Interstellar Medium

Bright Nebulae of M33

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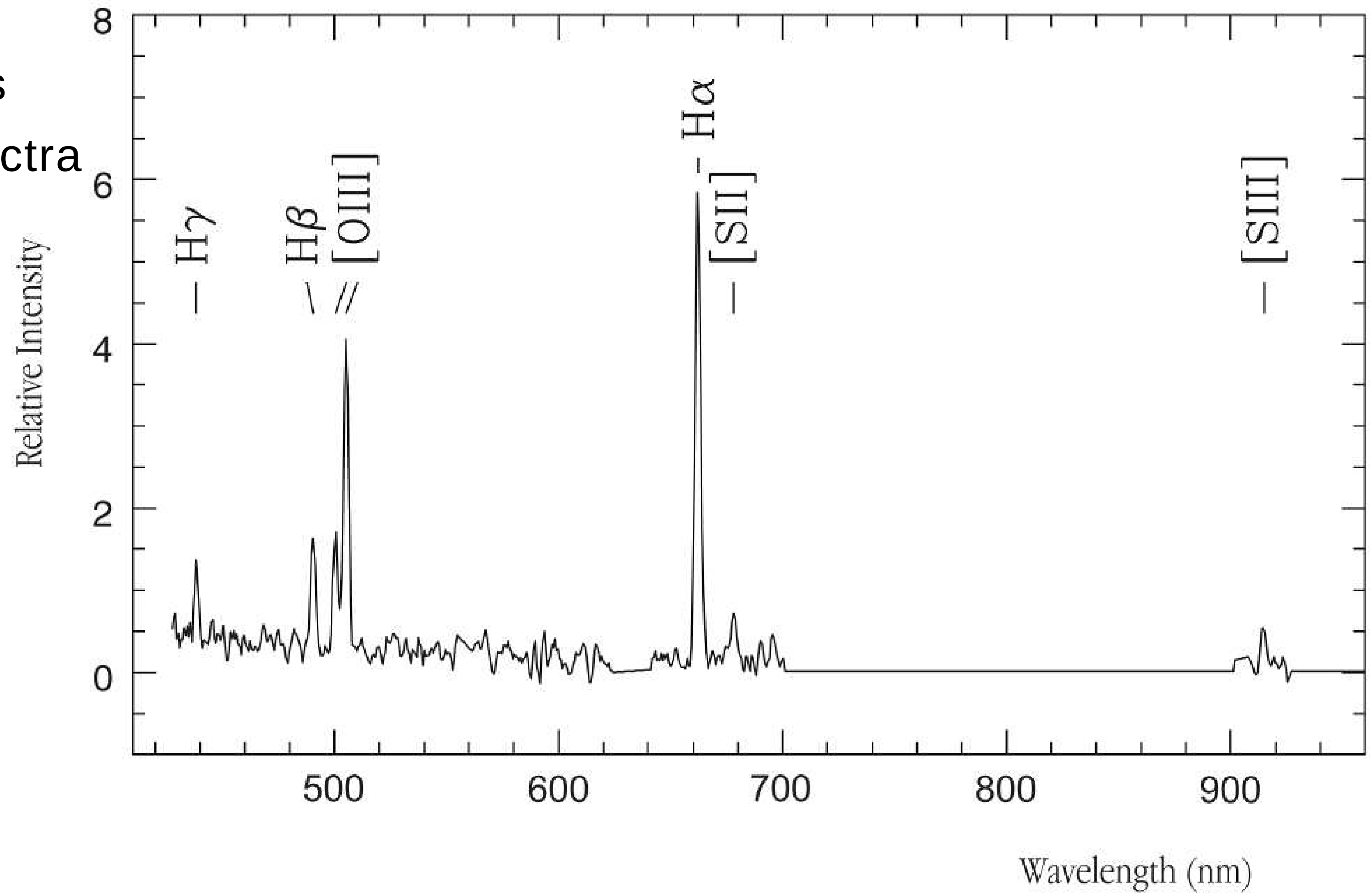
Part 1. Photoionized Nebulae

Thomas Shahan flkr site

Brief Reminder

- Extended sources
- Emission line spectra
- Forbidden lines
- Permitted H lines
- Continuum



Spectrum of Virgo Intracluster HII Region
(VLT YEPUN + FORS 2)

ESO PR Photo 04e/03 (16 January 2003)

Photoionization Equilibrium

Photoionization of a diffuse gas cloud by UV photons

- The ionization equilibrium: Balance between photoionizations and recombinations

- Assume a pure H cloud surrounding a single hot star

$$N_{\mathrm{HI}} \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(\mathrm{HI})\mathrm{d}\nu = N_\mathrm{e} N_\mathrm{p} \alpha(\mathrm{HI}, T)$$

The mean intensity in first approximation:

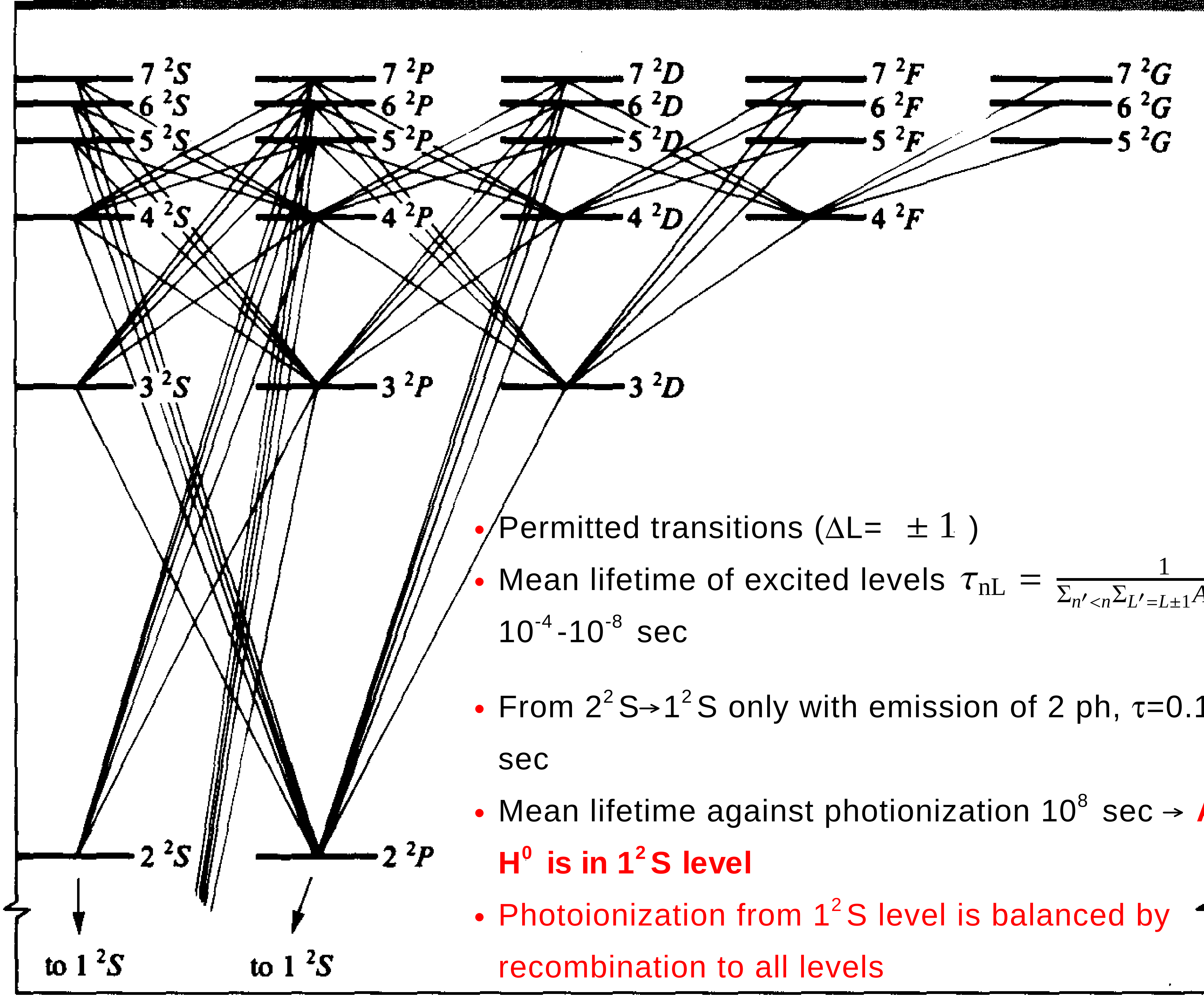
$$4\pi J_\nu = \frac{R^2}{r^2}\pi F_\nu(0) = \frac{L_\nu}{4\pi r^2}$$

Strömgren Sphere

Very large volume, few hundreds pc, with very thin skin "transition zone" 0.01 pc. Hydrogen is nearly fully ionized inside, and neutral outside.

To investigate a model HII region

- Examine photoionization cross-sections and recombination coefficients for H
- Consider radiative transfer
- Calculate the structure of HII region
- Include other abundant elements, they are important for the thermal balance



- Permitted transitions ($\Delta L = \pm 1$)
- Mean lifetime of excited levels $\tau_{nL} = \frac{1}{\sum_{n'<n}\sum_{L'=L\pm1} A_{nL,n'L'}}$ 10^{-4}-10^{-8} sec
- From $2^2S \rightarrow 1^2S$ only with emission of 2 ph, τ=0.12 sec
- Mean lifetime against photionization 10^8 sec $\rightarrow$ **All H^0 is in 1^2S level**
- Photoionization from 1^2S level is balanced by recombination to all levels
- Following quickly by radiative transition downward

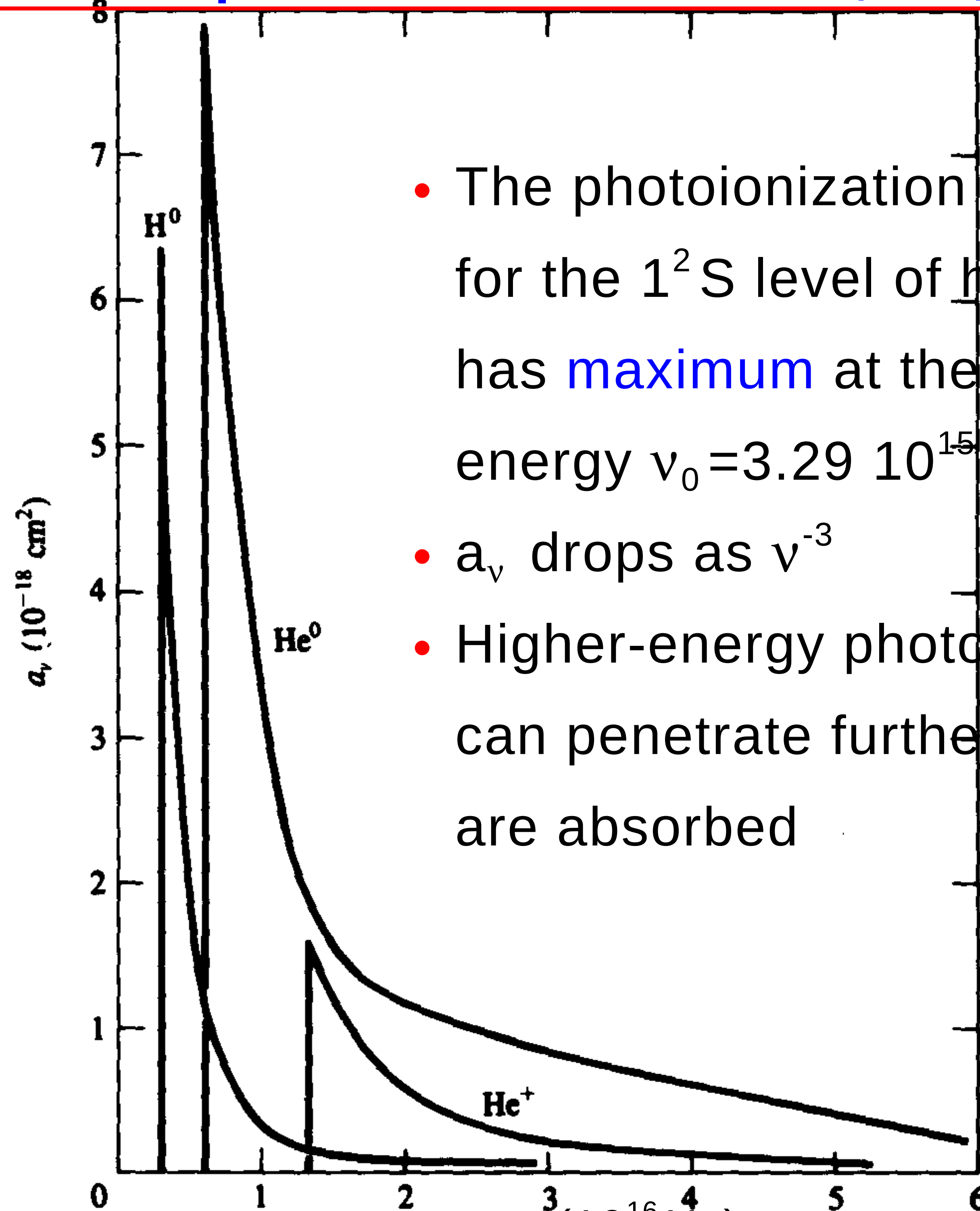
Osterbrock

Basic (Nebular) Approximation

- All hydrogen is in ground state
- Photoionization from 1^2S level is balanced by recombination to all levels
- Following quickly by radiative transition downward

This approximation is quite good, and greatly simplifies calculations of physical conditions in the nebulae uilibrium

Photoionization absorption cross section of H^0, He^0, and He^+



- The photoionization cross-section for the 1^2S level of hydrogenic ions has maximum at the threshold energy $\nu_0 = 3.29\ 10^{15}\ s^{-1}$ or $\lambda = 912 Å$
- a_ν drops as ν^{-3}
- Higher-energy photons on average can penetrate further before they are absorbed

ν (10^{16} Hz)

Osterbrock

Distribution of electrons

- The photoelectrons have initial distribution of energies that depends on J_ν
- The cross-section for elastic-scattering collisions between electrons is large $4\pi(e^2/mv^2)^2 \sim 10^{-13}\,cm^2$. These collisions set up Maxwell energy distribution
- All other cross-sections are MUCH smaller. Therefore, the electron-distibution is Maxwellian.
- All collisional processes occur at rates fixed by the local temperature defined by this Maxwellian.

$$f(v) = \frac{4}{\sqrt{\pi}}\left(\frac{m}{2kT}\right)^{3/2} v^2 e^{-mv^2/kT}$$

Recombination

- The recombination coefficient to a level n^2L

$$\alpha_{n^2L}(\mathrm{H}^0, T) = \int_0^\infty v\sigma_{nL}(\mathrm{H}^0, v) f(v) \mathrm{d}v \ ,$$

- Where $\sigma_{nL}(\mathrm{H}^0, v)$ is the recombination cross-section on level n^2L for the electrons with velocities v
- The cross- sections σ varies as v^{-2} . The recombination coefficient $\alpha \sim v\sigma \approx T^{-1/2}$
- The recombination cross-sections are $10^{-21...-22}$ cm^2. Much smaller that the geometrical cross-section of an atom.

NB! e-e cross-section 10^7 times LARGER.

Recombination

- In the nebular approximation, recombination to level n^2L quickly leads thru downward transition to 1^2S.
- The total recombination coefficient

$$\alpha_{\mathrm{A}} = \sum_{n,L} \alpha_{n^2L}(\mathrm{H}^0, T) = \sum_n \alpha_n(\mathrm{H}^0, T)$$

- Numerical values can be found in Osterbrock.
- A typical recombination time $\tau=1/N_e\alpha_A=3\ 10^{12}/N_e$ sec
- or $10^5/N_e$ yr
- Derivations from ionization equilibrium are ordinarily damped out in times of this order of magnitude

Intermediate Summary

- We briefly discussed formation of forbidden lines. We will talk about it in more detail later. How forbidden lines are excited?
- Nebular approximation What is that?
- Photoionization of hydrogen From which level?
- e-e collisions establish temperature Why?
- Recombinations on excited levels Following by what?

We are ready to write radiative transfer equation for pure H nebula and calculate its structure.

Photoionization of Pure Hydrogen Nebula

Idealized problem: a single hot star in a homogeneous static cloud of hydrogen.

Write ionization equilibrium equation

The equation of radiative transfer for radiation with $\nu > \nu_0$

$$\frac{dI_\nu}{ds} =$$

What is on the right hand side of the radiative transfer equation?

How photons are destroied? How they are emitted?

Photoionization of Pure Hydrogen Nebula

Idealized problem: a single hot star in a homogeneous static cloud of hydrogen.

The equation of radiative transfer for radiation with $\nu>\nu_0$

$$\frac{dI_\nu}{ds} = -N(\mathrm{H}^0)a_\nu I_\nu + j_\nu$$

I_ν is the specific intensity of radiation, j_ν is the local emission coefficient for ionizing radiation

Lets divide the radiative field into two parts: a ”stellar” part. resulting from starlight, and a ”diffuse” part, resulting from the emission of ionized gas.

$$I_\nu = I_{s\nu} + I_{d\nu}$$

Photoionization of Pure Hydrogen Nebula

How stellar radiation field changes with the distance?

$$4\pi J_{\nu s} = \pi F_{\nu s}(r) = \ldots$$

Photoionization of Pure Hydrogen Nebula

How stellar radiation field changes with the distance?

$$4\pi J_{\nu s} = \pi F_{\nu s}(r) = \pi F_{\nu s}(R) \times \frac{R^2 e^{-\tau_\nu}}{r^2},$$

where $\pi F_{\nu s}(r)$ is the standard notation for the flux of stellar radiation at r, $\pi F_{\nu s}(R)$ is the flux at the surface, R is the radius of the star, and τ_ν is the radial optical depth at r.

$$\tau_\nu(r) = \int_0^r N_{H^0}(r')a_\nu dr' = \frac{a_\nu}{a_{\nu_0}}\tau_0(r)$$

where τ_0 is optical depth at the threshold

"On the Spot" approximation

If nebula is optically thick every diffuse radiation-field photon is absorbed elsewhere in the nebula

$$4\pi \int \frac{j_\nu}{h\nu} dV = 4\pi \int N_{H^0} \frac{a_\nu J_{\nu d}}{h\nu} dV$$

On the spot approximation photons are are absorbed "on the spot", i.e. close to the point where they were generated

$$J_{\nu d} = \frac{j_\nu}{N_{H^0} a_\nu}$$

This is good approximation, because the diffuse radiation field photnos have ν approx ν_0 → large a_ν → small mean free path (write expression for the mean free path)

Ionization Equilibrium

Ionization Equilibrium

$$N_{\mathrm{H}^0} \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(\mathrm{H}^0) \mathrm{d}\nu \;=\; N_{\mathrm{e}} N_{\mathrm{p}} \alpha(\mathrm{H}^0, T)$$

Stellar radiation field

$$4\pi J_{\nu s} = \pi F_{\nu s}(r) = \pi F_{\nu s}(0) \times \frac{R^2 \mathrm{e}^{-\tau_\nu}}{r^2}$$

Number of photons from the recombinaiton on ground level

$$4\pi \int_{\nu_0}^{\infty} \frac{j_\nu}{h\nu} d\nu = N_{\mathrm{p}} N_{\mathrm{e}} \alpha_1(H^0, T).$$

Substituting it in the eqiation of ionization equilibrium

$$\frac{N_{\mathrm{H}^0} R^2}{r^2} \int_{\nu_0}^{\infty} \frac{\pi F_\nu(R)}{h\nu} a_\nu \mathrm{e}^{-\tau_\nu} \mathrm{d}\nu \;=\; N_{\mathrm{e}} N_{\mathrm{p}} \alpha_{\mathrm{B}}(\mathrm{H}^0, T)$$

where

$$\alpha_{\mathrm{B}}(\mathrm{H}^0, T) = \alpha_{\mathrm{A}}(\mathrm{H}^0, T) - \alpha_1(\mathrm{H}^0, T) = \sum_2^{\infty} \alpha_n(\mathrm{H}^0, T)$$

Ionization Equilibrium

Equation of ionization equilibrium

$$\frac{N_{\mathrm{H}^0} R^2}{r^2} \int_{\nu_0}^{\infty} \frac{\pi F_\nu(R)}{h\nu} a_\nu e^{-\tau_\nu} d\nu = N_e N_p \alpha_B(\mathrm{H}^0, T)$$

Physical meaning: In optically thick nebulae, the ionizations caused by stellar photons are balanced by recombinaitons to excited levels of H. The recombinations to the ground level generate ionizing photons that are immediately absorbed, but have no net effect on the overall ionization balance

- Cross-sections a_ν and optical depth are known functions of ν
- When stellar spectrum $\pi F_\nu(R)$ is input, the integral $\int_{\nu_0}^{\infty} \frac{\pi F_\nu(R)}{h\nu} a_\nu e^{-\tau_\nu} d\nu$ can be tabulated.

Strömgren Sphere

Equation of ionization equilibrium

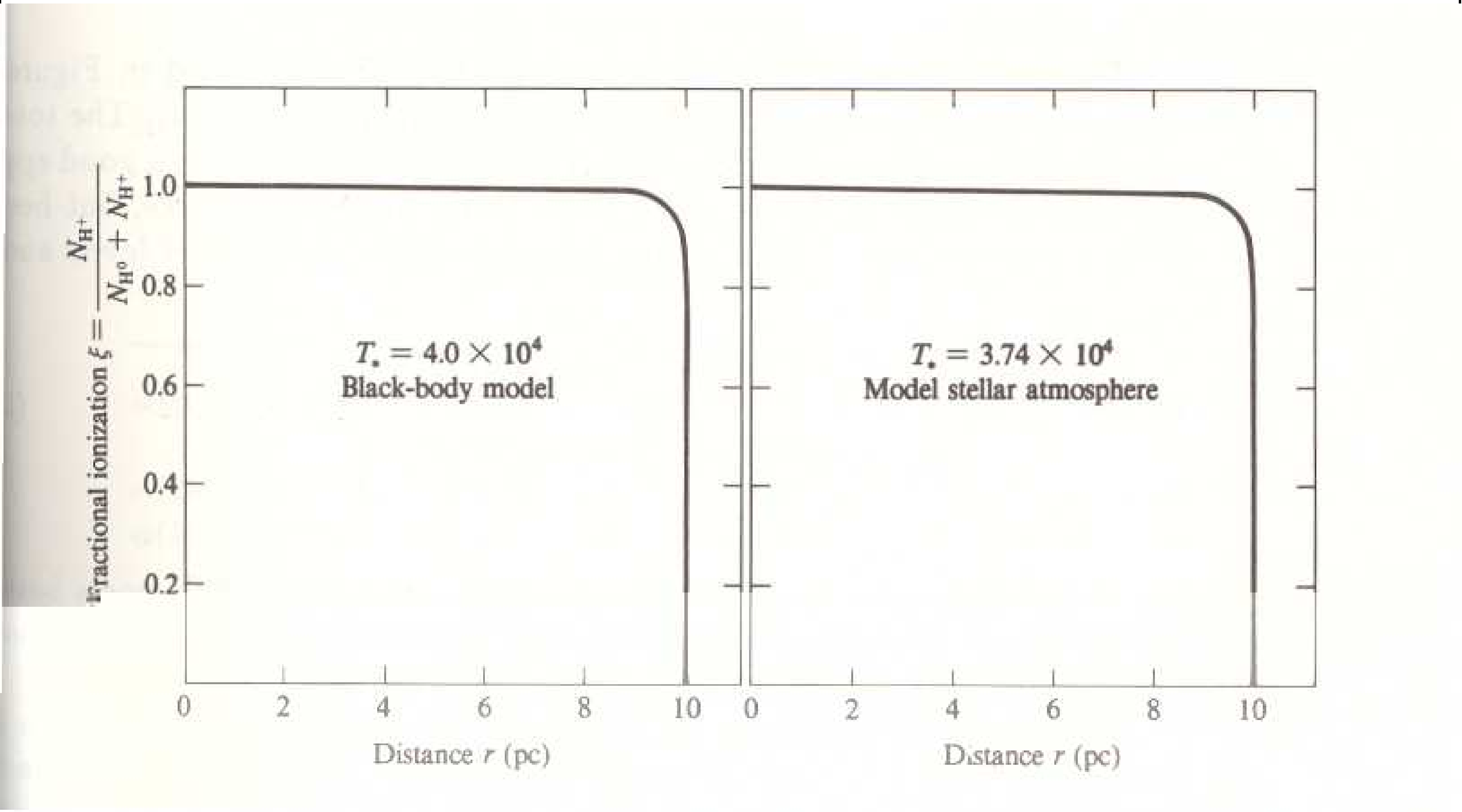
$$\frac{N_{\mathrm{H}^0} R^2}{r^2} \int_{\nu_0}^{\infty} \frac{\pi F_\nu(R)}{h\nu} a_\nu \mathrm{e}^{-\tau_\nu} \mathrm{d}\nu = N_\mathrm{e} N_\mathrm{p} \alpha_\mathrm{B}(\mathrm{H}^0, T)$$

$$\tau_\nu(r) = \int_0^r N_{H^0}(r') a_\nu dr' = \frac{a_\nu}{a_{\nu_0}} \tau_0(r)$$

These two equations are integrated outwards to find

$N_{H^0}(r), N_\mathrm{p}(r), N_\mathrm{e}(r)$

Ionization structure of two homogeneous pure-H model HII regions



Osterbrock, Fig. 2-3

Strömgren Sphere

Equation of ionization equilibrium

$$\frac{N_{\mathrm{H}^0} R^2}{r^2} \int_{\nu_0}^{\infty} \frac{\pi F_\nu(R)}{h\nu} a_\nu \mathrm{e}^{-\tau_\nu} \mathrm{d}\nu = N_\mathrm{e} N_\mathrm{p} \alpha_\mathrm{B}(\mathrm{H}^0, T), \quad \tau_\nu(r) = \int_0^r N_{H^0}(r') a_\nu dr' = \frac{a_\nu}{a_{\nu_0}} \tau_0(r)$$

To find radius r_1: $\frac{d\tau_\nu}{dr} = N_{\mathrm{H}^0} a_\nu$, and integrate over r.

$$R^2 \int_{\nu_0}^{\infty} \frac{\pi F_\nu(R)}{h\nu} d\nu \int_0^{\infty} d(-\mathrm{e}^{-\tau_\nu}) = \int_0^{\infty} N_\mathrm{e} N_\mathrm{p} \alpha_\mathrm{B}(\mathrm{H}^0, T) r^2 dr$$

Ionization is nearly complete ($N_p = N_e$ approx N_H) within r_1, and nearly zero outside r_1 ($N_p = N_e$ approx 0):

$$4\pi R^2 \int_{\nu_0}^{\infty} \frac{\pi F_\nu(R)}{h\nu} d\nu = \int_0^{\infty} \frac{L_\nu}{h\nu} d\nu = \frac{4\pi}{3} N_\mathrm{H}^2 \alpha_\mathrm{B} r_1^3 = Q(H^0)$$

The total number of ionizing photons balances the total number of recombinations to excited levels within Strömgren sphere of volume $4\pi r_1^3/3$.