Interstellar Medium 7-oct-2019.

Tutorial on thursday on atomic medium
- prepare before thursday.

Ionization and recombination

Warm ionized medium and HII regions
$H\alpha$: hydrogen $n=3 \to n=2$
Lot of structures visible.

- Why do they emit in $H\alpha$?
- What do we learn from this?

Rosette Nebula → evolved HII regions
- gas is ionized by UV photons from stars
- could (but not here) also ionize hydrogen by collissions → warm enough gas ($T \gtrsim 100.000$ K).
HII regions don't have such temperatures

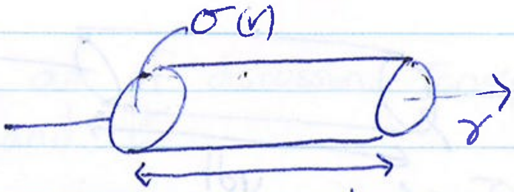
SNR are not photo-ionized. Rather the blast wave is so energetic that it ~~ionized~~ ionizes the medium ($k_BT \sim 10^6$ K)

Also opposite effect: recombination.
In equilibrium: # ionizations / sec = # recombinations / sec.

$$X + h\nu \mapsto X^+ + e^-$$

$$\rho_{pei} \, [cm^{-3} \, s^{-1}] = \int_{\nu_{min}}^{\nu_{max}} n_x \frac{u}{h\nu} \sigma_{ph.ion}(\nu) \, c$$

photon electron ionization



$$\delta l = c\,dt$$

For hydrogen like:

$$\sigma_{pe}(\nu) = \sigma_0 \left(\frac{h\nu}{Z^2 I_H} \right)^{-3}$$

Z: nuclear charge

I_H: 13.6 eV

σ_0 — H: $6.3 \cdot 10^{-18}\ \mathrm{cm}^{-2}$

Photo-ionization cross section peaks at ionization edge. $\sigma_{pe} = 0$ for energy below 13.6 eV. Cross section quickly drops for energies above threshold.

Ionization edge for carbon is lower than for hydrogen. C is already ionized in neutral ISM.

In soft x-ray, there are inner shell absorptions for carbon and oxygen.

Reverse process bit more complex, ~~but~~ when proton captures electron, atom that is formed can be in any quantum states. Thus cross section depends on quantum state.

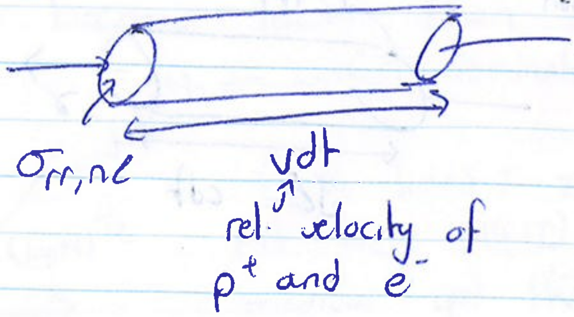
$$\zeta_{rr,nl} = n_e n_p \alpha(T)$$

T: temperature

α: total cross section $\sum_{n,l}$ all states

rr: radiative recombination

nl: hydrogen quantum numbers



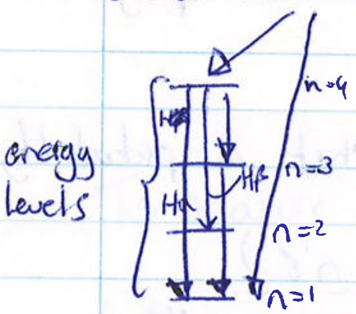
$$\alpha_{tot} = \sum_{n,\ell} \alpha_{n,\ell}$$ ↖ depend on T

α is 'recombination efficiency' into state n, ℓ

$$\alpha_{n\ell} = \int \sigma_{rr,n\ell}(v)\, v\, f(v)\, dv$$

↑ maxwell velocity distribution ($= f(v,T)$)

Draine goes into more detail.
Essentially every atom in groundstate, so photo-ionization goes from ground to excited states. Recombination however, can go to all allowed states and not just to ground state.



Different possibilities for decay. If immediately to ground state, recombination ejected photon can re-ionize other hydrogen atom and effectively nothing happens. In ISM this is true, in IGM, (since low density) this is not necessarily true.

! ↳ 'On the spot approximation'

Hβ : Hα are fairly well fixed. HII regions always have the same temperature (10^4 K).

! Recombinations are lines caused by recombination. ~~Most other optical lines that we all see later~~ Eg 21 cm of course not.

We leave qn. m out of discussion. Energy levels are independent of m and ℓ.

! Know Lyα, Balmer α

$Ly\alpha$ only observed from space (UV). Balmer all in UV

Why would one want to observe any other line than $H\alpha$, given that ratios are relatively fixed?
→ Because of dust. HII regions are always dusty regions. We can detect almost any quantum number recombination line ~~in~~ ~~$H\alpha$~~ of hydrogen.

$$A_{n+1,n} = A_{ul} = \frac{5.3 \cdot 10^9}{n^5} \, s^{-1}$$

Only for large n, A becomes small (e.g. $n=100$, radio recombination lines if $A \approx 1$) Otherwise extremely fast transitions. Only at very high n density will play a role.

Suppose atoms recombine to $n=4$. What is probability of $H\beta$ $(4 \to 2)$ decay?

$$\underset{\text{probability}}{\Gamma}(nl \to n'l') = \frac{A(nl \to n'l')}{\sum_{n''l'', n''<n} A(nl \to n''l'')}$$

branching ratio

$$\underbrace{n_e n_p \, \alpha(nl)}_{\substack{\text{recombination} \\ \text{rate into } (n,l)}} \; \underbrace{\Gamma(nl \to n'l')}_{\substack{\text{fraction going} \\ \text{to } H\beta}}$$

This is just for one channel. We need also consider transitions through other channels that happen to end up in ~~channel~~ $n=4$.

Each $H\beta$ gives energy $h\nu$ per 4π sr. Thus emissivity is given by

$$j_\nu = \frac{h\nu}{4\pi} n_e n_p \alpha(nl) \Gamma(nl \to n'l') \phi_\nu$$

- QM fuzzyness
- velocity distr.

Now with all higher levels

$$j_\nu = \frac{h\nu}{4\pi} n_e n_p \underbrace{\Gamma(nl \to n'l')}_{\text{depends only on } A_{ul}} \left[\alpha(nl) + \sum_{\substack{n' > n \\ n'l'}} \alpha(n'l') \underbrace{P(n'l' \to nl)}_{\text{only } A_{ul}\text{'s no } T, \rho \text{ dependence}} \right]$$

α has T dependence

$\rightarrow$ f(T)

Temperature dependence of α is fairly slow.

When ignoring weak T dependence, j_ν is just a constant.

'On the spot approx':

$\boxed{\text{CASE B}}$

- $\lambda < 912$ Å, medium optically thick
- ~~Lya~~ All Lyman lines optically thick for $\lambda < 912$ Å.
- Everything related go ground state are thus set to zero.

$$j_\nu \Big|_{\text{case B}} = \frac{h\nu}{4\pi} n_e n_p \alpha_B(T)$$

proportional to $\propto n^2$

Does not ~~so~~ trace ~~A~~ masses, rather densities

Ratio for any two lines is fixed.

$H\alpha$ ~~Lr~~ : $H\beta$ can be used to trace extinction, since ratio is fixed. $\frac{H\alpha}{H\beta} \approx 3.1$