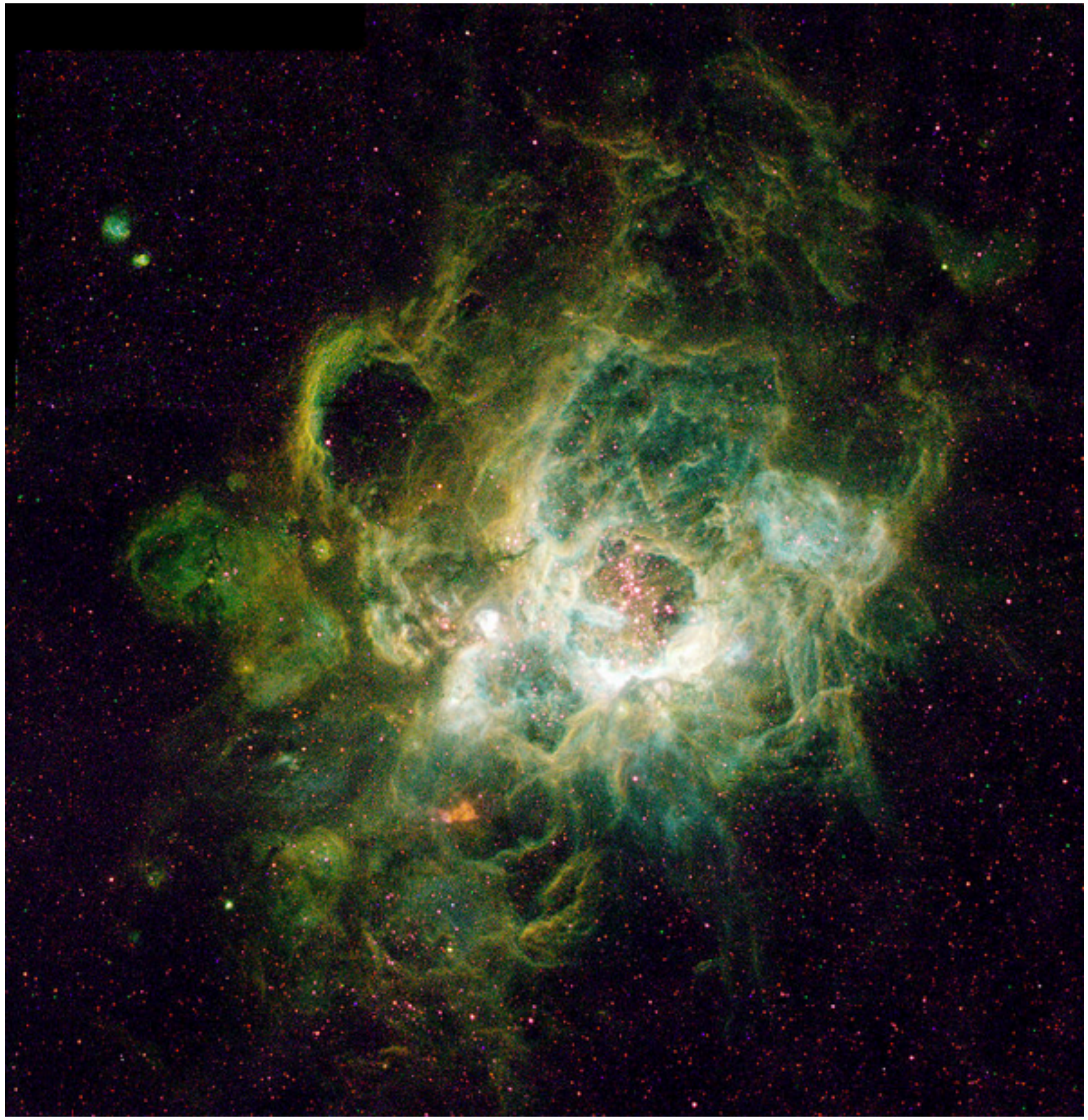
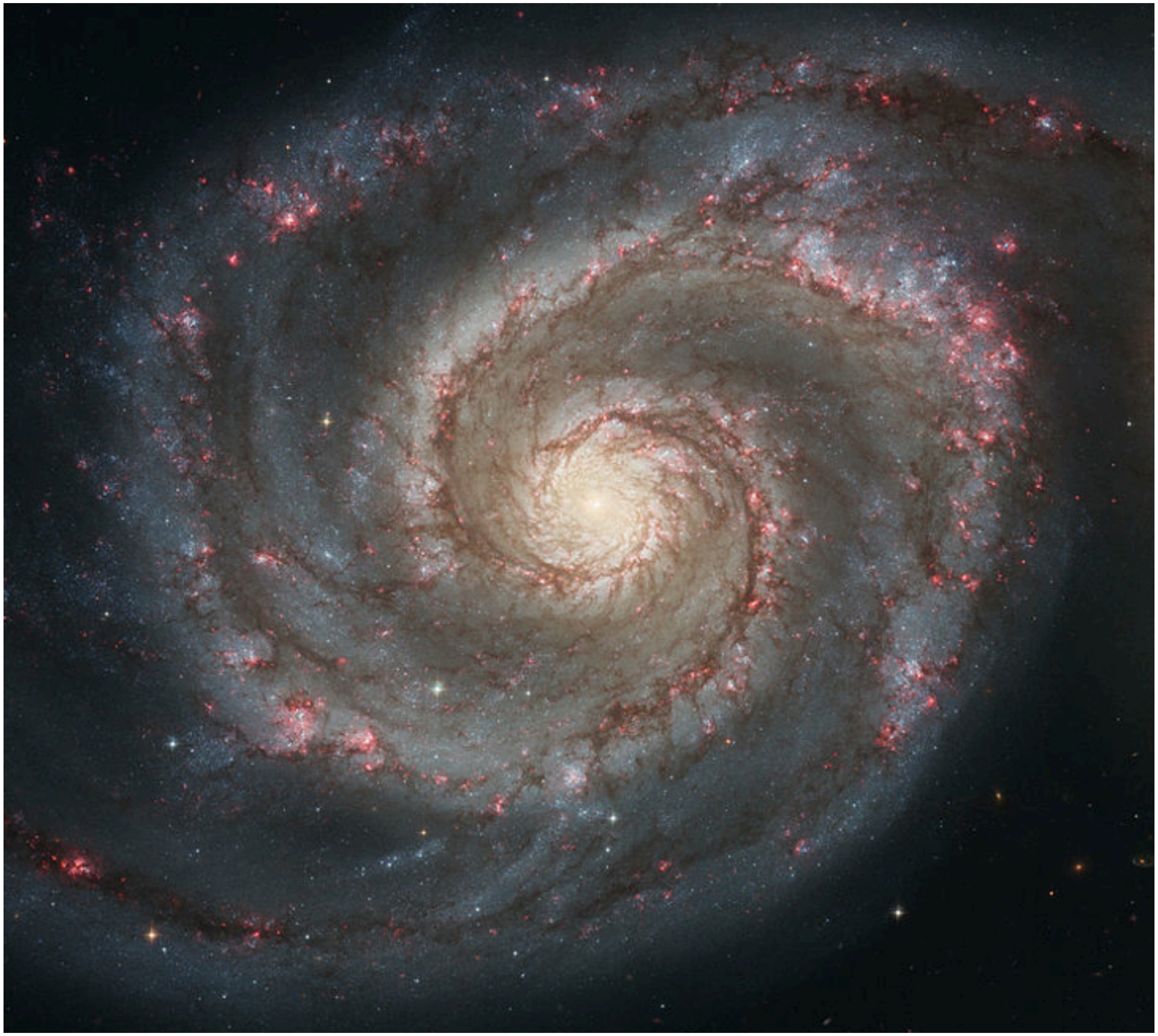
Orion nebula: discovered in 1610



Facts about HII regions

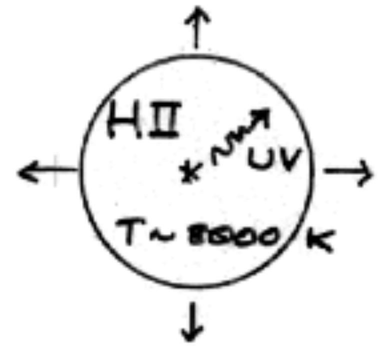
- Everything starts with a giant molecular cloud
  - Cold molecular gas ~10-20 K and dense n~100/cm^3
- Under gravitational collapse a bright star forms
  - Its bright FUV radiation ionizes the surrounding nebula
  - Typical temperatures of ~8000 K
  - They can be observed at Radio and IR, optically thick at other wavelengths
  - Also Hα at 6560 Å (e.g. 3->2 transition in H)
- Radiation pressure from the star will eventually blow the gas away
  - Inefficient process: only ~10% of the gas is used to form stars, the rest is blown away (also from SN explosions)
- H_{II} regions are seen in most galaxies except in ellipticals
  - In spirals they are concentrated in the arms
  - They can be used to study the chemical composition of distant galaxies

Whirlpool Galaxy



Introductory Summary

The far ultraviolet radiation (FUV) from an O or B star Ionizes its immediate neighborhood and produces an HII region. Strömgren developed the theory in 1939 for a spherical model where the HII region slowly expands into uniform HI.



HII regions illustrate basic processes that operate in all photoionized regions of the ISM: super-Lyman radiation ($\lambda <$ 916.6 Å - FUV or X-rays) photoionize sH:

$$h\nu + H \rightarrow H^{+} + e.$$

The H+ ions recombine radiatively

$$H^{+} + e \rightarrow H + h\nu.$$

• The balance between these two reactions determines the ionization fraction.

• Any excess photon energy above the ionization potential (IP = 13.6 eV) is given to the ejected electron and is then equilibrated in collisions with ambient electrons, thereby heating the HII region.

Real HII regions are rarely spherical. Nonetheless, Strömgren's theory Illustrates the basic roles of photoionization and recombination.

NGC 3603

Rosette

North American

Shapley's Planetary Nebula

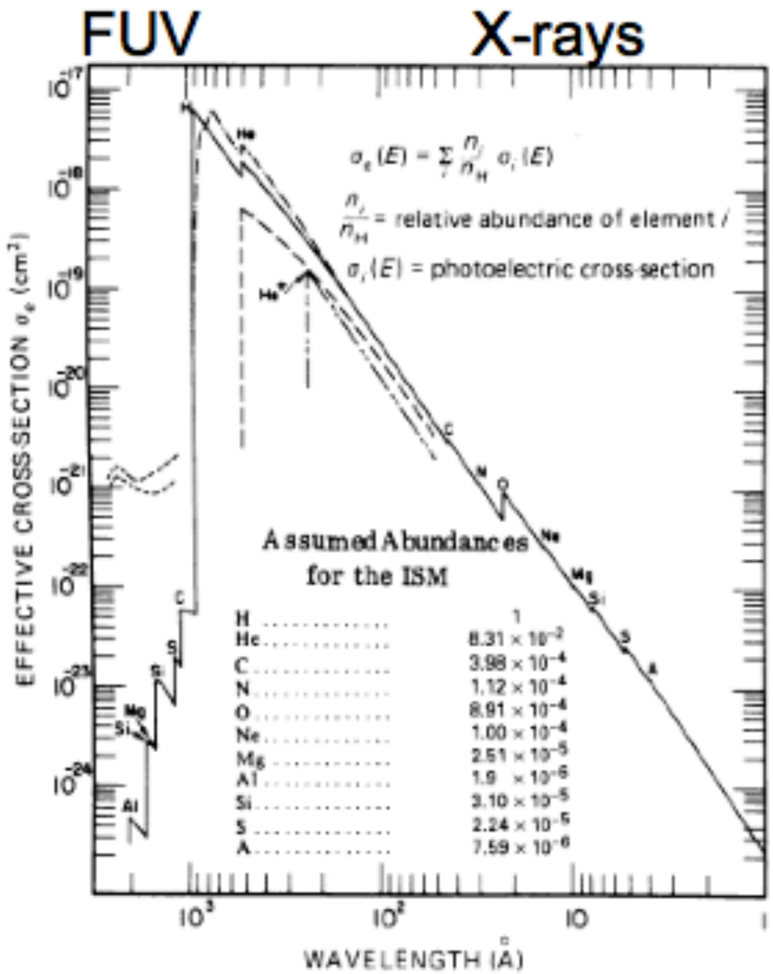
Photo-ionization

The ISM is opaque at 911 Å (the H Lyman edge) & partially transparent in the FUV and in the X-ray band above 1 keV.

Ionizing photons come from

1. Massive young stars*
2. Hot white dwarfs
3. Planetary nebula stars
4. SNR shocks

* Table 2.3 of Osterbrock & Ferland give T(O5V) ≈ 46,000 K (BB peak at $3kT$ or 12 eV) & 3×10^{49} ionizing photons/s



Absorption cross section per H nucleus
(1-2000 Å, averaged over abundances)

Photo-ionization Equilibrium

- Number of photo-ionizations = Number of recombinations
  - Per volume / per second

$$n_{H^0} \int_{\nu_t}^{\infty} F(\nu)\alpha(\nu)d\nu = n_e n_p \beta(T_e)$$

- Introducing the ionization parameter ξ
  - $n_e=n_p= (1-\xi)n_H$
  - $n_H^0 = \xi\, n_H$

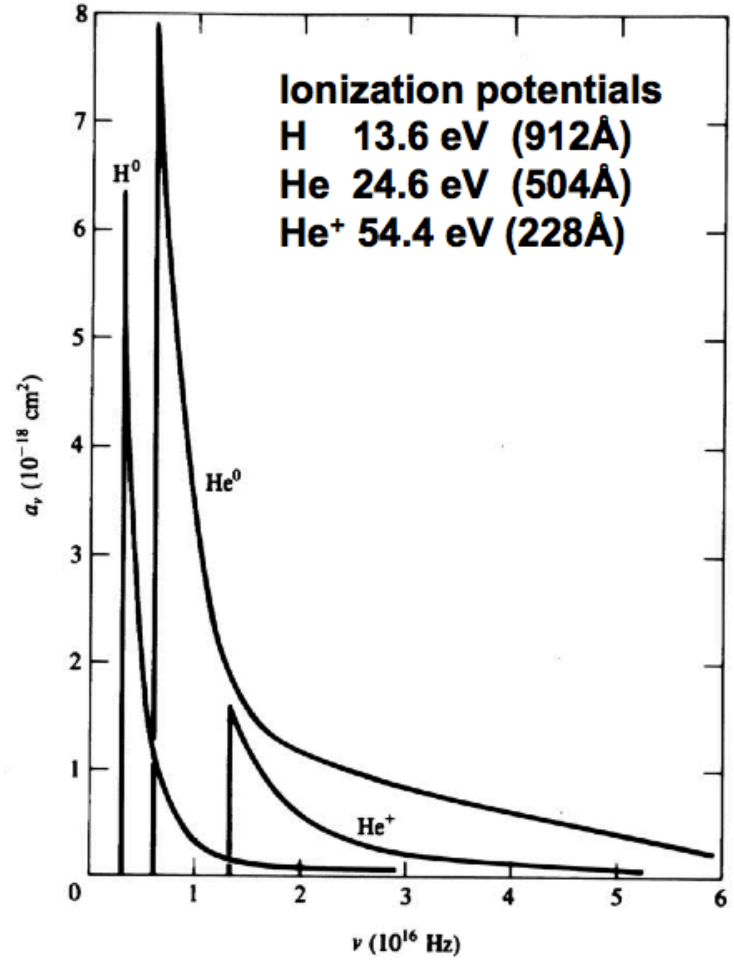
$$\xi n_H \int_{\nu_t}^{\infty} F(\nu)\alpha(\nu)d\nu = (1-\xi)^2 n_H^2 \beta(T_e)$$

Example

$$\xi n_H \int_{\nu_t}^{\infty} F(\nu)\alpha(\nu)d\nu = (1-\xi)^2 n_H^2 \beta(T_e)$$

- Region of gas at 5pc from a T~40000 K star (O6.5v star)
- Emitted ionizing photons ~1e49 ph/s
- Cross section ~6e-18/cm2
- β(8000K)~4e13 cm^3 s^{-1}

$$\int_{\nu_t}^{\infty} F(\nu)d\nu = 10^{49}\, ph/s$$



- Ionization timescale of ~1e8s s
- Recombination timescale of ~1e11 s
- ξ~1e-4 -> fully ionized
- Mean free path ~0.01 pc
  - Transition between ionized to neutral is fast

Strömgen Radius (=radius of the nebula)

- For an optically thick nebula, none of the ionizing photons escape the nebula :

$$\begin{pmatrix}\text{Total \# of ionizing} \\ \text{photons/sec emitted}\end{pmatrix} = \begin{pmatrix}\text{Total \# of recombinations} \\ \text{into excited levels of } H^0 \text{ per second}\end{pmatrix}$$

$$\int_{\nu_t}^{\infty} \frac{L(\nu)}{h\nu} d\nu = \frac{4\pi}{3} R_s^2 n^2 \beta \overline{(1-\xi)}^2$$

- R_s~1.2 pc for a 10^3 cm^{-3} nebula

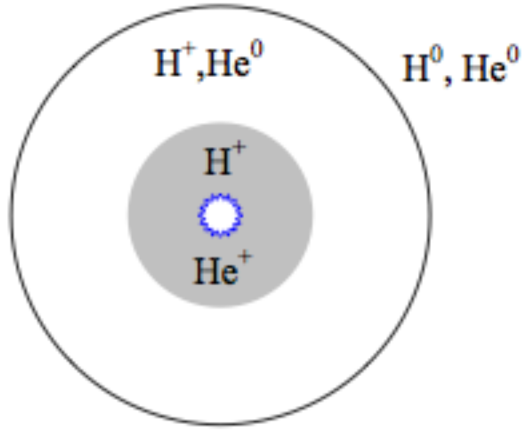
Spectral type	T_{eff} (K)	$L(10^5 L_\odot)$	N_{Lyc} (10^{49} photons s^{-1})
O3	51 200	10.8	7.4
O4	48 700	7.6	5.0
O5	46 100	5.3	3.4
O6	43 600	3.7	2.2
O7	41 000	2.5	1.3
O8	38 500	1.7	0.74
O9	35 900	1.2	0.36
B0	33 300	0.76	0.14

[a] Stellar parameters for main sequence stars.

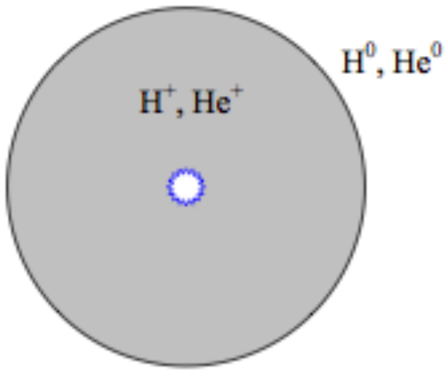
Dust and He

- Dust will compete with H for ionizing photons
  - Dust absorbed UV photons, heat up to ~50 K and radiates in the IR
  - Dust removes ionizing photons ->it shrinks the dimension of the nebula
- Intense star formation is hostile to dust
  - Grains evaporate
- The cross section to ionize He is larger than that of H
  - If hν>24.4 eV, then photons will ionize mostly the He

Cool stars (T<40000K)



Hot stars (T>40000)



Thermal Equilibrium

- Photo-electrons dissipate their energy by Coulomb scattering and thermalize (e.g. Maxwellian)
  - $h(\nu-\nu_0)=0.5\ mv^2=3/2\ kT$
- At equilibrium : Heating = Cooling
  - Heating = photo-ionization
  - Cooling = recombination, free free emission, collisional excitation

$$n_{H^0}\int_{\nu_t}^{\infty}\frac{4\pi B(\nu,T)\alpha(\nu)h(\nu-\nu_t)d\nu}{h\nu}=G(H^0)$$

Total Energy released per ionization per volume

$$n_{H^0}\int_{\nu_t}^{\infty}\frac{4\pi B(\nu,T)\alpha(\nu)d\nu}{h\nu}=n_e n_p \beta(H^0,T)$$

$$G(H^0)=\frac{3}{2}kT\cdot\ n_e n_p \beta(H^0,T)$$

$T \sim T^*$

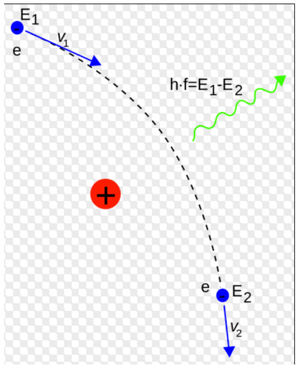
Cooling

- Recombination: removes heat from the thermal e^- plasma

$$L_r(H) = n_e n_p kT \cdot \beta(H,T)$$

Rate of removed hear per H

- Free – free (aka Bremmstrahlung)



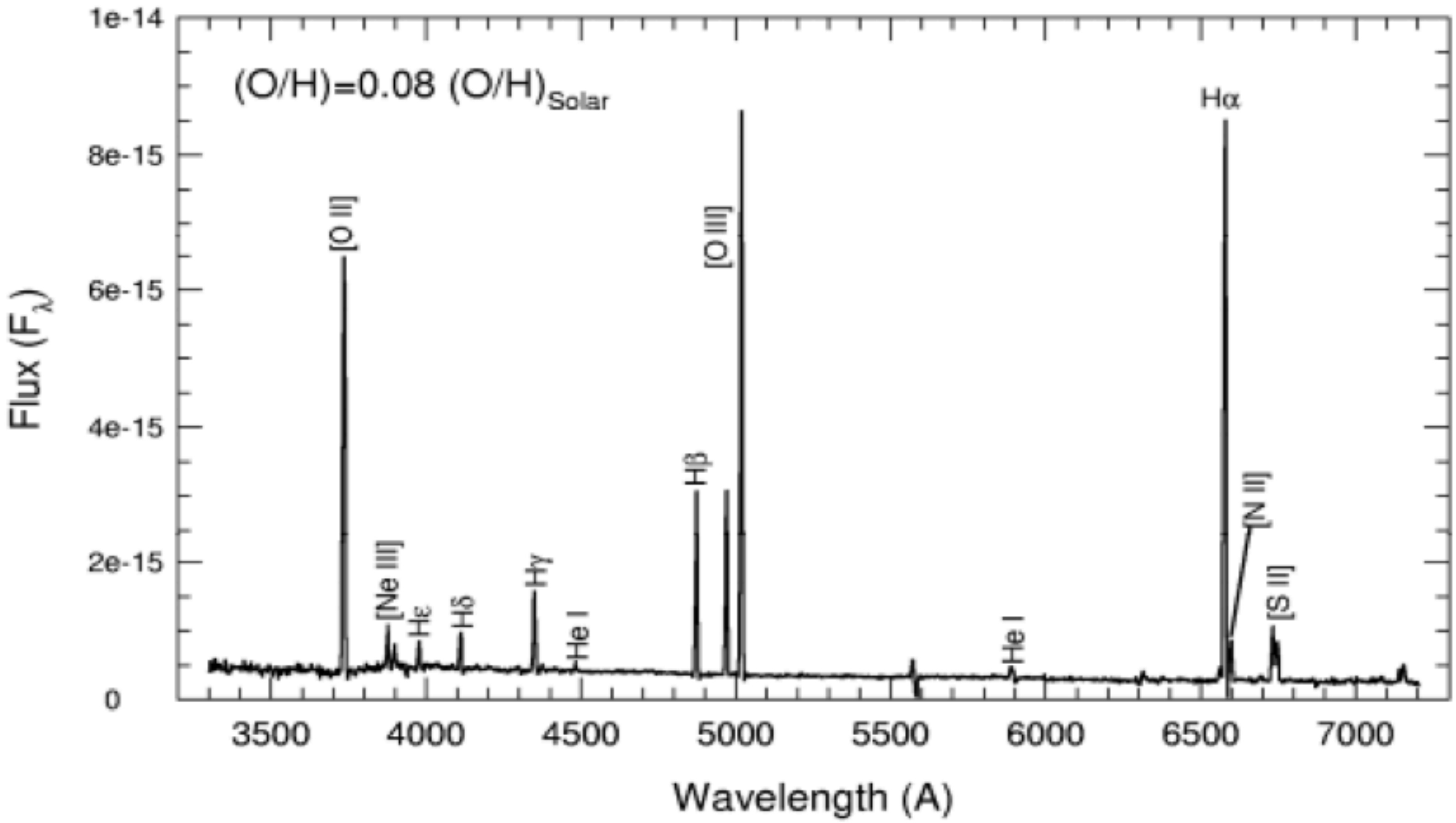
$$L_{ff}(Z) = 1.42 \times 10^{-27} Z^2 T^{1/2} g_{ff} n_e n_+$$

g≈1

Bremmstrahlung is pretty inefficient, however it cools a tiny biy

- Collisional cooling:
  - e^- can excite O^+, O^{++}, N^+ which require a typical potential of ~eV
    - *H and He require ~10eV, so they are disfavoured*
  - The nebula is optically thin for these line photons

Typical spectrum of an HII region

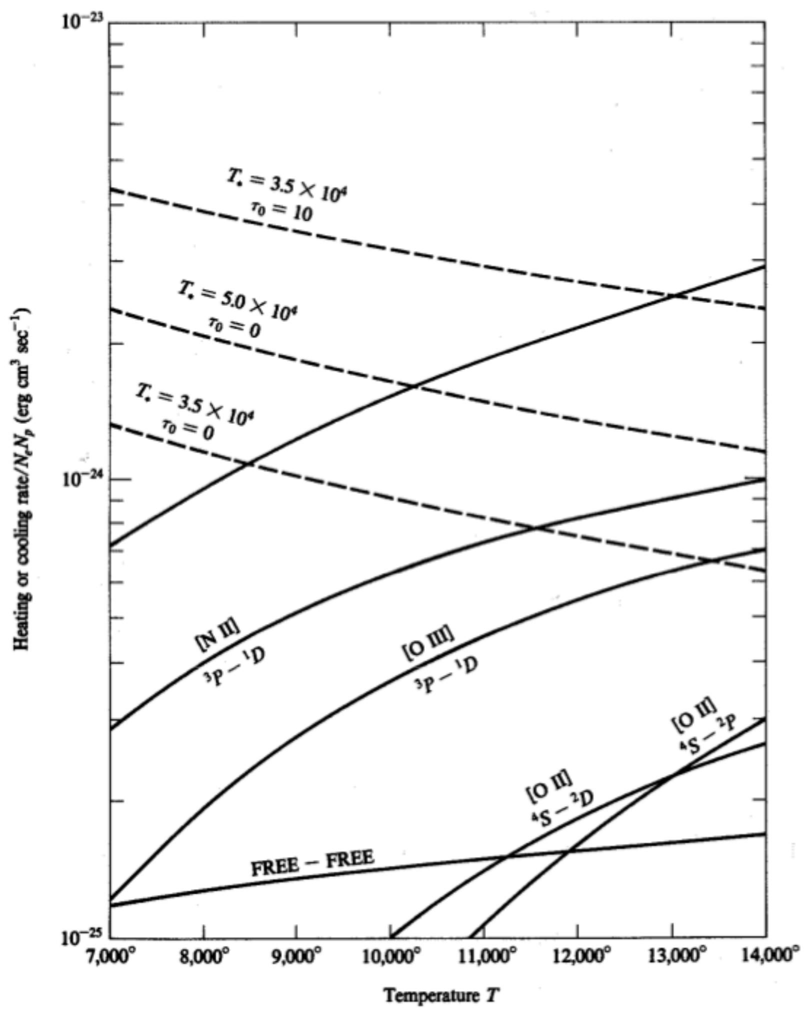


HII regions also have continuum emission due to e.g. :

1. Free-bound emission (electron recombines)
2. Free free emission

Thermal Equilibrium

- $G = L_R + L_{ff} + L_c$
  - Can be re-written as `net effective rate', $G - L_R = L_{ff} + L_c$



OB associations & Bubbles

- O and (early type) B stars are short lived massive stars
- Form in loosely organized groups
  - OB associations
- Found at the center of HII regions (these are the `classic' HII regions)
- Their strong winds push the surrounding material, while the UV ionizes it
  - Bubble (see the bubble nebula)
  - Size limited by the energy of the star (~10^{51} erg)

Super – Bubbles !

- Similar to bubble BUT much larger
  - Several OB stars going SN
  - Lifetime of the $5x10^7$ yr
  - Size up to 1.5 kp !
  - Densities of $2x10^{-2}/cm^3$ ← it's a cavity
  - Filled with $\sim 10^6$ K gas (emit in X-ray!)
  - We see them as large holes in HI, shells of HII

N44, LMC

Effects of Super-bubbles in the ISM

- Super bubbles stir up and enrich the ISM of heavy elements
- Supply warm gas to the interstellar halo (orthogonally to the disk) via chimney effect
- Enrich the Inter-galactic medium (!) of heavy metal generated in SN explosions and their ejecta
- Explain the turbulent ISM
- Explains the hot gas in the Galactic halo

The Local Interstellar Medium

- A few cool clouds (5000 K) surrounding the solar system itself
- The Local Bubble ($10^{6.5}$ K gas) and Loop 1 (the same) were once the same bubble. (~15 Myr ago)
- More SNe occured, separating the two bubbles- six in the LB (~12 Myr ago)
- OB associations only exist in Loop 1 now; the LB will be squeezed out of existence soon.

624 B. Y. Welsh and R. Lallement: Local hot gas

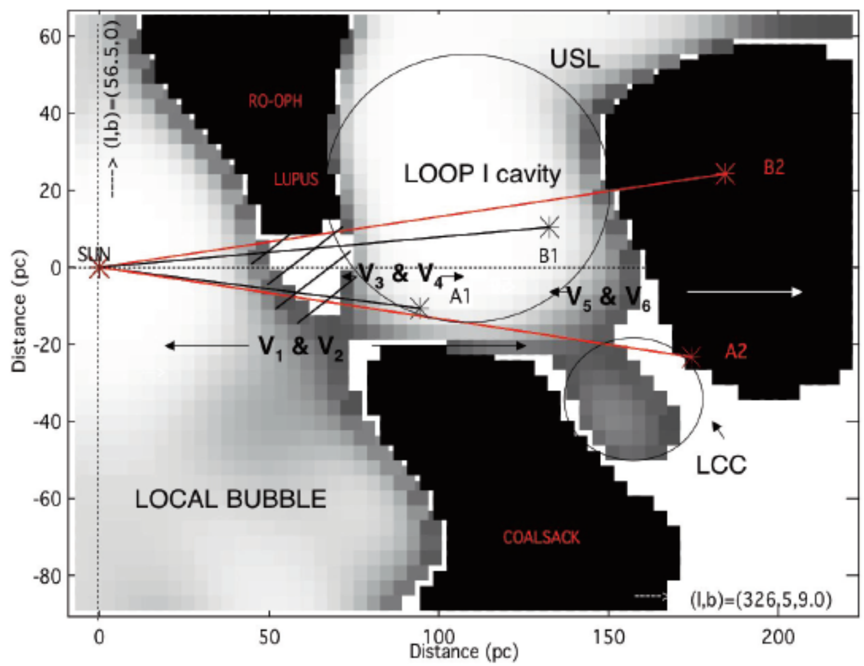
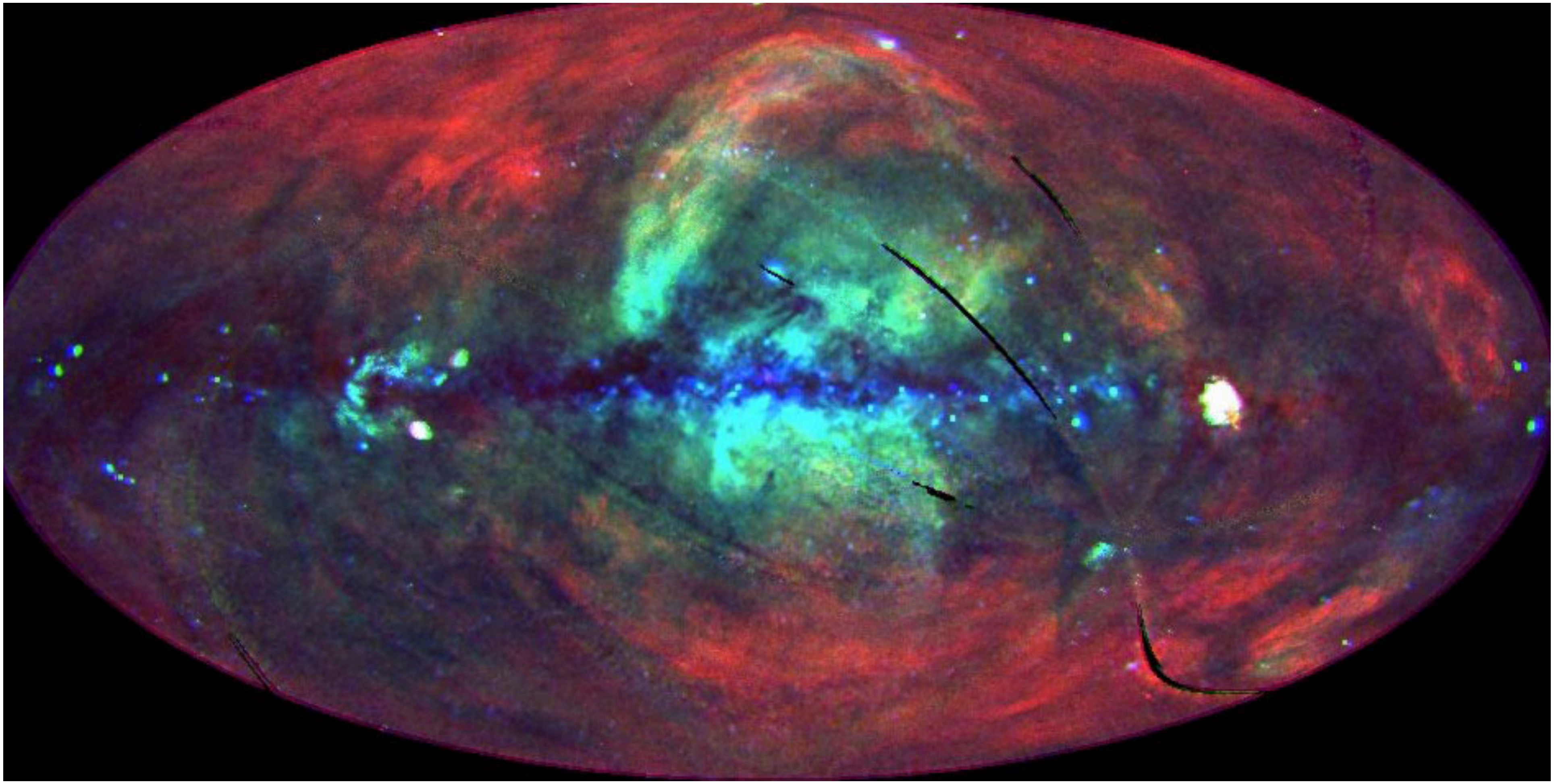


Fig. 6. Schematic map of the 2-D distribution of neutral (NaI) gas close to the galactic plane within 250 pc of the Sun. Dense gas is shown by dark shading, and hatch lines locate the area of interaction between the Local Bubble cavity and the adjacent Loop I superbubble. The approximate boundaries of the Upper Scorpius Loop (USL) and Lower Centaurus Loop (LCC) are also show. The distance estimates to the six cloud components (V_1 to V_6) are indicated by arrows. The sight-lines to the target stars A1 (HD 128345), A2 (HD 127381), B1 (HD 138769) and B2 (HD 142256) are also shown.

ROSAT all-sky Image



Recap on HII regions

- Observations:
  - Regions of ionized gas around early type stars (O, B)
  - T~8000K, n=10-100cm^{-3}, optically thick
  - Emission line spectrum with collisionally excited elements

- Ionization = Recombination
  - HII regions are fully ionized
  - Ionization times of ~3 years
  - Recombination times of ~thousands of years
  - Transition from HII to HI is sharp
    - *Mean free path of ionizing photons is small*
- Stroemgren radius
  - Tipically ~1pc
- Super-bubbles
  - Kpc size, stir up and enrich the ISM
  - Provide hot gas to the Galactic halo