Physics of Ionized Gasses in the Interstellar Medium

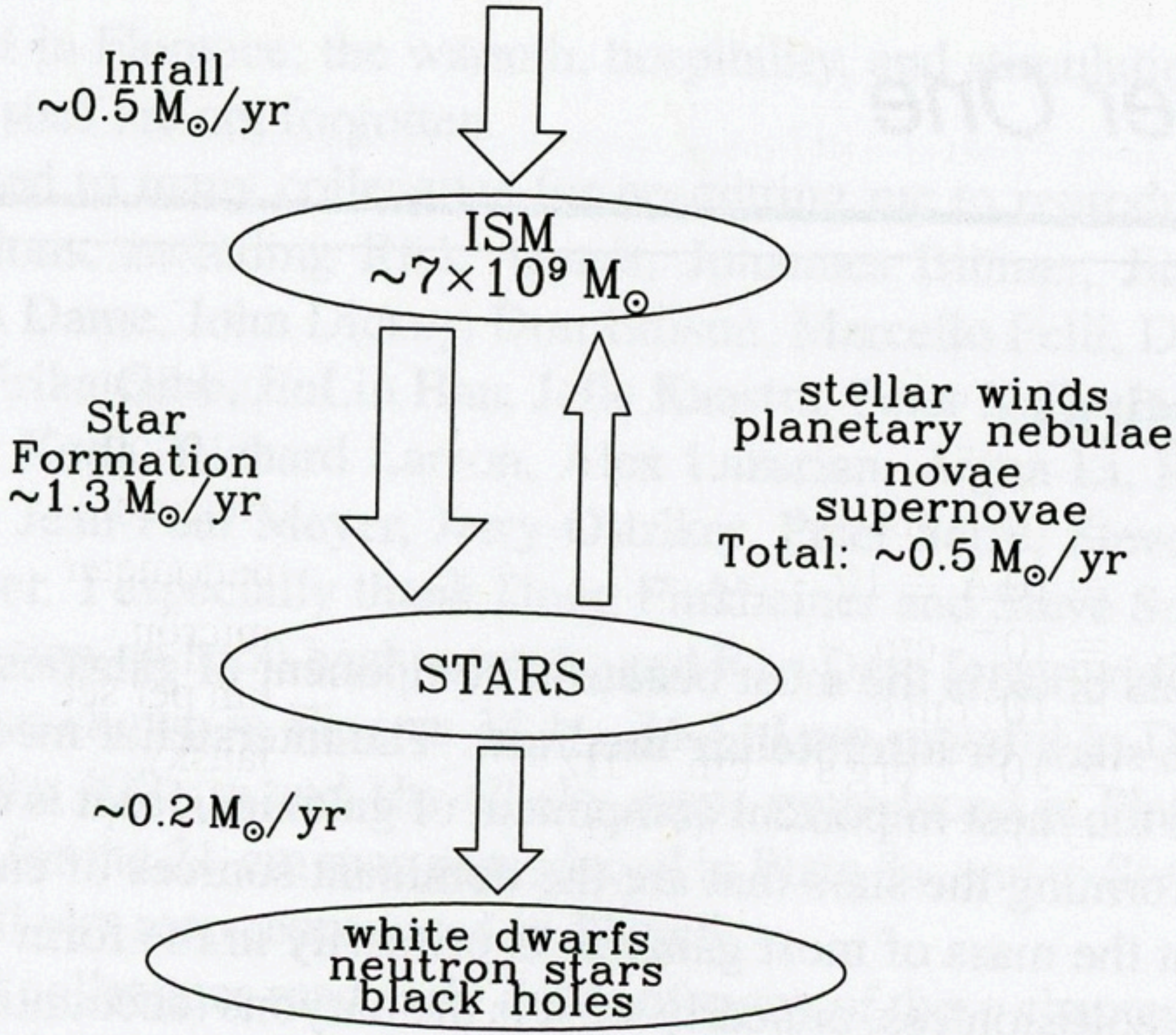
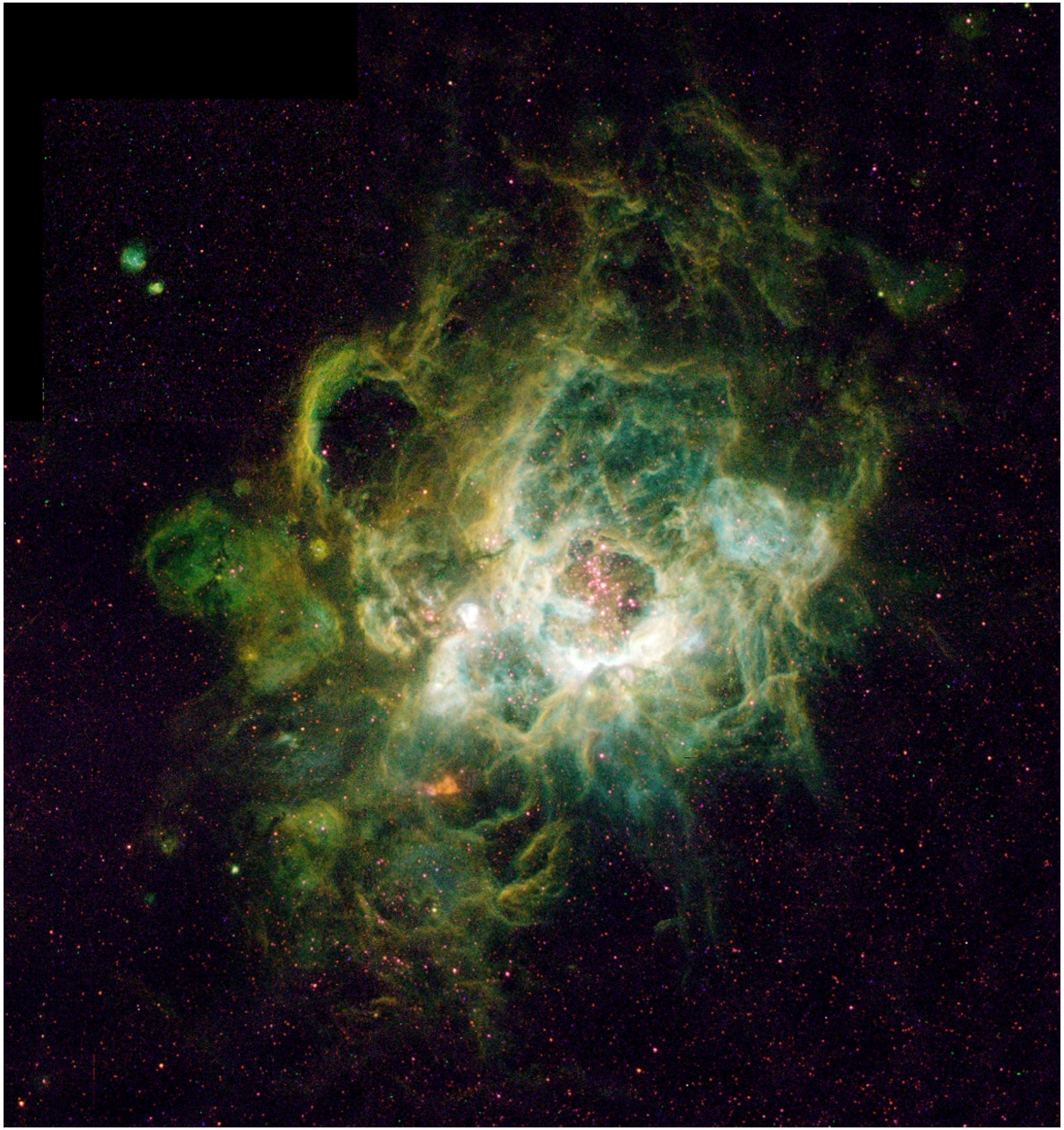


Figure 1.1 Flow of baryons in the Milky Way. See Table 1.2 for the ISM mass budget, and §42.4 for the value of the star formation rate in the Milky Way.



NGC 604

To understand the spectacular H II regions and planetary nebulae observed in the optical part of the spectrum by HST, we need to consider the physical processes which create these regions of ionized gas. The source of ionization may be the ultraviolet radiation from hot stars or, in some cases, collisional heating by shock waves.

The Saha equation for the fractional ionization of hydrogen:

$$\frac{n_e n(H^+)}{n(H^0)} = \frac{(2\pi m_e kT)^{3/2}}{h^3} e^{-I_H/kT}$$

$$\text{where } I_H = 13.60 \text{ eV}$$

This equation applies under conditions of thermodynamic equilibrium, such as would be found in a stellar interior. In that case, radiation field would be given by the Planck function for the temperature T. But in the ISM, the radiation field is very dilute and this equation does not apply.

In the ISM we must consider the balance between the processes which ionize a neutral atom and the processes which recombine electrons and ions. In other words, we need to consider the details of physical processes and the nature of the radiation field (if that is the main cause of ionization).

At the low densities of the ISM, a proton may capture an electron into any of the energy levels of the resulting hydrogen atom (including the ground state). An electron captured to an excited state will then make one or more jumps (with the emission of radiation) to a lower level, finally ending in the ground state. The rate at which such recombinations occur can be calculated for any level, and summing over all levels gives the total recombination rate as a function of the temperature and density of the gas, The total rate of recombinations per unit volume is given by $n_e \; n(H^+) \; \alpha_B(T)$

where $\alpha_B(T) \;=\; 2.54 \times 10^{-13}(T/10^4)^{-0.8163} \;\; cm^3 \; s^{-1}$

Note: This is the usual "case B", where the recombinations to the ground state are canceled since the photon released is absorbed and causes a canceling re-ionization. If the gas cloud is so thin that those photons escape, this is "case A", and we include recombinations directly to ground level:

$$\alpha_A(T) \;=\; 4.13 \times 10^{-13}(T/10^4)^{-0.7131} \;\; cm^3 \; s^{-1}$$

That is the first half of the equation. The second half is the rate of ionization. Usually, the ionization is photoionization, which occurs when a neutral atom or ion absorbs a photon with energy greater than the ionization potential. For hydrogen the ionization potential is 13.60 eV, which corresponds to radiation of wavelengths less than 912 Å. So we must consider the absorption cross section of hydrogen for radiation as a function of frequency (wavelength). For hydrogen, the cross section σ(ν) can be expressed exactly, but the expression is pretty ugly. However, a good approximation is given by

$$\sigma(\nu) \;=\; \sigma_0 \left(\frac{h\nu}{I_H}\right)^{-3} \qquad \text{where} \quad \sigma_0 = 6.3 \times 10^{-18} \; cm^2$$

For frequencies below the ionization potential, σ(ν) is zero. σ is greatest at the threshold and then decreases as the inverse of ν cubed at higher frequencies. The cross section for helium has a similar behavior, but atoms and ions with more electrons will show more complex cross sections. The cross sections for species other than H (and other single electron ions like He II) must be obtained through difficult numerical computation.

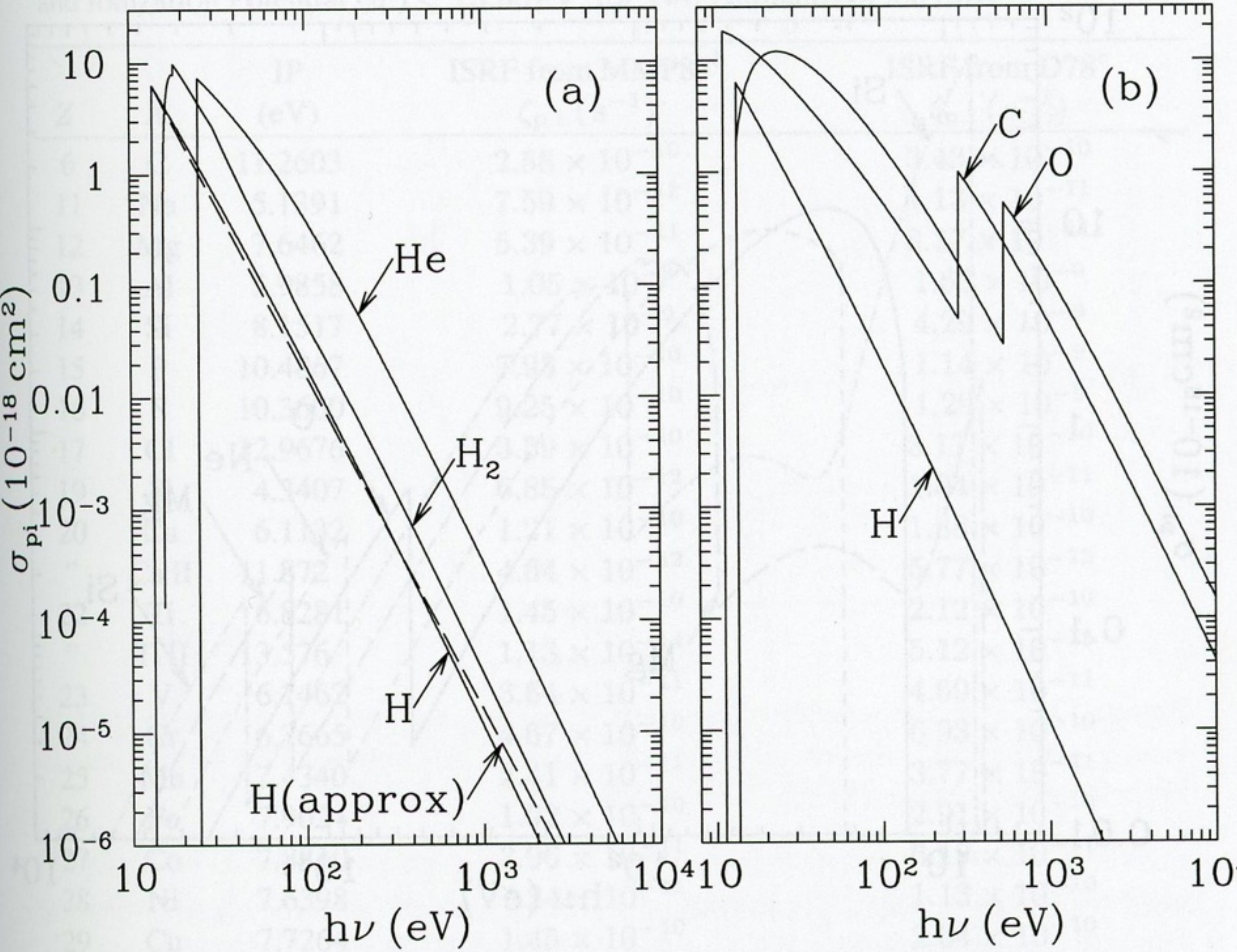


Figure 13.1 Photoionization cross sections for H, H_2, He, C, and O. The dashed line in (a) shows the power-law approximation (13.3) for H.

Photoionization cross sections of H & He

If $J(\nu)$ is the mean intensity of the radiation, the number of ionizations per unit volume will be given by the expression:

$$rate \;=\; n(H^0) \int_{I_H}^{\infty} \frac{4\pi J(\nu)}{h\nu} \sigma(\nu)\, d\nu$$

Since the units of $J(\nu)$ are per steradian, the 4π is needed to include radiation from the whole sphere. Further, the product $4\pi\, J(\nu)\, \sigma(\nu)$ is the energy absorbed, but we want the number of photoionization events. Thus we must divide by $h\nu$, the energy of each photon.

Equating the ionization rate with the recombination rate then gives us the equation we can solve for the ratio of ionized H (protons) to neutral H atoms:

$$n(H^+)\, n_e \alpha_B(T) \;=\; n(H^0) \int_{I_H}^{\infty} \frac{4\pi J(\nu)}{h\nu} \sigma(\nu)\, d\nu$$

Similar equations can (must!) be written for the balance between each adjacent pair of atoms and ions:

$$(He^0, He^+), (He^+, He^{++}), (O^0, O^+), (O^+, O^{++}), (O^{2+}, O^{3+}), \ldots \quad \text{etc.}$$

Then, given the radiation field $J(\nu)$, we can write a computer program to solve for the relative abundances of all the different ions in the gas making up the ISM or nebula.

Heating by Photoionization

The electrons ejected by the photoionization of H are the main source of heating for most nebulae. When a photon of energy hν ionizes an H atom, the ejected electron carries energy $(h\nu - I_H)$ so that the heating per unit volume, H, is seen to be

$$H \;=\; n(H^0)\int_{I_H}^{\infty} \frac{4\pi J(\nu)}{h\nu}\sigma(\nu)(h\nu - I_H)\; d\nu$$

There is similar heating by the other elements, most importantly helium, but the He/H abundance ratio is usually only ~0.1, so heating by He is of secondary importance.

At first sight, one might think that the heating would vary greatly in H II regions because the intensity of the stellar radiation, J(ν), drops as the inverse square of the distance from the source. But the observed temperature of the ionized gas is fairly uniform, around 10,000 K. Part of the reason is that in addition to the integral, the equation for H is proportional to the abundance of atomic H. But if the intensity J decreases, this causes the fraction of neutral H to increase, thus conpensating for the decrease in J in the integral for H.

To understand the temperature of ionized gas fully, we need to consider the other part of the process, the cooling, C, which balances the heating H. The heating and cooling depend on temperature in different ways (the cooling increases exponentially with temperature) and so the gas settles at the temperature where C(T)=H. We will return to this later.

Ionization Potentials

The ionization potential of the various ions is key to understanding the structure of nebulae and which spectral lines will appear in the spectra. For example, the IP of some elements is lower than the IP of hydrogen, 13.6 eV. These elements include C, Mg, Si and S. This means that these elements can be ionized even in regions where the H is neutral. We never expect to find neutral carbon or sulfur in an ionized nebula.

The IP of helium and especially of ionized helium are quite important. The IP of helium is 24.6 eV, quite a bit higher than hydrogen. Than means that for B stars, the amount of radiation with energy >24.6 eV is much less than the total of hydrogen ionizing radiation. As a result, the helium may be ionized only close to the star, but be neutral throughout most of the nebula.

Even more extreme is the case of He II (helium with just one electron left). Its energy levels are just like the hydrogen levels multiplird by 4. The IP of He+ is 54.4 eV (4×13.6). When He++ recombines (→He+), we see He II lines in the spectrum. This is a sure sign of a very hot star (>60,000 K) like the central star of a planetary nebula or of a power-law spectrum from the central engine of an active galaxy.

Ionization Potentials (eV)

Element		I→II	II→III	III→IV	IV→V	V→VI	VI→VII	VII→VIII
1	H	13.5984						
2	He	24.5874	54.416					
3	Li	5.3917	75.640	122.454				
4	Be	9.3227	18.211	153.894	217.719			
5	B	8.2980	25.155	37.931	259.375	340.226		
6	C	11.2603	24.383	47.888	64.494	392.089	489.993	
7	N	14.5341	29.601	47.449	77.474	97.890	552.072	667.046
8	O	13.6181	35.121	54.936	77.414	113.899	138.120	739.293
9	F	17.4228	34.971	62.708	87.140	114.243	147.163	185.189
10	Ne	21.5645	40.963	63.423	97.117	126.247	154.214	207.271
11	Na	5.1391	47.286	71.620	98.91	138.40	172.183	208.50
12	Mg	7.6462	15.035	80.144	109.265	141.270	186.76	225.02
13	Al	5.9858	18.829	28.448	119.992	153.825	190.477	241.76
14	Si	8.1517	16.346	33.493	45.142	166.767	205.267	246.481
15	P	10.4867	19.769	30.203	51.444	65.025	220.422	263.57
16	S	10.3600	23.338	34.790	47.222	72.594	88.053	280.948