We have seen that photons with an energy higher than 13.6eV, the binding energy of hydrogen, strongly interact with neutral hydrogen, photoionizing it and hence giving its energy to a free electron, heating up the medium.

Free electrons can't absorb photons. Compton scattering is extremelly inefficient, so ionized hydrogen regions are largely transparent to photons.

★HOW CAN THE ISM COOL DOWN??

This is necessary for matter to clump together and make stars, planets, etc.

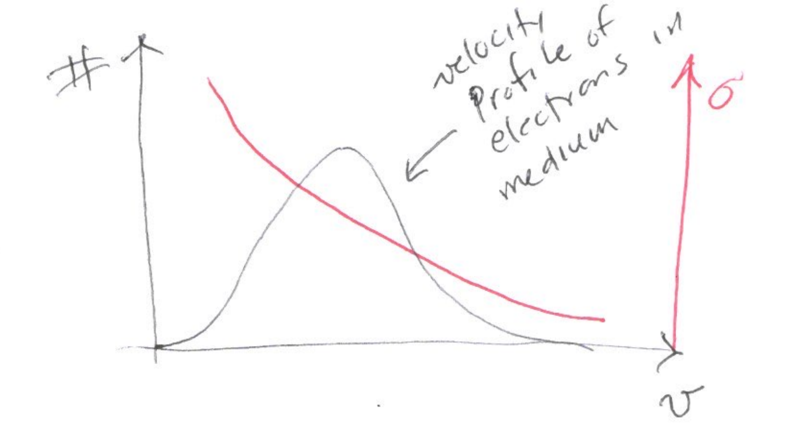
One mechanism is electron-proton recombination, but it can't be the only one.

$\Gamma = \alpha n_e n_p \overline{\Delta E}$ heating function - rate per volume at which photons deposit energy J/v·s

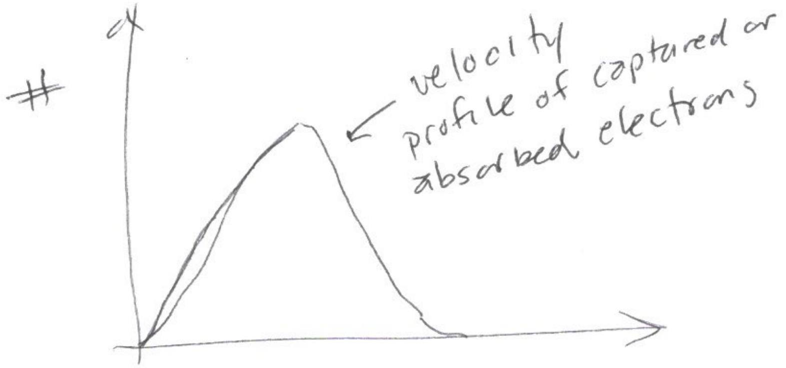
For thermodynamic equilibrium

$\alpha n_e n_p \overline{\Delta E} = \alpha n_e n_p \overline{E_R}$, so $\overline{E_R} = \overline{\Delta E}$

The electron velocity distribution is the Maxwell-Boltzmann with temperature T_e, the electron kinetic temperature.



The absorption e-p cross-section decreases with increasing energy, as you showed in ~~Problem~~ the homework.



The mean electron energy is $\frac{3}{2}k_B T_e$, but $\bar{E}_R < \frac{3}{2}k_B T_e$ necessarily.

If $\bar{E}_R = \overline{\Delta E}$, $\overline{\Delta E} < \frac{3}{2}k_B T_e$ and $T_e > \frac{2}{3k_B}\overline{\Delta E}$

But we saw that $k_B T_c \le \overline{\Delta E} \le 2.7\, k_B T_c$

$$T_e > \frac{2}{3\cancel{k_B}}\cancel{k_B} T_c = \frac{2}{3} T_c$$

$$T_e > \frac{2}{3\cancel{k_B}} 2.7 \cancel{k_B} T_c = \frac{5.4}{3} T_c$$

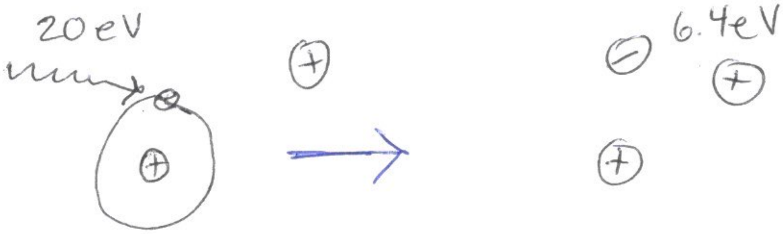
T_c was the "color temperature" of star producing radiation.

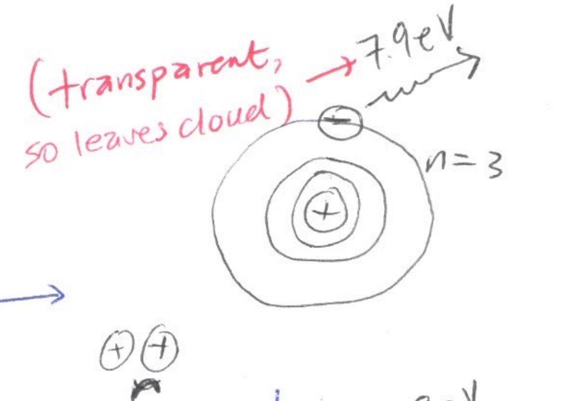
It is observed that even though T_c is 30,000K – 50,000K, T_e is always less than 10,000K, there ought to be other mechanisms in place.

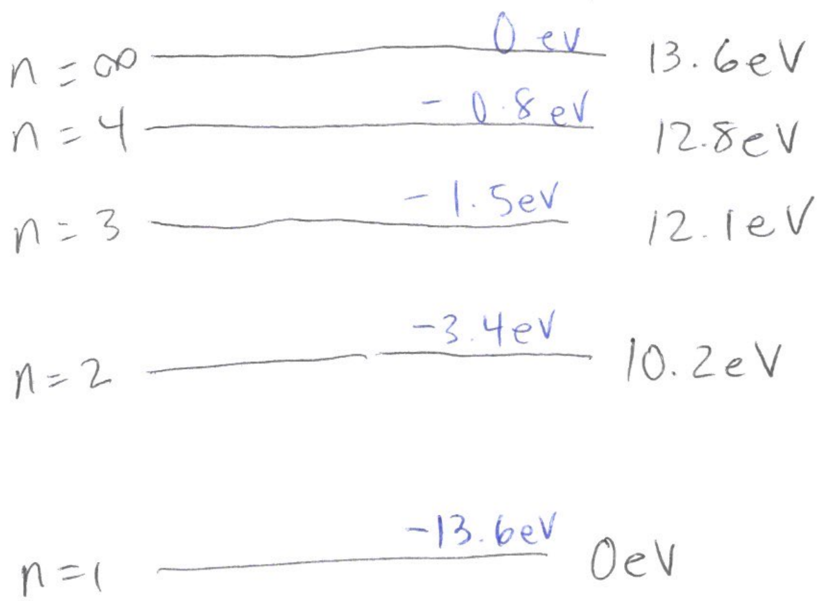
The particles are in thermodynamic equilibrium, ~~but the~~ among themselves, but not with radiation, since radiation can escape the cloud. Therefore, the cloud will <u>not</u> have a black-body spectrum.

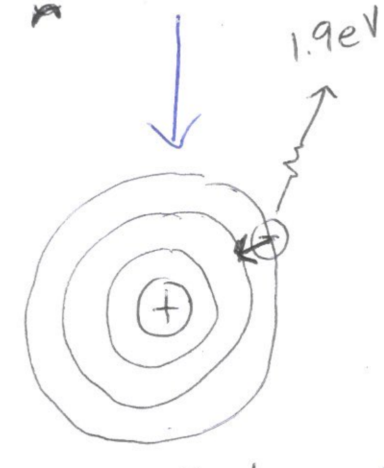
☆ ALL COOLING MECHANISMS INVOLVE RADIATION LEAVING THE CLOUD

One such mechanism:

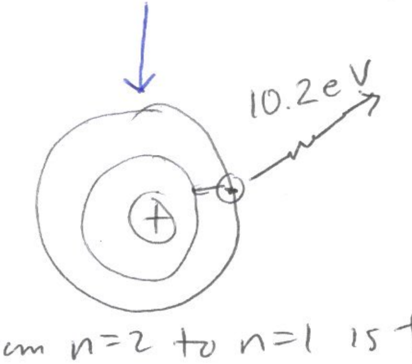








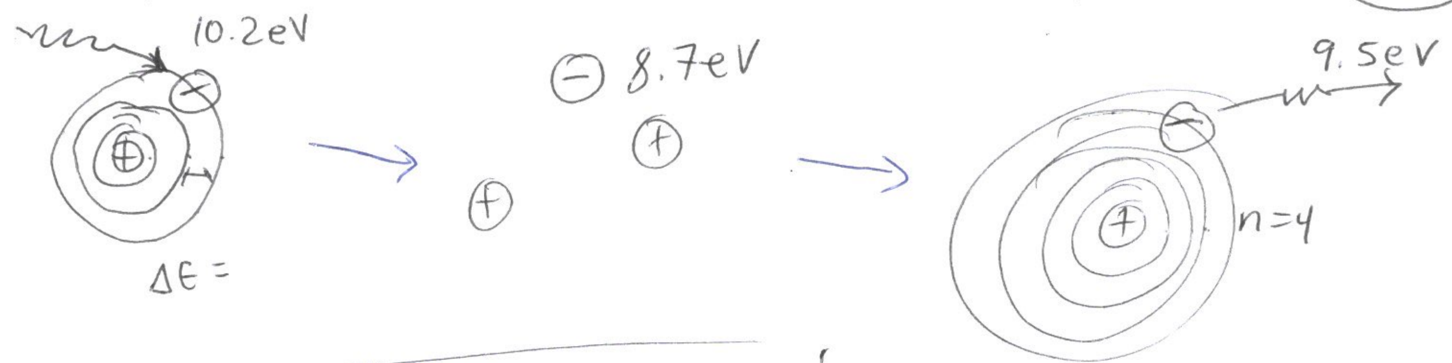
From n=3 to n=2 is the Balmer alpha Hα



From n=2 to n=1 is the Lyman alpha Lα

Perhaps the 7.9eV photon can leave the cloud easily, but the 1.9eV and particularly the 10.2eV photons will be easily and readily absorbed by other Hydrogen atoms, can do a random walk.

Other possibilities exist but are less likely



The ratio between the excited/ground states is given, as we saw before, by

$$n_a/n_b = g_a/g_b \, e^{-(E_a - E_b)/k_B T}$$

Then $n=4 \rightarrow n=2$ $\xrightarrow{2.6eV}$

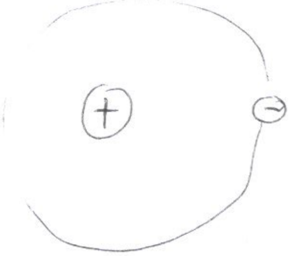
$n=2 \rightarrow n=1$ $\xrightarrow{10.2eV}$

Also, two or more photons can be produced as long as the total energy is the same, so a 4.9 eV and 5.3 eV instead of the $L\alpha$, but again this could be rare.

★ THE BOTTOM LINE IS THAT THE $L\alpha$ PHOTONS CAN GET "TRAPPED" IN THE CLOUD FOR LONG TIMES

$$\Lambda = \alpha n_a n_b (E_b - E_a)$$

★ RIGHT AFTER THE BIG BANG, ONLY THIS MECHANISM WAS AVAILABLE. THE CREATION OF "METALS" WAS A GAME CHANGER.



Consider the hydrogen atom in its ground state. There is a difference between its true ground state with the spins of the ~~hydrogen~~ proton and the electron anti-aligned and the aligned case $\uparrow\uparrow$ $\uparrow\downarrow$
$\oplus$ $\ominus$

Remember that the first orbital can hold 2 electrons

[illegible]	(s orbitals only)	2	
[illegible]	(s+p orbitals)	8	10
[illegible]	(s+p+d orbitals)	18	28
	s+p+d+f	32	

$\epsilon = h\nu$ $\quad c = \lambda\nu$ $\quad \nu = \frac{c}{\lambda}$

$\frac{hc}{\lambda}$

$\lambda = \frac{hc}{\epsilon}$

$\lambda = \frac{(4.135\times10^{-15}\,eV\cdot s)(3\times10^{8}\,\frac{m}{s})}{8\times10^{-3}\,eV}$

Now consider singly ionized carbon C II

First 2 electrons in $n=1$ $\ell=0$ 1s orbital

Next 2 electrons in $n=2$ $\ell=0$ 2s orbital

Last 1 electron in $n=2$ $\ell=1$ 2p orbital

The last electron can be spin up or spin down, so the total angular momentum can be $J = L + S$ $\quad 1 + 1/2 = 3/2$

$1 - 1/2 = 1/2$

In "Russell-Saunders" notation $^{2S+1}L_J$, $\quad 2S+1 = 2(1/2)+1 = 2$

total electron spin

$^2P_{1/2}$, $^2P_{3/2}$ The difference in energy between these 2 states is 8 meV $\lambda = 1.55\times10^{-4}\,m = \frac{1\times10^9\,nm}{1\,m}$ 0.15mm 92K

Notice that the energy levels remain the same, the only thing that changes is the total angular momentum

This is a <u>rotational</u> state! ~~Ad~~ And can be excited by collisions with electrons, protons, atoms, molecules, etc

No need to absorb photons, but when the CII goes back to its ground state, it emits a photon in the <u>far infrared</u> which is not really absorbed by hydrogen, although it might still be absorbed by dust, etc.

Oxygen is the most abundant "metal"

A particularly important case is doubly ionized oxygen OIII

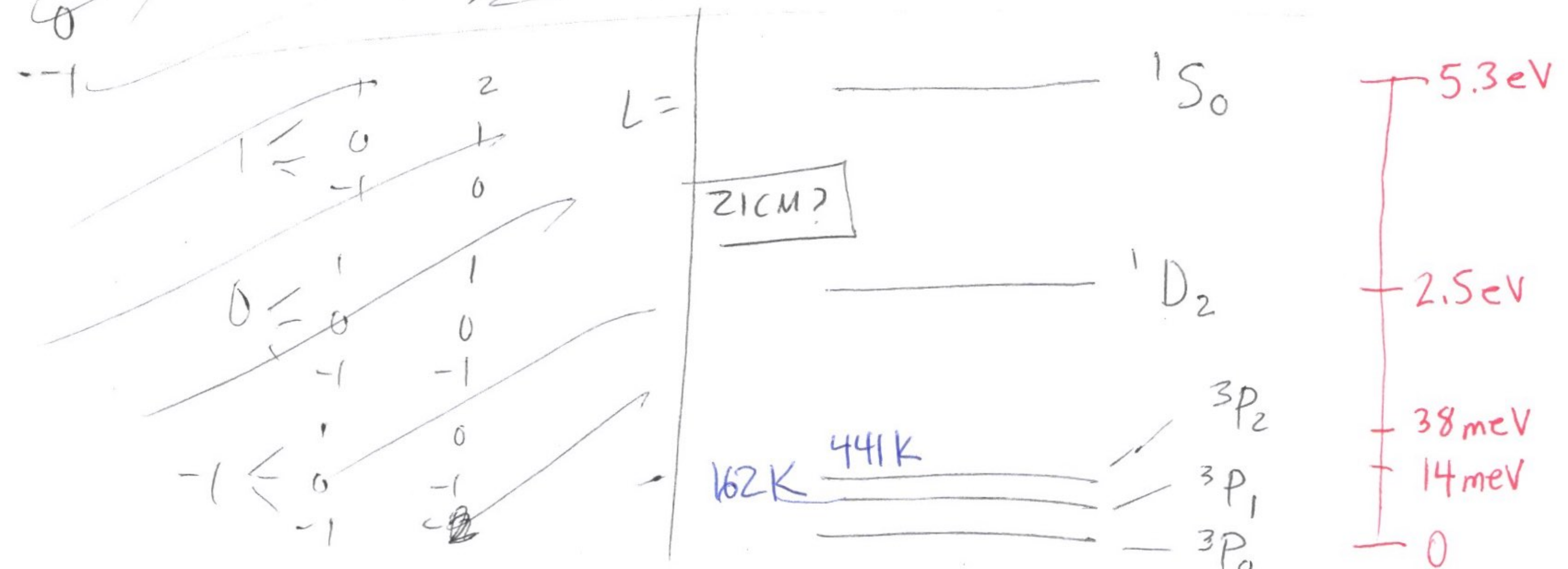
First 2 electrons in $n=1$ $\ell=0$

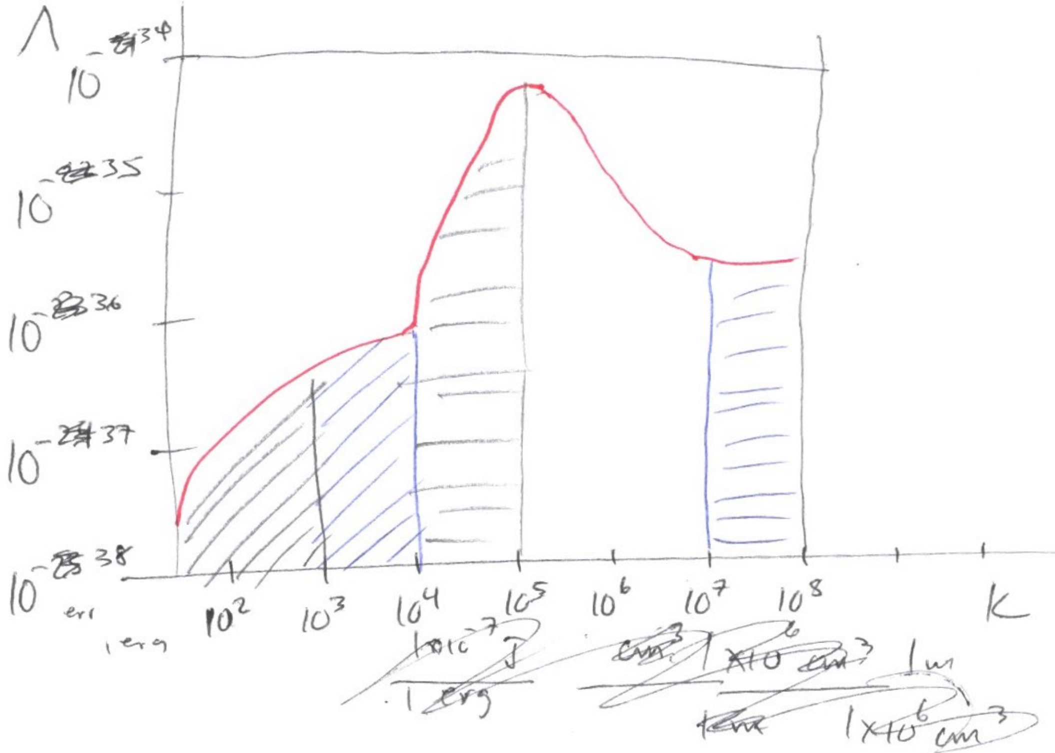
Next 2 electrons in $n=2$ $\ell=0$

Last 2 electrons in $n=2$ $\ell=1$ $\quad +\frac{1}{2}+\frac{1}{2},\ +\frac{1}{2}-\frac{1}{2},\ -\frac{1}{2}-\frac{1}{2}$ → $1,\ 0,\ -1$

~~J = L + S can be 2 1+1 = 2~~

$\ell = 1$, ~~$\ell = -1$~~





Molecular emission (rotational)

Metal emission (rotational)

Recombination

Bremstrahlung (radiation stopping)