

# Interstellar Matter and Gas–Dust Nebulae

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## Introduction

The space between stars is not empty. It contains matter distributed non-uniformly, which generally consists of three types of clouds: **dark, cold, dense molecular clouds**, more diffuse **neutral clouds**, the so-called **HI clouds**, and finally **ionized HII clouds**.

In reality, the situation is more complex. The interstellar medium also contains much more diffuse regions occupying large volumes, as well as extremely dense but small structures, including **star-formation regions**, from which stars—namely **protostars**—are formed.

In this section we focus on **HII-type clouds**, as they have historically been the most thoroughly studied. These different types are interconnected and may transform into one another. In this sense, there exists a **circulation of matter during the evolution of the Galaxy**.

The **Galaxy** is a stellar system within which our **Solar System** is located. When viewed from the outside, it represents a rotating ellipsoid whose central plane resembles a disk approximately **30 kpc in diameter** and about **3 kpc thick**. For an observer located in the central plane, the galactic disk appears as the **Milky Way**.

The disk rotates with a velocity of approximately **200 km/s**.

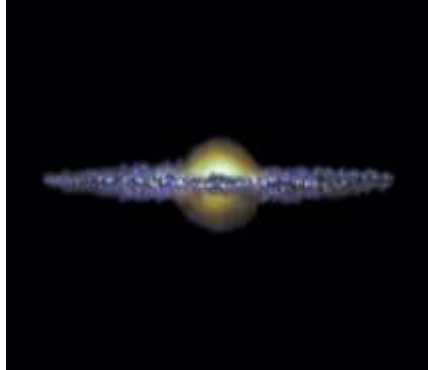


Figure 1 ([Link](#))

## Observational Data and Classification of Interstellar Clouds: H<sub>2</sub>, HI, and HII Regions, and Diffuse Hot Rarefied Regions in Our Galaxy

In star-formation regions, once thermonuclear reactions begin in newly formed **O-type stars**, the region of the cloud surrounding the star undergoes rapid changes, taking the form of an **ultra-compact HII region (UCHII)**. As they evolve with time, these regions eventually transform into **classical HII regions**, from the description of which we will begin our discussion of the properties of the **interstellar medium (ISM)**. However, first we clarify several general principles related to radiation.

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## 2.1 Radiation of Atoms and Ions under Cloud Conditions

### 2.1.1 Atomic Spectra

First, let us recall the main principles related to **atomic spectra**.

A **spectral line** arises when an atom transitions from one energy state  $E_1$  to another state  $E_2$ , and the line frequency  $\nu$  is given by the relation

$$h\nu = E_1 - E_2.$$

The energy level of an atom represents the sum of several contributions, for example:

- the total kinetic energy of the atom's motion, which affects the wavelengths of spectral lines through **Doppler shifts**;
  - the energies of electrons as they move around the nucleus;
  - exchange forces between electrons that ensure the parallel alignment of **spin vectors**;
  - electrostatic interactions between electrons related to their **angular momenta**;
  - the interaction between the magnetic moments of electrons and the magnetic field generated by the motion of electrons around the nucleus (**fine structure**, L–S coupling);
  - the interaction between the **magnetic moment of the nucleus** and the magnetic field mentioned above (**hyperfine structure**);
  - the interaction of the atom's magnetic field with an **external magnetic field (Zeeman effect)**;
  - **relativistic corrections**.
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## 2.2 The Hydrogen Atom

In the simplest case, the energy level of an atom is the sum of the **kinetic energy of the electron** and the **potential energy in the field of the nucleus**. According to **quantum theory**, only certain orbits are allowed. These are described by the **principal quantum number  $n$** , and their energies are proportional to  $1/n^2$ .

When the state of an atom changes through the emission or absorption of a photon, the **wavenumber  $\omega$**  of the photon (the number of wavelengths per centimeter) is given by

$$\omega = R \left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right), \quad (1)$$

where  $n_1$  and  $n_2$  are integers ( $n_2 > n_1$ ), and

$$R = 109678 \text{ cm}^{-1}$$

is the **Rydberg constant**.

Some details about the **spectral lines of the hydrogen atom** are presented in **Table 1**.

**Table 1. Main spectral lines of the hydrogen atom**

| Series         | Line        | Wavelength, $\mu\text{m}$ |
|----------------|-------------|---------------------------|
| Lyman, $n = 1$ | Ly $\alpha$ | 0.1216                    |

|                   |             |        |
|-------------------|-------------|--------|
|                   | Ly $\beta$  | 0.1026 |
|                   | Ly $\gamma$ | 0.0973 |
|                   | Ly limit    | 0.0912 |
| Balmer, $n = 2$   | H $\alpha$  | 0.656  |
|                   | H $\beta$   | 0.486  |
|                   | H $\gamma$  | 0.434  |
|                   | H limit     | 0.365  |
| Paschen, $n = 3$  | P $\alpha$  | 1.876  |
|                   | P $\beta$   | 1.282  |
|                   | P $\gamma$  | 1.094  |
|                   | P limit     | 0.820  |
| Brackett, $n = 4$ | Br $\alpha$ | 4.052  |
|                   | Br $\beta$  | 2.626  |
|                   | Br $\gamma$ | 2.166  |
|                   | Br limit    | 1.459  |
| Pfund, $n = 5$    | Pf $\alpha$ | 7.460  |
|                   | Pf $\beta$  | 4.654  |
|                   | Pf $\gamma$ | 3.741  |
|                   | Pf limit    | 2.279  |

It should be noted that orbital angular momentum is also quantized. The orbital quantum number ( $l$ ) can take integer values ranging from 0 to  $(n-1)$ . The ( $z$ )-component of the angular momentum

is also quantized and is characterized by the magnetic quantum number ( $m$ ), which can take integer values from  $(-l)$  to  $(+l)$ .

The energy levels of real atoms depend not only on the principal quantum number ( $n$ ), but also on the orbital quantum number ( $l$ ). In the presence of an external magnetic field, they also depend on the magnetic quantum number ( $m$ ).

In addition, there is a considerably weaker interaction between the electron's intrinsic magnetic moment and the magnetic field generated by its orbital motion. This interaction is known as spin-orbit coupling, or ( $l$ - $s$ ) coupling. The electron spin quantum number is ( $s=1/2$ ), while the spin magnetic quantum number ( $m_s$ ), which describes the ( $z$ )-component of the spin, can take the values  $(+1/2)$  and  $(-1/2)$ .

The different possible combinations of angular momenta lead to the splitting of energy levels and to the appearance of the fine structure of atomic spectra. In the hydrogen atom, for example, the energy difference associated with the fine structure is approximately ( $10^{-5}$ ) of the energy difference between levels with different principal quantum numbers.

The states corresponding to the orbital angular momentum values ( $l=0, 1, 2, 3, \dots$ ) are denoted by the letters (S), (P), (D), (F), ..., respectively.

Taking the magnetic moment of the atomic nucleus into account leads to the hyperfine structure of the energy levels. In the case of the hydrogen atom, the transition between the hyperfine levels of the ground state is particularly important, as it produces radio emission at a frequency of 1420 MHz, corresponding to a wavelength of approximately 21 cm.

### 3. Multi-Electron Atoms

The energy structure of many atoms is described within the L-S, or Russell-Saunders, coupling approximation, when the spin-orbit interaction energy is smaller than the energies associated with the spin and orbital angular momenta.

Each atomic energy state is described both by the quantum numbers of the individual electrons, which are denoted by lowercase letters, and by the total quantum numbers of the entire atom, which are denoted by uppercase letters:

$(n_1, l_1, s_1), (n_2, l_2, s_2), \dots, L, S, J, M_J$ .

Here,  $L$ ,  $S$ , and  $J$  are the quantum numbers of the total orbital angular momentum, total spin, and total angular momentum, respectively.  $M_J$  is the quantum number of the  $z$ -component of the total angular momentum.

Since the L and S angular momenta are added vectorially, the total angular momentum is determined by the following relation:

$$J = L + S.$$

For example, if  $S = 1$  and  $L = 2$ , then  $J$  can take the values 1, 2, or 3, depending on the relative orientation of the L and S angular momenta.

The corresponding quantum numbers determine the energy states of electrons in atoms, which are also referred to as quantum states or terms. As the atomic number increases, electrons progressively fill the electron shells in accordance with the Pauli exclusion principle. According to this principle, each electron in the system must possess a unique set of quantum numbers:

$$(n, l, m, s).$$

The first shell, for which  $n = 1$ , is called the K shell. Since only  $l = 0$  is possible when  $n = 1$ , this shell can contain a maximum of two electrons.

The atom with one electron is hydrogen, while the atom with two electrons is helium. The electrons in helium have the values  $s = +1/2$  and  $s = -1/2$ .

In the next shell, the L shell, the principal quantum number of the electrons is  $n = 2$ .

Therefore, the orbital quantum number can take the values  $l = 0$  or  $l = 1$ . The  $l = 0$  state has the lowest energy. For example, the lithium atom, whose atomic number is  $Z = 3$ , has a filled K shell and one electron in the  $l = 0$  state of the L shell.

The successive filling of electron shells according to this principle gives rise to the periodic table of the elements.

For example, for the  $l = 1$  subshell, the magnetic quantum number can take the values  $m = -1, 0$ , or  $+1$ . Therefore, this subshell can contain a maximum of six electrons, with two spin states for each  $n, l, m$  combination.

Each value of the orbital quantum number corresponds to a particular type of subshell. Thus:

$l = 0$  corresponds to the s subshell,

$l = 1$  corresponds to the p subshell,

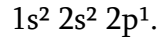
$l = 2$  corresponds to the d subshell,

$l = 3$  corresponds to the f subshell, and so on.

Accordingly, the subshells are designated as follows:

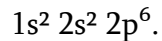
1s, 2s, 2p, 3s, 3p, 3d, 4s, 4p, 4d, 4f, and so on.

Thus, an atom is described by the structure of its electron shells and subshells. For example, for the boron atom, whose atomic number is  $Z = 5$ , the electronic configuration is:



The superscript indicates the number of electrons in the corresponding subshell.

The first subshells, 1s, 2s, and 2p, are completely filled in the neon atom. The atomic number of neon is  $Z = 10$ , and its electronic configuration is:

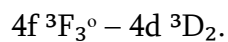


### 3.1 Electronic Transitions

Electrons can undergo transitions from one state to another as a result of various interactions. Atomic states are described by the principal quantum number  $n$ . Each such state is split into fine-structure levels according to the values of the total spin  $S$ , the orbital angular momentum  $L$ , and the total angular momentum  $J$ . When this coupling is represented as  $J = L + S$ , it is referred to as the L–S coupling approximation.

The state of the outer shell of an atom before and after a transition is characterized by the quantum number  $L$  of the total electronic orbital angular momentum. The possible values of  $L$  are denoted by the letters S, P, D, F, and so on.

For example, the transition in calcium corresponding to a wavelength of  $2.263 \mu\text{m}$  is denoted as follows:

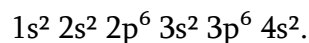


The superscript on the left indicates the multiplicity of the level,  $2S + 1$ , where  $S$  is the total electronic spin quantum number. The subscript on the right indicates the total angular momentum quantum number  $J$ .

In this case, the outer electron undergoes a transition from the 4f state to the 4d state. At the same time, the atom as a whole passes from a triplet state with F orbital angular momentum to a D state. The total angular momentum quantum number  $J$  changes from 3 to 2, while the parity of the wave function changes from odd to even.

A state with odd parity is denoted by the superscript letter “o” on the right, derived from the English word “odd.”

The ground-state electronic configuration of neutral calcium, Ca I, is:



### 3.2 Selection Rules: Allowed and Forbidden Spectral Lines

The theory of the interaction between atoms and radiation shows that only certain combinations of quantum states are favorable for the emission or absorption of radiation. Electric dipole transitions are an example of such transitions. Other types of transitions, such as magnetic dipole or electric quadrupole transitions, are considerably weaker and are therefore less probable.

Accordingly, certain selection rules are defined for the quantum numbers of the initial and final states. These rules are as follows:

1. Only one electron may change its state.
2. The orbital quantum number  $l$  may change only by one unit:

$$\Delta l = \pm 1.$$

This condition corresponds to an electric dipole transition.

3. The change in the quantum number  $J$  must satisfy the following condition:

$$\Delta J = 0, \pm 1.$$

4. In the case of L–S coupling, the following selection rule also applies:

$$\Delta L = 0, \pm 1.$$

5. The total spin quantum number does not change:

$$\Delta S = 0.$$

For this reason, intercombination transitions, such as transitions between singlet and triplet states, are very weak.

According to the selection rules, an electron in the  $2^2S$  state of the second level of neutral hydrogen cannot make a direct transition to the ground  $1^2S$  level. However, this transition can occur through a two-photon process.

#### 4. Pure Hydrogen Clouds as an Introduction to the Study of the Interstellar Medium: Ionization Structure, Density, and Temperature

##### The Strömgren Sphere

##### 4.1 Ionization Structure of a Static H II Nebula

##### 4.1.1 Photoionization and Recombination

##### Radiation

Let us consider a cloud whose ionization is produced by a single hot O-type star with an effective temperature of  $T_{\text{eff}} \approx 30,000$  K. If the recombination time is shorter than the dynamical, or motion-related, timescale, the ionization structure of the nebula may be regarded as time-independent, that is, static.

Since the recombination rate is lower than the rate of spontaneous transitions, the neutral hydrogen atoms produced after each recombination rapidly reach the ground state through cascade transitions. For electronic transitions between atomic levels, see Section 3 above.

Thus, at every point in such a nebula, the number of photoionizations from the ground state is balanced by the number of recombinations to all levels of the hydrogen atom.

Let us define the quantity  $x$ , which characterizes the degree of ionization:

$$x = \frac{n_p}{n_p + n_{\text{HI}}}, \quad (1)$$

where

$$n = n_p + n_{\text{HI}},$$

and the nebula is assumed to consist entirely of hydrogen.

#### 4.1.2 Ionization Rate

The number of ionization events occurring per unit volume and per unit time, referred to as the ionization rate, is given by

$$r_i = n_H \int_{\nu_0}^{\infty} \alpha(\nu) J(\nu) d\nu, \quad (2)$$

where  $\nu_0 = E_H/h$  is the threshold frequency for hydrogen ionization, and  $E_H = 13.596\text{eV}$  is the ionization energy of hydrogen.

The photoionization cross-section depends approximately on frequency as

$$\alpha(\nu) \propto (\nu_0/\nu)^3.$$

Let us assume that

$$\alpha(\nu) \approx \alpha(\nu_0) = \alpha_0 = 6.8 \times 10^{-18} \text{ cm}^2.$$

The ionization rate can then be written as

$$r_0 = n_H \alpha_0 \int_{\nu_0}^{\infty} J(\nu) d\nu = n(1 - x)J, \quad (3)$$

where  $J$  is the total flux of photons capable of ionizing hydrogen, and

$$n_H = n(1 - x)$$

is the density of neutral hydrogen. Here,  $n$  is the total hydrogen number density.

#### 4.1.3 Recombination Rate

Recombination may occur to any energy level of the hydrogen atom. It is followed by cascade transitions to lower levels, eventually reaching the ground state.

The number of recombinations occurring per unit volume and per unit time is proportional to the product  $n_e n_p$ , or, in the case of a medium consisting entirely of hydrogen, to  $x^2 n^2$ . The recombination rate is given by

$$r_r = \sum_j n_p n_e \beta_j(T), \quad (4)$$

where the summation is performed over all energy levels of the hydrogen atom.

The energy of the photon emitted during recombination is

$$h\nu = E_{kin} + E_H/n^2 = E_H(E_{kin}/E_H + 1/n^2), \quad (5)$$

where  $E_{kin}$  is the kinetic energy of the free electron at the moment of recombination, and  $n$  is the principal quantum number, which should not be confused with  $n$  denoting the particle number density.

Assuming  $T_e = 10^4$  K and  $E_{kin} = (3/2)kT_e$ , we obtain

$$E_{kin}/E_H = 0.1,$$

and therefore

$$h\nu = E_H(0.1 + 1/n^2). \quad (6)$$

It is evident that, for recombination to the ground state, where  $n = 1$ , the energy of the emitted photon is

$$h\nu = E_H \cdot 1.1 \geq E_H,$$

Thus, this photon is capable of ionizing a neighboring hydrogen atom. This corresponds to the on-the-spot approximation. This approximation is applicable provided that the linear dimensions of the region are relatively large, greater than 0.1 pc, and that the corresponding optical depth is  $\tau > 1$  for number densities greater than 10 (see below).

Therefore, the first term in the above summation, corresponding to  $j = 1$ , may be neglected, because recombination to the ground state is immediately followed by photoionization from that state. The recombination rate can therefore be written as

$$r_i = \sum_{j \neq 1} n_p n_e \beta_j(T) = x^2 n^2 \beta^{(2)}, \quad (7)$$

where

$$\beta^{(2)} = \sum_{j \neq 1} \beta_j(T), \quad (8)$$

and the recombination coefficient is approximately given by

$$\beta^{(2)} = 2 \times 10^{-10} T^{-3/4} \text{ cm}^3 \text{ s}^{-1}. \quad (9)$$

#### 4.1.4 Variation of the Ionizing Flux

Assuming that dust is absent from the medium, the variation of the ionizing flux can be written as

$$\frac{d}{dr}(4\pi r^2 J) = -4\pi r^2 n(1-x)\alpha_0 J, \quad (10)$$

Since

$$4\pi r^2 J = S_{UV}(r) \quad (11)$$

we obtain

$$\frac{dS_{UV}}{dr} = -n(1-x)S_{UV}. \quad (12)$$

The quantity

$$d\tau_H = n(1-x)\alpha_0 dr \quad (13)$$

represents the change in the optical depth of neutral hydrogen over a distance  $dr$ .

After integration, we obtain

$$S_{UV}(r) = S_{UV}^* \exp(-\tau_H) \quad (14)$$

where

$$\tau_H = \int_0^r n(1-x)\alpha_0 dr. \quad (15)$$

Here,  $S_{UV}^*$  is the flux of ionizing photons emitted from the stellar surface. Therefore,

$$J(r) = \frac{S_{UV}^*}{4\pi r^2} \exp(-\tau_H). \quad (16)$$

**Table 1. Intensity of hydrogen-ionizing photons near the star**

| $M/M_{\odot}$ | Spectr. | $T_{\text{eff}}$ [K] | $S_{\text{UV}}^* [\text{s}^{-1}]$ | $R_s$ [pc] |
|---------------|---------|----------------------|-----------------------------------|------------|
| 100           | –       | 52500                | $2.0 \cdot 10^{50}$               | 9.6        |
| 80            | –       | 51300                | $1.4 \cdot 10^{50}$               | 8.5        |
| 60            | –       | 47900                | $7.5 \cdot 10^{49}$               | 6.9        |
| 50            | O5 V    | 41200                | $5.6 \cdot 10^{49}$               | 6.3        |
| 23            | O8 V    | 36300                | $5.0 \cdot 10^{48}$               | 2.8        |
| 17.5          | B0 V    | 33500                | $1.6 \cdot 10^{48}$               | 1.9        |
| 8.3           | B3 V    | 25000                | $1.0 \cdot 10^{46}$               | 0.3        |

#### 4.1.5 Degree of Ionization

At distances close to the star, the variation of the ionizing flux is mainly caused by geometrical dilution, whereas at larger distances the absorption of radiation becomes important.

Ionization equilibrium is established when the ionization and recombination rates are equal:

$$r_i = r_r.$$

In this case, we obtain

$$\frac{x^2}{1-x} = \frac{J\alpha_0}{n\beta^{(2)}}. \quad (17)$$

Within the H II region, hydrogen is almost completely ionized. This can be demonstrated by numerically evaluating Equation (17).

Neglecting radiation absorption, which is justified for number densities of a few  $\text{cm}^{-3}$  and distances of several parsecs, we obtain

$$J(r) = \frac{S_{\text{UV}}^*}{4\pi r^2}. \quad (18)$$

Let us assume that  $S_{\text{UV}}^* = 10^{49} \text{ s}^{-1}$ ,  $r = 1 \text{ uql}$ ,  $n = 1 \text{ cm}^{-3}$ , we then obtain  $J(r) = 10^{11} \text{ cm}^{-2} \text{ s}^{-1}$ .  $T = 10^4 \text{ K}$ ,  $\beta^{(2)} = 2 \cdot 10^{-13} \text{ cm}^3 \text{ s}^{-1}$  and therefore

$$\frac{x^2}{1-x} = 10^6 \gg 1, \quad x \leq 1, \quad (19)$$

Since  $\frac{x^2}{1-x} = \frac{x^2+1-1}{1-x} = \frac{1}{1-x} - (1+x) \approx \frac{1}{1-x}$ , it follows that  $1-x \approx 10^{-6}$  u  $x \approx 1$ :

This means that hydrogen is practically fully ionized within the H II region.