7. Interstellar Medium

7.1 Nebulae

Emission nebulae are diffuse patches of emission surrounding hot O and early B-type stars. Gas is ionized and heated by radiation from the parent stars. In size, nebulae have diameters up to several pc. They have a characteristic spectrum dominated by emission lines of atomic hydrogen and OII (O^+) and OIII (O^{2+}). The electron density is usually in the range 10^2 cm^{-3} to 10^4 cm$^{-3.}$ The mass of gas lies between $10^2 M_\odot$ and $10^4 M_\odot$.

Planetary nebulae are produced in the evolution of the parent star in which the outer atmosphere is ejected and the material is heated and ionized by the hot core (100,000-200,000K) of the star. They are called planetary because in appearance they were thought to look like planets. They have densities $n_e \sim 10^2$ - 10^5 cm^{-3}, M~0.1-1 $M_\odot$. Spectra are characterized by H and He, OIII, NeIII, NeV emission lines.

HII regions (HII means H^+) are emission nebulae with low n_e (detected in the radio). There are also compact (diameter <0.5 pc) and ultracompact (diameter <0.15pc) HII regions—heavily reddened with the internal source (protostar) obscured. For them $n_e \sim 5 \times 10^3$ cm^{-3}

$$M > 30\, M_\odot .$$

They are ionized and heated by an O or B star at an early evolutionary stage and are surrounded still by a cocoon of dust.

The kinetic temperature of all these objects ranges between 4000K-15,000K.

Reflection nebulae Reflection nebulae consist of dust and gas and they are close to cool non-ionizing B stars —radiation is mostly starlight reflected by dust.

Ionization structure

Hydrogen is ionized when it absorbs a photon with an energy $E > 13.6$eV or wavelength $\lambda < 91.2$ nm. 13.6eV is the ionization potential of H. 91.2 nm is the threshold wavelength. 91.2 nm is called the Lyman limit. Photoionization is the process

$$H + \nu \rightarrow H^{+} + e \quad . \tag{7.1}$$

The efficiency of photoionization is described by a cross section $\sigma_H(\nu)$ cm^2 and it is such that in a path length ds, the specific intensity I_ν is diminished by $I_\nu\ \kappa_\nu ds$ where κ_ν is an absorption coefficient equal to $n_H \sigma_H(\nu)$ cm^{-1}. It differs from the mass absorption coefficient on p. 5-20 by the mass.

Thus

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu \quad . \tag{7.2}$$

Define optical depth

$$\tau_\nu = \int_0^s n_{\mathrm{H}} \sigma_{\mathrm{H}}(\nu)\, ds \,. \tag{7.3}$$

Then

$$I_\nu(s) = \mathrm{I}_\nu(0) \exp\left(-\tau_\nu\right) \,. \tag{7.4}$$

Check solution by substituting in (7-2).

The H^+ ions recombine into excited levels of H(n) which radiate

$$\mathrm{H}(n) \rightarrow \mathrm{H}(n') + \nu_{nn'} \tag{7.5}$$

giving rise to the recombination spectrum that is one of the ways of identifying the object. The recombination can be described by a recombination coefficient $\alpha(T)$ cm^3 s^{-1} and it is such that the number of recombinations is $\alpha(T) n_e n\,(\mathrm{H}^+)$ cm^{-3} s^{-1}. Assume that the nebulae consists only of hydrogen, is fully ionized out to a distance r_s and beyond r_s the gas is neutral. Assume also that all the ionizing photons are absorbed by the gas. Then the total number of ionizations per second equals the total number of recombinations per second.

The total number of ionizations per second is given by the luminosity L_ν in photons with frequency $\nu > \nu_{\mathrm{H}}$ divided by the photon energy

$$\Gamma = \int_{\nu_{\mathrm{H}}}^{\infty} \frac{L_\nu}{h\nu} \, d\nu = Q_{\mathrm{H}} \ \mathrm{s}^{-1} \ , \text{ say.} \qquad (7.6)$$

The total number of recombinations is

$$\left(\frac{4}{3}\pi r_s^{\,3}\right) n_e n\left(\mathrm{H}^+\right)\alpha\left(T\right) \ \mathrm{s}^{-1} \ . \qquad (7.7)$$

Hence

$$r_s^{\,3} = \frac{3}{4\pi} \frac{Q_{\mathrm{H}}}{n_{\mathrm{H}}^{\,2}\alpha\left(T\right)} \qquad (7.8)$$

since

$$n(\mathrm{H}^+) = n_e = n_{\mathrm{H}} \qquad (7.9)$$

when all H is ionized.

r_s is called the Stromgren radius.

Figure 6-1 shows the fluxes calculated from theoretical models of the emergent radiation from stars as functions of frequency for effective temperatures from 25000K to 50,000K for different values of the surface gravity $\log_{10}$g. The HI edge occurs at 3.3×10^{15} Hz and the HeI edge at 6.0×10^{15} Hz.

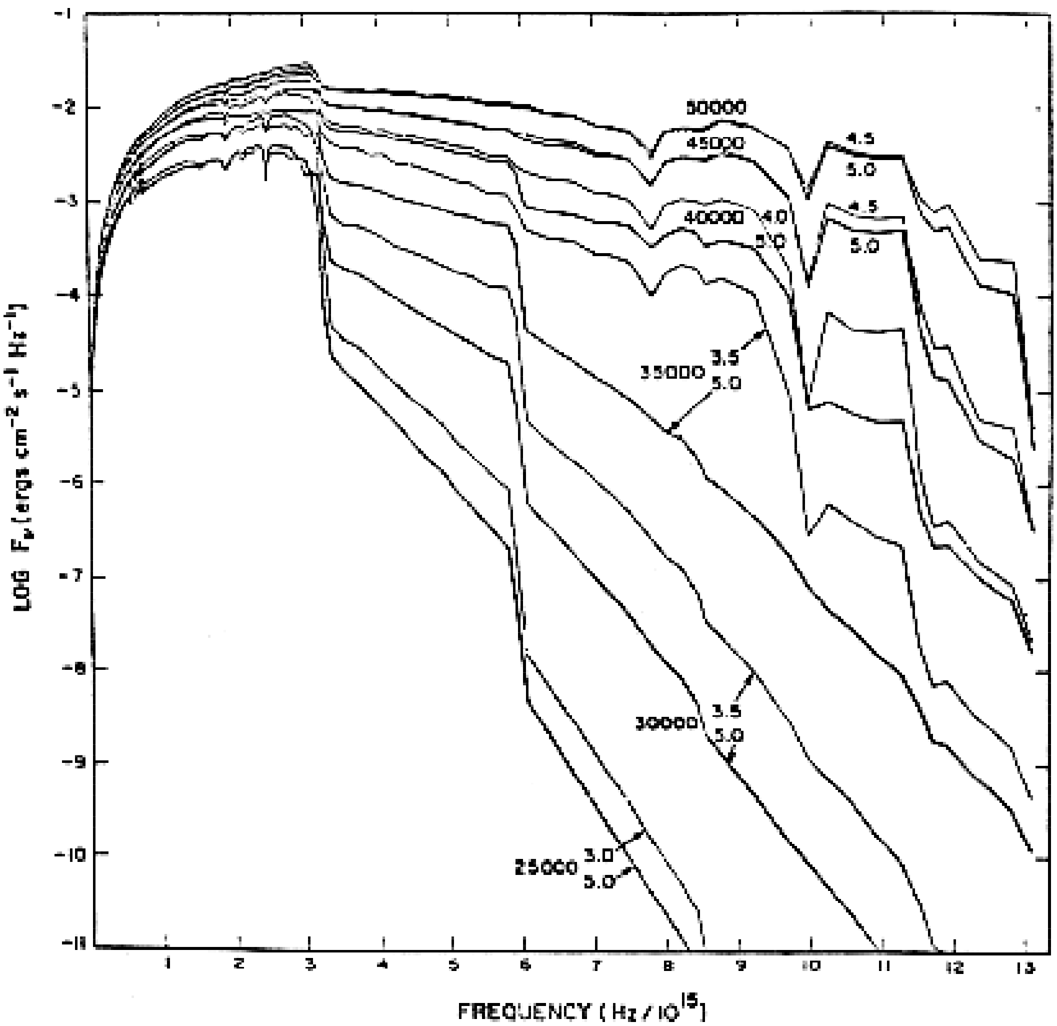

Fig. 7.1

The labels refer to the effective temperature of the star and to the gravitational acceleration at the surface in the form of $\log_{10} g$ where $g = GM/R^2$

The Table shows the size of the ionized region with a temperature of 10^4 K for several hot stars. Q_H depends on the effective temperature of the star.

Spectral Type	$T_{eff}(K)$	$\log Q_H$ s^{-1}	$r_s n_H^{2/3}$	$n_H = 300$ cm^{-3} r_s(pc)
O4	52,000	50.0	148	3.3
O5	50,200	49.8	125	2.8
O6	48,000	49.4	92	2.0
O7	45,200	49.0	68	1.5
O8	41,600	48.7	54	1.2
O9	37,200	48.4	43	0.9
B0	32,200	47.6	23	0.5
B1	22,600	45.2	4	0.2

Fully ionized and neutral regions are separated by a transition region given approximately by

$$\tau_\nu = 1 = \sigma_H(\nu) n_H l. \tag{7.10}$$

σ_H (Lyman limit) $= 6.3 \times 10^{-18}$ cm^2 so if $n_H = 300$,

$$l = 10^{-4} \text{ pc.}$$

The ionized zones are sharply delineated (if we ignore the dynamics of the gas). The gas is heated by photoionization

$$H + \nu \rightarrow H^{+} + e \tag{7.11}$$

which yields electrons with energy $h\nu$ - 13.6 eV (1eV ~ 11,600K equivalent). The energetic electrons exchange energy in collisions with the ambient electrons and relax to a Maxwellian velocity distribution. The heated gas cools by exciting levels of ions like OII and OIII which radiate and the photons escape. The cooling curve increases rapidly with temperature above 5000K and keeps the temperature below 15,000K even when the stellar temperature is 200,000K.

7.2 Interstellar Gas and Dust

There are atoms, molecules and ions in the space between the stars and there are solid particles called dust grains. The presence of dust is manifested by the appearance of dark patches in the sky for which the light from the background stars is obscured. The presence of gaseous material in the intersellar medium is indicated by narrow absorption lines seen towards stars and by the detection of emission lines from so-called molecular clouds. The interstellar medium causes a reddening of starlight. Blue photons suffer greater extinction and greater scattering than red photons and the relative weakening of the blue radiation gives rise to the apparent reddening.

The distance modulus equation for a star (p.2-17) is modified to

$$m_\lambda = M_\lambda + 5 \log_{10} D - 5 + A_\lambda \tag{7.12}$$

where A_λ is the number of magnitudes of absorption and scattering (together called *extinction*). The stellar intensity I_{λ_o} is reduced according to

$$\frac{I_\lambda}{I_{\lambda_o}} = e^{-\tau_\lambda} \tag{7.13}$$

where τ_λ is the optical depth. Then, recalling the definition of magnitudes,

$$\begin{aligned} m_\lambda - m_{\lambda_o} &= -2.5 \log_{10} \left(e^{-\tau_\lambda}\right) \\ &= 2.5\, \tau_\lambda \log_{10} e = 1.068\, \tau_\lambda \; . \end{aligned} \tag{7.14}$$

Now m_λ - $m_{\lambda_o} = A_\lambda$ since $A_{\lambda_o} = 0$.

So

$$A_\lambda = 1.086\, \tau_\lambda \; . \tag{7.15}$$

If λ is a visible wavelength λ = 550 nm, A_λ is written A_V and A_V is called the visual extinction.

The optical depth is

$$\tau_\lambda = \int_0^s n(s)\, \sigma_\lambda\, ds \tag{7.16}$$

where $n(s)$ is the number density at s and σ_λ is the extinction cross section. If it is constant (no change in composition along the line of sight where extinction occurs),

$$\tau_\lambda = \sigma_\lambda \int_0^s n(s)ds = N_g \sigma_\lambda \tag{7.17}$$

where N_g is the column density in cm^{-2}. To obtain A_V for a distant star, we measure m_V for a star of the same spectral type near to the observer, such that for it A_V=0. Then knowing the distances of both stars, we can derive A_V from the flux ratios or magnitude differences.

Alternatively and more easily we can use the reddening for which we do not need distances. The reddening is obtained by comparing the variation with wavelength of the apparent magnitudes of the identical near and far stars.

Label the stars 1 and 2. Let $m_1(\lambda)$ and $m_2(\lambda)$ be the measured apparent magnitudes. Choose two wavelengths λ_a and λ_b and write

$$\Delta m_1 = m_1(\lambda_a) - m_1(\lambda_b) \tag{7.18}$$

$$\Delta m_2 = m_2(\lambda_a) - m_2(\lambda_b) \tag{7.19}$$

for the magnitude differences at wavelengths λ_a and λ_b for each star. Then

$$\Delta m_1 - \Delta m_2 = A_{\lambda_a}(1) - A_{\lambda_b}(1) - \left[A_{\lambda_a}(2) - A_{\lambda_b}(2)\right] . \tag{7.20}$$

For a nearby star,

$$A_{\lambda_a}(1) = A_{\lambda_b}(1) = 0$$

so

$$\Delta m_1 - \Delta m_2 = A_{\lambda_a}(2) - A_{\lambda_b}(2) \tag{7.21}$$

which is the color index

$$E(\lambda_a\text{-}\lambda_b) \ .$$

It describes the selective extinction due to interstellar dust.

The reddening is usually described by the color index $E(\lambda - \mathrm{V})$ where V indicates the V filter (see p. 2-11). With λ the mean of the blue filter around 450 nm, $E(B\text{-}\mathrm{V})$ is the color excess.

Observations show that

$$A_{\mathrm{V}} \sim 3.1\ E(\mathrm{V}\text{-}B) \ . \tag{7.22}$$

The factor 3.1 depends on the nature of the dust grains.

Fig. 7.2 shows the variation of E_λ - E_{V} with wavelength. The “bump” is suggestive of grains with a graphite core.

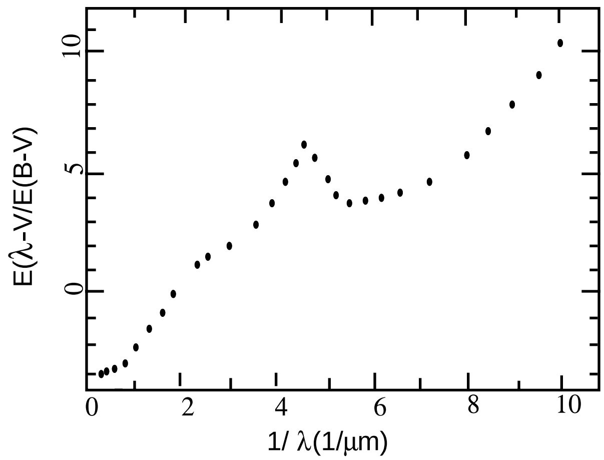

Fig. 7.2

We can also measure absorption due to gas and the column density of the gas N_g is found to be proportional to N_d , showing that the gas and the dust are uniformly mixed. The grains absorb starlight and permit molecules to form in denser regions where they are detected in emission in the millimeter and radio regions.

7.2.1 Phases

Broadly characterized, the interstellar medium has three phases: a hot phase at 10^6 K, a warm phase at 10^4 K and a cold phase at 100K. In the cold phase are still colder dense regions called molecular clouds.

Molecules are found in these dense molecular clouds. The clouds can be very large. They may contain over $10^6 M_\odot$ of gas and dust and they are the sites of star formation. They are usually cold with T ~ 20K. Over one hundred different molecules have been found. The largest so far is the carbon chain molecule $HC_{11}N$.

A large fraction of the volume of the galaxy is occupied by a hot gas, whose presence is established by absorption of highly ionized material such as O^{5+} and by the emission of X-rays.

7.2.2 Hot gas

The most prominent example of hot gas is the *solar corona* where temperatures of 10^6 K or more occur. The corona is a diffuse hot ionized gas, stretching away from the Sun. The different elements are in *coronal equilibrium*. In a hot gas, atoms are ionized sequentially by the collisions of fast electrons. The ionization can be represented by

$$e + A^{m+} \rightarrow e + A^{(m+1)+} + e \; . \qquad (7.23)$$

It occurs at a rate

$$n_e n(A^{m+}) \, \mathrm{k}(A^{m+}) \, \mathrm{cm}^{-3} \, \mathrm{s}^{-1} \qquad (7.24)$$

where the n's are number densities and $k(A^{m+})$ is the ionization rate coefficient in units of $\mathrm{cm}^3 \, \mathrm{s}^{-1}$. The efficiency of ionization by an electron of energy E can be described by a cross section $\sigma((A^{m+}(E))$ cm^2 which depends on E and on the ion A^{m+}. The rate coefficient $k((A^{m+}/T)$ is obtained by averaging the product $\mathrm{v}\sigma$ over the Maxwellian velocity distribution

$$k\left(A^{m+}/T\right)=\left(\frac{m}{2\pi kT}\right)^{3/2}\int e^{-m\mathrm{v}^2/2kT}\mathrm{v}^2 \qquad (7.25)$$

$$\times\left(\mathrm{v}\sigma\right)d\mathrm{v}\ \ \mathrm{cm}^3\ \mathrm{s}^{-1}.$$

The ions produced by electron impact ionization recombine radiatively

$$A^{(m+1)+} + e \ \rightarrow\ A^{m+} + \nu \qquad (7.26)$$

with a rate coefficient $\alpha(A^{m+}/T)$ which is also a function of T, at a rate

$$n_e n(A^{(m+1)+})\ \alpha(A^{m+}/T)\ \mathrm{cm}^{-3}\ \mathrm{s}^{-1}\ . \qquad (7.27)$$

In equilibrium,

ionization rate = recombination rate

$$n_e n(A^{m+})\ k(A^{m+}/T)$$

$$= n_e n\ \ (A^{(m+1)+})\ \alpha(A^{m+}/T) \qquad (7.28)$$

so

$$\frac{n\left(A^{(m+1)+}\right)}{n\left(A^{m+}\right)} = \frac{k\left(A^{m+}/T\right)}{\alpha\left(A^{m+}/T\right)} \quad . \tag{7.29}$$

The ratio of ion densities is a function only of temperature. This is *coronal equilibrium*. From measurements of the abundance ratio of different ion stages, T can be derived.

Fig.7-3 shows the results of calculations for ions of oxygen. Calculations like this are used to understand the behavior of hot gases.

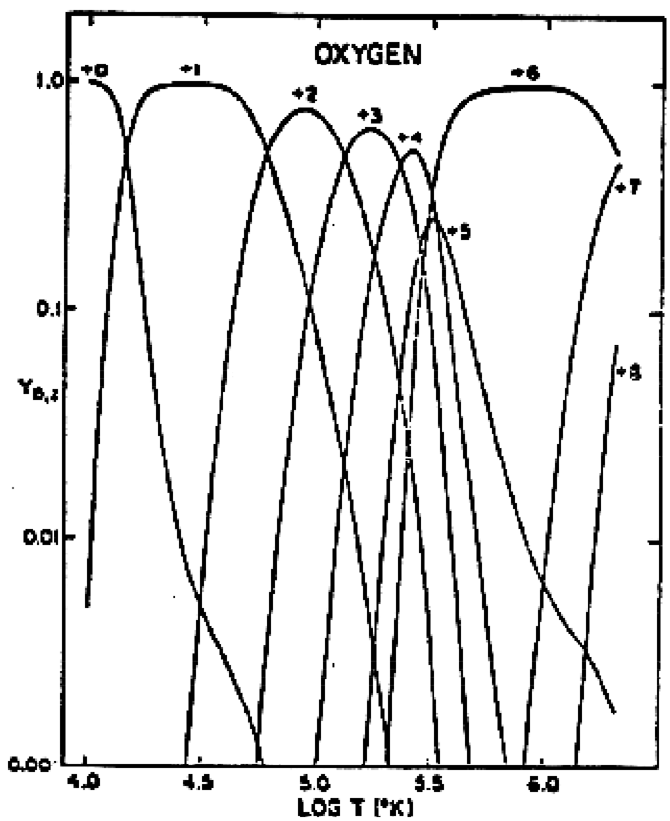

Fig. 7-3