The Interstellar Medium : JAP course
Galaxies and ISM

Lecture 6

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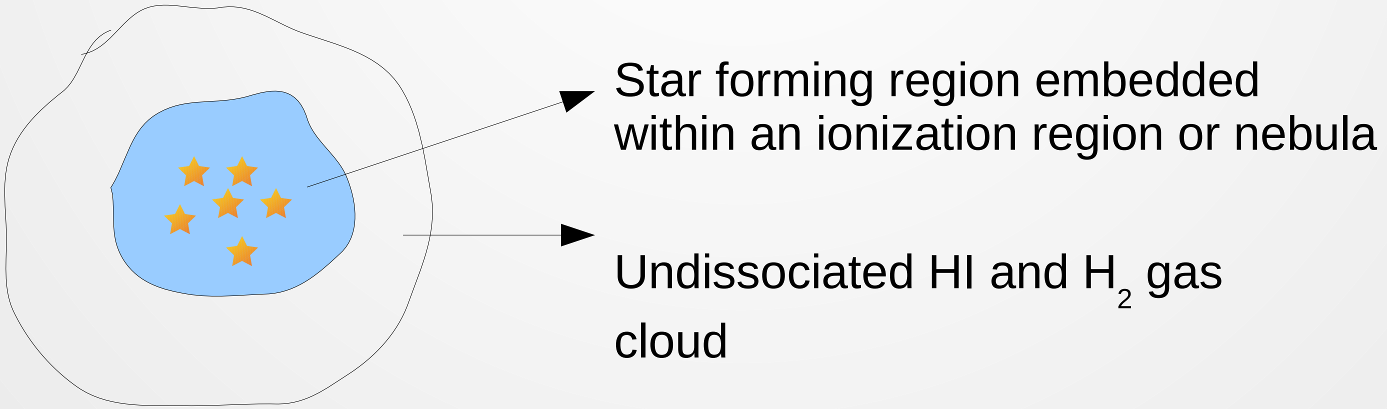
Radiatively Excited Regions

- Stars form due to the collapse of cold molecular clouds. As the cloud collapses, it fragments and the fragments keep contracting until protostars form within the clouds. The protostars finally evolve into stars. In a cloud many stars form together with a distribution of masses. The distribution function is called the **initial mass function (IMF)**.
- The star forming region within a cloud ionizes the surrounding region resulting in an ionization nebula or HII region. The nebula lies within the HI cloud (see figure below). In some cases if there are very massive stars in the cluster (such as O and B type stars), most of the neutral gas is blown away leaving large HII regions around the star cluster.
- The optical spectra from star forming regions are rich in emission lines such as the Balmer lines (Hα and Hβ). Other lines are the [OII], [OIII], [SII], [NII] forbidden lines.
- These radiatively excited regions or ionization bubbles around star forming regions are made up of mainly electrons, protons and H atoms and have typical densities of 1000 particles /cm^3. The cloud sizes are typically a few pc.



Radiatively Excited Regions ….. contd

- The temperature of the O and B type stars is 2 to 6×10^4 K. The temperature of the ionization regions is 5×10^3 to 10^4 K. The source of energy in these regions is the kinetic energy given to the electrons at photoionization in the clouds.
- In the following lecture we will study the equilibrium, sizes and energetics of these ionized regions.
- Assumption : (I) we will assume that a radiatively excited region around stars is mainly composed of electrons, protons and H atoms. The fraction of molecules dissociated by stellar radiation is low.
- (ii) we will also assume that the ionization nebulae or clouds are static. Compared to the timescale of atomic processes, cloud dynamical timescales are very long and hence the cloud is assumed to be static.

Physical Processes

- Let I_H be the ionization potential of the H atom. When photons have $h\nu > I_H$ then the electron is ejected from the atom and the reverse reaction produces recombination.

$$H + h\nu \leftrightarrow p + e$$

- The recombination energy is equal to the k.e. of the e and the binding energy of that level (I_H / n^2). Then there is a cascade to lower levels which gives more photons. Lines such as the balmer and Lyman series lines are given out.
- In equilibrium : ionization = recombination

  We will use this to determine the degree of ionization of hydrogen atoms.

- Particle temperature : The ionized gas contains 3 types of particles : electrons, protons and H atoms. The energy source is the k.e. of electrons after the H atoms are photoionized by UV photons from the star. The energy distribution of the electrons reflects the energy distribution of the photons.
- All the particles have Mawellian distribution of velocities because collisions transfer energy between the particles. Hence one temperature T_e is enough to characterize the particle energy.

Thermalization of energy

- There is a hierarchy in the thermalization of energy.

Electrons ejected from atoms (photoionization)

↓

Electron – electron collisions ==> electron – proton collisions equalizes the energies

↓

Proton - hydrogen atom collisions transfer energy to H atoms

- However, this hierarchy assumes a redistribution of energy through elastic collisions. Actual collisions are inelastic and there is some loss of energy.
- The gas temperature is termed as the electron temperature T_e. It has typical values of $5x10^3$ to 10^4 K.

Recombination of protons and electrons

- The ionization fraction of the gas is given by the balance between the ionization and recombination rates for the hydrogen atom in the nebula surrounding the star or star forming region.
- The recombination rate depends on the (i) number density of electrons and protons (n_e and n_p); for pure H nebula, $n_e = n_p$. (ii) Electron temperature T_e.
- This is because the probability of the recombination into a level 'n' in the H atom depends on electron energy, and the rate of e and p encounters depends on e velocity distribution.
- So the net recombination rate into a level n is given by,

  $dN(n)/dt = n_e n_p \beta_n(T_e) = n_e^2 \beta_n(T_e)$ where β_n is the recombination rate into level n. The total recombination rate into level n is given by

  $dN_R/dt = \Sigma\ (n=1 \rightarrow \mathrm{inf})\ dN(n)/dt$
- On the spot assumption : in the local region a recombination to level n=1 is immediately balanced by ionization, so that $dN_R/dt = \Sigma\ (n=2 \rightarrow \mathrm{inf})\ dN(n)/dt$
- We also approximate that $dN_R/dt = dN(n=2)/dt$ because energetically this is the most important contribution. So finally obtain,

$$dN_R/dt = n_e^2 \beta_2(T_e) \quad \text{where} \quad \beta_2(T_e) = 2\times10^{-16} T_e^{-3/4}\ \mathrm{m^{-3} s^{-1}}$$

Ionization of Hydrogen

- The ionization of the hydrogen atom can take place in any excited state (n>=2). However, the time in the excited state is very short. Then the atom comes back to ground state.
- Assumption : we can assume that hydrogen is in the ionized state (p) or H atom ground state.
- Consider an element at a distance r from the star which is receiving ionizing photos from the star. If I_H is the ionization energy and the number of photons with $h\nu > I_H$ crossing unit area in unit time is say J(r) $m^{-2}s^{-1}$, then the ionization rate is ,

$$dN_1/dt = \alpha_0 n_H J$$

where α_0 is the ionization crossection of the H atom in the ground state (in rigorous treatments this crossection depends on the energy of the incident photon). We will assume it is constant and equal to photon of energy $h\nu = I_H$. Its value is given as,

$$\alpha_0 = 6.8\text{x}10^{-22}\ m^2$$

- The degree of ionization is defined as,

$$n_e = xn \quad \text{where x=ionization fraction and } n=(n_p + n_H)$$

Or, $$n_H = (1\text{-}x)n \quad \text{where } 0 \le x \le 1$$

Ionization of Hydrogen ……. continued

- For the balance of ionization and recombination

$$x^2 n^2 \beta_2(T_e) = \alpha_0 (1-x) nJ$$

or, $$x^2/(1-x) = J\alpha_0/n\beta_2(T_e)$$

- Assume that J is determined only by geometric dilution of radiation from the star. This is fine until the edge of the nebula. Then,

$J = S(*)/4\pi r^2 \quad m^2 s^{-1}$ where S(*)= rate of ionizing photons from star

- An example : typical values for a star of type O6.5 :

$S(*) = 10^{49}\ s^{-1} \quad n=10^8\ m^{-3} \qquad r = 1pc \qquad T_e = 10^4\ K$

- Then we can calculate $J\alpha_0/n\beta_2(T_e)$. We get,

$x^2/(1-x) = 2.9x10^4$ or $(1-x) \sim 3.4x10^{-5}$

- Therefore gas is nearly fully ionized. So in radiatively excited regions around stars, when there is a balance between recombination and ionization, the gas is approximately fully ionized or x~1.

Sizes of Ionized Regions and the Stromgren Sphere

- Stars are embedded inside clouds. So the sizes of the ionized regions around a star or star cluster is limited to the volume of gas that a star can ionize so that recombination rate is equal to the rate of emission of ionizing photons.

$$dN_R/dt = J \quad \text{or} \quad n_e^2 \beta_2 = S(*)/4\pi R^2$$

- Let the radius at which this balance happens be R_s. It is given by,

$$R_s = (3/4\pi \times S(*)/n_e^2 \beta_2)^{1/3}$$

- This radius is called the Stromgren radius and the sphere of ionized gas around the star or star cluster is called Stromgren sphere. The gas inside the sphere is ionized.
- Typical values for the Stromgren sphere are :

$$S(*) = 10^{49}\ s^{-1}$$

$$T_e = 10^4\ K$$

$$R_s = 7 \times 10^5 n^{-2/3}\ pc$$

$$\text{So for } n = 10^8\ m^{-3} \implies R_s = 3\,pc$$

How Sharp edged are the nebulae?

- In the previous derivation we have assumed that the region $r<R_s$ is completely ionized and hence there is a sharp turnover from almost fully ionized to neutral gas i.e. HI.
- But it can be shown using flux reduction due to absorption and geometrical dilution that the the photon flux decreases sharply over a distance $\Delta r \sim 10/(n\alpha_0)$ where α_0 is the ionization crossection of the H atom and n is the number density.

  (Please read the relevant section in Dyson and Williams which gives the derivation).
- Putting in the values : α_0 = 6.8x10-22 m2 then $\Delta r \sim 0.49/n[cm^{-3}]$ pc

  For R_s = 3pc and n = 100 cm^{-3}

  $\Delta r / R_s \sim 0.49/100x3 \sim 0.0016$

- So the ionized regions or nebulae are very sharp and the changes in the ionization take place very sharply at the edge of an ionized cloud. So we are justified in taking the geometrically diluted flux until the cloud edge.

Temperature of pure hydrogen nebulae

- There is a continuous energy input from the photoionization of H atoms. This makes the gas hotter.
- But cooling happens when the electron recombines and excess energy is given away as radiant energy. This energy can leave the cloud and hence cools the ionized cloud.
- The equilibrium temperature is determined by the balance of this heating and cooling.

  Let N_R = recombination rate per unit time and unit volume

  Q=average energy injected per photoionization J = flux of ionizing photons

- Rate of gas heating $G = Q \times dN_R/dt$

  Rate of cooling is $L = (3kT_e/2)dN_R/dt$

  For balance : $(3kT_e/2)dN_R/dt = Q \times dN_R/dt$ and $\mathbf{T_e = 2Q/3k}$

- The Q depends on (i) radiation field of the star or star cluster in the cloud center and (ii) distance of gas element from star. If the star radiates as a black body then average energy injected per photoioinzation is $Q \sim kT_{star}$. So that $\mathbf{T_e = 2T_{star}/3}$
- **Typical values :** T_{star} ~3 to 6×10^4 K. So, T_e ~ 2 to 4×10^4 K

Temperature of H nebulae and other cooling processes

- **Although the predicted temperatures are** T_e ~2 to $4x10^4$ K the observations show that T_e is never greater than 10^4 K. So there must be some other cooling processes that we are missing. They are :

  (i) thermal bremmstrahlung emitted from the plasmaand observed at radio frequencies.

  (ii) collisional excitation of the H atoms.

  (iii) collisional ionization of the H atoms.

- But even these cooling processes are not enough and reduce T_e to only $2x10^4$ K.
- The reason is that elements heavier than H such as O, He, N etc are important coolants. Even though they are less abundant, their cooling is more efficient because their ionization potentials are larger than H.
- For example : the atom O and ionized O+, O++ or [OI], [OII], [OIII]. The first ionization potention of [OI] is similar to H i.e. 13.6eV. But for [OII] it is 35.1eV. So if O is ionized by hot stars it is a good coolant and is excited to higher states by collisions with H atoms.
- Most of these coolants are due to forbidden transitions of elements such as O, N, He.

End of Sixth Lecture