

# *I*NTERSTELLAR MEDIUM

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# I Introduction

Studying the interstellar medium is fundamental to understand the stellar formation. Molecular gas, cool enough, is needed to start to collapse and to compress. The condition for the gravitational collapse is given by the Jeans length and mass,

$$\lambda_J = \left( \frac{\pi c_s^2}{G \rho} \right)^{1/2}, \quad (1)$$

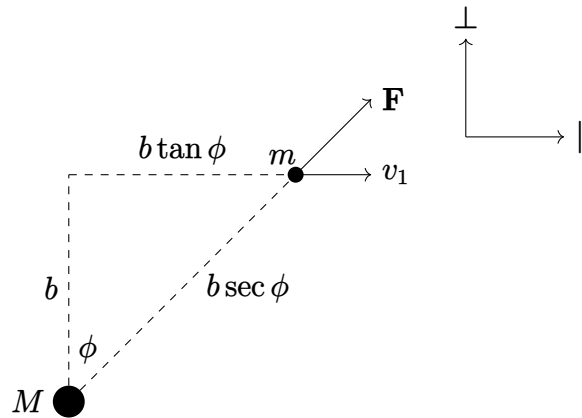
Speed of sound  
Density of the cloud

$$M_J = \frac{4\pi}{3} \rho \frac{\lambda_J^3}{8},$$

The Jeans mass is the mass of a cloud that is stable against gravitational collapse. If the cloud is more massive than the Jeans mass, it will collapse.

## Particle collisions

In elastic collisions, the total kinetic energy is conserved. Looking at the diagram, the target has a mass  $M \gg m$  and the projectile has a mass  $m$ . The target is at rest and the projectile has an initial velocity  $\mathbf{v}$ . The impact parameter  $b$  is the distance of closest approach where there is no interaction between particles.



The transfer of momentum is described with,

$$\begin{aligned} \Delta p_{\perp} &= \int_{-\infty}^{\infty} F_{\perp} dt \\ &= \int_{-\infty}^{\infty} \frac{Z_1 Z_2 e^2}{(b / \cos \phi)^2} \cos \phi dt \\ &= \frac{Z_1 Z_2 e^2}{b^2} \int_{-\pi/2}^{\pi/2} \cos^3 \phi \frac{d(b \tan \phi)}{v_1}, \quad \text{as } \frac{d|\mathbf{r}|}{dt} = v_1 \\ &= \frac{Z_1 Z_2 e^2}{b v_1} \int_{-\pi/2}^{\pi/2} \cos^3 \phi \frac{d\phi}{\cos^2 \phi} \\ &= \frac{2 Z_1 Z_2 e^2}{b v_1}. \end{aligned} \quad (2)$$

The classical approximation is still valid if  $b \gg a_0$ , where

**Note** (Bohr radius).

$$a_0 = \frac{\hbar^2}{m_e e^2} = 5.292 \times 10^{-9} \text{ cm}, \quad (3)$$

the wave function of the target electron will not be effected.

For de-excitation of ions due to electron collisions, the coefficient is given by

**Definition .1** (De-excitation rate coefficient).

$$\langle \sigma v \rangle_{u \rightarrow l} \approx \pi a_0^2 \left( \frac{8kT}{\pi m_e} \right)^{1/2} \left( 1 + \frac{Ze^2}{a_0 kT} \right), \quad (4)$$

which comes from the conservation of energy,

$$\frac{1}{2} m_e v_{\max}^2 = \frac{1}{2} m_e v^2 + \frac{Ze^2}{r_{\min}}, \quad (5)$$

the momentum conservation,

$$v_{\max} r_{\min} = v b_{\text{crit}}, \quad (6)$$

and defining the average cross section, using the velocity distribution field,

$$\langle \sigma v \rangle = \int_0^\infty \sigma(v) v f(v) dv, \quad \text{where } \sigma = \pi b_{\text{crit}}^2 \quad (7)$$

## Statistical mechanics

The partition function is defined as

$$Z(T) = \sum_i g_i e^{-E_i/kT}, \quad (8)$$

where  $g_i$  is the degeneracy of the energy level  $E_i$ . For an isothermal system,

$$\frac{P(s_1)}{P(s_2)} = \frac{\Omega(s_1)}{\Omega(s_2)} \quad S = k \ln \Omega. \quad (9)$$

The relative number of particles in energy level  $j$  with respect to the energy level  $i$  is given by

**Definition .2** (Boltzmann equation).

$$\frac{N_j}{N_i} = \frac{g_j}{g_i} e^{-(E_j - E_i)/kT}. \quad (10)$$

The detailed balance is a statistical description of how many particles are in one state as opposed to the other. The ratio of number densities is proportional to the ratio of partition functions per unit volume,

$$\frac{\Pi_j n(P_j)}{\Pi_i n(P_i)} = \frac{\Pi_j f(P_j)}{\Pi_i f(P_i)}. \quad (11)$$

The rate coefficient per unit volume is,

$$R = n_A n_B \langle \sigma v \rangle_{AB} \quad \text{where} \quad \langle \sigma v \rangle_{AB} = \int_0^\infty \sigma_{AB}(v) v f(v) dv. \quad (12)$$

The Saha equation is used to describe the ionization of a gas, it links the number of atoms in the ionization state versus the other. It is given by,

**Definition .3** (Saha equation).

$$\frac{n_{i+1}}{n_i} = \frac{2}{n_e} \frac{Z_{i+1}(T)}{Z_i(T)} \left( \frac{2\pi m_e kT}{h^2} \right)^{3/2} e^{-E_i/kT}, \quad (13)$$

↑ Ionization ratio      ↑ Electron density      ↑ Partition function ratio      ↑ Ionization potential

The last term assumes that the temperature is not too high, making the lowest energy term important and it is in the local thermodynamic equilibrium.

## Quantum mechanics

Molecular transitions are important for the interstellar medium. The more symmetric the molecule, the weaker emission lines it will have, due to the lack of the permanent dipole moment. The dipole moment is given by,

$$\mu_L = \frac{e\omega r_e^2}{2c} \quad L = m\omega r_e^2 = \sqrt{j(j+1)}\hbar. \quad (14)$$

# Spectral lines

## 1.1 Electron transitions and configurations

The spectroscopic notation is a way to describe the energy levels of an atom or a molecule,

**Definition 1.1** (Spectroscopic notation).

$$^{2S+1}L_J^{(p)} \quad (1.1)$$

Spin multiplicity points to  $2S+1$   
Orbital angular momentum points to  $L$   
Total angular momentum points to  $J$   
Term parity points to  $(p)$

The parity characterizes whether the wave function changes sign under reflection of all electron positions through the origin. It is blank for even parity and *o* for odd parity. The selection rules for the transitions are,

- Parity must change
- $\Delta L = 0, \pm 1$
- $\Delta J = 0, \pm 1$ , but  $\Delta J = 0 \rightarrow 0$  is forbidden
- Only one single electron wavefunction  $n\ell$  can change with  $\Delta\ell = \pm 1$
- $\Delta S = 0$  for electric dipole transitions

This approximation is valid when radiation involved has  $\lambda \gg a_0$ . Each electron is affected by the electric field produced by all other charges within the atom,

$$D_{ki} = \int \psi_k^*(\mathbf{r}) \mathbf{D} \psi_i(\mathbf{r}) d\mathbf{r}. \quad (1.2)$$

Dipole approximation points to  $\mathbf{D}$

Forbidden lines are when one of the rules is not satisfied, while the **semi-forbidden lines** are where the spin selection rule is violated, and are much weaker than intersystem (permitted) transitions.

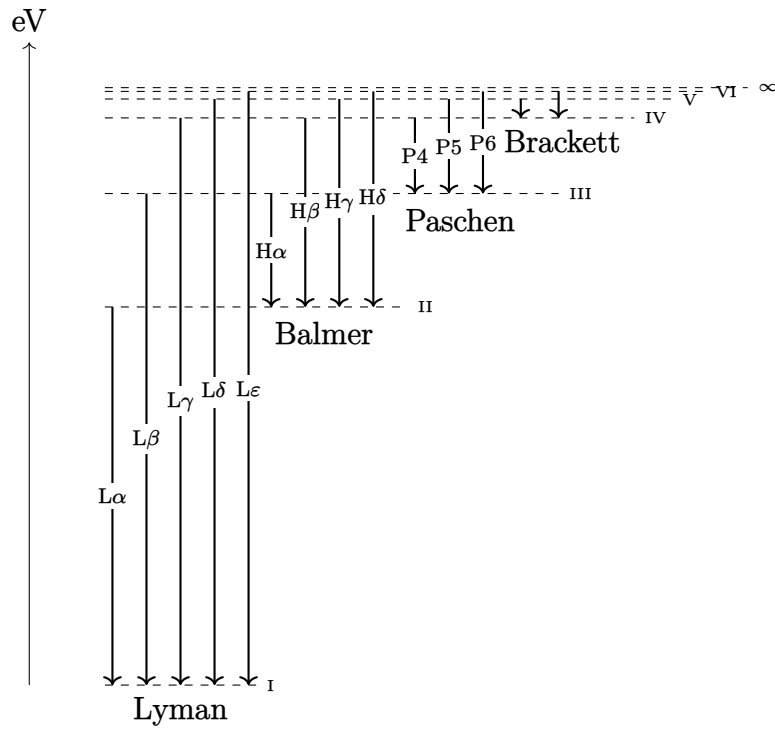
## Hydrogen transitions

The different series of transitions are,

- Lyman series ( $n = 1$ ) in the UV
- Balmer series ( $n = 2$ ) in the visible
- Paschen series ( $n = 3$ ) in the IR
- Brackett series ( $n = 4$ ) in the far IR
- Pfund series ( $n = 5$ ) in the far IR

The energy levels of hydrogen are given by the Rydberg formula,

$$E_n = -\frac{13.6 \text{ eV}}{n^2}. \quad (1.3)$$



## 1.2 Line profiles

The natural line profile is Lorentzian,

$$\phi(\nu) = \frac{1}{16\pi^2} \frac{4\gamma_{ul}}{(\nu - \nu_{ul})^2 + \gamma_{ul}^2}, \quad (1.4)$$

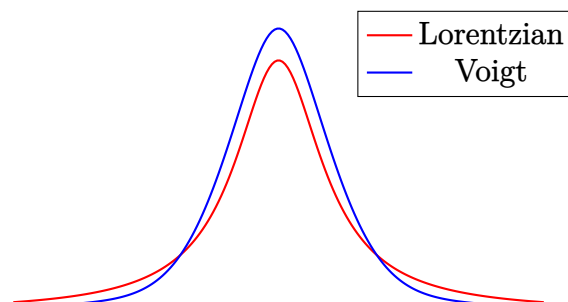
Natural line width  $\sum_{E_j < E_u} A_{uj} + \sum_{E_j < E_l} A_{lj}$   
Frequency of the transition,  $(E_u - E_l)/h$

In addition to this, the Voigt profile is a convolution of the Lorentzian and Gaussian profiles,

**Note** (Voigt profile).

$$\phi(\nu) = \frac{1}{\sqrt{2\pi}} \int dv \frac{e^{-v^2/2\sigma^2}}{\sigma v} \frac{1}{16\pi^2} \frac{4\gamma_{ul}}{(\nu - (1 - v/c)\nu_{ul})^2 + \gamma_{ul}^2} \quad (1.5)$$

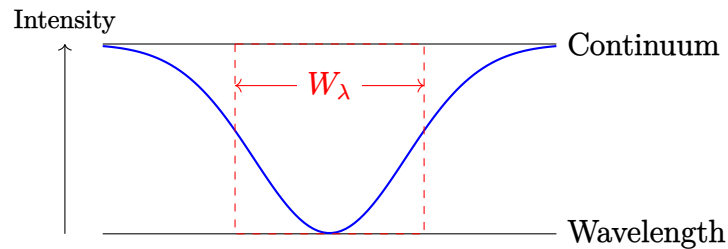
which originates from the Doppler effect and the uncertainty principle.



## Equivalent width

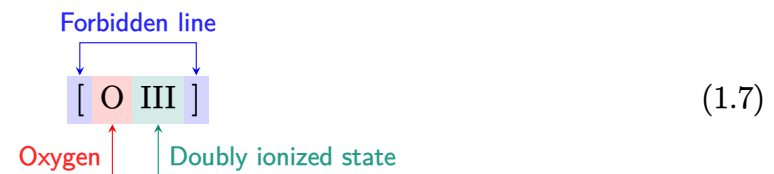
The spectral line **equivalent width** is defined as the area under the curve that is equivalent to the area of a rectangle of width  $\Delta\lambda$  and height  $I(\lambda)$ ,

$$W_\lambda = \int \left(1 - \frac{I(\lambda)}{I_c}\right) d\lambda. \quad (1.6)$$



## Forbidden line notation

Forbidden lines are transitions from metastable states and are written inside square brackets as,



## 1.3 Interstellar radiation fields

The energetic photons can be divided into (most to least energetic),

- Synchrotron radiation – galactic radiation from relativistic electrons in magnetic fields
- CMB
- Starlight – UV photons from stellar photospheres
- Mid and far IR emission – dust grains heated by starlight
- Emission from plasma – at  $T > 10,000$  K – free-free, free-bound, bound-bound, X rays

The ISM radiation fields determine the degree of ionization, gas and dust temperature and dynamics, and the dissociation degree of molecules.