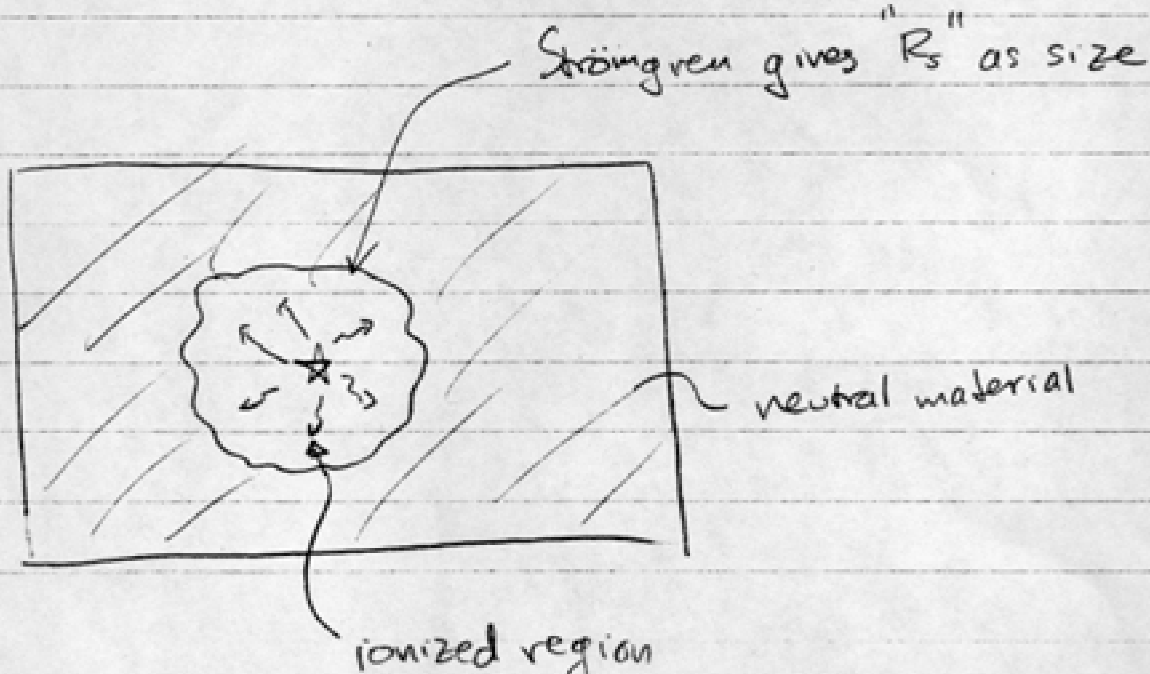
Astronomy 208 v. Y2K Meeting #16

Order for next sections: HII Regions — Th Rodriguez-Gaspar et al
then SNR + Hot ISM — Tues Williams et al
(incl shock discussions)

Still Remaining (7 meetings after Thanksgiving −1 for Paolo?)
- more on S.F. & winds from young & evolved ★'s
- ISM in external galaxies
- IGM / ISM at $z >> 0$

Today Basics of HII Regions



? Time evolution

? Effects of clumpiness/structure

? Effects of/on gas composition

4. Interactions of Photons with the ISM

4.1 HII Regions & PDRs

(a.) <u>Strömgren Sphere</u> : "Equilibrium" where ionizations = recombns

(Strömgren B. 1939 ApJ <u>89</u>, 529)

X = # ionizing photons/sec from ☆ ($\lambda < 912$Å)

$\alpha n_e n_H$ = # recomb/sec / volume

$\uparrow$ = recombination coefficent ($\approx 3.1 \times 10^{-13}$ cm^{3}s^{-1} @ 8000K)

Assume all "H" & electrically neutral H^+ = proton

so $n_e = n_p$

Total ionized volume $= \frac{4}{3}\pi R_s^3$

So Ioniz = Recomb

$$X = \frac{4}{3}\pi R_s^3 \alpha n_e n_H$$

$$\boxed{R_s = \left(\frac{3X}{4\pi\alpha}\right)^{1/3} (n_e n_H)^{-1/3}}$$

often assumed that $n_e = n_H$ @ boundary

so $R_s = \left(\frac{3X}{4\pi\alpha}\right)^{1/3} n_H^{-2/3}$

Allows for gross estimates:

e.g. O6☆ $T_{eff} \cong 4.5 \times 10^4$ K ; $L \cong 1.3 \times 10^5 L_\odot$

Wiens Law $\Rightarrow \lambda_{max} = 640$Å (So assume all $\lambda < 912$Å & @ 640 Å)

$X = L / {}_{hc/\lambda_{max}} = 1.6 \times 10^{49}$ phot/sec $\boxed{\text{for } n_H = 5000 \quad R_s = 0.3\,\text{pc}}$

often inner due to clustering

Refinements:

Real ✱ spectrum: # ionizing photons/sec $= n_H \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(H)\, d\nu$

n_H = density

J_ν = mean intensity

$\frac{4\pi J_\nu}{h\nu}$ = # incident phot of freq ν

$a_\nu(H)$ = ionization x-secn for H by photons w/ $h\nu$

$\sim 6 \times 10^{-18}\ \mathrm{cm}^{-2}$ for H

BUT
- J_ν should really include reduction by scattering w/in the nebula
- Multiple ionizations by one photon
- Time Evolution

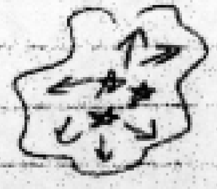
Return to Time Evolution for Rest of Today after looking @ possible morphologies

See Also

http://cfa-www.harvard.edu/~agoodman/hii.html

Types of Real H II Regions

Giant H II Regions (OBassn) — 5-50 pc, 1–100 cm^{-3}



e.g. 30 Dor, W3

Blister H II Regions — 1–10 pc, 10^2-10^3 cm^{-3} (see below)

Compact & Ultracompact — $\lesssim 1$ pc to $\ll 1$ pc, $> 10^3$ to $\gg 10^5$ cm^{-3}

Often produce → $\boxed{\text{champagne-flow}}$

e.g. (many) see Garay et al article

Ref: Tenorio-Tagle 1979

Note Geometry: $\boxed{\text{blister}}$

usually larger than "champagne flows"

e.g. Orion, S125, NGC 7538

FORMATION OF AN HII REGION
(Approximation)
for constant n

① ★ turns on __instantaneously__, emitting ionizing radiation @ rate $\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu$ $\frac{\text{photons}}{\text{sec}}$

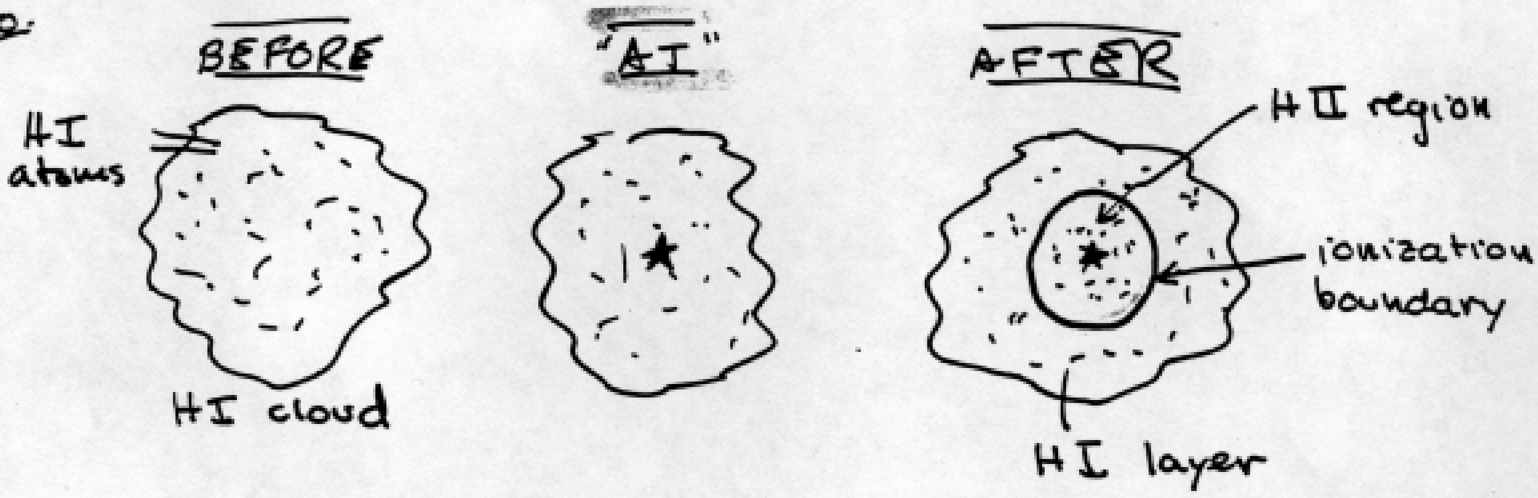
L_ν = luminosity @ ν

$h\nu_0$ = energy needed to ionize from ground state

② Assume ★ is in a cloud of HI gas with n_H $\frac{H}{cc}$

③ Photons move out @ c & ionize gas

__So.__



In this Approximation... growth analysis:

star emits photons @ rate

$$\boxed{\frac{d}{dt}(N_i) = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu}\, d\nu} \quad \frac{\text{photons}}{\text{sec}}$$

which ionize a spherical shell around ★ of radius R thickness dR $\Longrightarrow$

shell contains $\boxed{4\pi R^2 dR\, n_H}$ atoms of H I

rate of change of R given by

$$\boxed{\frac{dN_i}{dt} = 4\pi R^2 n_H \frac{dR}{dt}}$$

because each ionizing photon ionizes one n_H (ignoring recomb)

In H I gas m.f.p. $= \boxed{\delta = \frac{1}{n_H a}}$ a = ionization x-sectn $\approx 6\times10^{-18}\ \text{cm}^{-2}$ for H

$\Rightarrow \delta_H = 1.67\times10^{14}\ \text{cm} = \boxed{5\times10^{-5}\ \text{pc}}$

photon will ionize w/in 5×10^{-5} pc

But in ionized gas, relevant x-sectn is for scattering

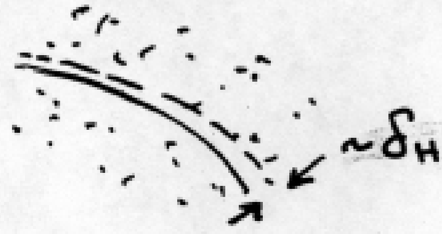
$\sigma \cong 6.7\times10^{-25}\ \text{cm}^2$ = very small

$\delta_i = \frac{1}{n\sigma} = \boxed{469\ \text{pc}!!}$ = very large m.f.p.

photon not bothered much

$\Longrightarrow$ very sharp transition @ ionization front

ere m.f.p gets very short



In the previous growth approx, we neglected <u>RECOMBINATION</u>, which will slow or halt growth.

[α = recombination rate coeff [$cm^3\,s^{-1}$]
= $4 \times 10^{-13}\ cm^3\,s^{-1}$ for H^+]

[t_{recomb} = recomb time = $\frac{1}{n_H \alpha}$ = 80 years]

Thus, including Recombinations, we find:

$$\underbrace{\frac{dN_i}{dt}}_{\text{ionizations}} = \underbrace{4\pi R^2 n_H \frac{dR}{dt}}_{\text{growth}} + \underbrace{\frac{4}{3}\pi R^3 n_p n_e \alpha}_{\text{recombinations}}$$

EQUILIBRIUM state = constant volume $\Rightarrow \frac{dR}{dt} = \emptyset$

$$\Rightarrow \boxed{R_s^3 = \frac{3}{4\pi n_e n_p \alpha}\frac{dN_i}{dt}} \Rightarrow \text{"Strömgren Radius"}$$

for <u>B0 to O5 ★'s</u> & <u>$n_H \simeq 10^3\ cm^{-3}$</u> $\boxed{R_s \sim 0.1 - 1\ pc}$

Recall

To get more quantitative, we need to consider

- → stellar spectrum to give $\frac{dN_i}{dt}$ ✓ O.K.
- → radiative transfer of ionizing photons ✓ O.K.
- → structure in neutral gas too hard for today
- → composition of neutral gas assume all H today

Define:
- n_{H° = volume dens. neut. H
- n_e = " " electrons (free)
- n_p = " " protons (free)
- J_ν = mean intensity of radiation field $= \frac{1}{4\pi}\int I_\nu \, d\Omega$
- $a_\nu(H)$ = ionization x-sectn $\xrightarrow[h\nu]{} \bullet H$
- $\alpha(H^\circ, T)$ = recomb. rate coeff ($cm^3 s^{-1}$)

Set

$$\frac{\text{ionizations}}{\text{time} \cdot \text{volume}} = \frac{\text{recombinations}}{\text{time} \cdot \text{volume}}$$

$$\downarrow \qquad\qquad \downarrow$$

then

$$\underbrace{n_{H^\circ} \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(H) \, d\nu}_{} = \underbrace{n_e n_p \alpha(H^\circ, T)}_{}$$

" Ionization Equilibrium Equation" for a Pure H Cloud.

In the H II region, the equ. of transfer is:

$$\frac{dI_\nu}{ds} = -n_{H^0} a_\nu I_\nu + j_\nu$$

I_ν is a bit complicated because some photons are from ★ & some from nebula itself

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

<u>Stellar Component</u>: ★ is only source ⇒ $j_\nu^{\star} = \emptyset$

so we have

$$4\pi J_{\nu s} = \pi I_{\nu s}(R_\star) \times \left.\frac{R_\star^2}{r^2} e^{-\tau_\nu}\right\} \begin{array}{l}\frac{1}{r^2} \text{ dilution} \\ \tau \text{ dilution}\end{array}$$

<u>Diffuse Component</u>: source of ionizing $h\nu$ is recaptures to the <u>ground state</u> (Lyman series)

so # ionizing photons $= 4\pi \int_{\nu_0}^{\infty} \frac{j_\nu}{h\nu} d\nu = n_p n_e \alpha_1(H^0, T)$

recomb. to ground state coeff

<u>Two</u> Approximations Possible

1. Optically <u>Thin</u> — ignore diffuse component
   say all Ly photons escape
2. Optically <u>Thick</u> — say all Ly photons absorbed & re-radiated (possibly @ longer λ)

Optically thick Case (More Interesting)

source func ionization xsect mean intensity

$$\underbrace{4\pi\int^{vol}\frac{j_\nu}{h\nu}\,dV}_{\text{emitted}} = \underbrace{4\pi\int^{vol} N_{H^\circ}\frac{a_\nu J_{\nu d}}{h\nu}\,dV}_{\text{absorbed}}$$

"On-the-spot" approximation: above eq. holds locally

so that: $$J_{\nu d} = \frac{j_\nu}{n_{H^\circ} a_\nu}$$

not too bad, since m.f.p. for abs. is short in τ high case

Substituting, we find that the equation of transfer

ionization equilibrium becomes

re-rad comp (source func) stellar comp

$$4\pi J_\nu = \frac{4\pi j_\nu}{n_{H^\circ} a_\nu} + \pi I_{\nu s}(R_*)\frac{R^2}{r^2}e^{-\tau_\nu}$$

$$\boxed{\frac{n_{H^\circ}R^2}{r^2}\int_{\nu_0}^{\infty}\frac{\pi I_{\nu s}(R_*)}{h\nu}e^{-\tau_\nu}a_\nu\,d\nu = n_e n_p\left[\alpha_{tot}(H^\circ,T) - \alpha_1(H^\circ,T)\right]}$$

allow for recomb ground state

recomb rate coeff to ground state

Notice that: $$\alpha_{TOT} - \alpha_1 = \alpha_2 = \sum_2^\infty \alpha_n(H^\circ,T)$$

$\Rightarrow$ recombinations to ground state produces photons which get trapped in nebula — they don't count (don't contribute to ionization balance)

Integrating the ionization equilibrium over r gives:

$$R^2\int_{\nu_0}^{\infty} \frac{\pi I_{\nu_s}(R)}{h\nu} \cdot \int_0^{\infty} e^{-\tau_\nu} a_\nu n_H^\circ \, dr\, d\nu = \int_0^{\infty} n_p n_e \alpha_2 r^2 dr$$

but recall $d\tau_\nu = n_H \alpha_\nu dr$ so

$$R^2\int_{\nu}^{\infty} \frac{\pi I_s(R)}{h\nu} \int_0^{\infty} e^{-\tau_\nu} d\nu\, d\tau_\nu = \int_0^{\infty} n_e n_p \alpha_2 r^2 dr$$

which gives

$$4\pi R^2 \int_{\nu_0}^{\infty} \frac{\pi I_{\nu s}(R)}{h\nu} d\nu = 4\pi \int_0^{\infty} n_e n_p \alpha_2 r^2 dr$$

So $\underline{\underline{\text{IF}}}$ $n_e = n_p = n_H$ for $r \le R_s$ and $n_e \approx 0 = n_p$ for $r > R_s$

we can replace ∞ radius with R_s which means

$$4\pi\int_0^{\infty} n_e n_p \alpha_2 r^2 dr = 4\pi n_H^2 \alpha_2 \frac{R_s^3}{3}$$

and use definition of Luminosity $L_\nu = 4\pi R_*^2 \pi I_\nu(R)$

and finally(!)

$$\boxed{\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu = \frac{4}{3}\pi R_s^3 n_H^2 \alpha_2}$$

R_s = Strömgren Radius!!