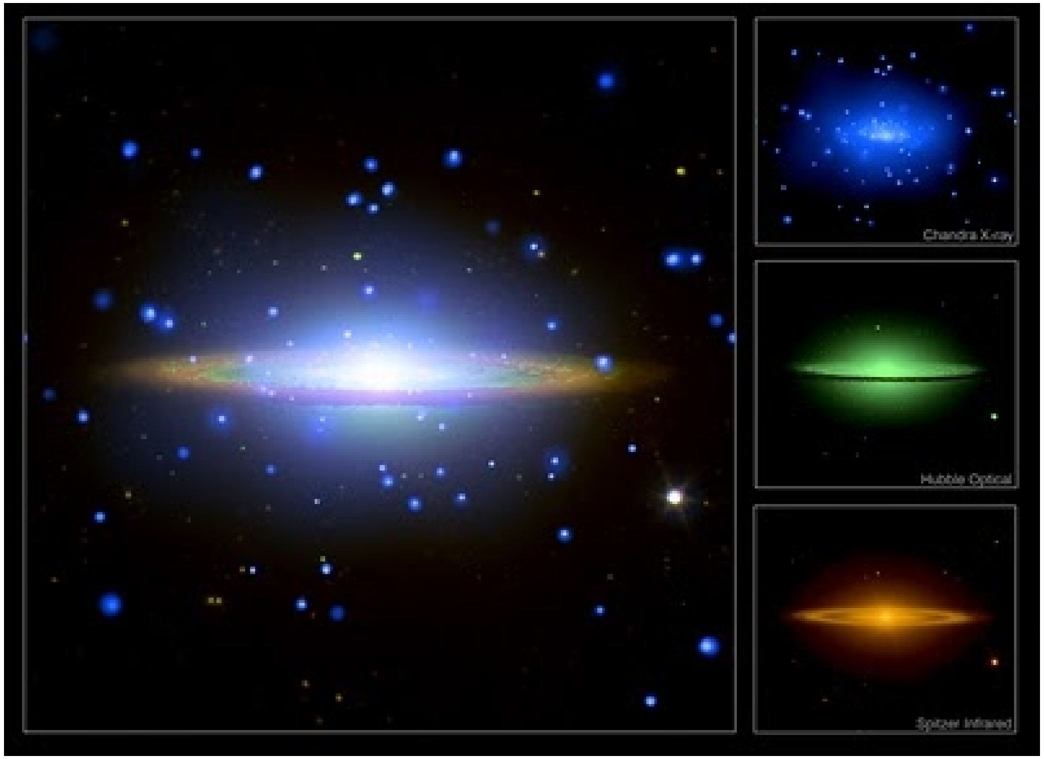
Summary of local conditions of the ISM

Four main phases, clearly visible in Spiral glaxies, more difficult to locate in ellipticals/lenticulars and irregulars



1. HIM

2. WIM

3. WNM

4. CNM

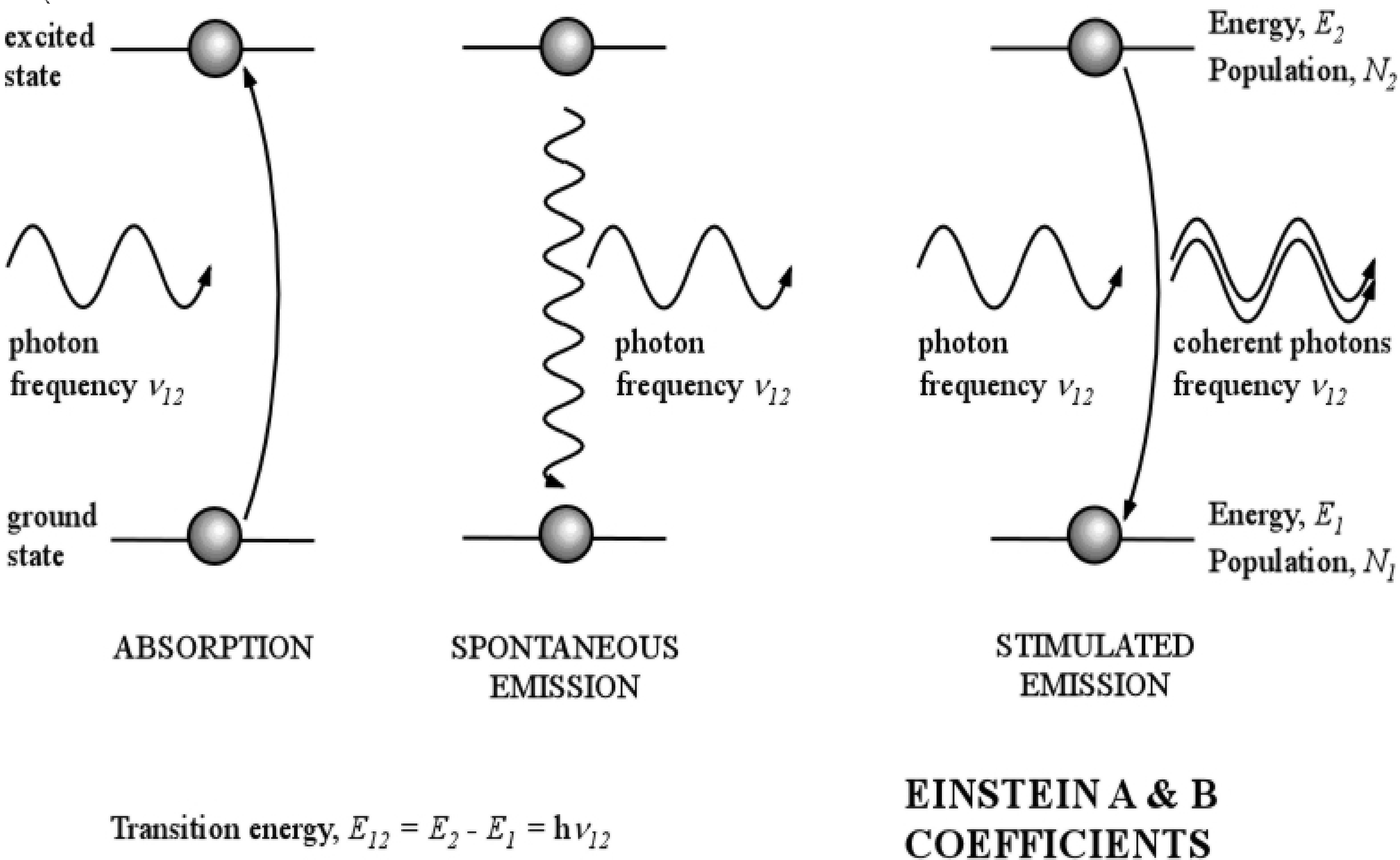
The LOCAL status of matter depends on energy transfer to/from the LOCAL environment.

Cooling and heating rates *determine the status of the diffuse matter.*
In this respect, the role of Dark Matter is neglected (since it is relevant mostly for his gravitational effects – see later on the rotation curve in spiral galaxies).

In the following we are going to consider line transitions.

Einstein's coefficients (0)

They are used to describe radiative interactions involving bound-bound electron transitions, based on quantum mechanics



Einstein's coefficients(1)

Given two atomic levels ***m*** *and* ***n*** *(m>n)*
the following definitions hold:

Spontaneous emission: $A_{mn}\ (sec^{-1})$ = *transition probability per unit time to go from level m to n by emission of a photon*

Absorption: $B_{nm}\bar{J}$ = *transition probability per unit time to go from level n to m via absorption of a photon*

Stimulated emission: $B_{mn}\bar{J}$ = *transition probability per unit time for emission due to incoming radiation*

$\bar{J}$ *represents the density of photons at the frequency* ν_{nm} *so that* $h\nu_{nm}$ *corresponds to the difference between the energy levels n and m*

Einstein's coefficients(2)

The set of emitted photons IS NOT monochromatic: the energy difference between the two levels is not infinitely sharp.

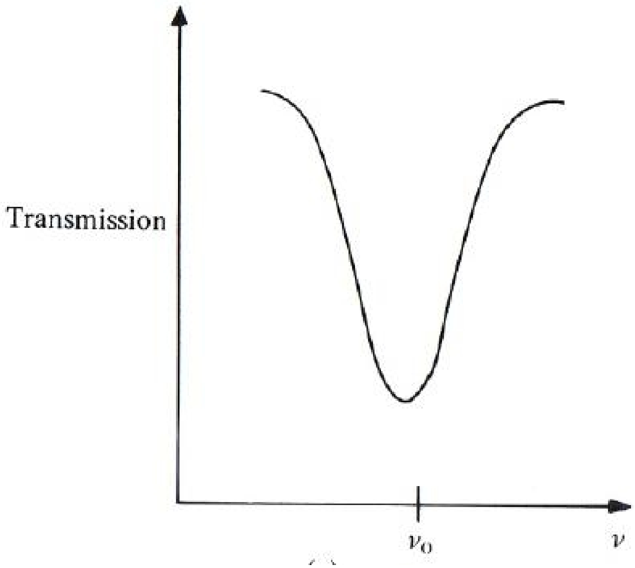
*It is described by the **line profile function (LPF) $\Phi(\nu)$** which is sharply peaked at the frequency ν_{nm}*

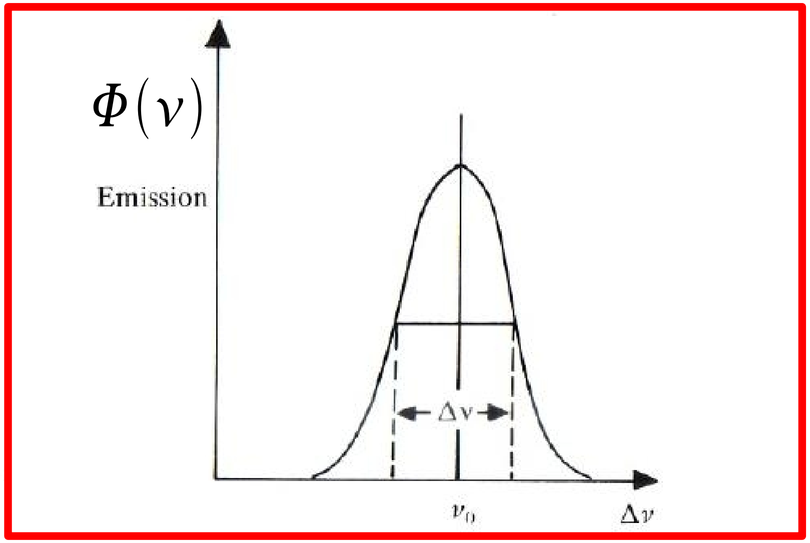
$$\int_0^\infty \Phi(\nu)\, d\nu = 1$$

represents the effectiveness of frequencies around ν_{nm} for causing transitions

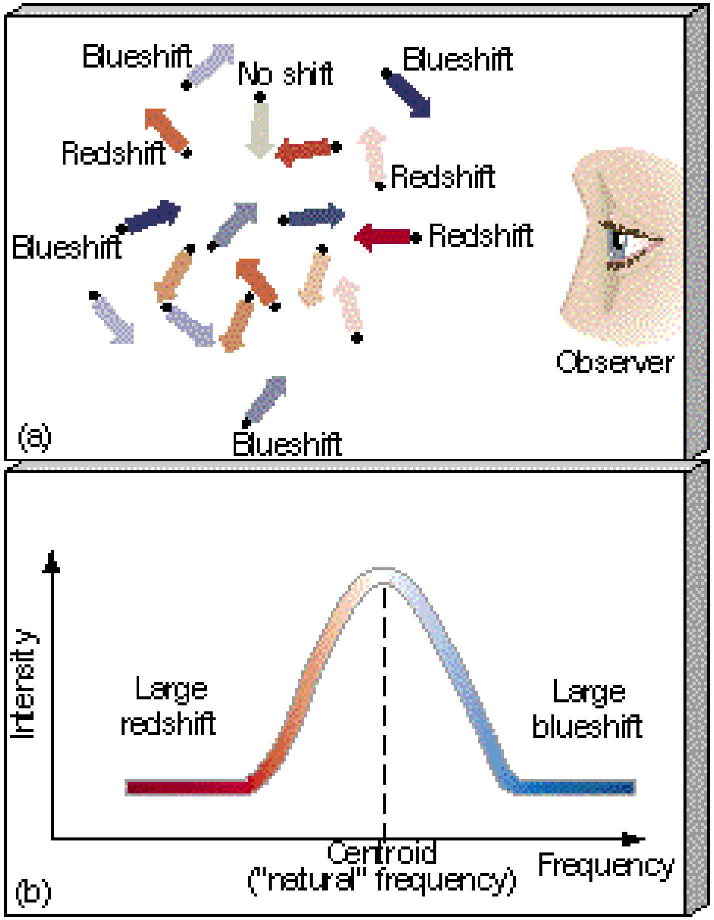
$$\bar{J} \equiv \int_0^\infty J_\nu \Phi(\nu)\, d(\nu)$$

If J_ν changes slowly with ν, then $\Phi(\nu)$ acts like a δ function





Doppler (thermal) broadening



Atoms are in (thermal) motion wrt the observer and the rest (atom) frame frequencies are either red- or blue- shifted. If v_r is the radial velocity

$$\Delta\nu = \nu_{obs} - \nu_{em} = \nu_{em}\frac{v_r}{c}$$

It is possible to derive the radial velocity (redshift/blueshift)

$$v_r = c\,\frac{\nu_{obs} - \nu_{em}}{\nu_{em}}$$

the shape of the line is modified, the total energy is not

***N.B. The centroid** (= "natural frequency") **remains unchanged**;*

only in the case that the

whole cloud is moving, then also the centroid is (Doppler) shifted

Spectral line broadening (2) – v_r and temperature

In case we are at thermal equilibrium (Maxwell-Boltzmann)

$$N(v_r)\,dv_r \simeq N_o v^2 e^{\frac{-m_a v_r^2}{2kT}} dv_r$$ *where* m_a *is the mass of the atom*

$$N(\nu)\,d\nu \simeq N_o e^{\frac{-m_a c^2}{2kT}\frac{(\nu_{obs}-\nu_{em})^2}{\nu_{em}^2}} d\nu$$

and in this case the Line Profile Function becomes (if we introduce the Doppler width)

$$\Delta\nu_D = \frac{\nu_{em}}{c}\sqrt{\frac{2kT}{m_a}}$$

$$\Phi(\nu) = \left(\Delta\nu_D\sqrt{\pi}\right)^{-1}\exp\left(-\frac{(\nu_{obs}-\nu_{em})^2}{(\Delta\nu_D)^2}\right)$$

Valid also in case of turbulence, once modified the Doppler width by introducing ξ, the rms of turbulent velocities (with Gaussian distribution)

$$\Delta\nu_D = \frac{\nu_{em}}{c}\sqrt{\frac{2kT}{m_a}+\xi^2}$$

Natural (Lorentz) broadening

an atom at an excited state has a finite lifetime

$$\Delta t \simeq \frac{1}{A_{mn}}$$

the energy difference is finite as well $\Delta E = \Delta h\nu$

the decay therefore follows the Heisemberg's Principle in the form

$$\Delta E \Delta t \geq \frac{h}{2\pi}$$

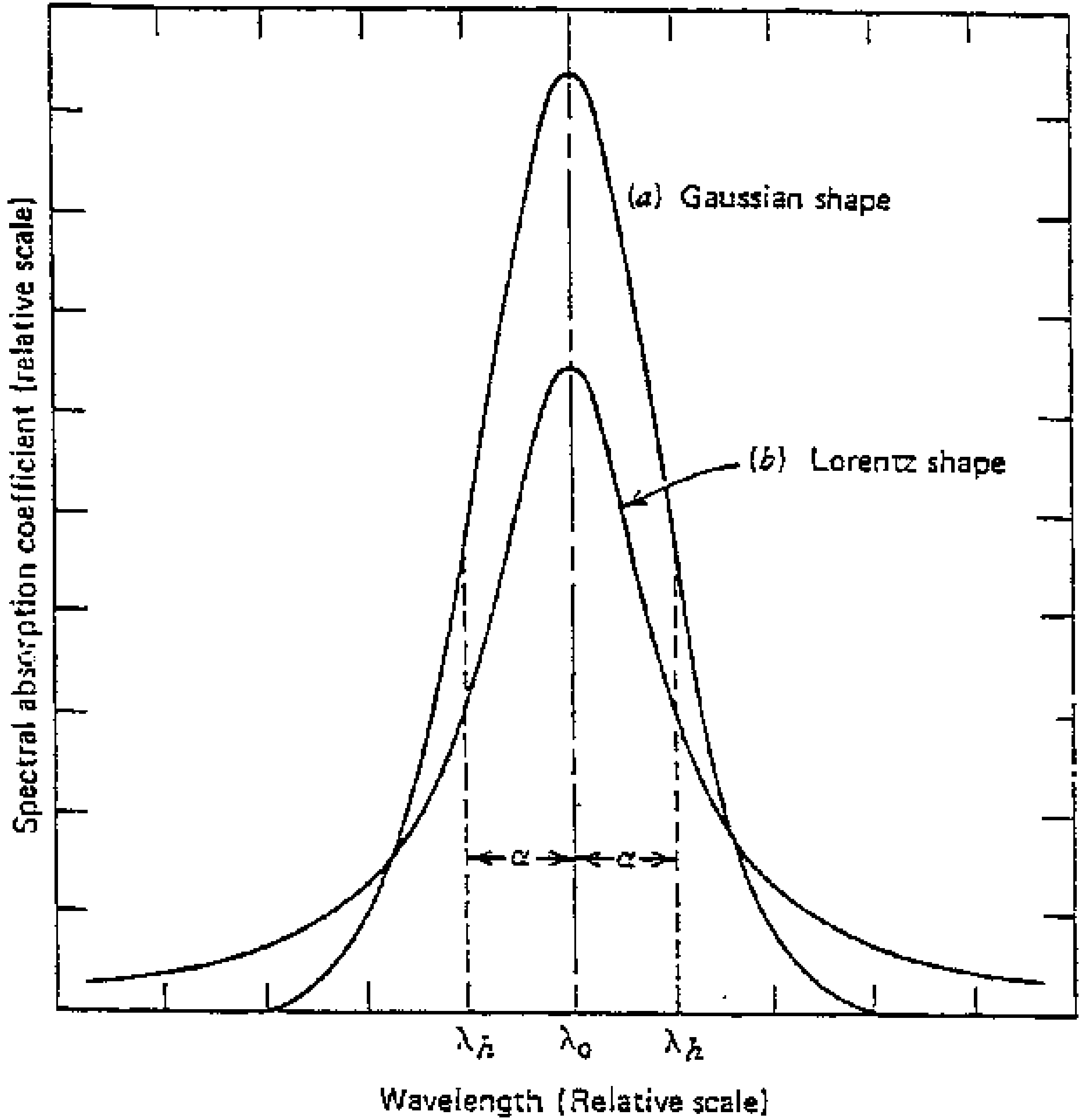
$$\Delta E \Delta t = \Delta h\nu \frac{1}{A_{mn}} \geq \frac{h}{2\pi}$$

$$\Delta \nu \geq \frac{A_{mn}}{2\pi}$$

*and this is **the minimum bandwidth** allowed for the transition between levels m,n*

***WARNING**: **large**/**small** values of imply **broad**/**narrow** lines*

Spectral line broadening 4)



Spectral line shape produced by: (a) Doppler broadening and (b) natural and collision broadening (taken from Levi (1968)).

Spectral line broadening (5)

the LPF for natural broadening is

$$\Phi(\nu) = \frac{\gamma/4\pi^2}{(\nu_{obs}-\nu_{em})^2+(\gamma/4\pi)^2} \qquad \textit{where} \qquad \gamma = \sum_m A_{nm}$$

or $\gamma = \gamma_u + \gamma_l$ *, in case there are transitions from a lower level too (inclusive of radiation field and appropriate* B_{mn}*)*

Collisional broadening

collisions introduce random changes to the phase of E/B field

$$\Phi(\nu) = \frac{\Gamma/4\pi^2}{(\nu_{obs}-\nu_{em})^2+(\Gamma/4\pi)^2}$$

where $\Gamma = \gamma + 2\nu_{coll}$; ν_{coll} *is the frequency of collisions per unit time an atom experiences.*

atoms hit other particles during emission (absorption). All broadening mechanisms coexist, with Doppler and Lorentz broadenings being dominant.

e-m waves are radiated at the same frequency of an oscillating charge

$$d(t) = q \cdot x_o \cos(\omega t)$$

in terms of quantum mechanics, we have probability densities

$$\Psi = \psi(x,y,z)\ e^{-2\pi i (E/h) t}$$

and the ***dipole*** *(i.e. nucleus + electron) may be written as*

$$d_x(t) = \int e \cdot x \Psi \Psi^* \, d\tau \qquad (\text{the same also for } y, z)$$

and more in general for a generic transition m to n

$$d_x^{mn}(t) = \int e \cdot x \Psi_m \Psi_n^* \, d\tau = \int e \cdot x \psi_m \psi_n^* \ e^{-2\pi i t (E_m - E_n)/h} d\tau$$

$$(\text{the same also for } y, z)$$

$$\vec{d}^{mn}(t) = e \cdot \vec{R}^{mn}(t)\ e^{-2\pi i t (E_m - E_n)/h}$$

where: $R_x^{mn}(t) = \int x \psi_m \psi_n^* \, d\tau$ [the same for $R_y^{mn}(t), R_z^{mn}(t)$]

i.e. $\vec{R}^{mn}(t) = \int \vec{r} \psi_m \psi_n^* \, d\tau$

Emitted power during dipole transitions

the meaning of A_{mn}:

$$P(t) = \frac{2e^2}{3c^3}\, a^2(t) = \frac{2e^2}{3c^3}\, \omega^4 x_o^2 \cos^2(\omega t)$$

$$\langle P(t)\rangle = \frac{2e^2}{3c^3}\frac{\omega^4 x_o}{2} = \frac{32\pi^4}{3c^3}\nu^4\left(\frac{e^2 x_o}{2}\right) = \frac{32\pi^4}{3c^3}\nu^4\langle \ddot{d}_x^2(t)\rangle$$

$$= A_{mn}\cdot h\nu_{mn} \qquad (\text{i.e. number of transitions per unit time} \times h\nu_{mn})$$

then we can derive the expression of the Einstein coefficient for spontaneous emission:

$$A_{mn} = \frac{32\pi^4\nu^3}{3hc^3}\langle \ddot{d}_x^2(t)\rangle$$

and going to 3-D

$$A_{mn} = \frac{64 e^2\pi^4\nu^3}{3hc^3}\vec{R}^{mn}\vec{R}^{mn} = \frac{64\pi^4\nu^3}{3hc^3}\left|P_{mn}\right|^2$$

where $\left|P_{mn}\right|$ *is the power emitted for* $m \rightarrow n$ *transitions* *example:*

$x_o = a_o = 5.3\ 10^{-9}$ cm (Bohr radius), $\nu_{mn} = 3.3\ 10^{15}$ Hz (Lya limit)
$p = ea_o/2 = 1.3\ 10^{-18}$ ues cm

we get:

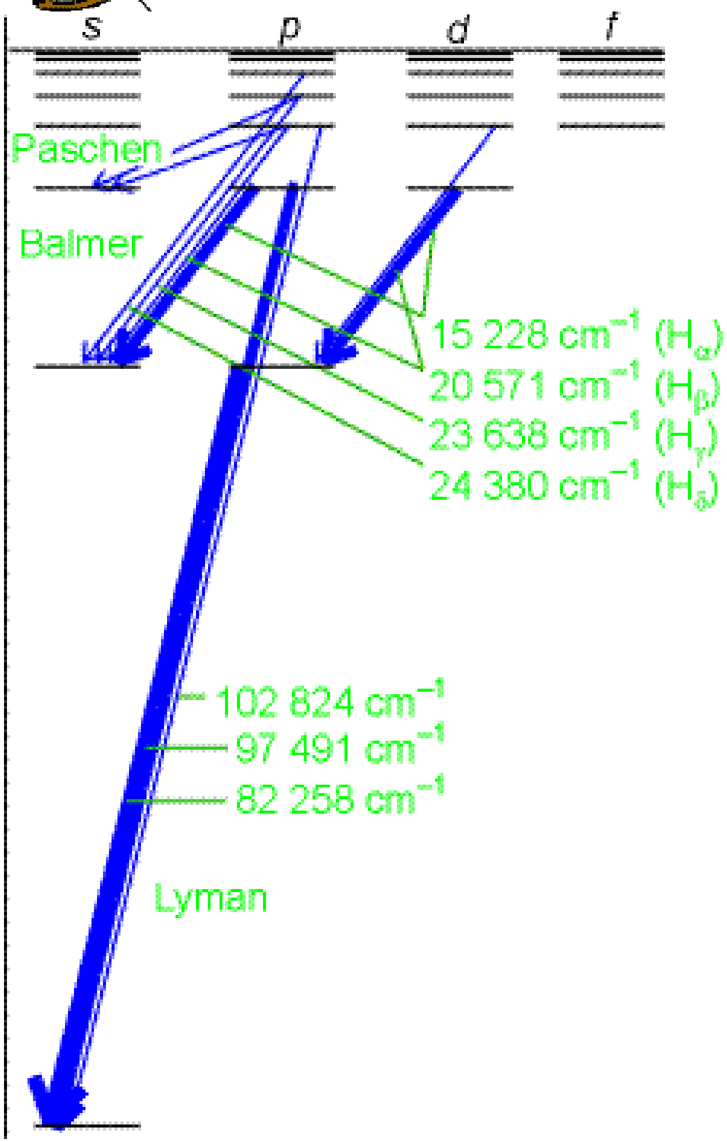
$$A_{\infty 1} = 3.5 \cdot 10^{8} \quad s^{-1}$$

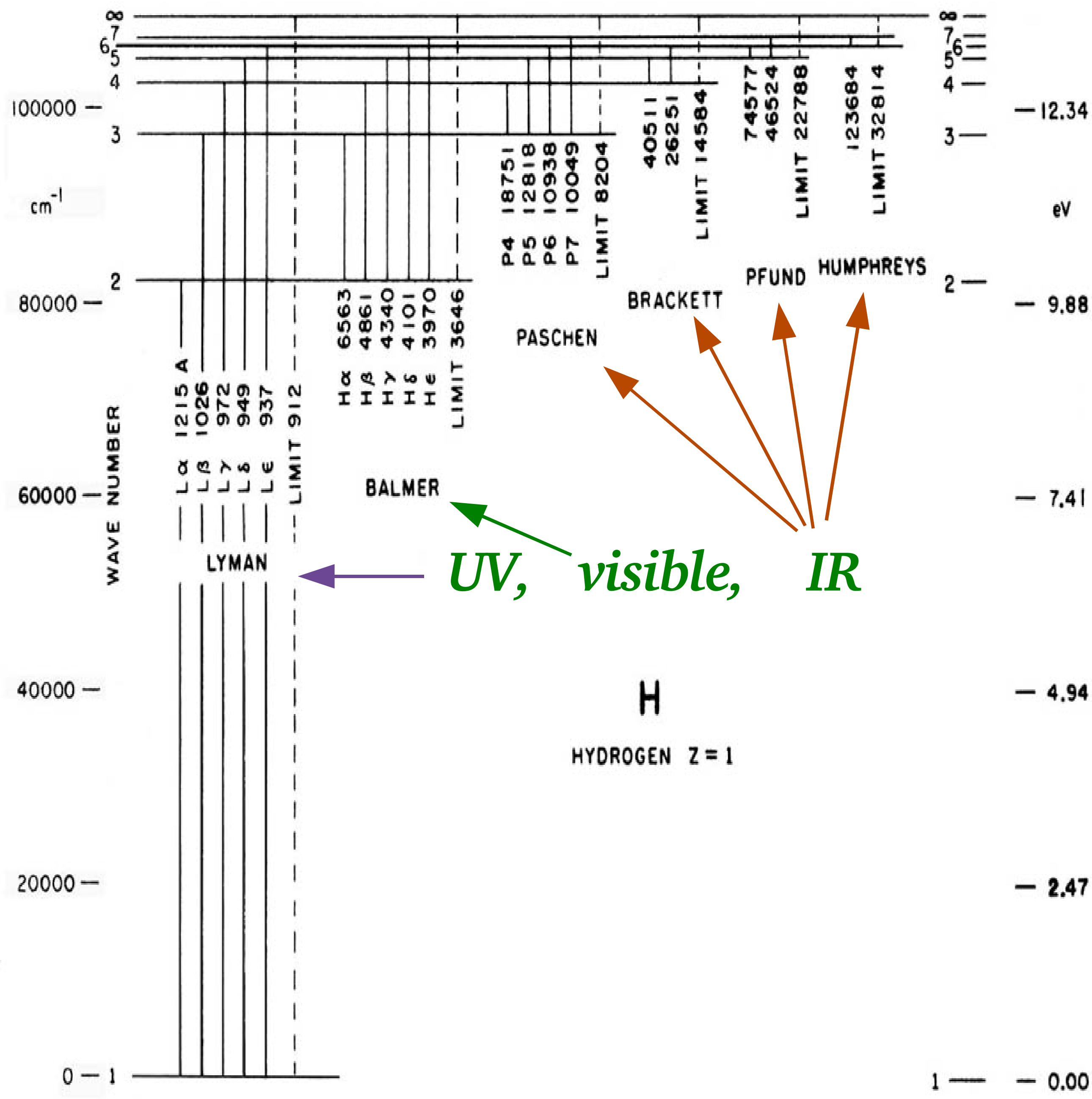
vectors $\vec{R}_{mn}$ can be arranged into a (symmetric) matrix and some elements are 0 meaning that the probability of the transition is 0, namely prohibited.

the value of the elements in the matrix may be intrepreted as oscillator strength for that transition.

Electric dipole transitions:
Selection rules: Δn arbitrary (but not 0), $\Delta l = \pm 1$ (parity change),
$\Delta L = 0, \pm 1$, $\Delta S = 0$, $\Delta J = 0, \pm 1$,
(for reference to notation see Rohlf, 1994 "Modern physics from α to Z_o")

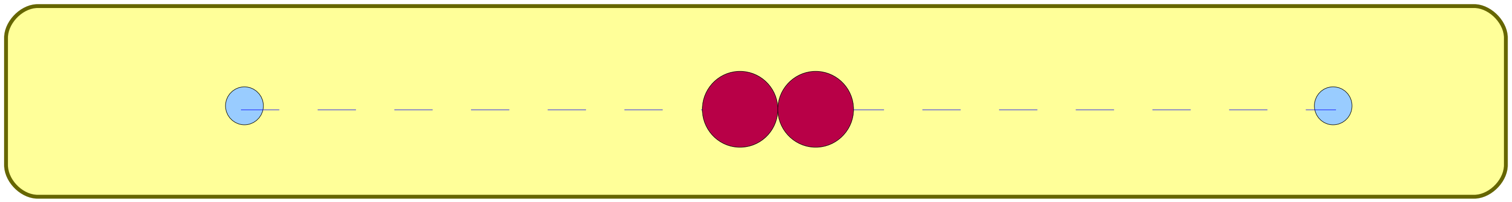
Hydrogen: Grotrian diagrams





Electric quadrupole

The quadrupole term can be non zero when the dipole is 0 (prohibited transition, second term of expansion of potential vector A);



in this case the integral becomes

$$q_x(t) = \int e \cdot x^2 \Psi_m \Psi_n^* \, d\tau \qquad (also \quad q_y(t),\; q_z(t))$$

A similar expression for A_{mn} can be derived as in the case of the dipole; all these transitions are termed prohibited, but their probabilities (A_{mn}) although smaller than in the dipole case, may be relevant

Selection rules: Δn arbitrary, $\Delta l = 0 \pm 2$, $\Delta J = 0, \pm 1, \pm 2$, $\Delta L = 0, \pm 1, \pm 2$ $\Delta S = 0$, $\Delta m = 0, \pm 1, \pm 2$

Magnetic dipole

The ***magnetic dipole*** *has to be considered and refers to hyperfine structure transitions, where energy levels differ by very small quantities*

Selection rules: $\Delta n = \Delta l = \Delta L = \Delta S = 0$, $\Delta J = 0, \pm 1$, $\Delta m = 0, \pm 1$

$$m(t) = m_o \cos(\omega t)$$

$$\langle P(t) \rangle = \frac{2}{3c^3}\omega^4 \langle m^2(t) \rangle = \frac{32\pi^4}{3c^3}\nu^4 \langle m^2(t) \rangle$$

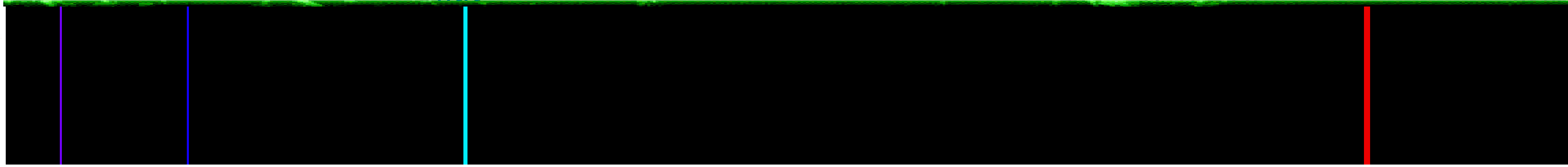
$$A_{mn} = \frac{64\pi^4}{3h}\frac{\nu^3}{c^3}|\mu_{mn}|^2$$

typical ratios for transitions:

$$\frac{A_Q}{A_D} \approx 3 \cdot 10^{-8} \qquad \frac{A_M}{A_D} \approx 5 \cdot 10^{-5}$$

for Einstein B coefficients we need a bit more patience....

Some examples of A_{mn} coefficients for electric dipole transitions



Line	wavelength (A)	oscillator strength	A_{mn} (s-1)
Lyman α	1215.67	0.41620	4.70E+008
Lyman β	1025.72	0.07910	5.58E+007
Lyman γ	972.54	0.02899	1.28E+007
Lyman limit	911.80		
H α	6562.80	0.64070	4.41E+007
H β	4861.32	0.11930	8.42E+006
H γ	4340.46	0.04467	2.53E+006
H δ	4101.73	0.02209	9.73E+005
H ε	3970.07	0.01270	4.39E+005
H limit	3646.00		
P α	18751.00	0.84210	8.99E+006
P β	12818.10	0.15060	2.20E+006
P γ	10938.10	0.05584	7.78E+005
P limit	8204.00		
B α	40512.00	1.03800	2.70E+006
B β	26252.00	0.17930	7.71E+005
B γ	21655.00	0.06549	3.04E+005
Blimit	14584.00		

From Allen's Astronomical quantities (p 70, 71) – ***warning!***

A_{mn} different from Dopita & Sutherland “Astrophysics of the Diffuse Universe”, p 19

Selection rules for electronic transitions

Electric dipole:

$\Delta n =$ arbitrary

$\Delta l = \pm 1$ (parity change)

$\Delta J = 0, \pm 1$ $J=0 \rightarrow J = 0$ forbidden

$\Delta L = 0, \pm 1$ $L=0 \rightarrow L = 0$ forbidden

$\Delta S = 0,$

Electric quadrupole:

$\Delta n =$ arbitrary

$\Delta l = 0 \pm 2$ (no parity change)

$\Delta J = 0, \pm 1, \pm 2$ $J=0 \rightarrow J = 0$ forbidden

$\Delta L = 0, \pm 1, \pm 2$ $L=0 \rightarrow L = 0$ forbidden

$\Delta S = 0$

Magnetic dipole:

$\Delta n = \Delta l = 0$

$\Delta J = 0, \pm 1$ $J=0 \rightarrow J = 0$ forbidden

$\Delta L = \Delta S = 0$

n, l=electron angular momentum (=0,...n-1), S= total spin, L= orbital angular momentum, J = L+S total angular momentum

Four Statistical laws (for thermal equilibrium):

Maxwell – Boltzmann (velocities i.e. energy for particles):

$$\frac{dN}{dv} \propto f(v) \propto v^2 e^{-mv^2/2kT_k} \approx v^2 e^{-v^2/2\sigma^2} \quad \text{where} \quad \sigma = \frac{kT_k}{m}$$

Planck (spectral distribution for radiation)

$$U(\nu) = \frac{4\pi}{c} B_\nu(T_P) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{h\nu/kT_P} - 1}$$

Boltzmann (energy level occupation in atoms, molecules)

$$\frac{N_n}{N_m} = \frac{g_n}{g_m} e^{-(E_n - E_m)/kT_{Bz}} = \frac{g_n}{g_m} e^{-h\nu_{mn}/kT_{Bz}}$$

Saha (ionization states)

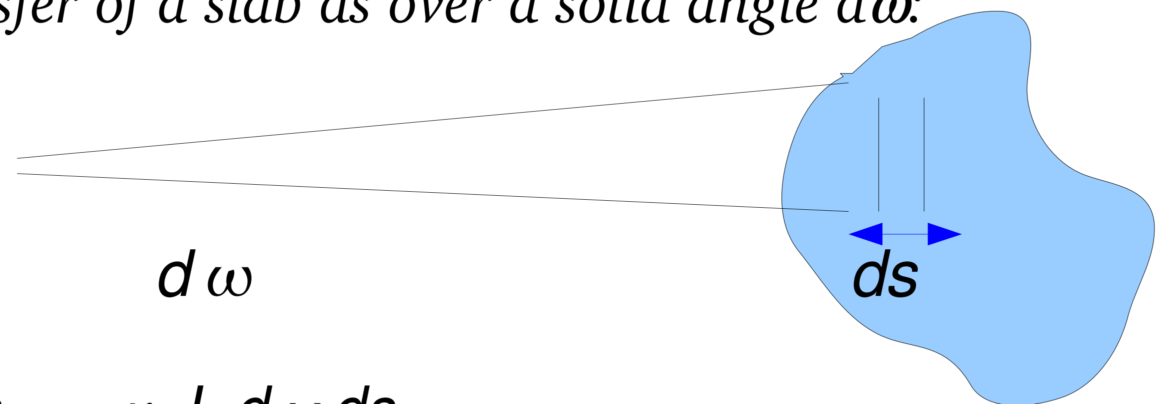
$$\frac{N_{i+1}}{N_i} = 2 \frac{u_{i+1}}{u_i} \frac{1}{N_e} \sqrt{\left(\frac{2\pi m_e kT_S}{h^2}\right)^3} e^{-(E_{i+1} - E_i)/kT_S}$$

$$\left(\sqrt{\frac{2\pi m_e kT_S}{h^2}}\right)^{-1} = \Lambda \text{ thermal de Broglie wavelength;} \quad ; \quad u_i = \sum_n g_{i,n} e^{-\chi_{i,n}/kT}$$

The equation of radiative transfer – rivisited

In case th. equilibrium we can relate A and B Einstein coefficients.

back to radiative transfer of a slab ds over a solid angle dω:



$$dI_\nu d\omega = \varepsilon_\nu d\omega ds - \kappa_\nu I_\nu d\omega ds$$

introducing the (infinitesimal optical depth) $d\tau \equiv \kappa_\nu ds$

$$\frac{dI_\nu}{d\tau_\nu} = \frac{\varepsilon_\nu}{\kappa_\nu} - I_\nu$$

(cloud) ***source function*** S_ν

in case of ThEq the source function is represented by the Planck's law *integrating…*

$$I_\nu = S_\nu\left(1-e^{-\tau_\nu}\right)+I_{\nu,o}\ e^{-\tau_\nu}$$

which gives the well known cases:

$$(1) \qquad I_\nu = \tau_\nu\left(S_\nu - I_{\nu,0}\right) + I_{\nu,0} \qquad if \quad \tau \ll 1$$

$$(2) \qquad I_\nu = S_\nu \qquad if \quad \tau \gg 1$$

in which we have either absorption (1) or emission (2) depending on the optical depth.

In case of line transitions (Lyα, β,..,Hα, β,.. CO, HI,…) the cloud is fully transparent (τ = 0) for $\nu \neq \nu_o$ giving $I(\nu)=I_o(\nu)$ while at the frequency of the line (ν_o) we have $I(\nu_o)$

*The line is in **emission** if* $I(\nu_o) - I_o(\nu_o) > 0$

*while it is in **absorption** when* $I(\nu_o) - I_o(\nu_o) < 0$

in general, in terms of temperatures, there is

absorption *if the intervening cloud is* ***colder*** *than the background (source)*

while there is ***emission*** *in case it is* ***hotter***

another way to discriminate between emission/absorption in terms of radiative transfer is:

$$\left(I_o e^{-\tau_o} + S_\nu\left(1-e^{-\tau_o}\right)\right) - I_o = \left(S_\nu - I_o\right)\left(1-e^{-\tau_o}\right)$$

always > 0

$S_\nu > I_o$ *then emission*

$S_\nu < I_o$ *then absorption*

example(1): stars

In case the optical depth is small but I_o is large absorption may be measured while emission is more difficult:

Cold gas

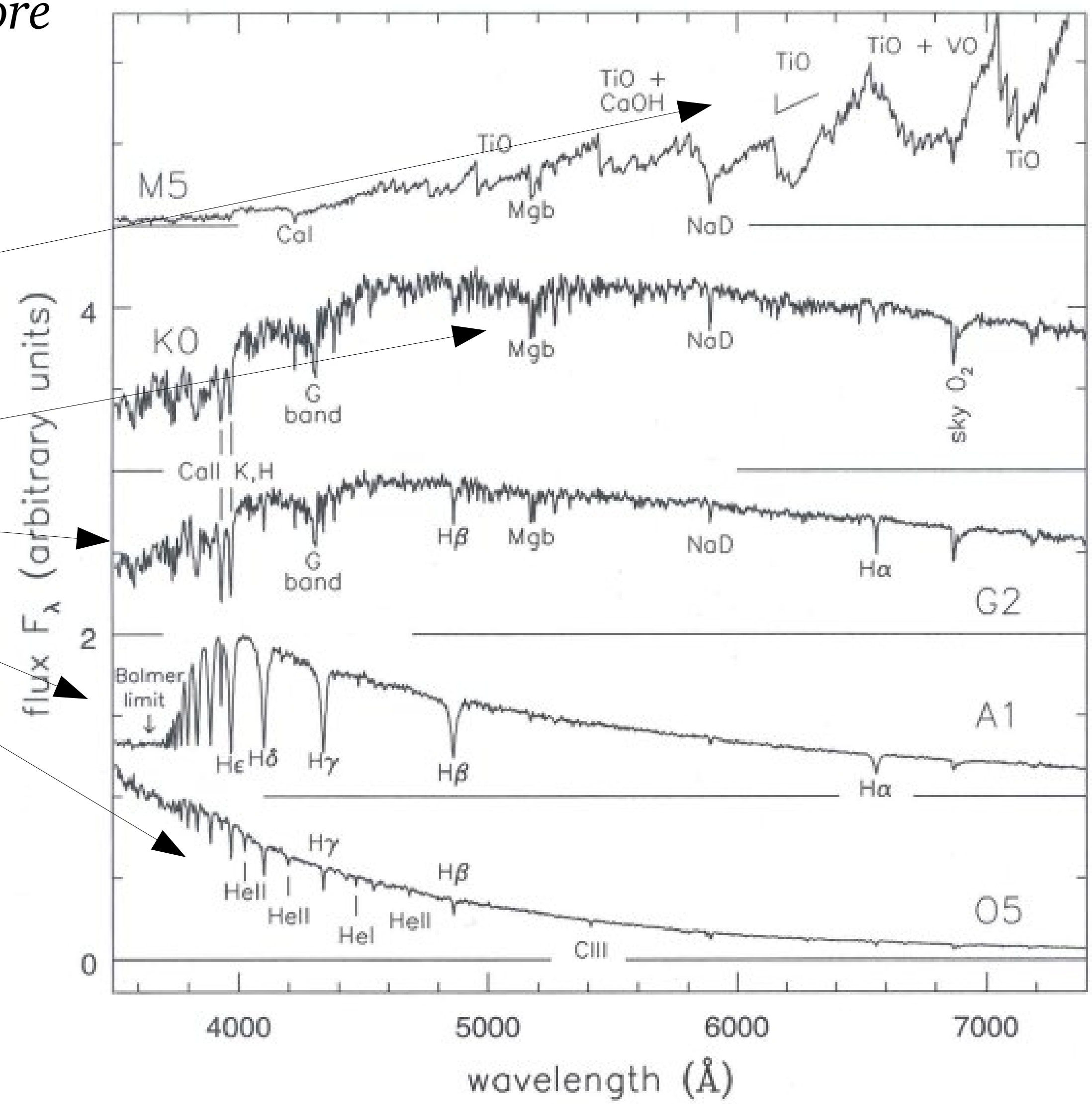


Figure 1.1 Optical spectra of main-sequence stars with roughly the solar chemical composition. From the top in order of increasing surface temperature, the stars have spectral classes M5, K0, G2, A1, and O5 – G. Jacoby *et al.*, spectral library.

example(2): "normal" (non active) galaxies

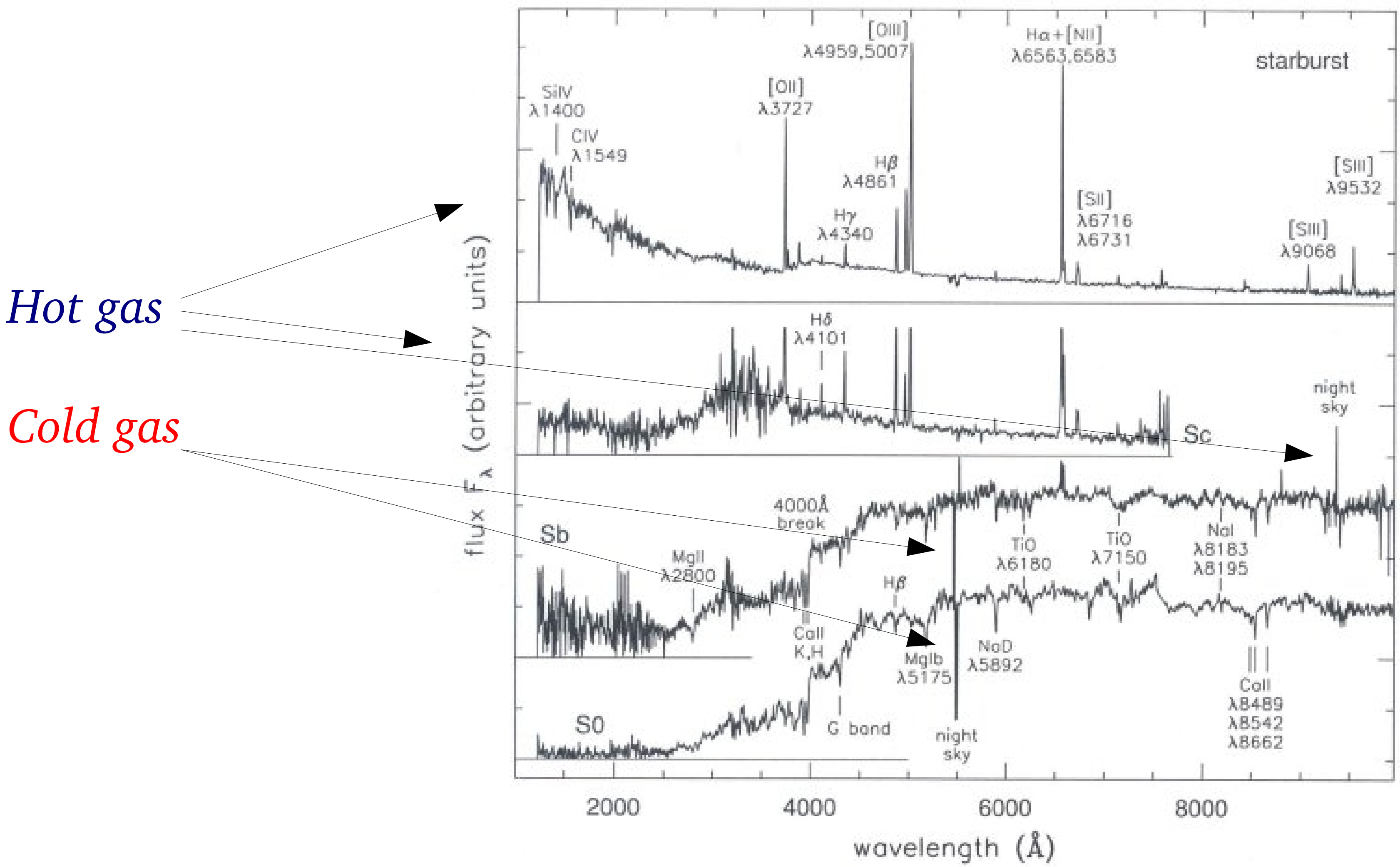
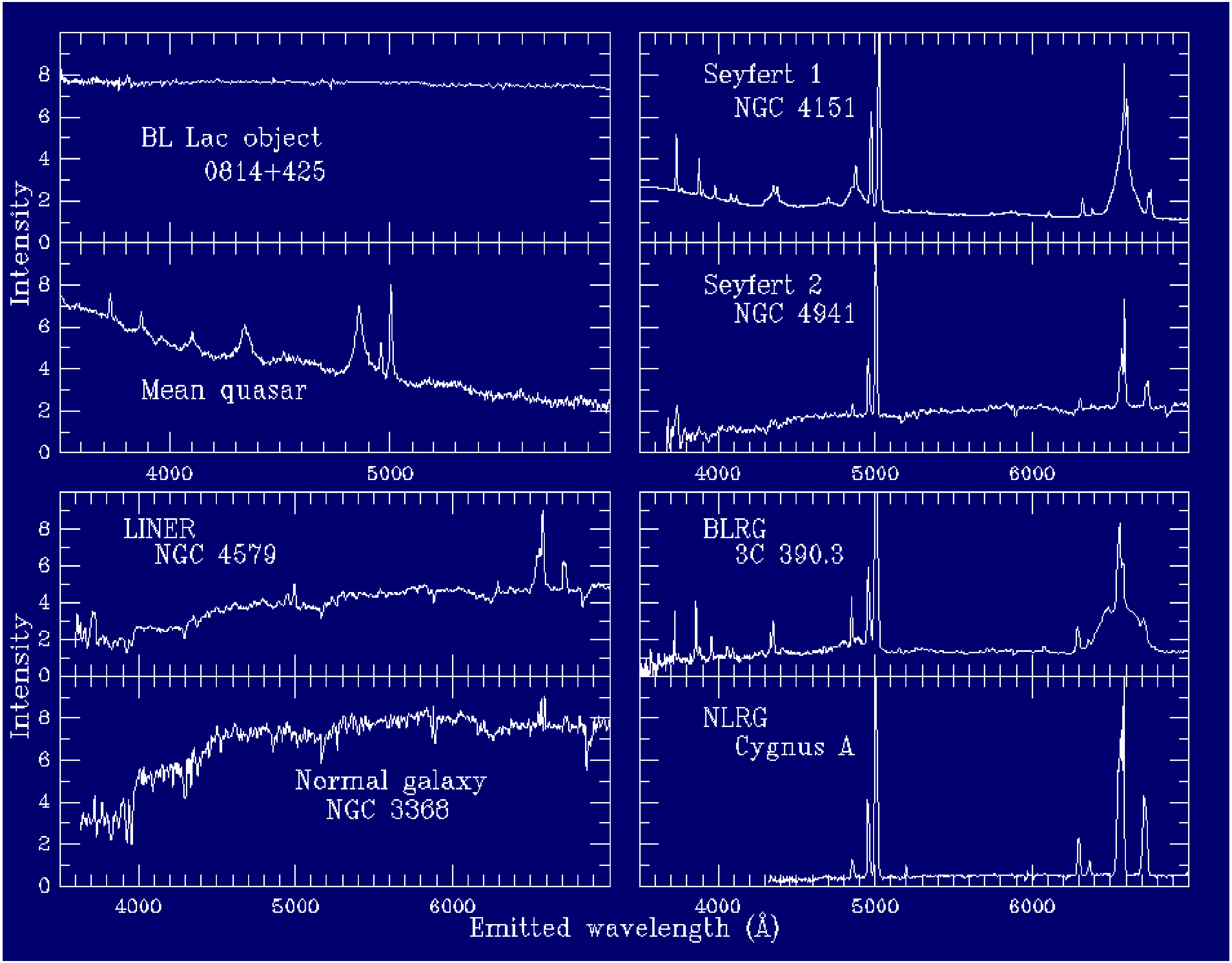


Figure 5.24 Spectra of galaxies from ultraviolet to near-infrared wavelengths; incompletely removed emission lines from the night sky are marked. From below: a red S0 spectrum; a bluer Sb galaxy; an Sc spectrum showing blue and near-ultraviolet light from hot young stars, and gas emission lines; a blue starburst galaxy, that has made many of its stars in the past 100 Myr – A. Kinney.

example(3): active galaxies (quasars)



The total (radiated) emitted energy in a cloud where a transition from a high state ***n*** *down to a lower energy state* ***m*** *is:*

$$\varepsilon_{em}=\int_{line}\epsilon_{\nu}d\nu=\frac{1}{4\pi}h\nu_{mn}\times N_m\times A_{mn}=\frac{N_m A_{mn} h\nu_{mn}}{4\pi}$$

in presence of a radiation field J(ν) the total absorbed energy is

$$\varepsilon_{ab}=\int_{line}\kappa_{\nu}d\nu=\frac{1}{4\pi}h\nu_{mn}J(\nu_{mn})[N_n B_{nm} - N_m B_{mn}]$$

where the stimulated emission is considered a "negative" absorption

if we can consider the continuum J(ν) constant within the line profile, then

$$I(\nu) = \frac{c}{4\pi}J(\nu)$$

and finally

$$\varepsilon_{ab} = \frac{h\nu_{nm}}{c} I_{\nu}\left(N_n B_{nm}-N_m B_{mn}\right)$$

Einstein's coefficients(5)

if we multiply $\varepsilon_{em}(\nu)$ and $\varepsilon_{ab}(\nu)$ times the line profile function $\phi(\nu)$ (assumed identical in both absorption and emission) we obtain

$$\epsilon_\nu = \frac{h\nu_{nm}}{4\pi}\phi(\nu) A_{mn} N_m$$

$$\kappa_\nu = \frac{h\nu_{nm}}{c}\phi(\nu)(B_{nm}N_n - B_{mn}N_m)$$

when there is equilibrium between emission and absorption (radiation at thermal equilibrium): the emitted energy balances the absorbed energy:

$$\varepsilon_{em} = \varepsilon_{ab}$$

In terms of Einstein coefficients

$$A_{mn}N_m = B_{nm}N_n J(\nu_{nm}) - N_m B_{mn} J(\nu_{nm}) = J(\nu_{nm})\left(N_n B_{nm} - N_m B_{mn}\right)$$

$$J(\nu_{nm}) = \frac{A_{mn}}{\left(N_n/N_m\right) B_{nm} - B_{mm}}$$

Einstein's coefficients(6)

in case of thermal equilibrium, we can use the Boltzmann equation for N_m*,* N_n

$$J(\nu_{nm}) = \frac{A_{mn}}{\left[(g_n/g_m)\, e^{h\nu_{nm}/kT}\right] B_{nm} - B_{mn}}$$

and

$$J(\nu_{nm}) = \frac{A_{mn}/B_{mn}}{\left[(g_n/g_m)\, e^{h\nu_{nm}/kT}\right] B_{nm}/B_{mn} - 1}$$

which ***must*** *be the Planck's BB radiation energy distribution:*

$$U_P(\nu) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{h\nu/kT} - 1}$$

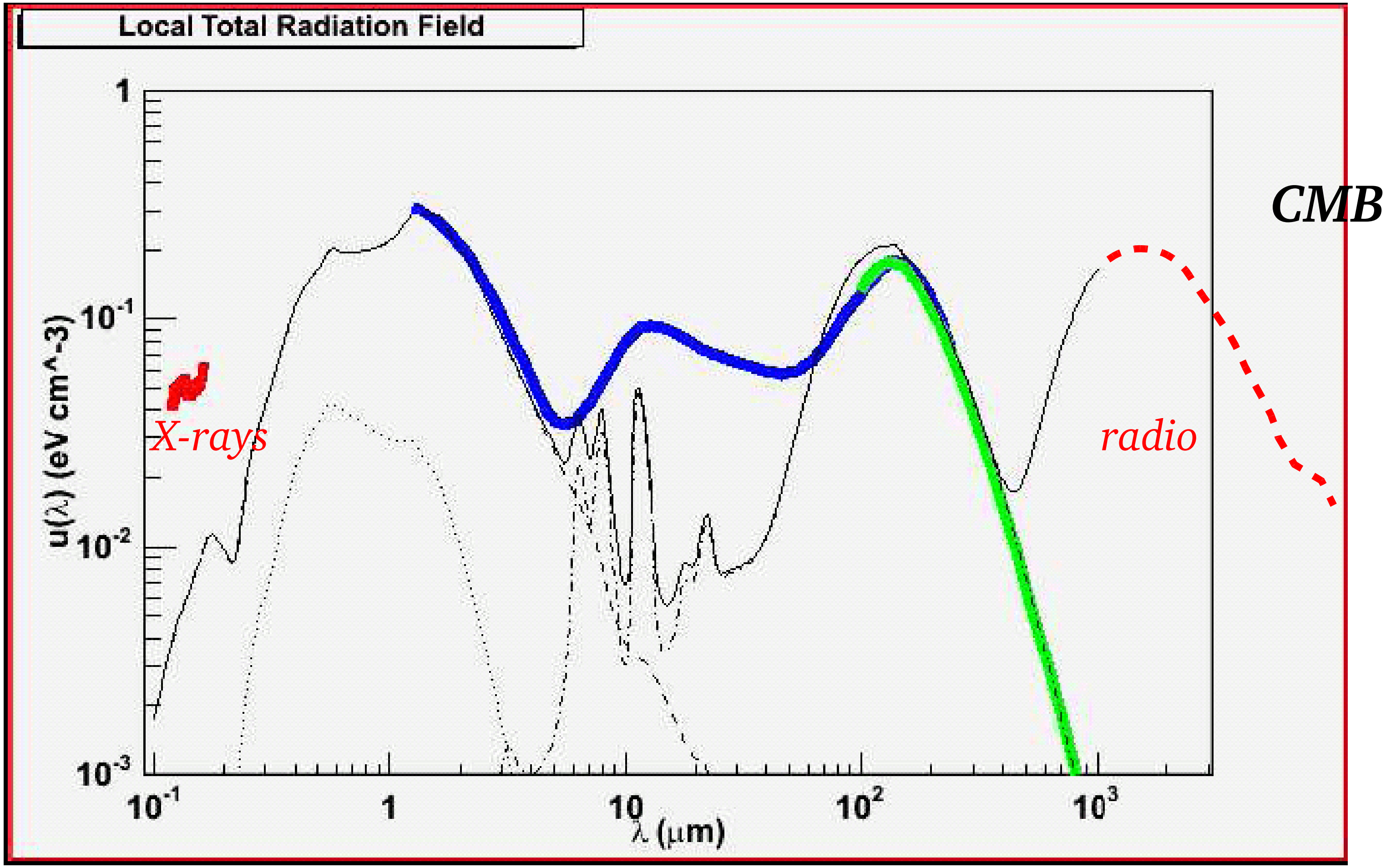
imposing the condition $J(\nu_{nm}) = U_P(\nu_{nm})$ *we get:*

$$B_{mn} = A_{mn} \frac{c^3}{8\pi h\nu_{nm}^3}$$

$$B_{nm} = \frac{g_m}{g_n} B_{mn}$$

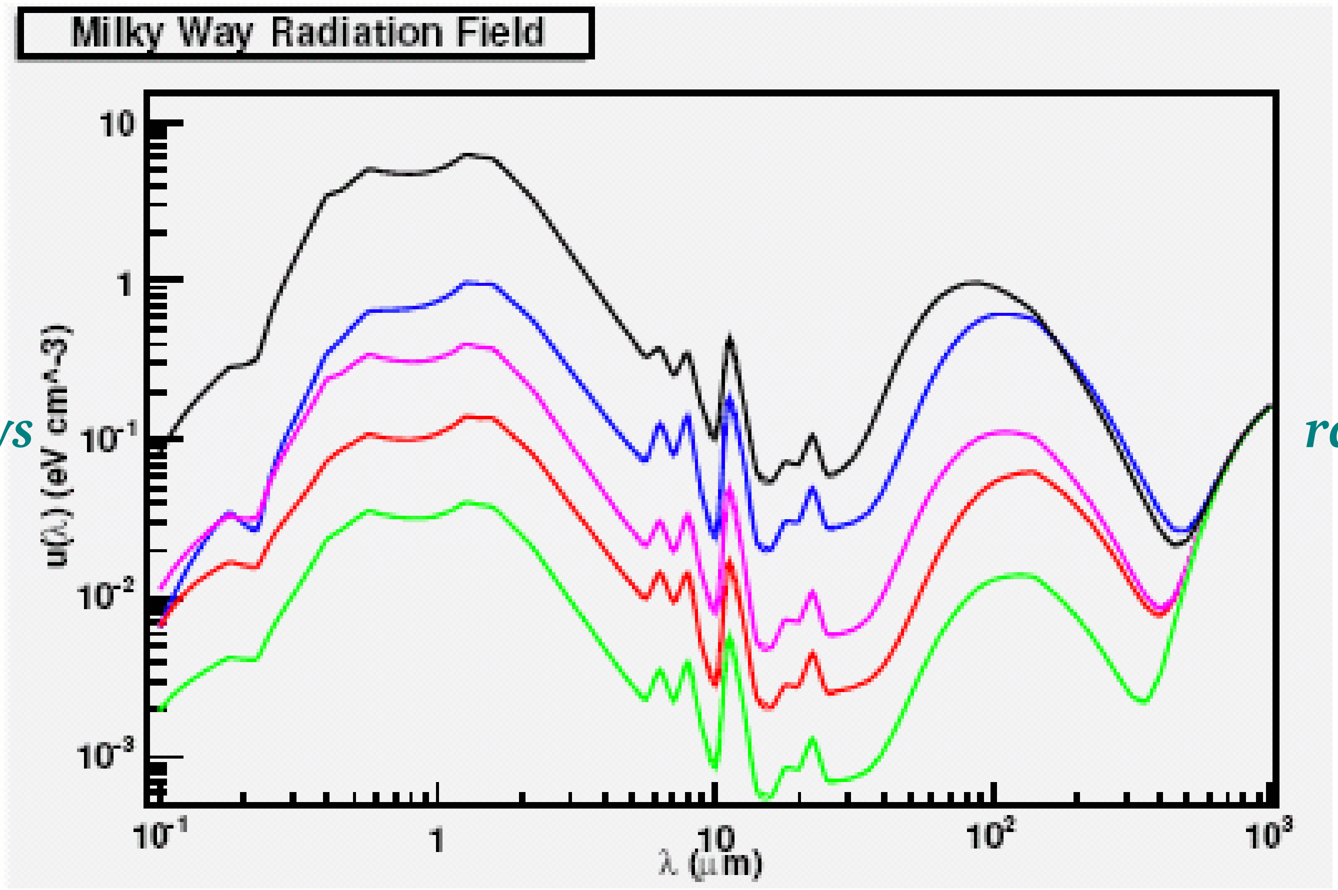
warning: there is a mistake in Rybicki-Lightman p. 30, equation (1.72b), with a $\boldsymbol{4\pi/c}$ *factor missing*

One word on the spectral energy distribution of J_ν in the ISM in a galaxy like ours, at a random position, far from stars



variation along various directions

X-rays



radio

Spatial variation of the total radiation field throughout the Galaxy.

Black line *: total radiation field for GC.*

Magenta line *: total radiation field for R=0, z=5 kpc,*

Blue line *: total radiation field for R= 4, z=0 kpc,*

Red line *: total radiation field for R=12, z=0 kpc,*

Green line *: total radiation field for R=20, z=0 kpc.*

*For Hydrogen, considering two energy levels **m** and **n**(<m) (m → n)*

$$A_{mn} \approx 2 \cdot 10^{10} \frac{m^{-3} n^{-1}}{n^2 - m^2}$$

$$B_{mn} = 2 \cdot 10^{10} \frac{m^{-3} n^{-1}}{n^2 - m^2} \frac{c^3}{8\pi h \nu_{nm}^3} \qquad B_{nm} = \frac{g_m}{g_n} B_{mn}$$

absorption may then be expressed in terms of B_{mn}, B_{nm} :

correction for stimulated emission

$$\kappa_\nu = \frac{h\nu_{nm}}{c} \Phi(\nu)(B_{nm} N_n - B_{mn} N_m) = \frac{h\nu_{nm}}{c} \Phi(\nu) B_{nm} N_n \left(1 - \frac{g_n}{g_m} \frac{N_m}{N_n}\right)$$

expressing also ϵ_ν in terms of Einstens coefficients, we can write the source function for thermal equilibrium:

$$S_\nu = \frac{\epsilon_\nu}{\kappa_\nu} = \frac{2h\nu^3}{c^2} \left(\frac{g_m}{g_n} \frac{N_n}{N_m} - 1 \right)^{-1}$$

$$\epsilon_\nu = \frac{h\cancel{\nu}_{nm}}{4\pi}\,\phi\cancel{(\nu)}\,A_{mn}N_m$$

$$\kappa_\nu = \frac{h\cancel{\nu}_{nm}}{c}\,\phi\cancel{(\nu)}\,(B_{nm}N_n - B_{mn}N_m)$$

$$S_\nu = \frac{\epsilon_\nu}{\kappa_\nu} = \frac{c}{4\pi}\,\frac{A_{mn}N_m}{B_{nm}N_n - B_{mn}N_m} \qquad \left(but \quad B_{nm} = \frac{g_m}{g_n}B_{mn}\right)$$

$$= \frac{c}{4\pi}\,\frac{A_{mn}N_m}{B_{mn}\left(\frac{g_m}{g_n}N_n - N_m\right)} = \frac{c}{4\pi}\,\frac{A_{mn}\cancel{N_m}}{B_{mn}\cancel{N_m}\left(\frac{g_m}{g_n}\frac{N_n}{N_m} - 1\right)}$$

$$since \; B_{nm} = A_{nm}\frac{c^3}{8\pi h\nu^3_{nm}} \qquad then$$

$$= \frac{c}{4\pi}\,\frac{\cancel{A_{mn}}}{\cancel{A_{mn}}\frac{c^3}{8\pi h\nu^3_{nm}}\left(\frac{g_m}{g_n}\frac{N_n}{N_m} - 1\right)} = \frac{2h\nu^3_{nm}}{c^2}\left(\frac{g_m}{g_n}\frac{N_n}{N_m} - 1\right)^{-1}$$

$$S_\nu = \frac{\epsilon_\nu}{\kappa_\nu} = \frac{2h\nu^3}{c^2}\left(\frac{g_m}{g_n}\frac{N_n}{N_m} - 1\right)^{-1}$$

With energy levels ***m*** *and* ***n***(<m) (m → n) *in* ***thermal equilibrium*** *the upper level (m) is less populated than the lower one (n) and then*

$$g_n N_m < g_m N_n$$

the term within brackets is > 0 as it is κ_ν.

in anomalous conditions this is not true anymore and a ***population inversion*** *occurs:*

$$g_n N_m > g_m N_n$$

stimulated emission is dominant (κ_ν and S_ν become negative!) and the incoming radiation is amplified.

This process is known as ***MASER*** *(Microwave Amplification for Stimulated Emission of Radiation) [LASER in the optical domain]*
*The "****pumping****" is the mechanism responsible for providing energy to maintain the population inversion (radiative / collisional)*

Masers in red giant stars:

TX Cam, distant ~ 1,000 ly, is about twice as massive as the Sun
Kemball and Diamond measured a value of 5 - 10 Gauss for the B field. It is much stronger than the average 1 Gauss strength of the principal components of the Sun's field. The VLBA images also showed a remarkably ordered structure of the magnetic field lines. "This suggests that the magnetic field of TX Cam follows the lines of longitude on the star" , i.e. TX Cam's magnetic field is structured similar to those of the Earth and Sun, which resemble the field of a bar magnet, with orderly field lines running from one pole to the other. The VLBA observations provide the first evidence for an ordered magnetic field in another star.

Every year, TX Cam, a star in the late stages of its lifetime, loses mass equal to one-third that of the Earth. "We don't yet understand the mechanism," Diamond says, "but the magnetic field plays a role." The star is losing mass from most of its surface, but, like the Sun, loses more from disturbed regions. VLBA observations of TX Cam and other stars have shown motion of the gas when observed at different times.

With the VLBA's capability to make detailed maps of the star's magnetic field and to monitor the mass-loss process, the researchers hope to shed some light on this longstanding mystery of stellar physics. Stars lose mass throughout their lifetimes through different processes that are still poorly understood. Kemball and Diamond, having shown that the VLBA is capable of making images detailed enough to study one such process, plan further observations that will reveal changes in the star's magnetic field over time.

"TX Cam is a variable star, like Mira, pulsing with a period of 557 days. We want to watch the changes in the structure of its circumstellar envelope and its magnetic field over an entire cycle," Diamond said. With the ultrasharp "vision" of the VLBA, they can make a "movie" of the changes and hopefully learn how the mass-loss process works. Such knowledge is important not only to understanding these stars but also to other problems in astronomy. For example, mass-loss from stars like TX Cam is second only to supernova explosions as a contributor to the interstellar medium, the tenuous gas and dust between the stars from which new stars and planets are formed.

Masers in red giant stars:

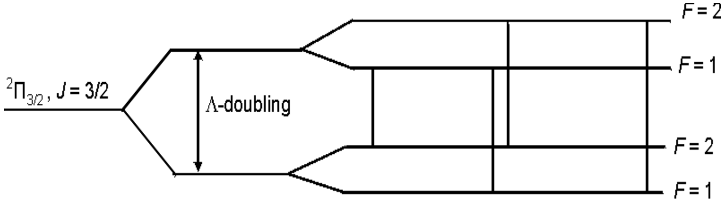
Cosmic masers are natural generators of high-intensity radio waves. They operate in region of interstellar space or circumstellar environment hosting certain molecular species and having appropriate physical conditions to excite ("pump") molecules. Molecules thus pumped amplify radio emission at frequencies intrinsic to energy transitions of these molecules. The pumping mechanism can be infrared radiation from the central stellar source or collisions of masering molecules with particles of the surrounding gas. For instance, favourable conditions for maser pumping can exist behind a shock front in circumstellar gas.

Masers are found in regions of active star formation, near protostellar or young stellar objects, as well as in gas-and-dust envelopes of late-type variable stars (Mira Ceti-type and semiregulars). Most widespread are masers on molecules of hydroxyl (OH), water vapour (H2O), methanol (CH3OH), silicon monoxide (SiO); rarer objects are masers on formaldehyde (H2CO) and hydrogen cyanide (HCN). Hydroxyl, water-vapour and fomaldehyde masers are encountered both in star-forming regions and late-type stars; SiO and HCN masers are found in envelopes of late-type stars; while methanol masers exist only in star-forming regions.

This page is about the joint French-Russian project on the studies of molecular masers, mainly hydroxyl but also invoking data on other molecular masers detected in the same objects to get a more complete physical picture of the circumstellar environment of stars, young and old.

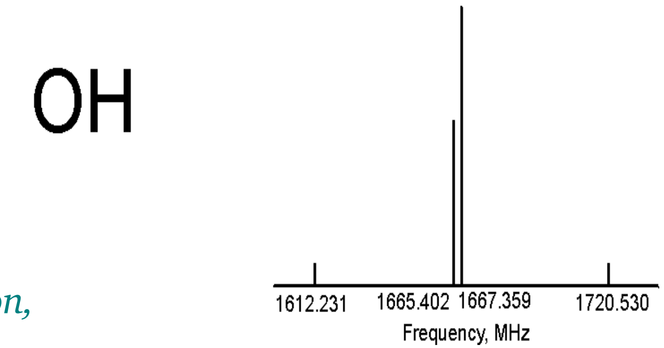
The following graph shows the structure of the energy levels of the lowest energy state of the hydroxyl radical. This lowest rotational state is split into two by so-called Lambda-doubling effect. In their turn, both Lambda-doubling sublevels are divided into two by hyperfine splitting due to interaction of the unpaired electron's spin with the magnetic oment of the hydrogen nucleus. Transitions between these four sublevels yield four spectral lines near the wavelength 18 cm. The two central lines near 1665 and 1667 MHz are the strongest, they are called main lines; the 1612 and 1720-MHz lines are weaker, they are called satellite lines. The main lines are strong in masers associated with star-froming regions. Often the 1665-MHz line, which in equilibrium conditions is weaker than 1667 MHz, exceeds it in intensity. Furthermore, the 1612-MHz line intensity in late-type stars is sometimes equal to or stronger than the main OH lines. Masers in the 1720-MHz line are rather rare and are found only near supernova remnants. Thus, of primary interest for our study are masers in the main lines and in the 1612-MHz satellite line.

Masers in red giant stars:



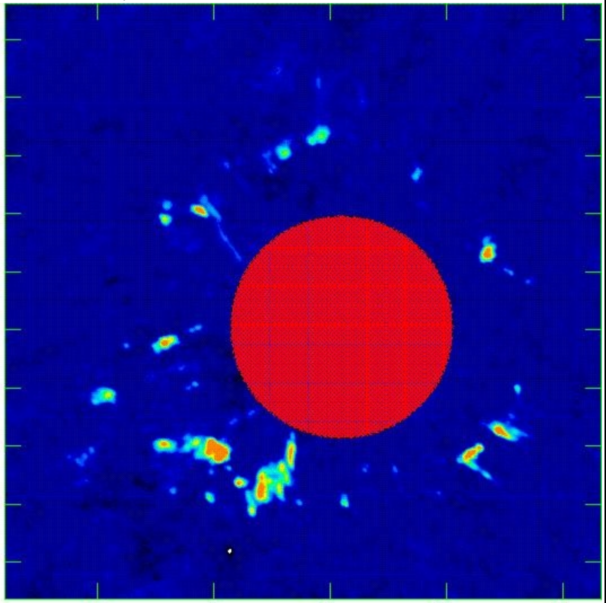
Energy levels and transitions in the ground rotational state of the OH molecule.

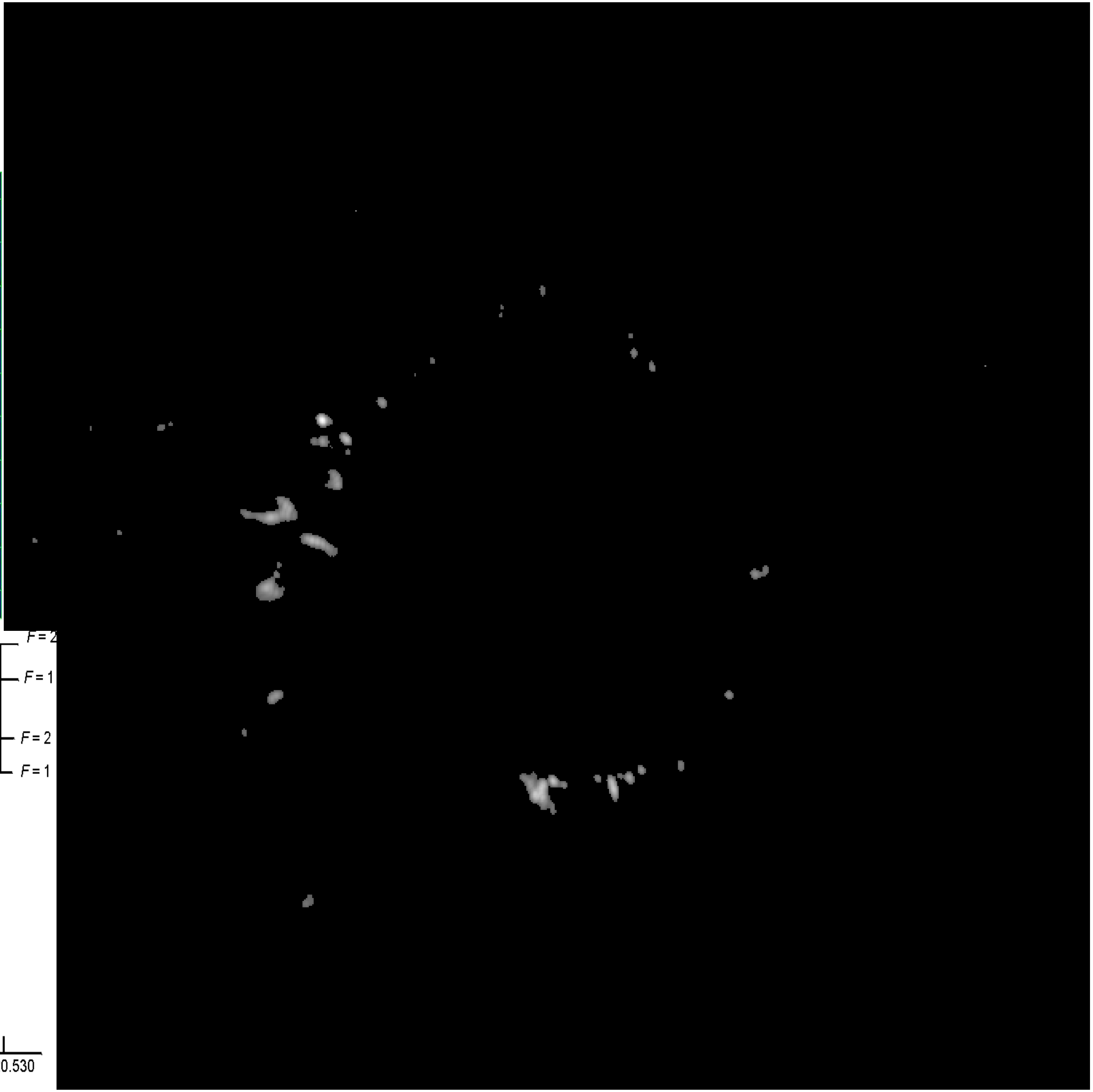
Joint observations of French and Russian radio astronomers began in late 1960s on the Nançay Radio Telescope with the Russian-made spectral receiver for the wavelength 18 cm (lines of the hydroxyl molecule OH). The high performance parameters of the Nançay telescope enabled the researchers to obtain quality observations of masers in many star-forming regions. Later improvements in the instrumentation now allow to measure all senses of polarisation of cosmic radiation, which largely broadens the capabilities of the instrument.

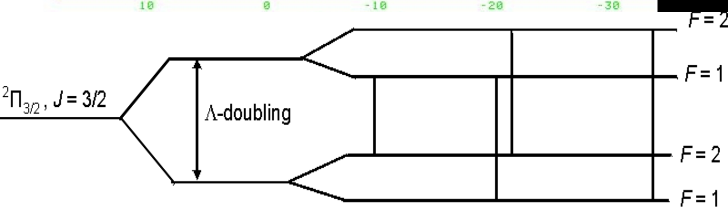


Up to now a great experience in spectral radio observations of molecular masers has been acquired by the French and Russian teams. Beginning from 1980 the Russian group has accumulated a large database of observations of variability of maser sources in star-forming regions in the H2O line on the 22-meter radio telescope in Pushchino (Moscow Region, Russia); a database of such duration and completeness has no analogs in the practice of the world radio astronomy. A big deal of maser studies has been done on the Nançay telescope, including OH line observations of star-forming regions, stellar envelopes and comets. In 2007 French and Russian groups resumed joint observations of OH masers on the Nançay Radio Telescope. Sample spectra of the OH line forsome maser sources are shown in the figures below. New promising data have already been obtained, including several detections of previously unknown masers, strong variability of some sources and complete pattern of polarisation of OH masers permitting to evaluate the magnetic field intensity near young stellar objects. In the meanwhile, the Russians have a possibility to continue the H2O maser line monitoring of the same list of maser sources in Pushchino. Parallel monitoring of the masers in the OH and H2O lines adds value to the radio study of the physics of circumstellar environment, since the lines are formed in the vicinity of the same stellar object, however in layers of material at different distances from the central star. Thus, tracing variations in both lines yields a cross-section of physical conditions near young stellar objects.

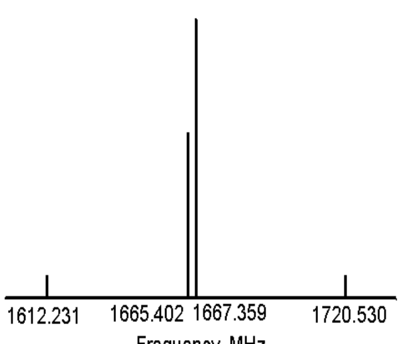
The SiO maser in TX Cam



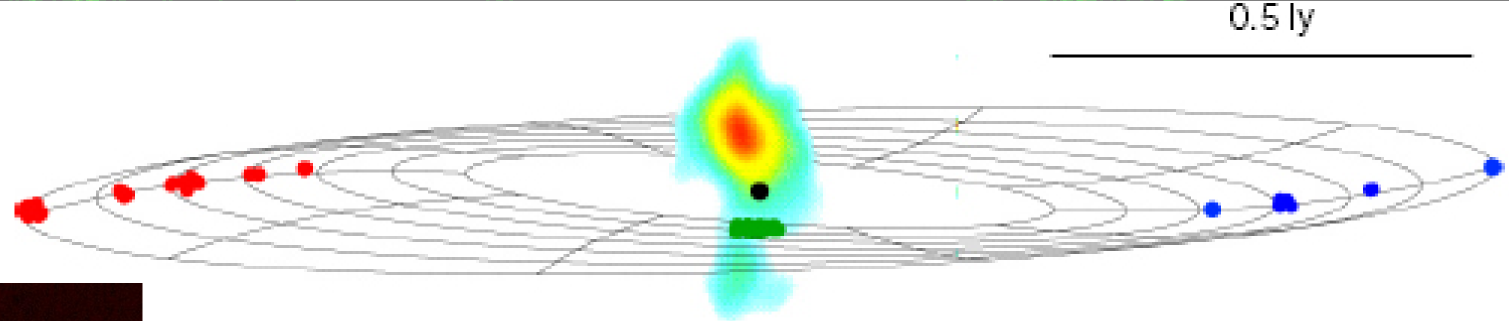




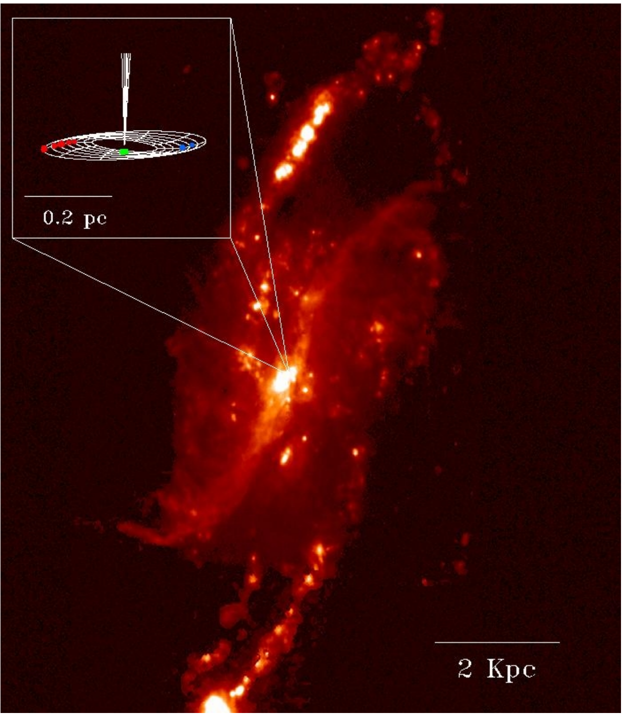
OH

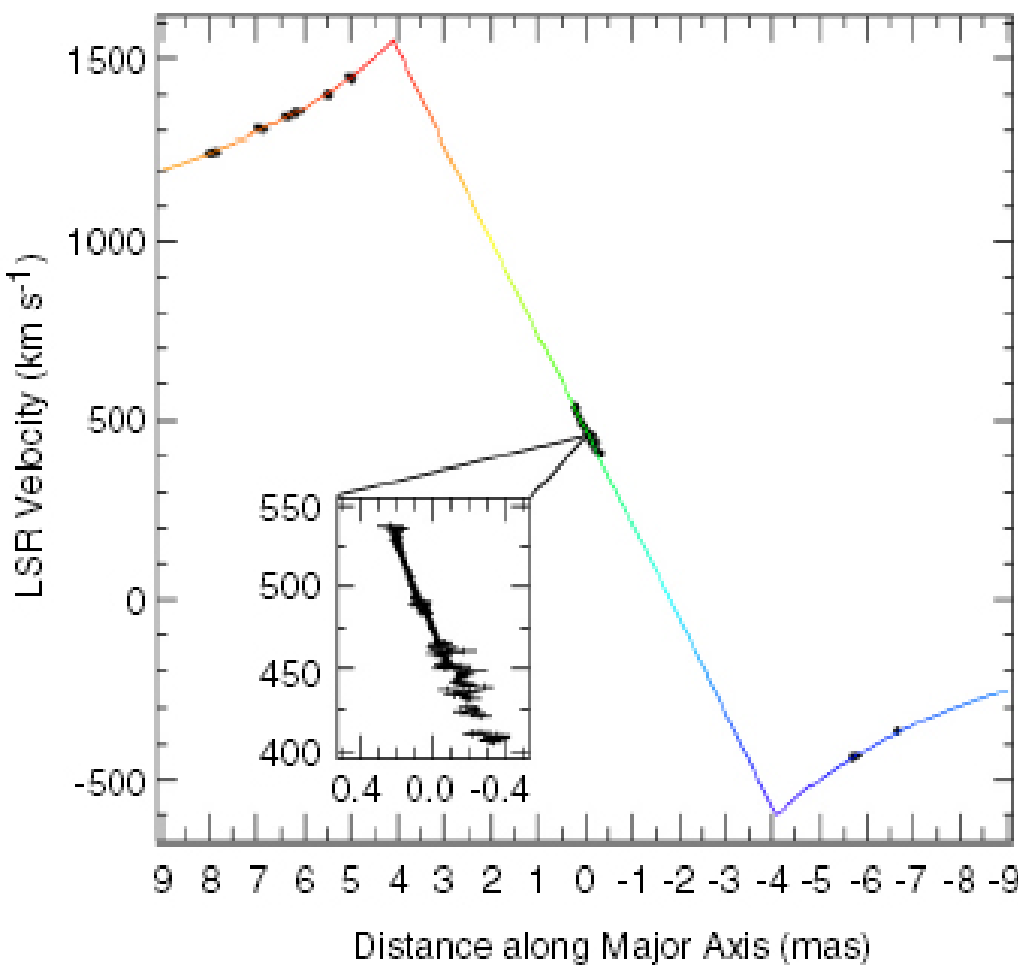


The megamaser in NGC 4258



Based on Herrnstein, Greenhill et al. 1998





Miyoshi et al. 1995

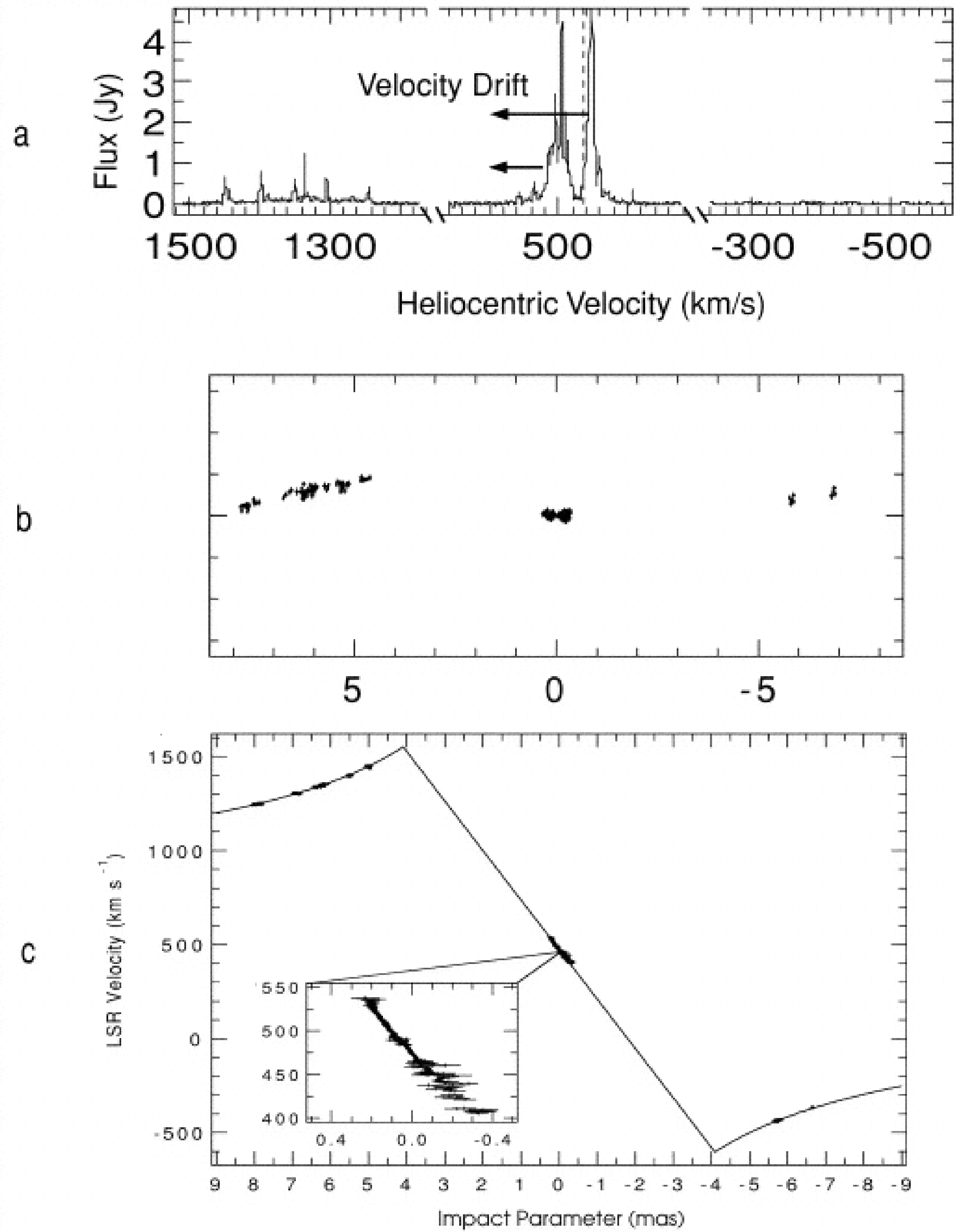
Arrangement : Greenhill

The megamaser in NGC 4258

Spectrum
(note the Doppler shift)

Image
(note the space distribution)

Combination of the two
observables over a model



Thermal Equilibrium (TE)

Let's consider the radiation orginated within the cloud: Kirchoff's law applies:

$$S_\nu = \frac{\epsilon_\nu}{\kappa_\nu} = B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

In astrophysics also other processes, beyond radiative transitions occur. Collisions between particles are relevant and obey the thermal-behaviour, while interactions with photons can be considered 'non-thermal' and may modify the TE condition, i.e. Boltzmann's & Saha's laws are not valid anymore.

It is possible to define ***LOCAL thermal equilibrium (LTE)****, in which the statistical laws and the above source function are approximately OK. In the ISM often even LTE does not hold, although some relations are still veryfied, and a new temperature T_{ex} can be defined to account for the relative populations of N_m and N_n:*

$$\frac{N_m}{N_n} = \frac{g_m}{g_n} e^{-h\nu_{mn}/kT_{ex}} \qquad \text{defining:} \quad T_{ex} = \frac{E_m - E_n}{k\cdot\ln(N_n g_m / N_m g_n)}$$

Collisional (excitation/de-excitation) rates (1)

Mechanical interactions between particles (atoms, molecules) may alter the energy state of bound electrons.
*Depends on individual electrostatic potential, relative velocity (v) and collisional partner particle density (N_p) defining a **cross-section (σ_{mn})**.*

Let's consider an atom with two energy levels (m > n)

$$v = v_{p1} - v_{p2} \qquad \sigma_{mn}(E) = \left(\frac{h^2}{8\pi m_e E}\right) \cdot \left(\frac{\Omega_{mn}}{g_m}\right)$$

Electron energy (v)

where Ω_{nm} defines the "collisional strength" (efficiency)
(de-excitation defines σ_{nm} in which indices n and m are swapped)

$$\Omega_{mn} = \frac{8\pi}{\sqrt{3}} \frac{1}{E_{mn}} \cdot g \cdot f_{ij} G(T)$$

where

$$f_{ij}(Z) = c Z^2 R_H \left(\frac{1}{m^2} - \frac{1}{n^2}\right) ; \quad g(l, Z) = \frac{4l}{3(2l+1)} \cdot \left(\frac{h^3}{Z^2 c^3 m_e^2 e^2}\right)$$

Gaunt factor, weakly dependent on T

Collisional (excitation/de-excitation) **rates (2)**

At a given energy, the number of collision per unit time is

$$C(E) = N_p v \sigma(E)$$

Collisions are supposed to be **elastic** (anelastic are rare and are neglected) then we can consider Maxwell – Boltzmann distribution of velocities

once we change the expression of $\sigma_{mn}(E)$ to $\sigma_{mn}(v)$, **we define the collisional excitation/de-excitation rates Q_{mn}/Q_{nm}** as

$$Q_{mn} = \langle v \cdot \sigma_{mn}(v) \rangle = \int_o^\infty [v \cdot \sigma_{mn}(v)] \phi(v,T) dv \approx \langle v \rangle \cdot \langle \sigma \rangle$$

$$\text{where} \quad \phi(v,T) = \frac{4\pi}{\zeta^3 (2\pi)^{3/2}} v^2 e^{-v^2/2\zeta^2}$$

$$\zeta^2 = \langle v_x^2 \rangle = \langle v_y^2 \rangle = \langle v_z^2 \rangle = kT \cdot \left(\frac{1}{m_{p1}} + \frac{1}{m_{p2}} \right)$$

where m_{p1} and m_{p2} are the masses of the two colliding particles (**atom** and **collisional partner** respectively)

Collisional (excitation/de-excitation) **rates (3)**

At thermal equilibrium, excitation balances de-excitation:

$$N_n N_p Q_{nm} = N_m N_p Q_{mn}$$

and then it is possible to derive:

$$g_m Q_{mn} = g_n Q_{nm} e^{-\Delta E/kT} \qquad where\, \Delta E = E_n - E_m (>0)$$

*In general the most common collisional partners are **free electrons**, for which it is possible to show that :*

$$\sigma_{mn} \sim v^{-2}$$

From the expression of Q_{mn}, given that $v^2 \sim T$ and $\zeta \sim T^{1/2}$, then

$$\phi(v,T) \approx \frac{v^2}{\zeta^3} e^{-v^2/2\zeta^2} \quad but \quad \zeta^2 \approx kT \quad then \quad \phi(v,T) \approx T^{-1/2}$$

$$Q_{nm} = \frac{h^2}{(2\pi m_e)^{3/2}(kT)^{1/2}} \cdot \frac{\Omega_{nm}}{g_n} = 8.63 \cdot 10^{-6} \frac{\Omega_{nm}}{T^{1/2} g_n} \quad cm^3\ s^{-1}$$

(parameters computed for electrons as collisional partners)

Collisional (excitation/de-excitation) rates (4)

(cont'd) electrons are the collisional partners of the most common ions in the ISM: C^+, O^+, Si^+, N^+, Ne^+, ... all having $\Omega_{nm} \sim 1$ (transitions to the ion ground state (m=1)). With typical temperatures of about 10^4 K (and $g_n \sim 1$)

$$Q_{nm} \approx 10^{-5} \; cm^3 s^{-1}$$

to be compared with the competing radiative de-excitation (A_{nm}).

For different collisional partners (HI, H_2, ... other molecules) mainly interacting with HI and molecules (H_2, CO, ...) there are slight changes on the numerical value of Ω_{nm} (masses are different!).

For transition to/from ground state (m=1)

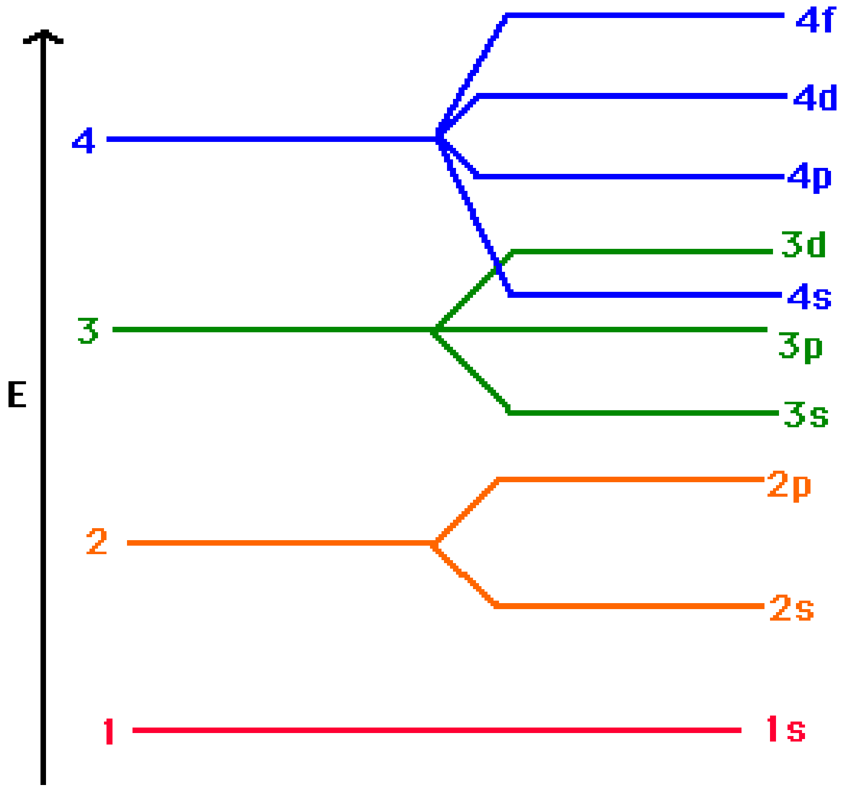
examples:

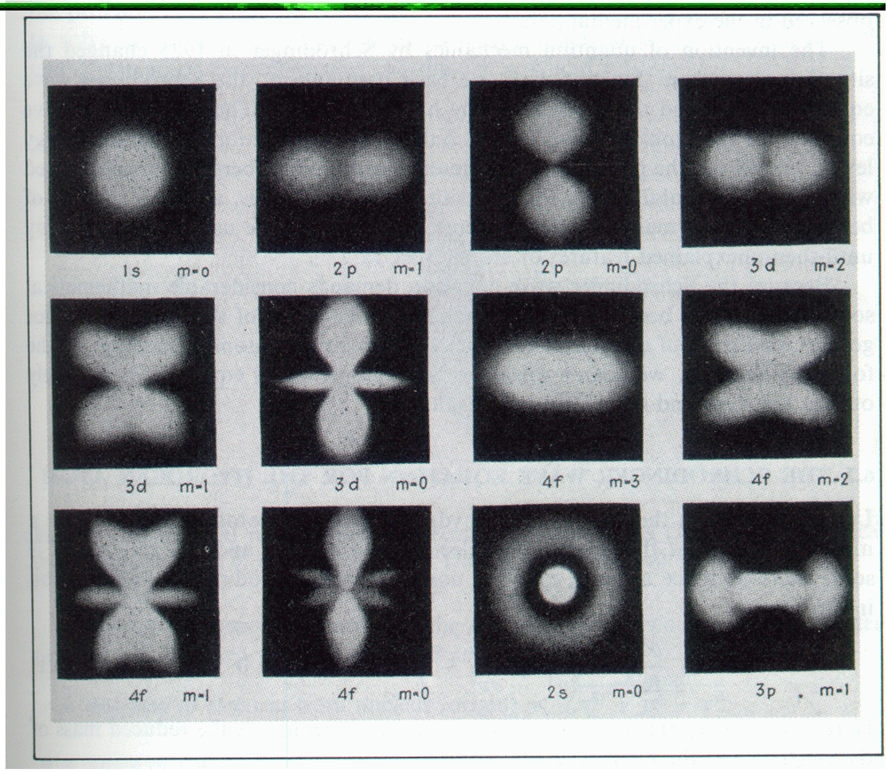
(1) H – H collision ($T \sim 10^3$ K) we get $\quad Q_{nm} \approx 10^{-10} \; cm^3 s^{-1}$

(2) H – H_2 collision ($T \sim 10^2$ K) we get $\quad Q_{nm} \approx 3 \cdot 10^{-12} \; cm^3 s^{-1}$

exercise: application to OIII lines, examples (compute also Ω_{mn} of HI)

Fine structure of Energy levels



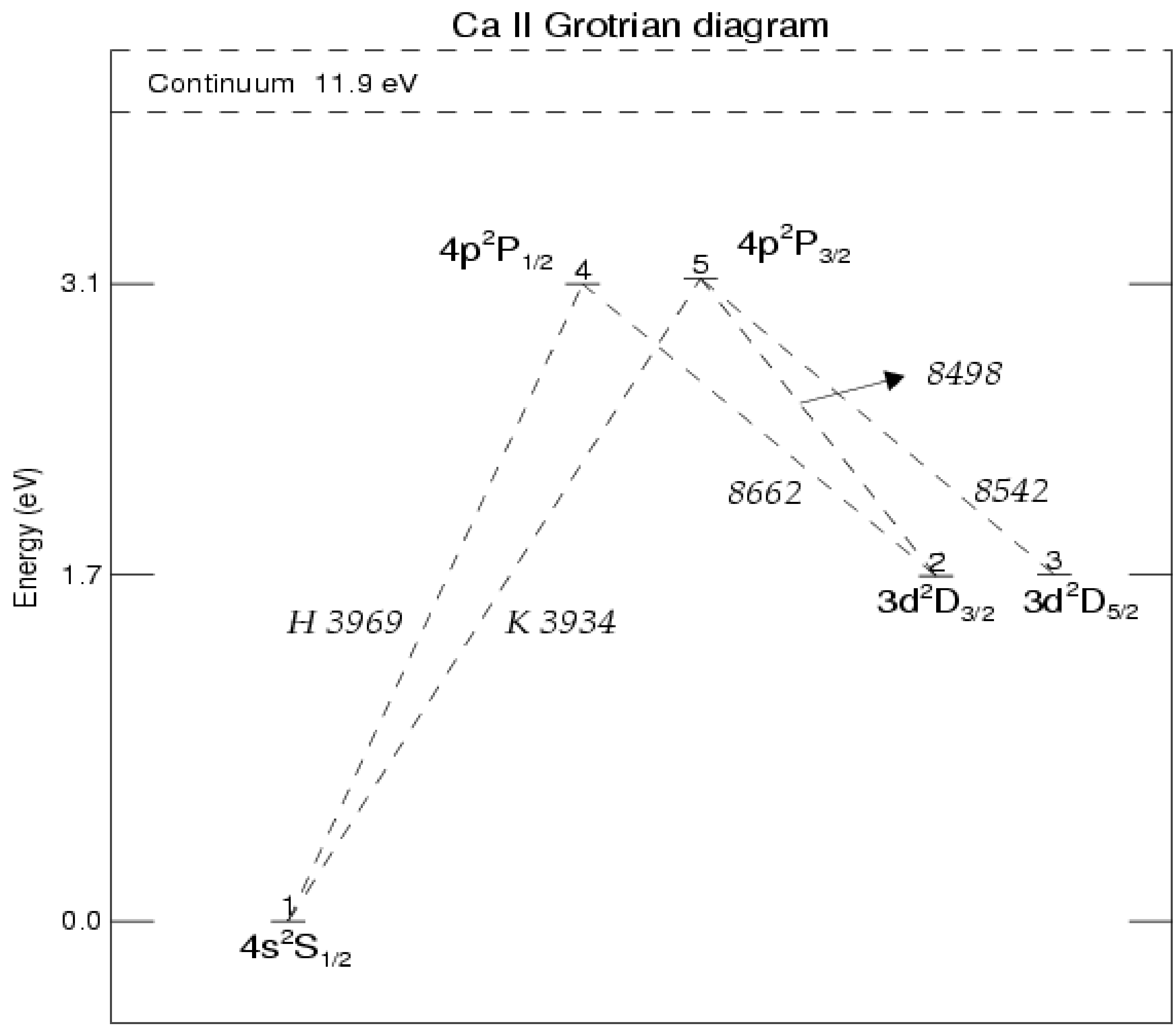


For an electron the electric potential within an atom is not simply that from the Coulomb's law. Atoms with many e^- *(Li,...C,N,O,...): the interaction between orbiting electrons and their spins raises the degeneracy of the "n" states so that each "l" level has a slightly different energy.*
*The "m" levels remain undistiguishable unless an external strong magnetic field is applied to the atom (**Zeeman splitting**).*
Further, there is a spin-orbit coupling providing further energy structrue. Some atoms may have double, triple, multiple lines closely packed (see CaII, [OIII] doublet).

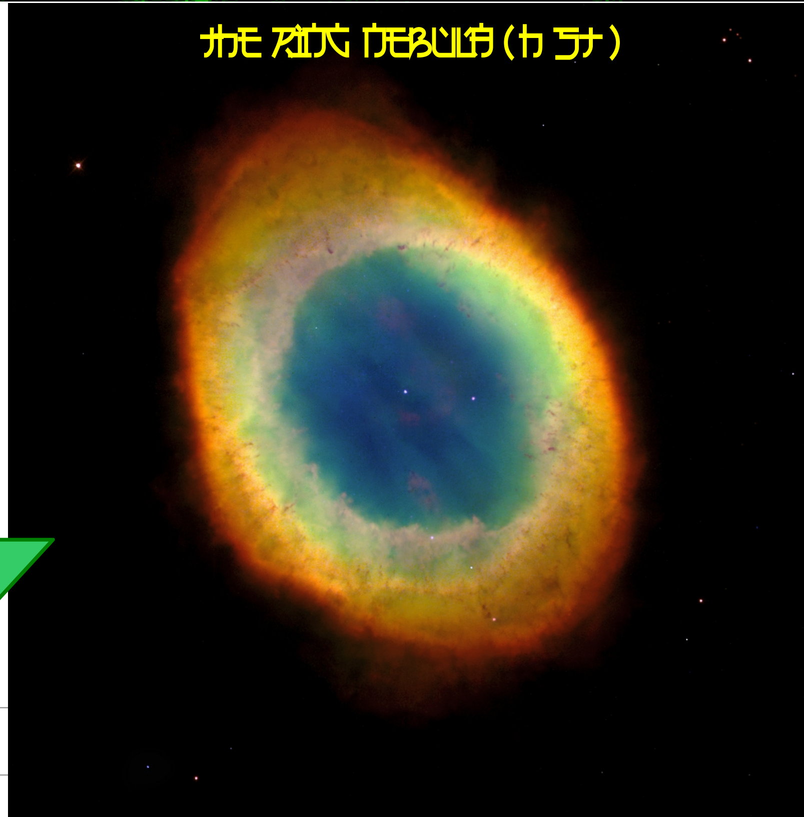
The binding energy does not depend on the main quantum number alone anymore!!!!!

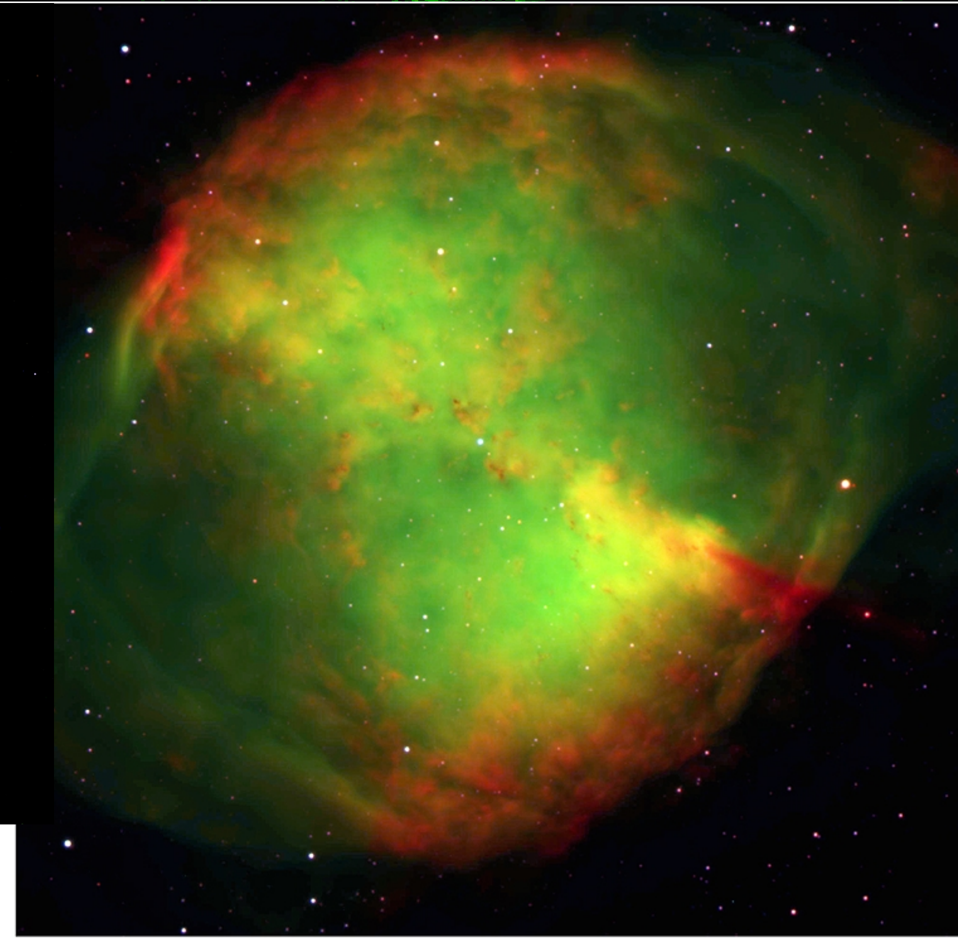
$$E_{nj}^{exact} = mc^2\left[\left(1+Z\alpha\left(n-j-1/2+\sqrt{(j+1/2)^2-Z^2\alpha^2}\right)^{-1}\right)^{-1/2}-1\right] \quad \textit{where } j = l+s$$

Fine structure *of Energy levels: CaII lines*



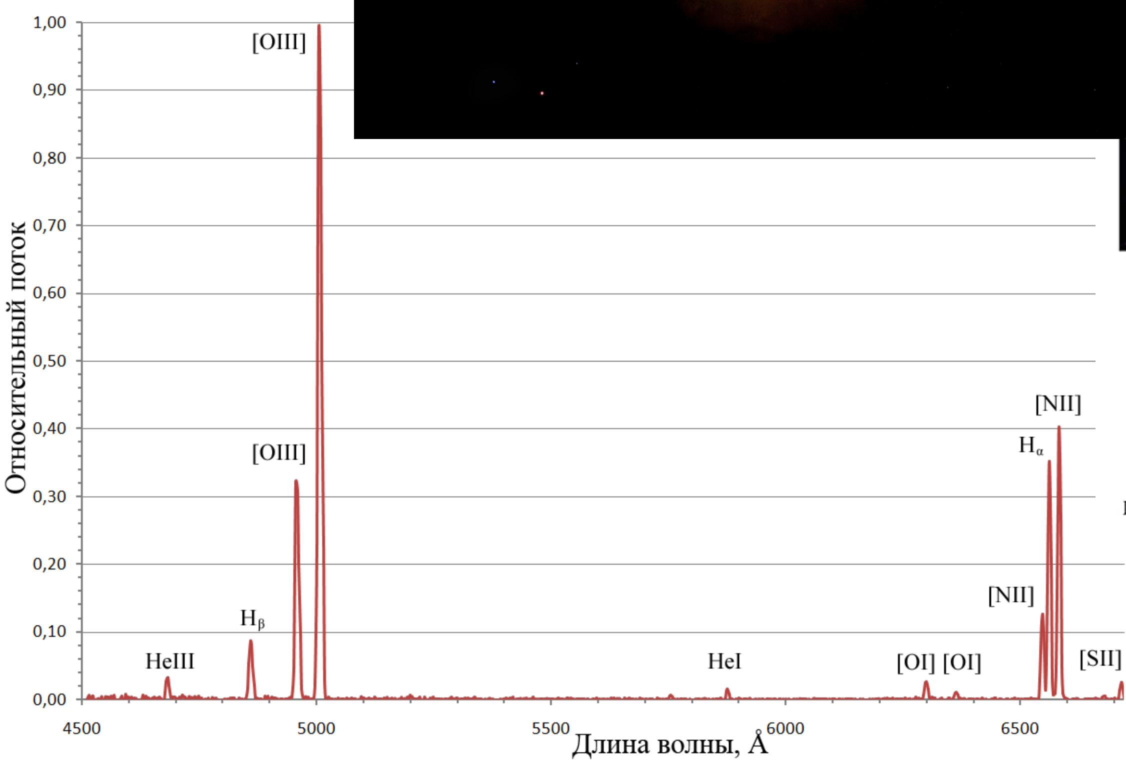
Forbidden lines: Nebulium (alias [OIII])



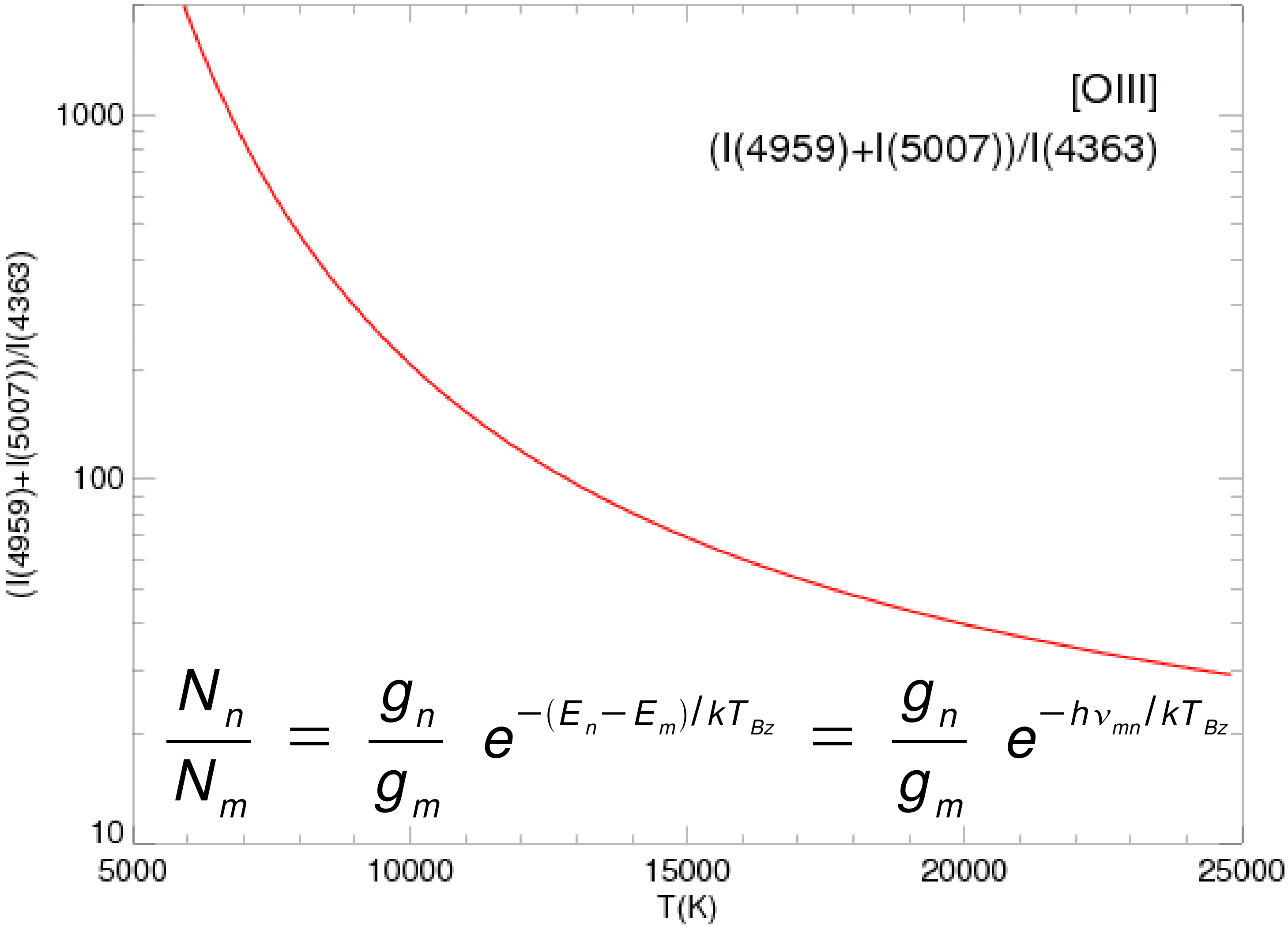


Planetary Nebula NGC 6853 (M 27) - VLT UT1+FORS1

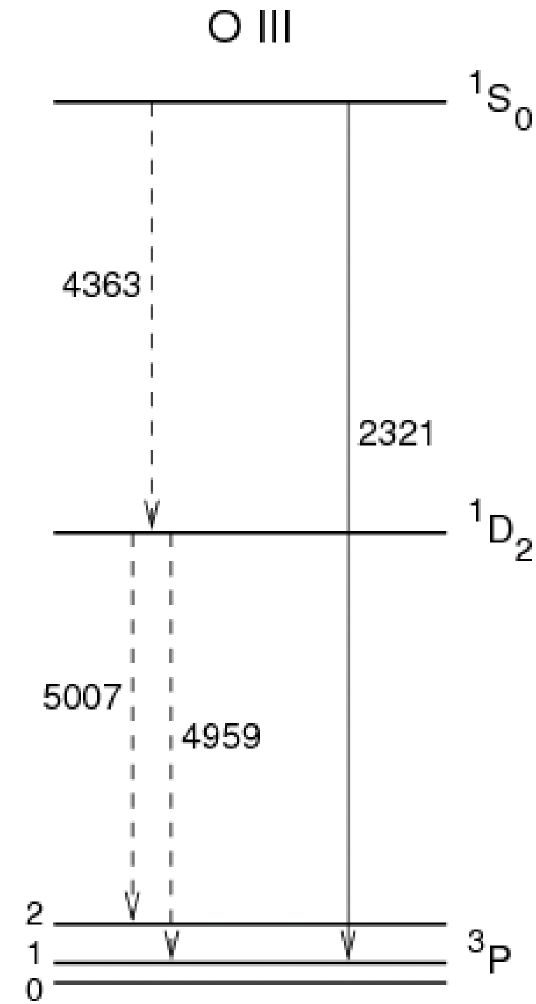
ESO PR Photo 38a/98 (7 October 1998)



[OIII] lines diagnostics



$$\frac{N_n}{N_m} = \frac{g_n}{g_m} e^{-(E_n - E_m)/kT_{Bz}} = \frac{g_n}{g_m} e^{-h\nu_{mn}/kT_{Bz}}$$



Line ratios provide information on the temperature (note that these values are typical of HII regions!)