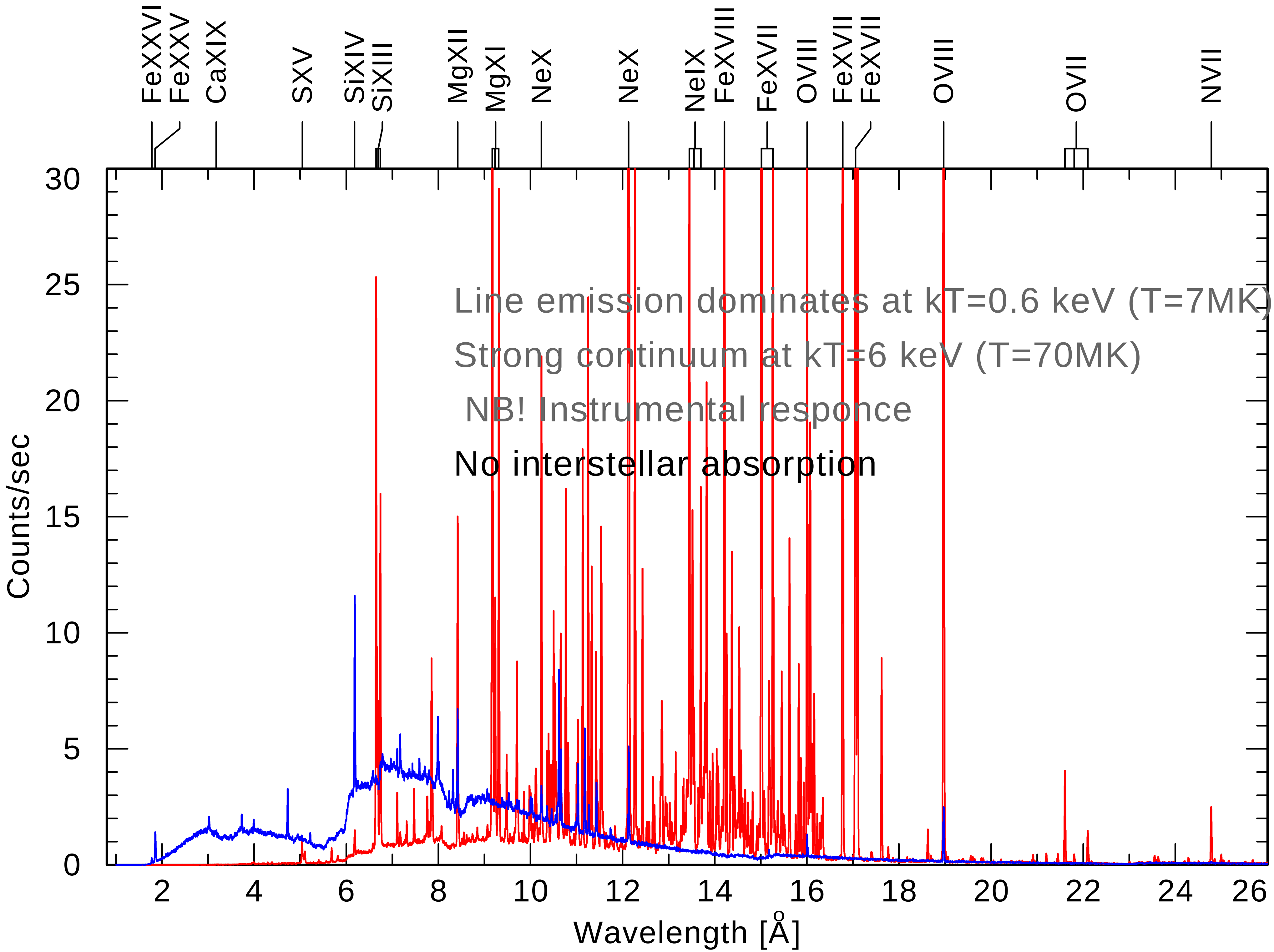
See Grotrian diagrmans in Kallman+ 04, ApJSS 155, 675

Inner Shell Processes

Auger ionization - inverse process

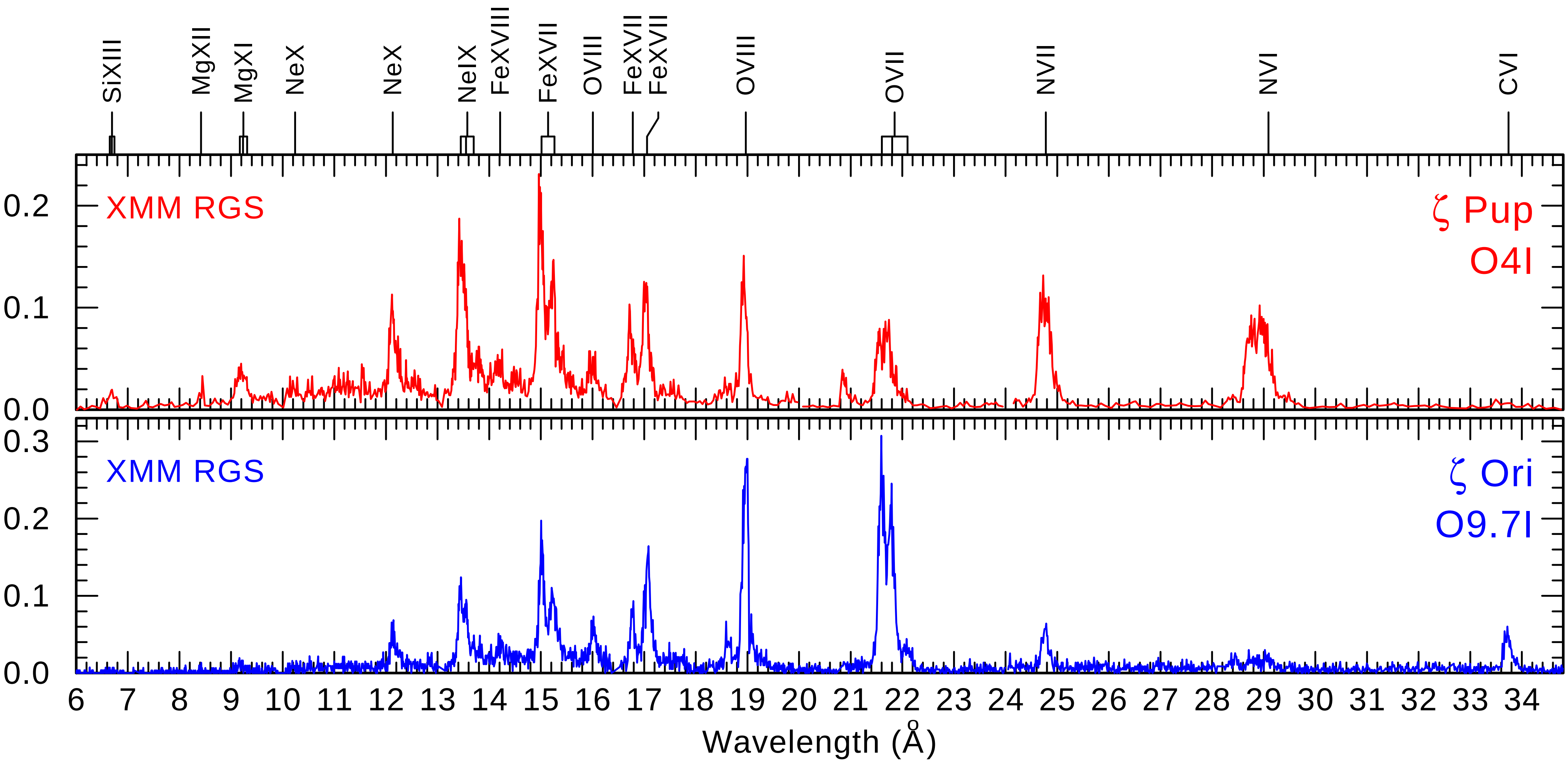


APEC simulated spectra for two different T(Chandra MEG+1)



High-Resolution X-ray Spectra

? Find He-like ions ?

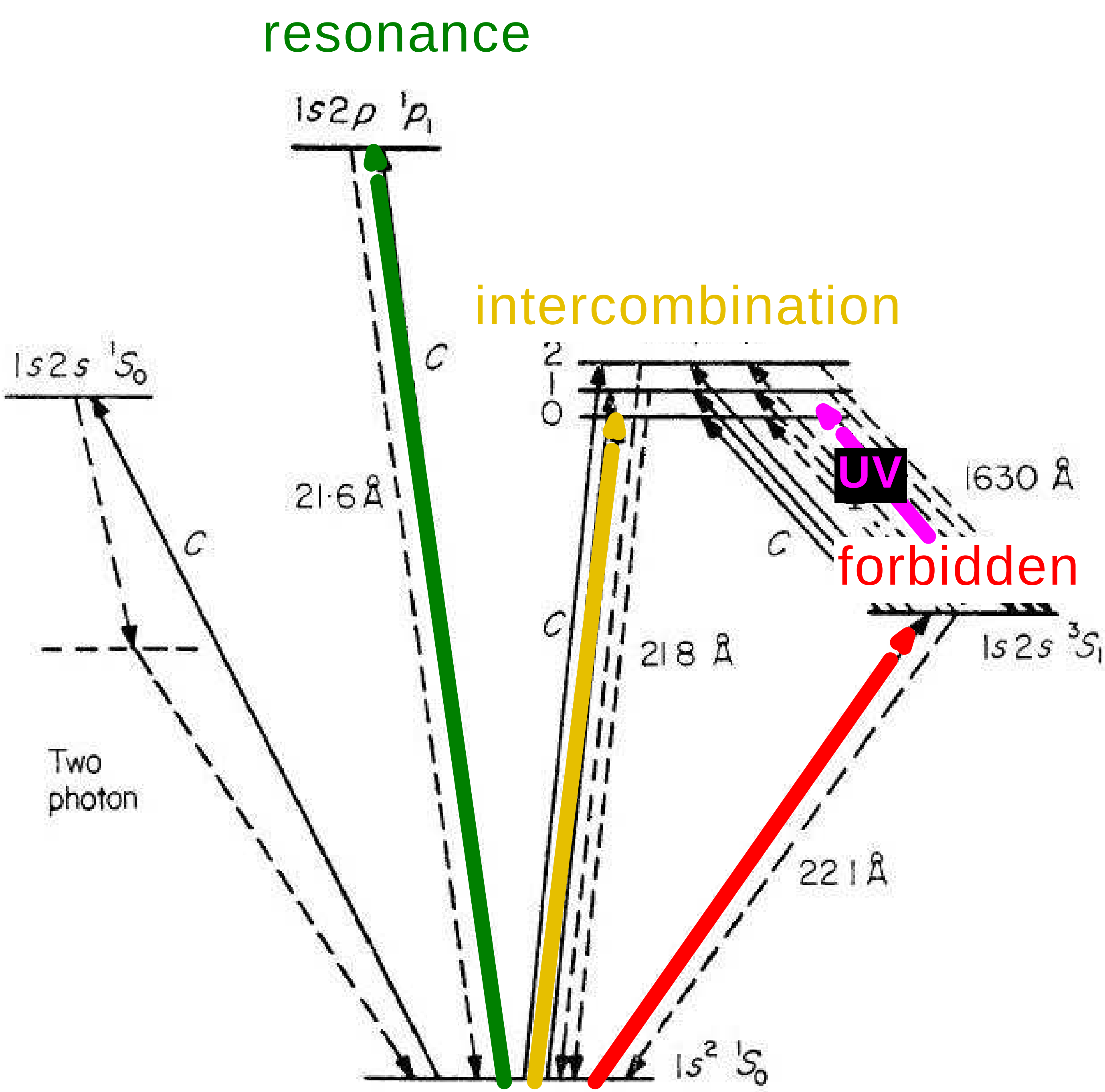


- * Overall spectral fitting → plasma model, abundunces
- * Line ratios → $T_X(r)$, spatial distribution
- * Line profiles → velocity field, wind opacity

Common X-ray diagnostics: lines of He-like ions

Ratio of forbidden to intercombination line flux depends on ?

- UV flux dilutes with r^{-2}
- f/i ratio estimator for distance where the hot gas is located
- Requires knowledge of stellar UV field

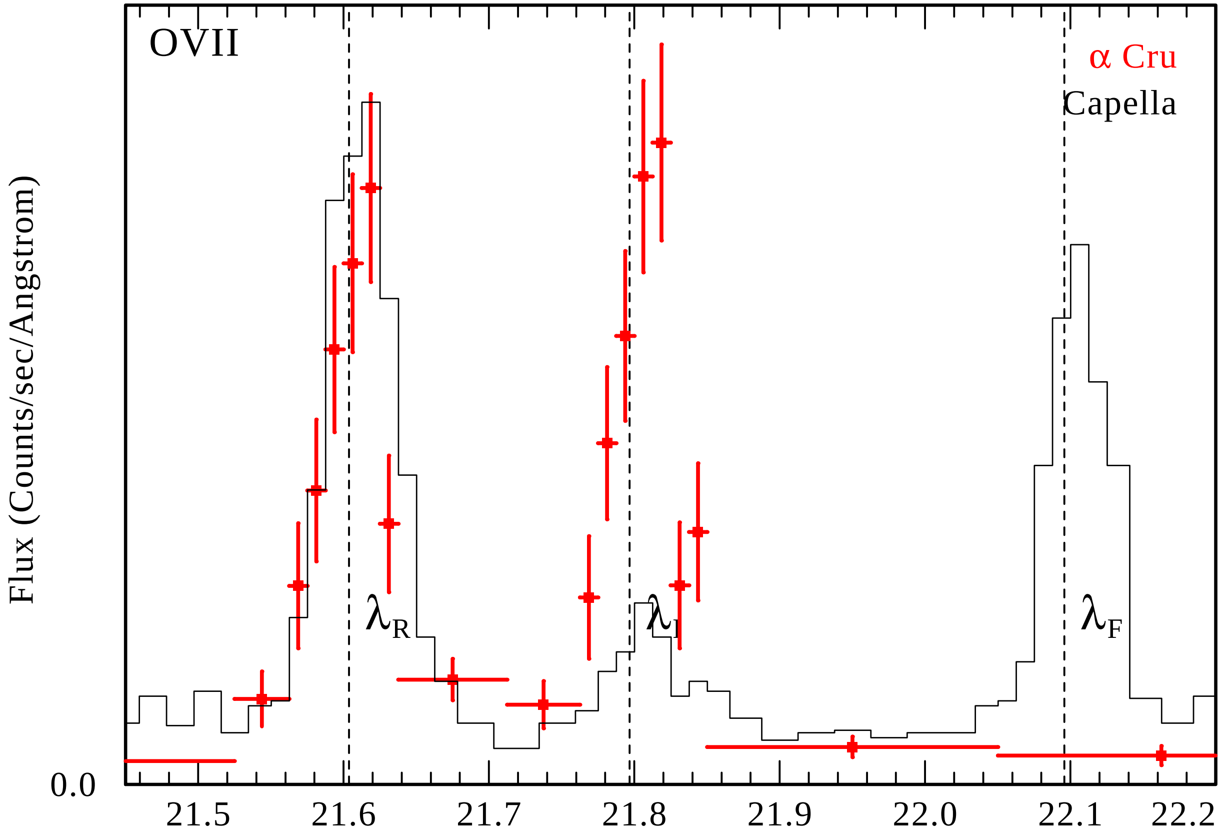


OVII

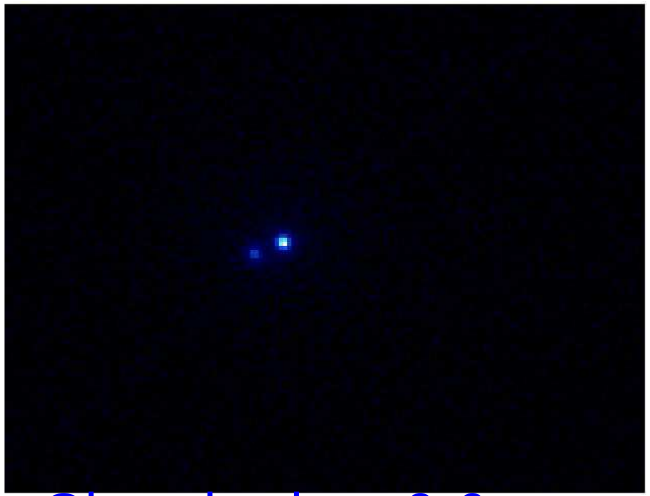
Gabriel & Jordan 1969

Comparing OVII in early and solar type stars

- B0.5IV+BV at d=98 pc
- X-ray brightest massive star on sky
- Soft spectrum, narrow lines
- compare to solar type star



Oskinova etal. in prep



Chandra has 0.6 arcsec resolution