~~50 × 50 × 10 × 1.5~~

~~= 60 000~~

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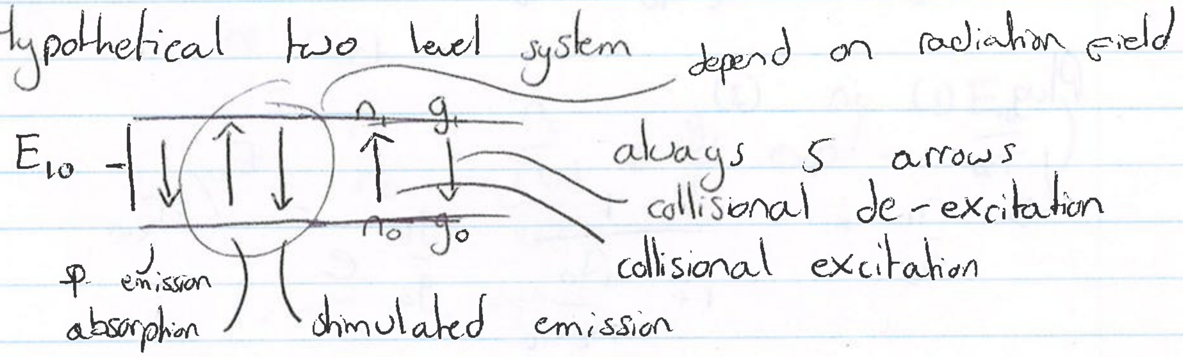
Collisional excitation and nebular diagnostics

- Why is eg O III ~~as~~ b almost as bright ~~in~~ as Hα in many H II regions, whereas the ~~d~~ abundance is much lower ?

Setting up excitation problem. Book goes into more detail.

Hypothetical two level system



In some cases, collisions where not important. Generally need 5 however. Excitations and de-excitations are caused by collisions with other particles

n_c = density of collision partner. What that is depends on physics : H_2, HI, e^-

Upwards collisional excitation $k_{01}\, n_c$
Down " " " de- " " $k_{10}\, n_c$

Excitation ~~e~~ costs energy which comes from kinetic energy of gas.

QM : cross section for process.
For most things, cross sections and collision coefficients are well known.

k_{10} is going to depend on temperature, naturally since low T has low E_{kin}.

$\underset{0}{T}$ (1) $k_{01} = k_{10}\, e^{-E_{10}/k_B T} \dfrac{g_1}{g_0}$

(2) $\dfrac{dn_1}{dt} = -n_1 A_{10} + n_0 n_c k_{01} - n_1 n_c k_{10}$

(3) $\rightarrow$ $\dfrac{n_1}{n_0} = \dfrac{n_c k_{01}}{n_c k_{10} + A_0}$

Plug (1) in (3)

$\hookrightarrow$ $\dfrac{n_1}{n_0} = \dfrac{1}{1 + \dfrac{A_0}{n_c k_{10}}} \dfrac{g_1}{g_0} e^{-E_{10}/kT_{kin}}$

If no spontaneous decays, this is exactly the Bolzmann distribution.

$$n_{crit} = \frac{A_{10}}{k_{10}} \quad \begin{matrix} A_{10} - [s^{-1}] \\ k_{10} - [cm^3 s^{-1}] \end{matrix}$$

$$\boxed{\frac{n_1}{n_0} = \frac{1}{1 + \frac{n_{crit}}{n_c}} e^{-E_{10}/kT_{kin}}}$$

Property of molecule but depends on collision partner
~~Reve~~ Refers to transition and partner on Temp, but not on density

Limiting cases

$n_c \gg n_{crit}$: $\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{E_{10}}{kT}\right)$

- $\cancel{k} T_{ex} = T_{kin}$!
- levels are thermalized
- independent of n_c

~~$n_c \ll$~~

$n_c \ll n_{crit}$

- $\frac{n_1}{n_0} = \underbrace{\frac{n_c}{n_{crit}}}_{\ll 1} \cancel{e} \frac{g_1}{g_0} \exp\left(-\frac{E_{10}}{kT}\right)$
- $T_{ex} < T_{kin}$
- subthermal excitation
- depends on density of ~~ko~~ collision partner

If we know n_c and n, we know in what regimes we are.

n_{crit} ranges from small (~~Ca~~ C II ~~2.5~~ 25) to large (He V $1.8 \cdot 10^7$). These densities are however found in the ISM.

Now we add radiation to this, since there are situations where this is essential.

$$n_\gamma = \frac{c^2}{2h\nu^3} I_\nu$$

direction - averaged.

$$\bar{n}_\gamma = \frac{c^2}{8\pi h\nu^3} u_\nu$$

Black body : Planck function

photon occupation number

$$n_\gamma = \frac{1}{\exp(h\nu/kT_r) - 1}$$

Define this temperature as our T_r.

$$\frac{dn_1}{dt} = [\underbrace{n_0 \bar{n}_\gamma \frac{g_1}{g_0}}_{\text{absorption}} - \underbrace{n_1}_{\text{sp. emission}}(1 + \underbrace{\bar{n}_\gamma}_{\text{stimulated emission}})] A_0$$

$$+ \underbrace{n_0 n_c k_{01}}_{\text{col ex}} - \underbrace{n_1 n_c k_{10}}_{\text{col de-ex.}}$$

Need this result in mol. clouds (and) when lines are optically thick (because of absorption).

$$= n_0(n_c k_{01} + \bar{n}_\gamma \frac{g_1}{g_0} A_{10}) - n_1(n_c k_{10} + (1 + \bar{n}_\gamma) A_0)$$

Steady state thus above is zero :

$$\rightarrow \frac{n_1}{n_0} = \frac{n_c k_{01} + \bar{n}_\gamma \frac{g_1}{g_0} A_{10}}{n_c k_{10} + (1 + \bar{n}_\gamma) A_{10}}$$

Now the critical density in a more general way

$$n_{crit} = \frac{(1+\bar{n}_\gamma)\,A_{10}}{k_{10}}$$

$$\frac{n_1}{n_0} = \frac{1}{1+\frac{n_{crit}}{n_c}}\,\frac{g_1}{g_0}\exp\left(-\frac{E_{10}}{kT_{kin}}\right) + \frac{1}{1+\left(\frac{n_{crit}}{n_c}\right)^{-1}}\,\frac{g_1}{g_0}\exp\left(-\frac{E_{10}}{kT_r}\right)$$

Again limiting cases

$\bar{n}_\gamma \gg 1$ (strong radiation field)

↳ if $n_c \ll n_{crit}$: $T_{ex} = T_r$

HI (21 cm) line : $\frac{E_{10}}{k} = 0.0682\ k$

$A_0 = 2.88 \cdot 10^{-15}\ s^{-1}$

$k_{10} = 1.2 \cdot 10^{-10}\ cm^{-3}\ s^{-1}$ @ 100 k

$T_r = 2.73\ k + \underbrace{1\ k}_{\text{milky way / galaxy background rad field}} = 3.73\ k$

$\bar{n}_\gamma = 55 \quad \rightarrow \quad n_{crit} = 1.7 \cdot 10^{-3}\ cm^{-3}$

$T_S = T_{kin}$

Applications of this

Nebular Diagnostics

- Upper level temperatures (wrt expected temperatures)
- Critical densities (with respect to expected densities)

Using line with n_c < expected density, we are in the thermal regime. ~~Than~~ Lines are ~~not~~ thermalized so line ratio only depends on temperature.

Temperature of ionizing star differs a lot from H II region to H II region, however ~~Te~~ temperature of H II region is almost always near $T \sim 10^4$ K.

If $n \gg n_{crit}$, population of levels ~~are~~ is independent of density. Hence, line ratio of thermalized lines is good temperature probe. Opposite, $n \ll n_{crit}$, $\frac{n_1}{n_0} = \frac{n_c}{n_{crit}}$. ~~This again is independent of T~~ Ratio of two sub-thermal lines again produce good T estimator.

SII / OII diagrams for density estimation becaus one transition sub thermal and one thermalized.

Far infrared lines, very easily excited as Tex is low. So we probe density probe for OIII 4IR lines. If critical densities are different, OIII IR lines are good density probes.