



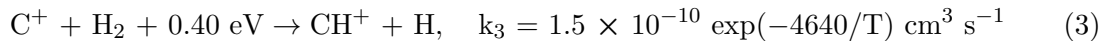
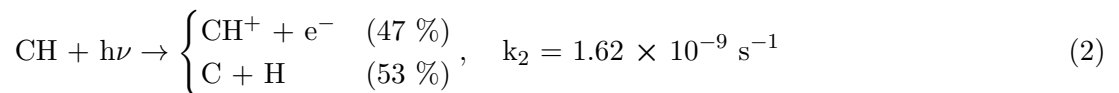
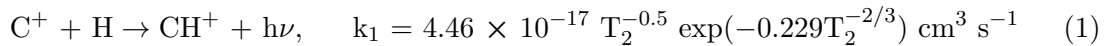
## Practice session: Interstellar Medium

Kapteyn Learning Community Sirius A

Give motivations and/or derivations for your answers.

### 1. Warming-up questions

- Examples of heating mechanisms in the ISM are heating through photon ionization ( $A + h\nu \rightarrow A^+ + e^-$ ) and heating via the photoelectric effect (ejection of electrons from dust grains). Explain two other heating mechanisms as well as two cooling mechanisms in the ISM.
- What is a photo dissociation region (PDR)?
- Give three examples of evidence for the existence of dust in the ISM.
- Consider the formation of  $\text{CH}^+$  in molecular clouds through these three channels:



Name the reaction type of each of these reactions.

### 2. Hydrogen clouds embedded in cold and warm neutral media

We observe an interstellar cloud with a temperature  $T = 100 \text{ K}$ ,  $n_H = 10^2 \text{ cm}^{-3}$ , and  $n_e = 10^{-1} \text{ cm}^{-3}$ . An important emission line is the CII fine structure line at  $157.74 \mu\text{m}$ . This line is produced because the ground state of ionized carbon splits into two fine structure levels  $^2\text{P}_{1/2}^0$  and  $^2\text{P}_{3/2}^0$ . The Einstein A coefficient of the line transition between the two levels:  $A_{10} = 2.4 \cdot 10^{-6} \text{ s}^{-1}$ . The de-excitation rate due to collisions with electrons is  $k_{10} = 4.53 \cdot 10^{-8} T_4^{-1/2} \text{ cm}^3 \text{ s}^{-1}$ . Where the temperature  $T_4$  has units of  $10^4 \text{ K}$ .

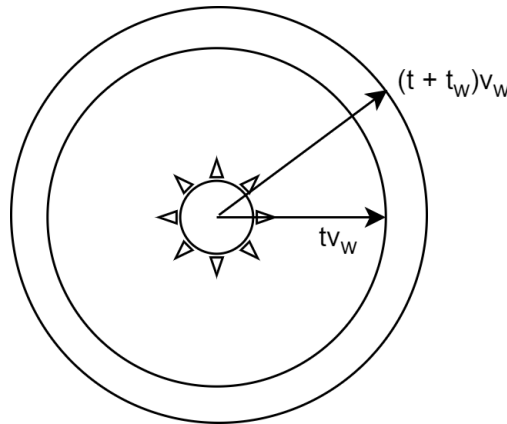
- Explain the concept of critical density and how it relates to the condition of local thermodynamic equilibrium (LTE).
- Calculate the critical density,  $n_{\text{crit}}$ , of the  $157.74 \mu\text{m}$  line.
- Calculate the collisional excitation coefficient,  $k_{01}$ , due to electrons using detailed balance for the hydrogen cloud.
- Calculate the relative populations,  $\frac{n_1}{n_0}$ , of the upper and lower level of carbon in the hydrogen cloud. Assume the two levels to be in statistical equilibrium and that the main collision partners are hydrogen atoms (with  $k_{10} = 1.38 \cdot 10^{-9} \text{ cm}^3 \text{ s}^{-1}$ ) and that the collision rate coefficients are in detailed balance.
- Now imagine finding this cloud in the cold neutral medium where typical turbulent velocities are  $0.8 \text{ km s}^{-1}$ . Calculate the full-width-half-maximum (FWHM) of the CII line in  $\text{km s}^{-1}$ .
- Calculate the FWHM of the HI 21 cm line in  $\text{km s}^{-1}$  assuming thermal and large scale turbulent motion broadening for the line profile, where  $v_{\text{turb}}$  follows a Maxwell-Boltzmann distribution.



- (g) Explain with sketches the Voigt profile in the context of the previous two questions.
- (h) Now instead imagine the hydrogen cloud in a warm neutral medium. First explain the two phases of the neutral medium. How does the pressure and temperature of the surroundings of the hydrogen cloud change when moving it from the cold to the warm neutral medium?

### 3. Stellar winds, and ISM, and stuff...

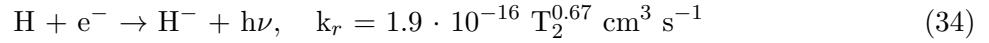
Consider a spherically symmetric stellar wind with mass-loss rate  $\dot{M}_w = 10^{-4} M_\odot \text{ yr}^{-1}$ , and wind speed  $v_w = 20 \text{ km s}^{-1}$ . Suppose that the mass loss continues steadily for a time  $t_w = 10^3 \text{ yr}$ . After this time the wind no longer loses mass and it continues to move outwards. Suppose that after a time  $t$ , the central star suddenly becomes an ionizing source emitting hydrogen-ionizing photons at a rate  $Q_0$ . So, after a time  $t + t_w$  the star starts to ionize the stellar wind. A protoplanetary nebula is created.



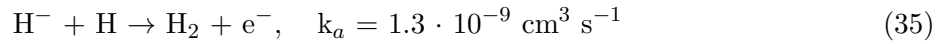
- (a) After a time  $t$ , the outflowing wind has a spherical outer surface and a spherical inner 'hole'. What is the number density of particles just inside the outer surface?  
**Hint:** What are the main constituents of this number density?
- (b) What is the number density just outside the inner hole?
- (c) Ignoring the expansion of the nebula during the ionization process, what is the minimum value of the ionizing photon rate,  $Q_0$ , required to ionize the hydrogen throughout the nebula? Given is the hydrogen recombination rate  $\alpha = 2.59 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$ .
- (d) Line ratios can be used to estimate the electron density or temperature in HII regions. Explain which conditions the selection of the line system must fulfill in order to be suited for measuring the electron temperature in the ionized nebula.
- (e) If the HII region contains sufficient dust, photoelectric heating by dust could take place, explain this process.
- (f) What is the recombination time just inside the outer surface? Compare this to the  $10^3$  year long dynamical age of the wind,  $t_w$ .
- (g) What is the difference between the cases A and B recombination? Which of them is a good description of the recombination process in the ionized nebula?

### 4. A problem that does not change much in time

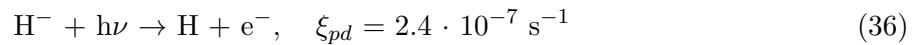
Consider the following radiative recombination reaction of hydrogen



where  $k_r$  is the rate coefficient. Furthermore, consider the reaction



which is a fast ion-neutral reaction with rate coefficient  $k_a$ . Note that  $\text{H}^-$  undergoes photoionization as well in the interstellar radiation field:



with the rate  $\xi_{pd}$ . Consider a neutral hydrogen cloud with density  $n_H = 30 \text{ cm}^{-3}$  and electron density  $n_e = 0.02 \text{ cm}^{-3}$ .

- What is the steady-state ratio  $\frac{n(\text{H}^-)}{n_H}$  ?
- What fraction of the  $\text{H}^-$  ions undergo the ion neutral reaction?
- Evaluate the quantity:

$$R_{\text{H}^-} \equiv \frac{k_a \cdot n(\text{H}^-) \cdot n(\text{H})}{n_H \cdot n(\text{H})} \quad (37)$$

Compare this to the ‘effective rate coefficient’ for formation of  $\text{H}_2$  by dust grain catalysis.

- Consider that the HI cloud would start to collapse and cool down. The cloud contains a high fraction of dust, what would be a good column density tracer?
- Explain what the X-factor is and what it could be used for in this cloud.