

## 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  $10^2 \text{ cm}^{-3}$  to  $10^4 \text{ cm}^{-3}$ . 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  $n_e \sim 10^2 - 10^5 \text{ cm}^{-3}$ ,  $M \sim 0.1-1 M_\odot$ . 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  $<0.5 \text{ pc}$ ) and ultracompact (diameter  $<0.15 \text{ pc}$ ) HII regions—heavily reddened with the internal source (protostar) obscured. For them  $n_e \sim 5 \times 10^3 \text{ cm}^{-3}$

$$M > 30 M_\odot .$$

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  $E > 13.6\text{eV}$  or wavelength  $\lambda < 91.2\text{ nm}$ . 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



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

Thus

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

Define optical depth

$$\tau_\nu = \int_0^s n_H \sigma_H(\nu) ds . \quad (7.3)$$

Then

$$I_\nu(s) = I_\nu(0) \exp(-\tau_\nu) . \quad (7.4)$$

Check solution by substituting in (7-2).

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



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  $\alpha(T)$   $\text{cm}^3 \text{s}^{-1}$  and it is such that the number of recombinations is  $\alpha(T)n_e n(H^+) \text{cm}^{-3} \text{s}^{-1}$ . 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  $L_\nu$  in photons with frequency  $\nu > \nu_H$  divided by the photon energy

$$\Gamma = \int_{\nu_H}^{\infty} \frac{L_\nu}{h\nu} d\nu = Q_H \text{ s}^{-1}, \text{ say.} \quad (7.6)$$

The total number of recombinations is

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

Hence

$$r_s^3 = \frac{3}{4\pi} \frac{Q_H}{n_e^2 \alpha(T)} \quad (7.8)$$

since

$$n(\text{H}^+) = n_e = n_H \quad (7.9)$$

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  $3.3 \times 10^{15}$  Hz and the HeI edge at  $6.0 \times 10^{15}$  Hz.

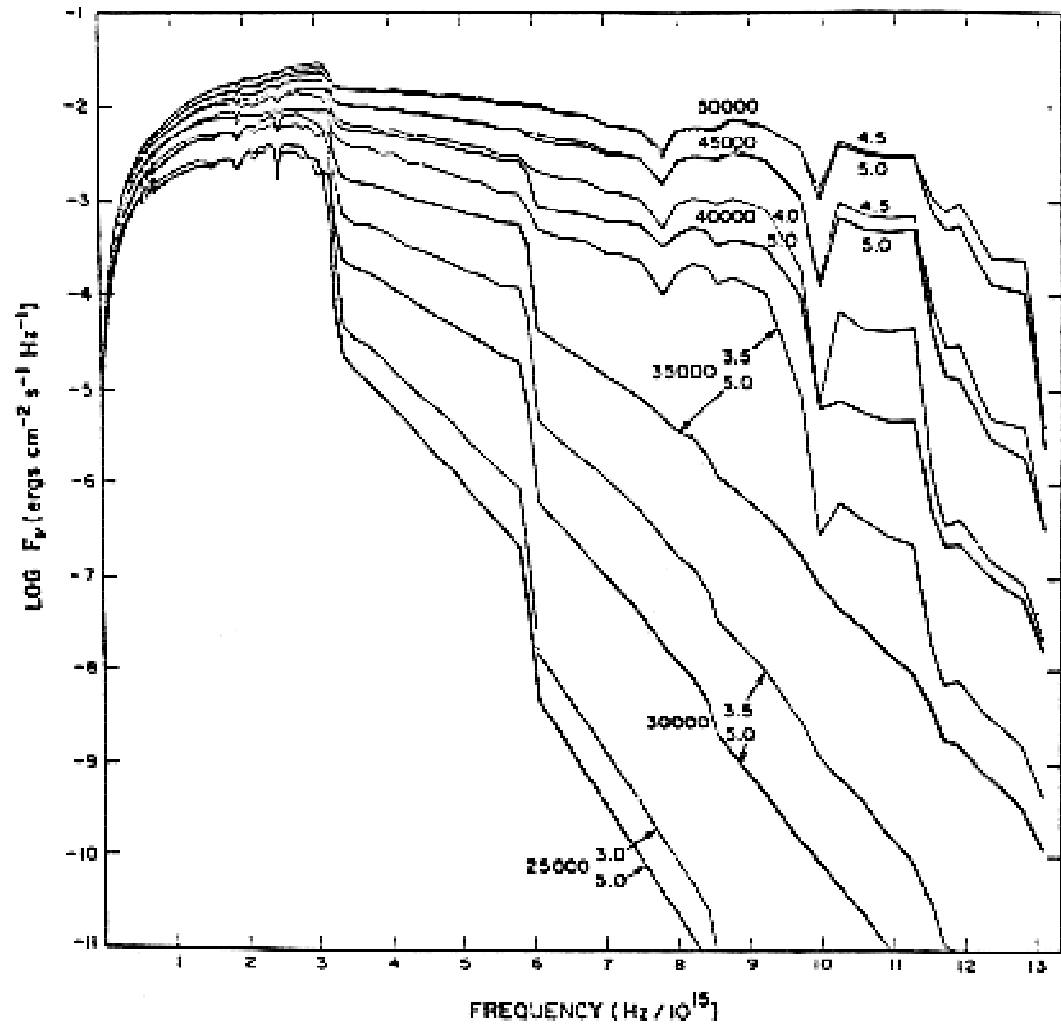


Fig. 7.1

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	$T_{eff}(K)$	$\log Q_H s^{-1}$	$r_s n_H^{2/3}$	$n_H = 300 \text{ cm}^{-3}$ $r_s(\text{pc})$
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

$$\tau_\nu = 1 = \sigma_H(\nu)n_H l. \quad (7.10)$$

$\sigma_H$  (Lyman limit) =  $6.3 \times 10^{-18} \text{ cm}^2$  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



which yields electrons with energy  $h\nu - 13.6 \text{ eV}$  ( $1\text{eV} \sim 11,600\text{K}$  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  $5000\text{K}$  and keeps the temperature below  $15,000\text{K}$  even when the stellar temperature is  $200,000\text{K}$ .

## 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

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

where  $A_{\lambda}$  is the number of magnitudes of absorption and scattering (together called *extinction*). The stellar intensity  $I_{\lambda_o}$  is reduced according to

$$\frac{I_{\lambda}}{I_{\lambda_o}} = e^{-\tau_{\lambda}} \quad (7.13)$$

where  $\tau_{\lambda}$  is the optical depth. Then, recalling the definition of magnitudes,

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

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

So

$$A_{\lambda} = 1.086 \tau_{\lambda} . \quad (7.15)$$

If  $\lambda$  is a visible wavelength  $\lambda = 550$  nm,  $A_{\lambda}$  is written  $A_v$  and  $A_v$  is called the visual extinction.

The optical depth is

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



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

$$\tau_\lambda = \sigma_\lambda \int_0^s n(s) ds = N_g \sigma_\lambda \quad (7.17)$$

where  $N_g$  is the column density in  $\text{cm}^{-2}$ . 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  $\lambda_a$  and  $\lambda_b$  and write

$$\Delta m_1 = m_1(\lambda_a) - m_1(\lambda_b) \quad (7.18)$$

$$\Delta m_2 = m_2(\lambda_a) - m_2(\lambda_b) \quad (7.19)$$

for the magnitude differences at wavelengths  $\lambda_a$  and  $\lambda_b$  for each star. Then

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

For a nearby star,

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

so

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

which is the color index

$$E(\lambda_a - \lambda_b) .$$

It describes the selective extinction due to interstellar dust.

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

Observations show that

$$A_V \sim 3.1 E(V - B) . \quad (7.22)$$

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

Fig. 7.2 shows the variation of  $E_\lambda - E_V$  with wavelength. The “bump” is suggestive of grains with a graphite core.

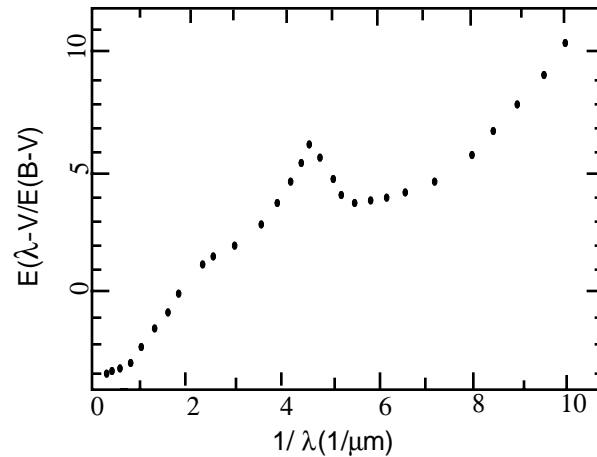


Fig. 7.2

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.

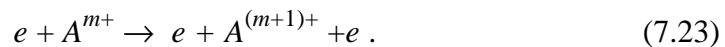
Molecules are found in these dense molecular clouds. The clouds can be very large. They may contain over  $10^6 M_\odot$  of gas and dust and they are the sites of

star formation. They are usually cold with  $T \sim 20\text{K}$ . Over one hundred different molecules have been found. The largest so far is the carbon chain molecule  $\text{HC}_{11}\text{N}$ .

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  $\text{O}^{5+}$  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



It occurs at a rate

$$n_e n(A^{m+}) k(A^{m+}) \text{ cm}^{-3} \text{ s}^{-1} \quad (7.24)$$

where the  $n$ 's are number densities and  $k(A^{m+})$  is the ionization rate coefficient in units of  $\text{cm}^3 \text{ s}^{-1}$ . The efficiency of ionization by an electron of energy  $E$  can be

described by a cross section  $\sigma(A^{m+}(E)) \text{ cm}^2$  which depends on  $E$  and on the ion  $A^{m+}$ . The rate coefficient  $k(A^{m+}/T)$  is obtained by averaging the product  $v\sigma$  over the Maxwellian velocity distribution

$$k(A^{m+}/T) = \left( \frac{m}{2\pi kT} \right)^{3/2} \int e^{-mv^2/2kT} v^2 \times (v\sigma) dv \text{ cm}^3 \text{ s}^{-1}. \quad (7.25)$$

The ions produced by electron impact ionization recombine radiatively



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

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

In equilibrium,

ionization rate = recombination rate

$$\begin{aligned} n_e n(A^{m+}) k(A^{m+}/T) \\ = n_e n(A^{(m+1)+}) \alpha(A^{m+}/T) \end{aligned} \quad (7.28)$$

so

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

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.

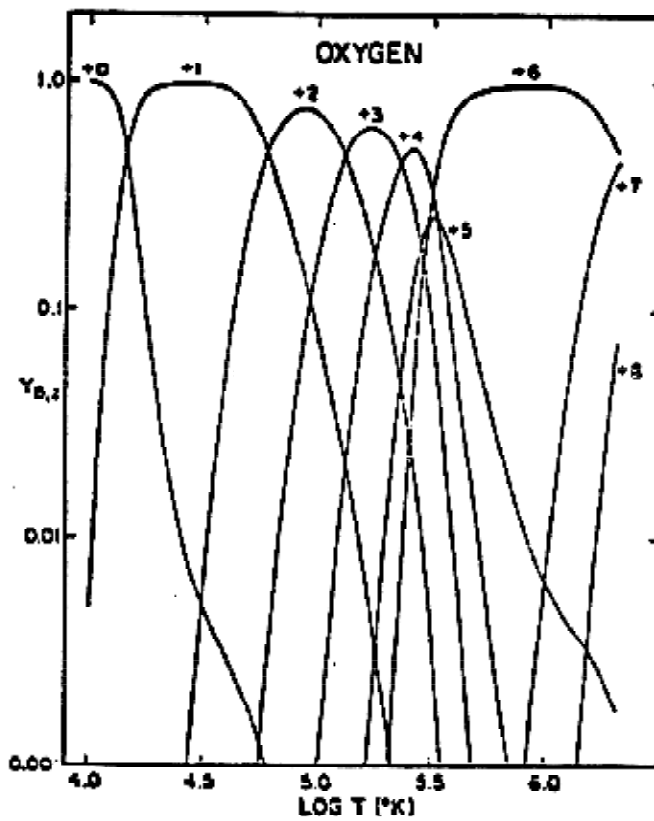
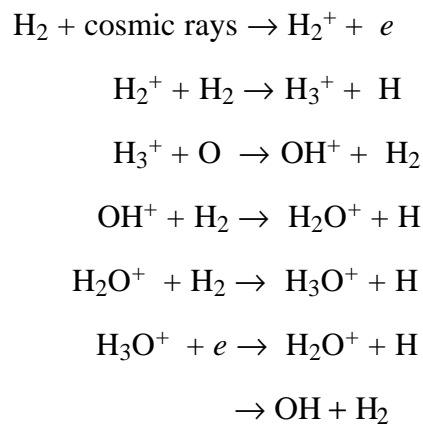


Fig. 7-3

### 7.2.3 Interstellar molecules

The first molecules detected in the interstellar medium were the simple diatomic species CH, CH<sup>+</sup> and CN. They were found through the presence of narrow absorption lines seen towards stars. The corresponding visual extinction  $A_v$  was about unity. Clouds, which are regions of enhanced density  $n(\text{H}) \sim 10\text{-}10^3 \text{ cm}^{-3}$ , with  $A_v$  less than or equal to 1 are called diffuse clouds. For  $A_v$  from 1 to 2.5 they are called translucent clouds. Clouds with higher  $A_v$  are called dense clouds. Dense clouds can be large up to the order of  $10^6 M_\odot$  and they are the sites of star formation. They are also the sites of complex molecules. The Table is a list up to March 1998. They are observed mostly through emission lines in the millimeter region of the spectrum. The chemistry that produces them is a mix of grain surface chemistry and cosmic ray driven chemistry. One sequence is



The reaction with O is a proton transfer reaction. The reactions with H<sub>2</sub> are abstraction reactions. The recombination reaction is called dissociative recombination.

Table 1. Observed interstellar and circumstellar molecules: March 1998.

Number of atoms							
2	3	4	5	6	7	8	≥ 9
Interstellar inorganic molecules (22)							
H <sub>2</sub>	H <sub>2</sub> O	NH <sub>3</sub>					
OH	H <sub>2</sub> S	H <sub>3</sub> O <sup>+</sup>					
SO	SO <sub>2</sub>						
SiO	HNO						
SiS	NH <sub>2</sub>						
NH	N <sub>2</sub> H <sup>+</sup>						
NO	N <sub>2</sub> O						
NS	H <sub>3</sub> <sup>+</sup>						
PN							
HCl							
SO <sup>+</sup>							
HF							
Interstellar organic molecules (73)							
CH <sup>+</sup>	HCN	H <sub>2</sub> CO	HC <sub>3</sub> N	OH <sub>2</sub> OH	HC <sub>5</sub> N	CH <sub>3</sub> OCHO	HC <sub>7</sub> N
CH	HNC	H <sub>2</sub> CS	C <sub>4</sub> H	OH <sub>2</sub> CN	CH <sub>3</sub> CCN	CH <sub>3</sub> C <sub>3</sub> N	CH <sub>3</sub> OCH <sub>3</sub>
CN	HCO	HNCO	CH <sub>2</sub> NH	CH <sub>3</sub> SH	CH <sub>3</sub> NH <sub>2</sub>	CH <sub>3</sub> COOH	CH <sub>3</sub> CH <sub>2</sub> OH
CO	OCS	HNCS	CH <sub>2</sub> CO	NH <sub>2</sub> CHO	CH <sub>3</sub> CHO	H <sub>2</sub> C <sub>6</sub>	CH <sub>3</sub> CH <sub>2</sub> CN
CS	HCO <sup>+</sup>	c-C <sub>3</sub> H	NH <sub>2</sub> CN	CH <sub>3</sub> NC	CH <sub>2</sub> CHCN		CH <sub>3</sub> C <sub>4</sub> H
C <sub>2</sub>	HOC <sup>+</sup>	I-C <sub>3</sub> H	HOCHO	HC <sub>2</sub> CHO	C <sub>6</sub> H		HC <sub>9</sub> N
CO <sup>+</sup>	HCS <sup>+</sup>	C <sub>2</sub> N	c-C <sub>3</sub> H <sub>2</sub>	C <sub>5</sub> H	c-C <sub>2</sub> H <sub>4</sub> O		HC <sub>11</sub> N
	C <sub>2</sub> H	C <sub>2</sub> O	CH <sub>2</sub> CN	H <sub>2</sub> CCCC			CH <sub>3</sub> C <sub>5</sub> N
	C <sub>2</sub> O	C <sub>3</sub> S	H <sub>2</sub> CCC	HC <sub>3</sub> NH <sup>+</sup>			CH <sub>3</sub> COCH <sub>3</sub>
	C <sub>2</sub> S	H <sub>2</sub> CN	HCCNC				
	CH <sub>2</sub>	C <sub>2</sub> H <sub>2</sub>	HNCCC				
		HOCO <sup>+</sup>	CH <sub>4</sub>				
		HCNH <sup>+</sup>	H <sub>2</sub> COH <sup>+</sup>				
Circumstellar molecules (19)							
CP	C <sub>3</sub>	HOCN	C <sub>5</sub>	C <sub>2</sub> H <sub>4</sub>		C <sub>7</sub> H	C <sub>8</sub> H
SiC	c-SiC <sub>2</sub>		SiH <sub>4</sub>				
SiN	NaCN		SiC <sub>4</sub>				
NaCl	MgCN						
AlCl	MgNC						
KCl							
AlF							