Interstellar Medium (ISM)

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ASIAA

Topics

An ISM lecture needs one semester.
We only briefly touch main topics and show some examples of numerical research (to motivate your further studies).

1. ISM Composition/Phases
2. Interaction with Radiation
3. Multi-Phase ISM
4. Dynamical Processes
5. Summary

1. ISM Composition/Phases

Elemental Composition (Solar)

Lodders (2010)

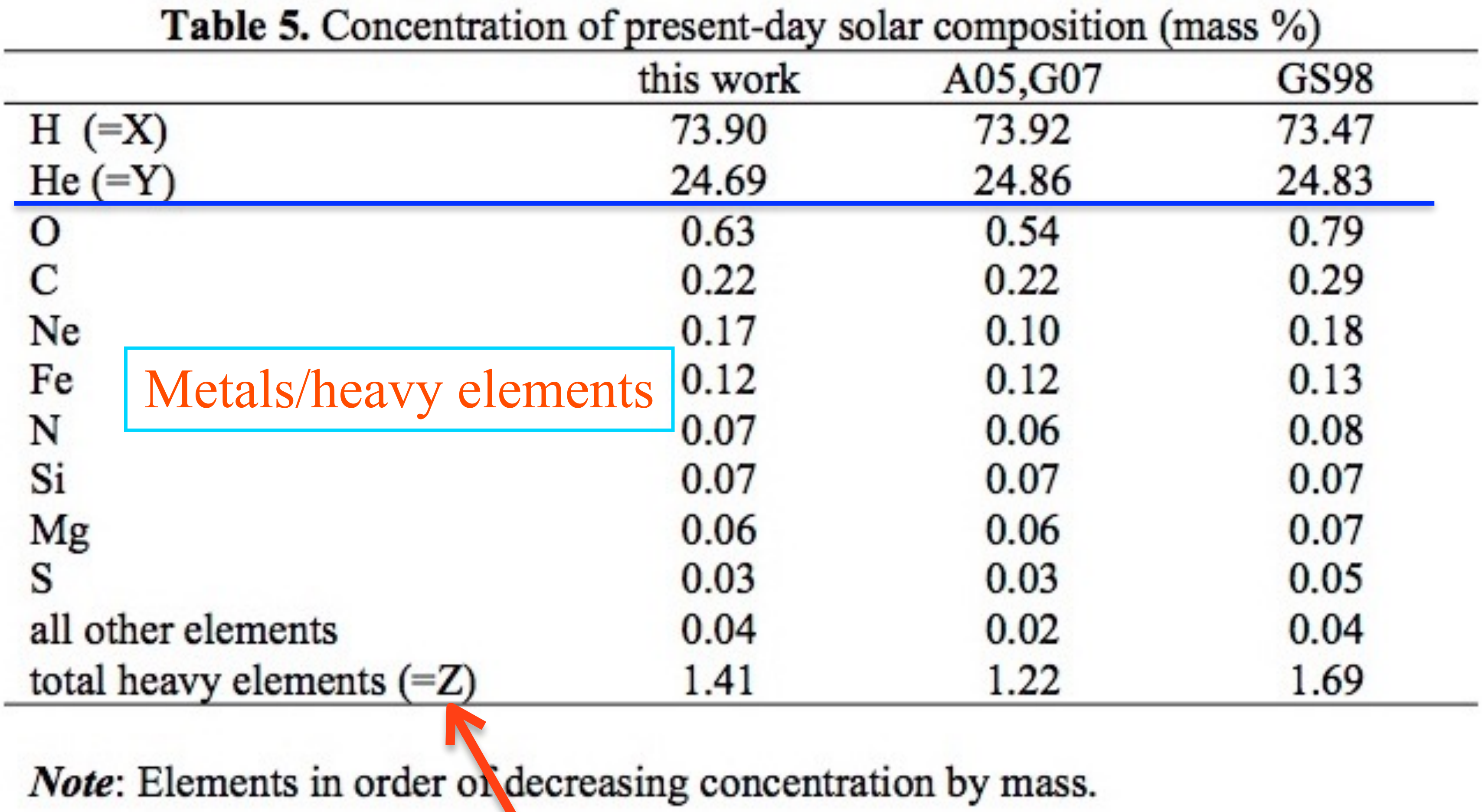


Table 5. Concentration of present-day solar composition (mass %)

	this work	A05,G07	GS98
H (=X)	73.90	73.92	73.47
He (=Y)	24.69	24.86	24.83
O	0.63	0.54	0.79
C	0.22	0.22	0.29
Ne	0.17	0.10	0.18
Fe	0.12	0.12	0.13
N	0.07	0.06	0.08
Si	0.07	0.07	0.07
Mg	0.06	0.06	0.07
S	0.03	0.03	0.05
all other elements	0.04	0.02	0.04
total heavy elements (=Z)	1.41	1.22	1.69

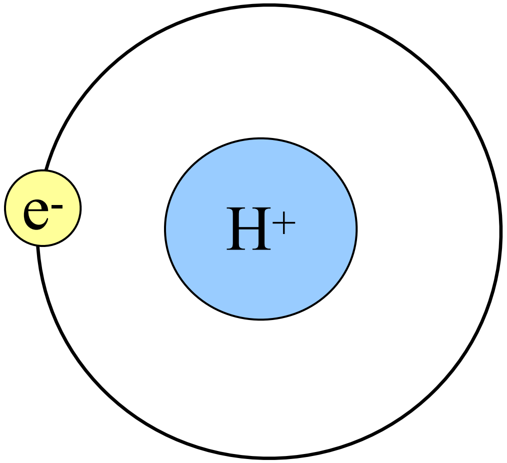
Note: Elements in order of decreasing concentration by mass.

Metals/heavy elements

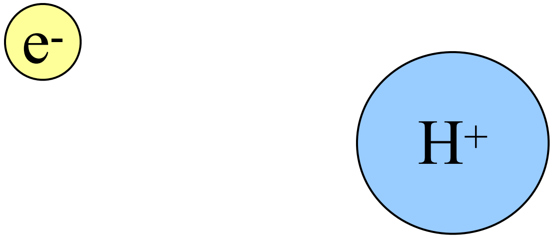
Metallicity

Hydrogen

atomic hydrogen H I



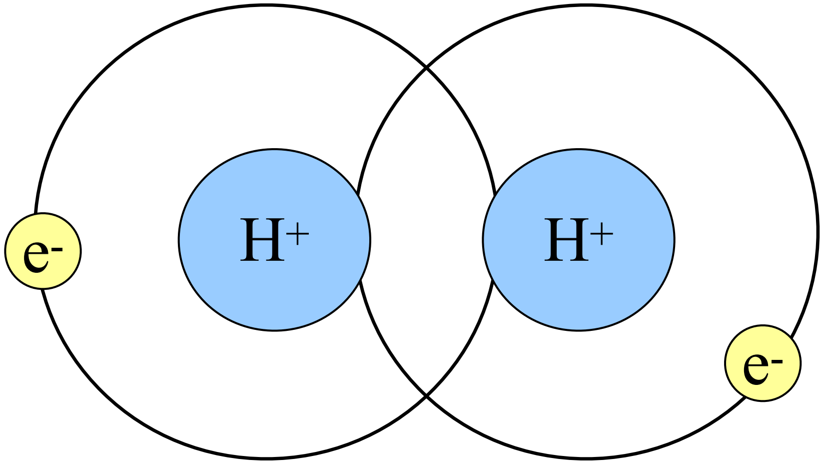
ionized hydrogen H II



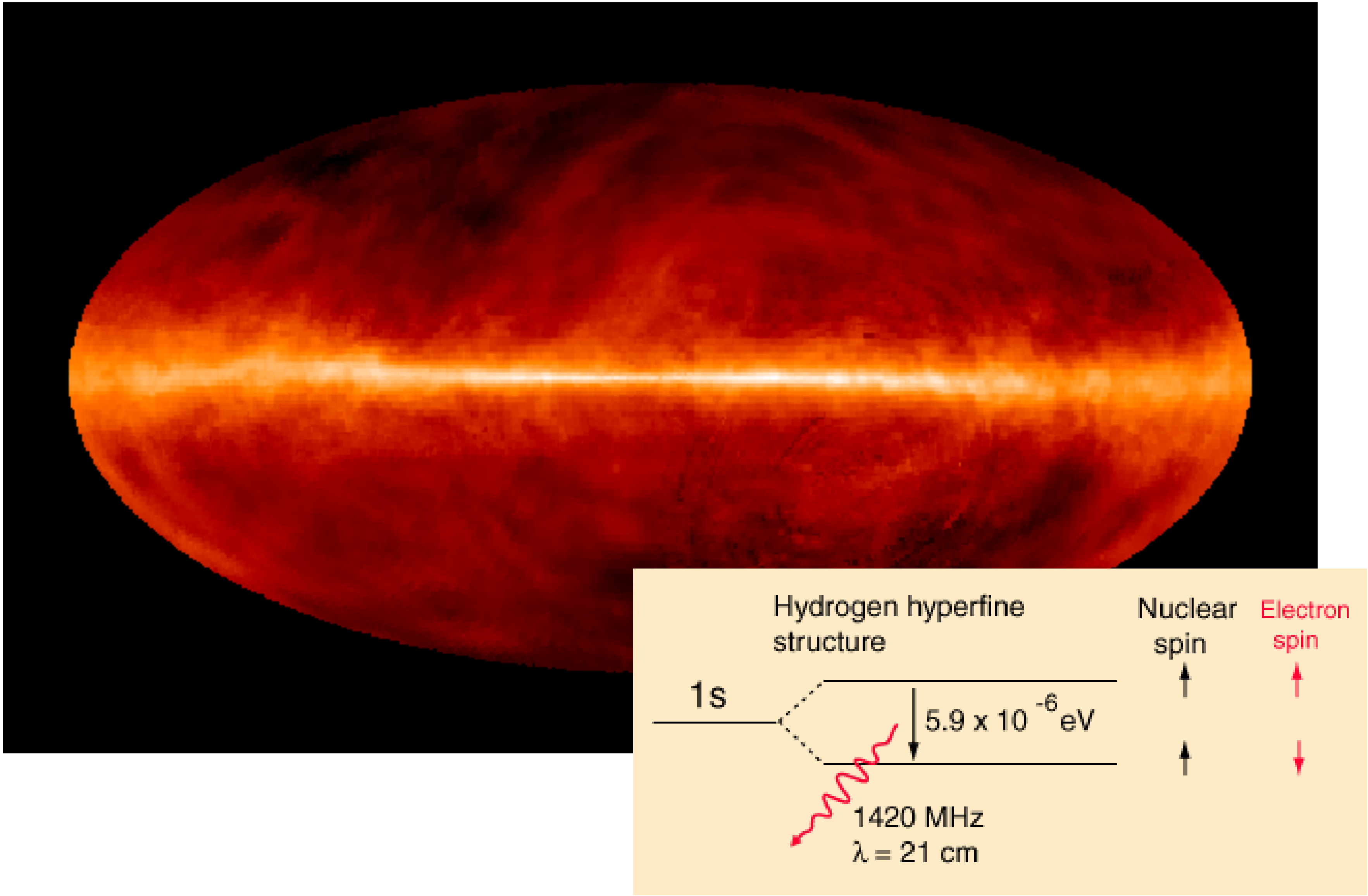
ionization potential: $E = 13.6$ eV

$E = h(c/\lambda) \rightarrow \lambda = 912$ Å

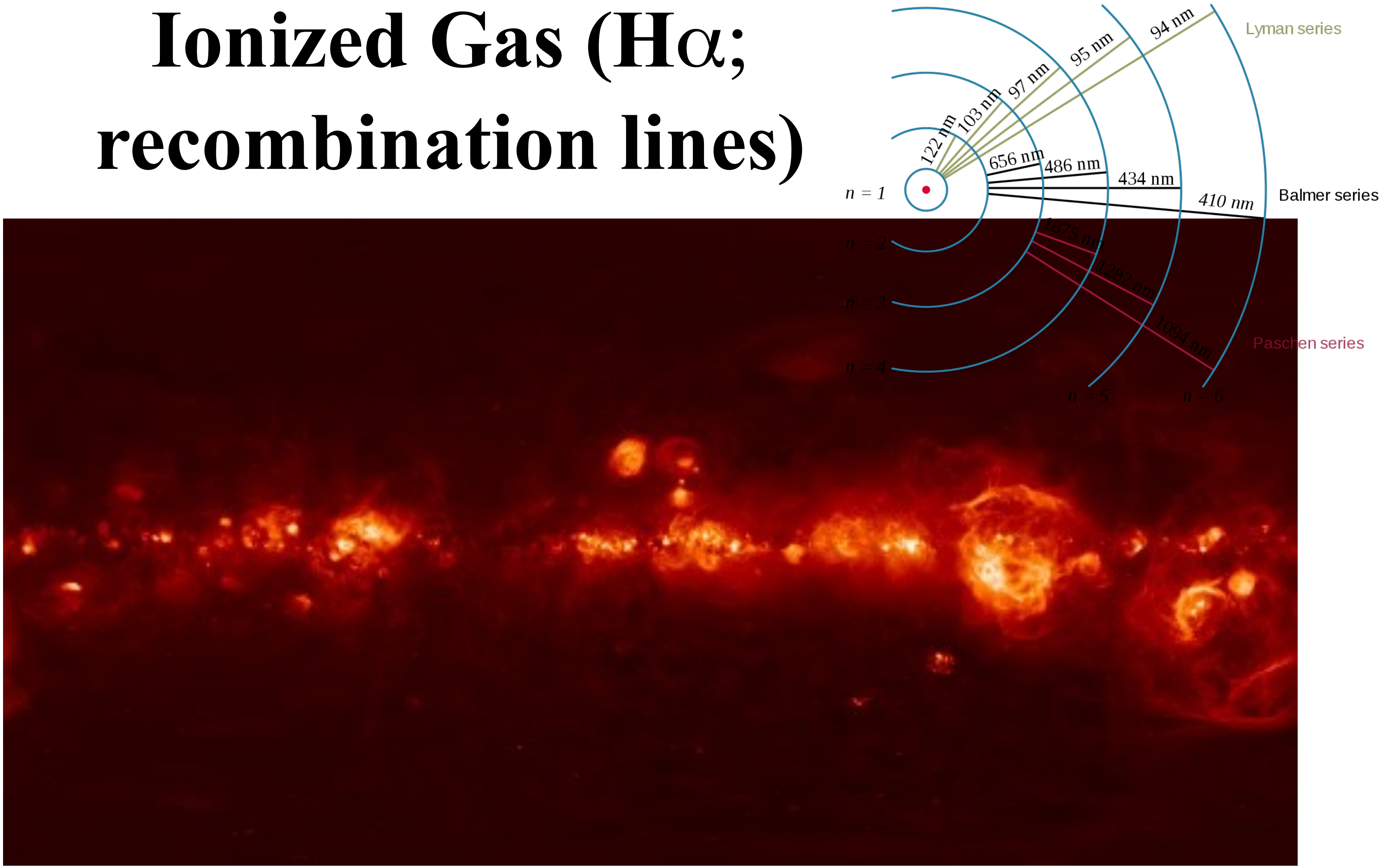
molecular hydrogen H_2



Atomic Hydrogen (21 cm)

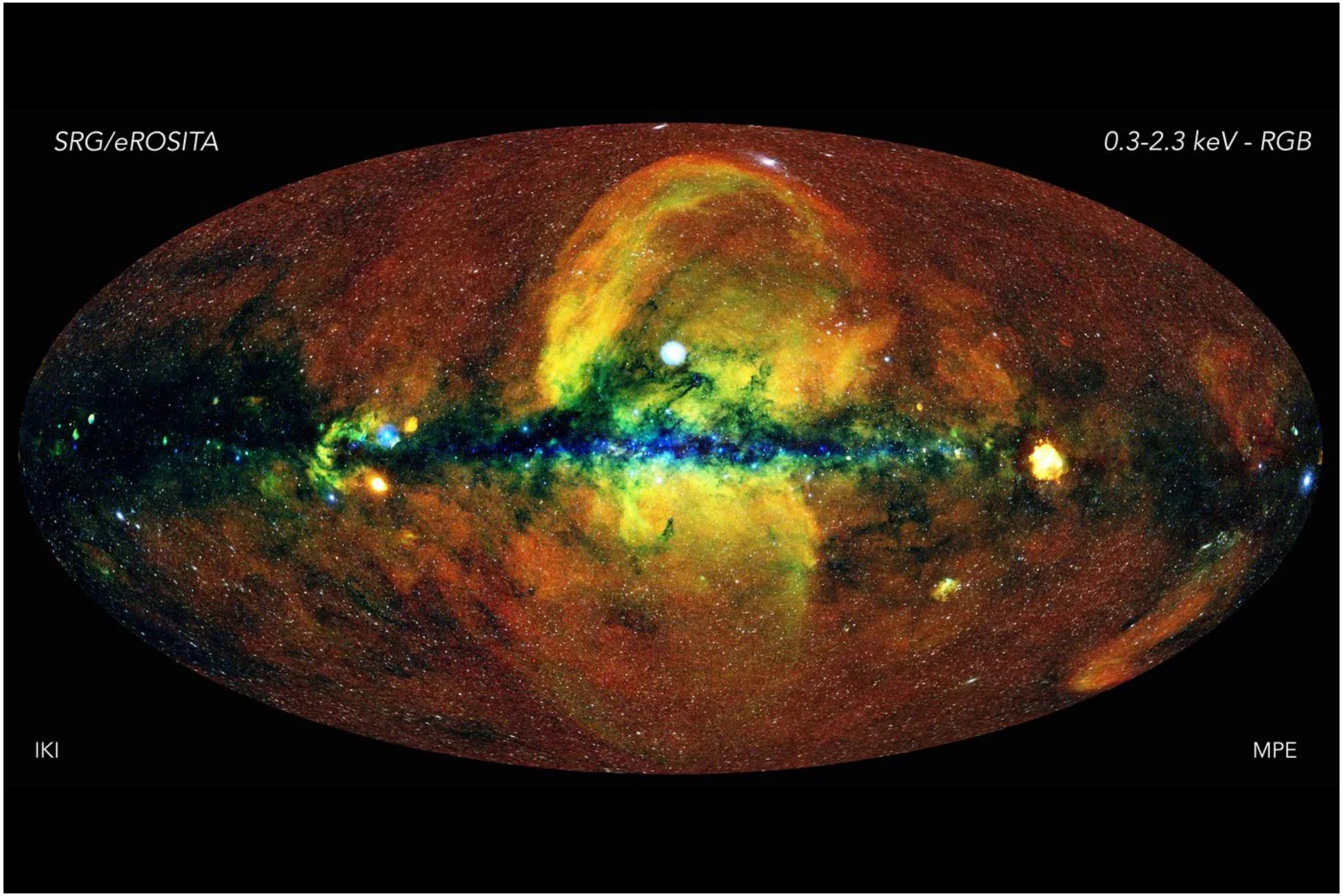


Ionized Gas (Hα; recombination lines)



H II regions ← mainly ionized by UV photons from OB stars
~ Recent star forming regions (star-formation tracer)

Hot Gas (X-Ray)



Diffuse hot gas (> 10^6 K) heated by supernovae, etc.

Molecular Gas (CO)

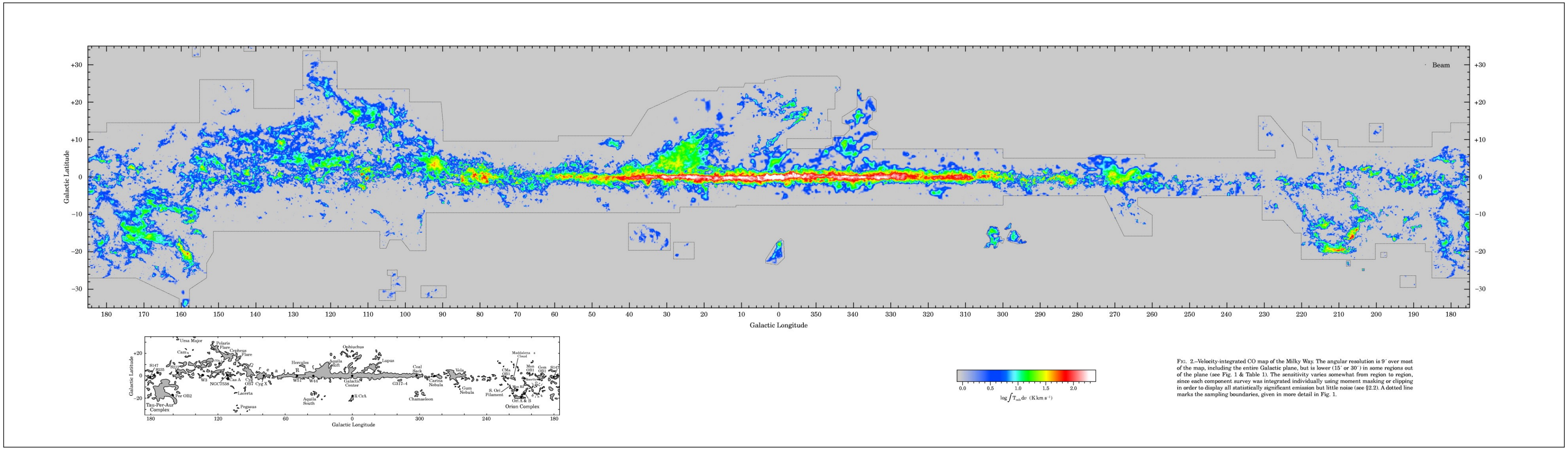


FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.

Dame et al. (2001)

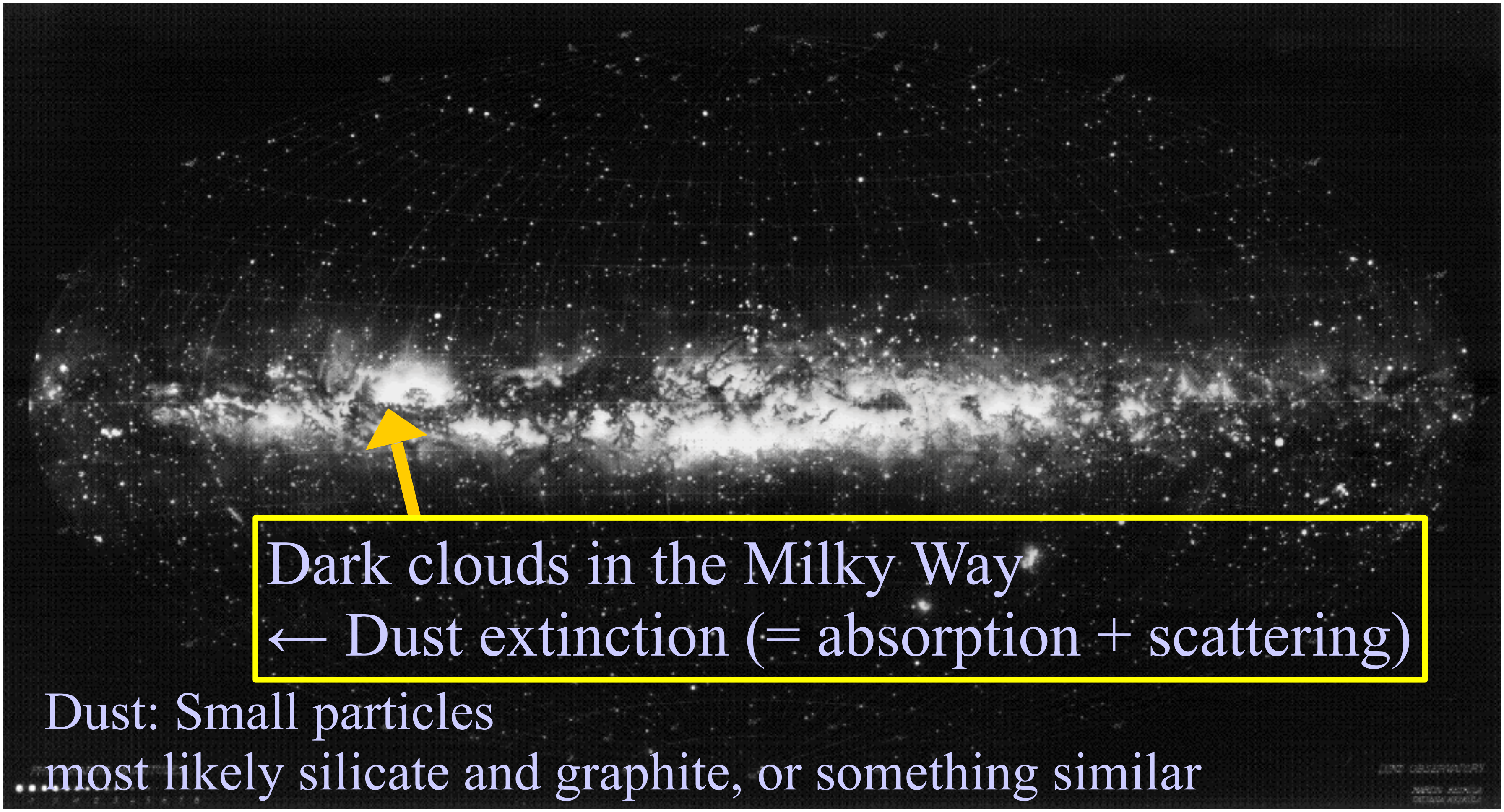
Useful tracer of cold H_2 gas:

CO-to-H_2 conversion factor

$X_{\mathrm{CO}} = N_{\mathrm{H_2}}/W_{\mathrm{CO}} = 1.8 \times 10^{20}\ \mathrm{cm^{-2}\ K^{-1}\ km^{-1}\ s}$ (in the MW)

Dust

Optical ($\lambda \sim 0.5\ \mu m$) Image of the Milky Way



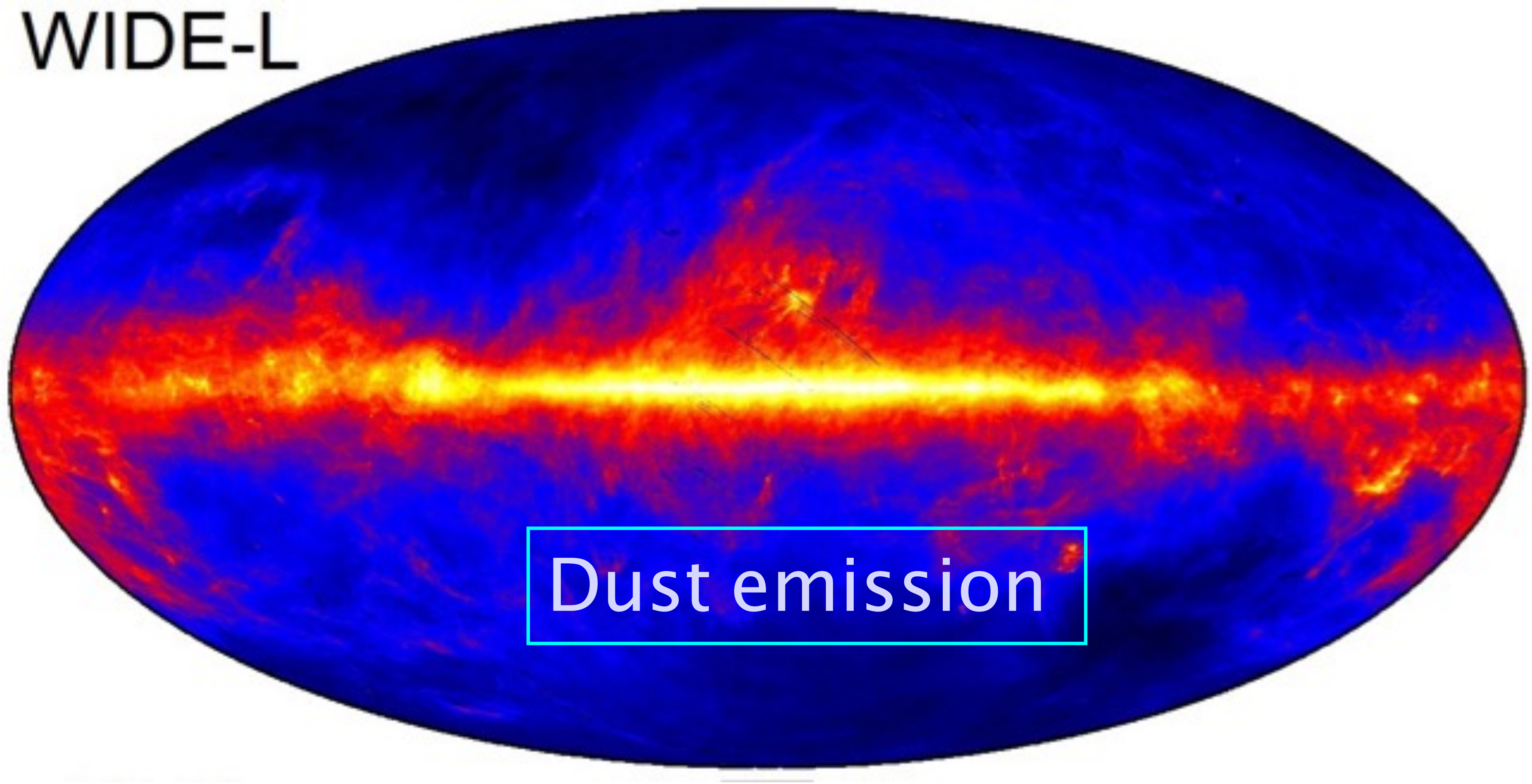
Dark clouds in the Milky Way
← Dust extinction (= absorption + scattering)

Dust: Small particles
most likely silicate and graphite, or something similar

Lund Observatory

Dust Emission in the Far Infrared

AKARI 140 μm

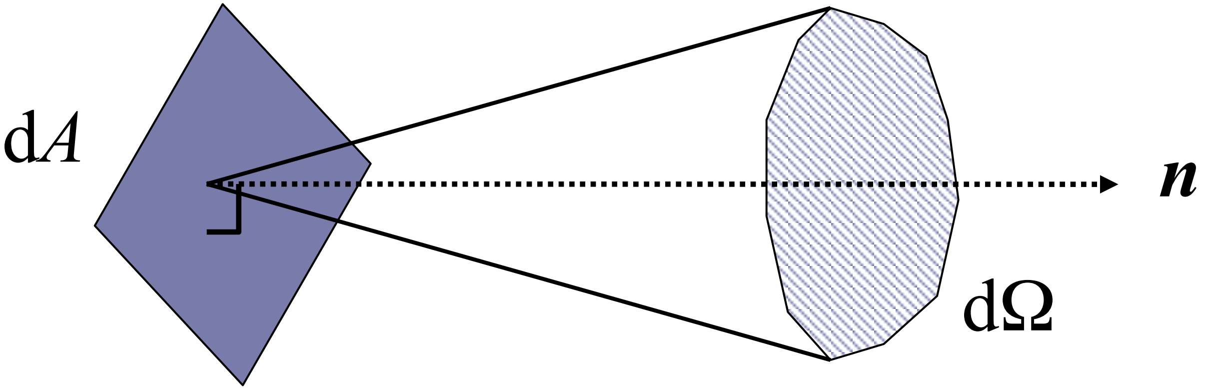


2. Interaction with Radiation

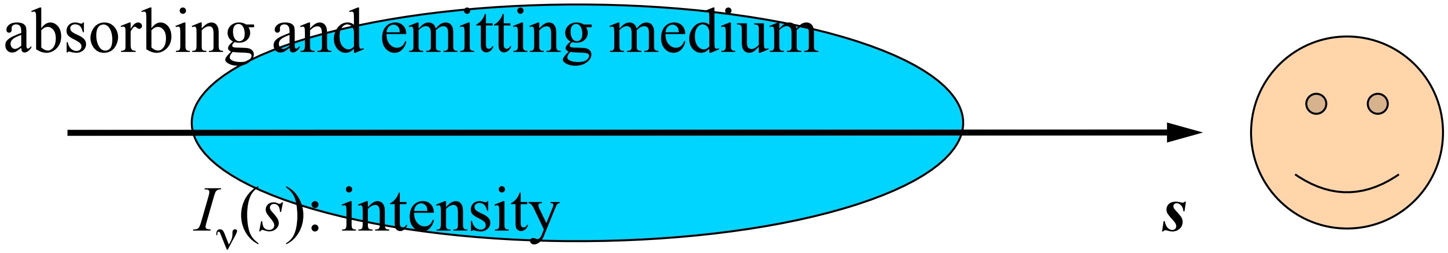
Radiation Transfer

Definition of Intensity (energy flow on a line)

$dE = I_\nu \, dA \, dt \, d\Omega \, d\nu$ I_ν [erg/cm^2/s/sr/Hz]



Radiation Transfer Equation



absorbing and emitting medium

$I_\nu(s)$: intensity

s

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\kappa_\nu \rho I_\nu + j_\nu$$

Absorption

κ_ν [cm^2/g]: mass absorption coefficient

ρ [g/cm^3]: density

Emission

j_ν [erg/cm^3/s/Hz]

Optical Depth

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\kappa_\nu \rho I_\nu + j_\nu$$

Optical depth: $d\tau_\nu = \rho\kappa_\nu ds$

$\propto$ "number of absorptions"

$\tau_\nu >> 1$: optically thick

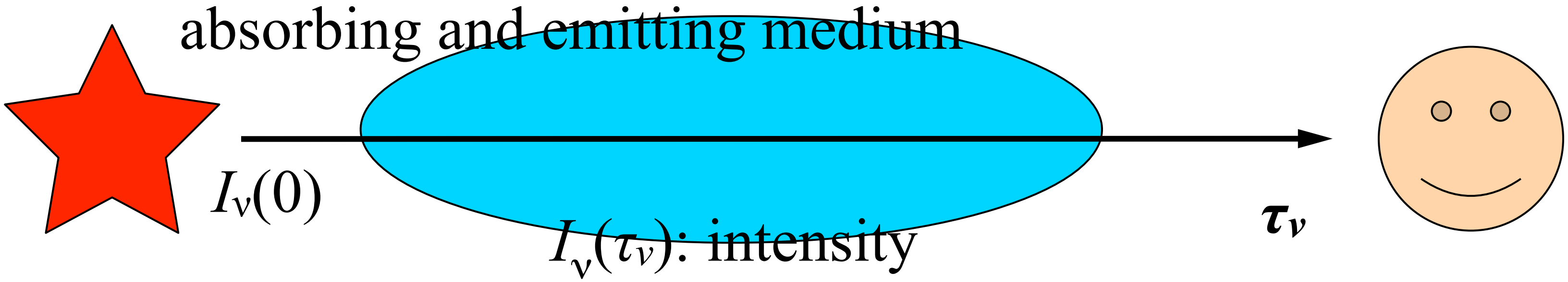
$\tau_\nu << 1$: optically thin

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$

$S_\nu = j_\nu/(\rho\kappa_\nu)$: source function

$S_\nu = B_\nu(T)$ (Planck function) for LTE

A Simple Solution



$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$

For a constant source function:

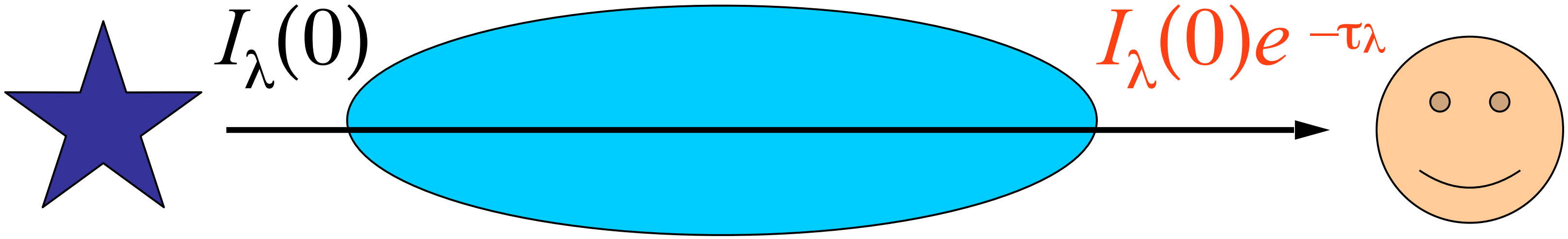
$$I_\nu(\tau_\nu) = \underbrace{I_\nu(0)\mathrm{e}^{-\tau_\nu}}_{\text{Extinction of bkg light}} + \underbrace{S_\nu(1 - \mathrm{e}^{-\tau_\nu})}_{\text{Emission}}$$

Dust Extinction

Magnitude: $m_\lambda = -2.5 \log I_\lambda + \text{const.}$

Extinction (= absorption + scattering):

$$\begin{aligned} A_\lambda &= m_\lambda(s) - m_\lambda(0) \\ &= 2.5[\log I_\lambda(0)e^{-\tau\lambda} - \log I_\lambda(0)] \\ &= (2.5 \log e)\, \tau_\lambda \end{aligned}$$



Extinction Curves

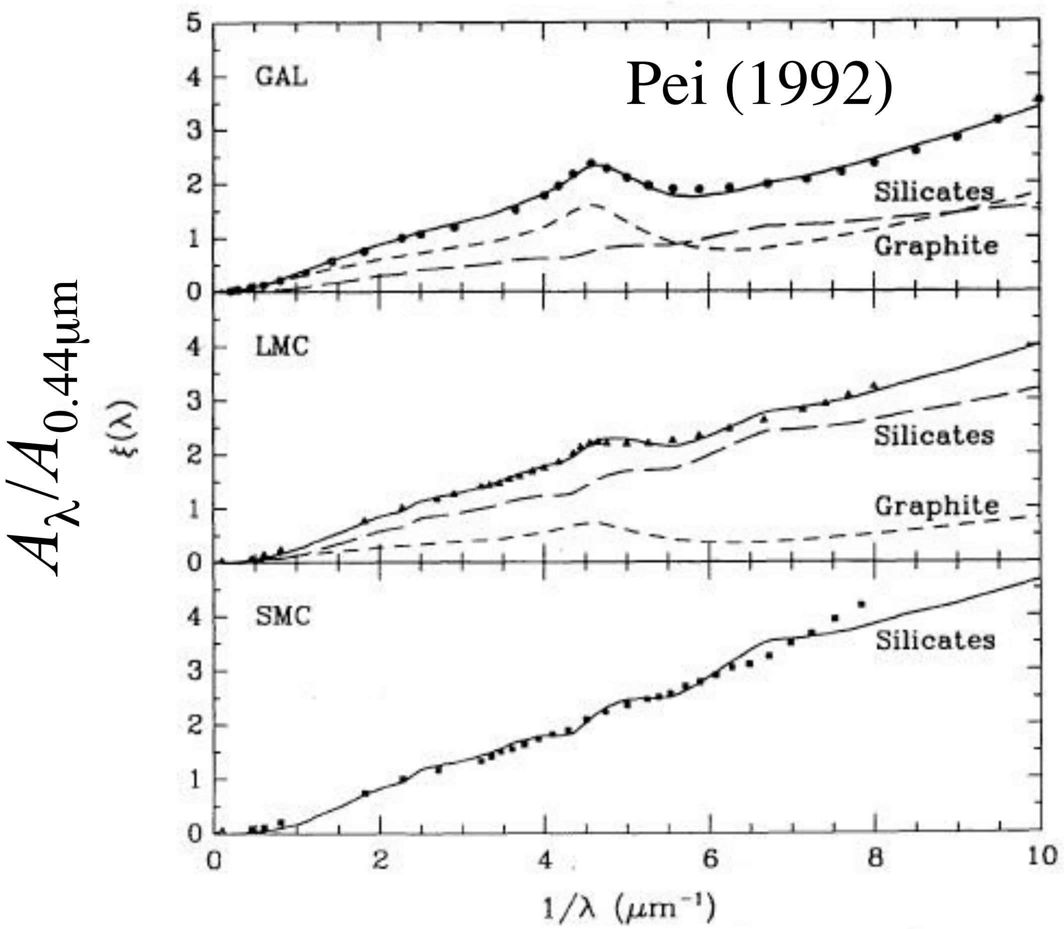


FIG. 5.—Comparisons between the model and empirical extinction curves in the Milky Way, LMC, and SMC. The short and long-dashed lines show, respectively, the relative contributions from graphite and silicate grains, with the sum of the two shown as the solid lines.

shorter wavelength

↓

larger extinction

“Reddening”

Grain size distribution

$n(a) \propto a^{-3.5}$

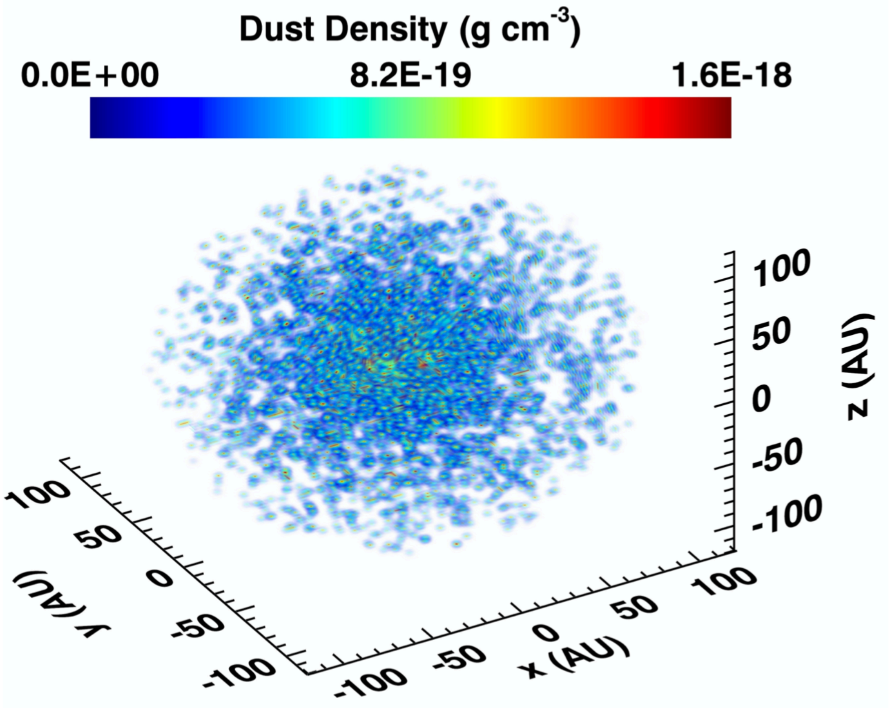
(Mathis et al. 1977)

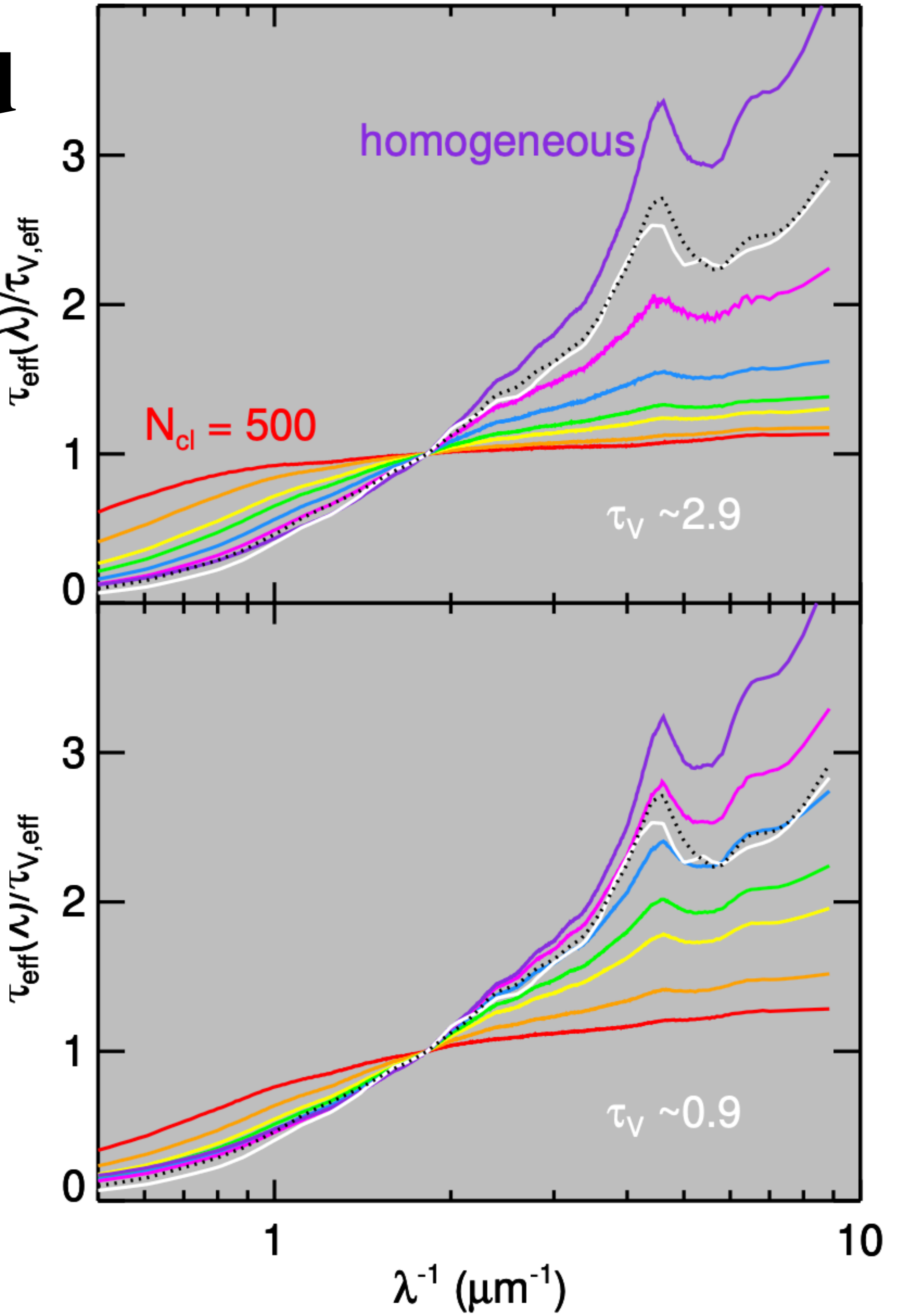
$a_{\min} = 0.005\ \mu\text{m}$

$a_{\max} = 0.25\ \mu\text{m}$

Effects of Complicated Dust Distribution

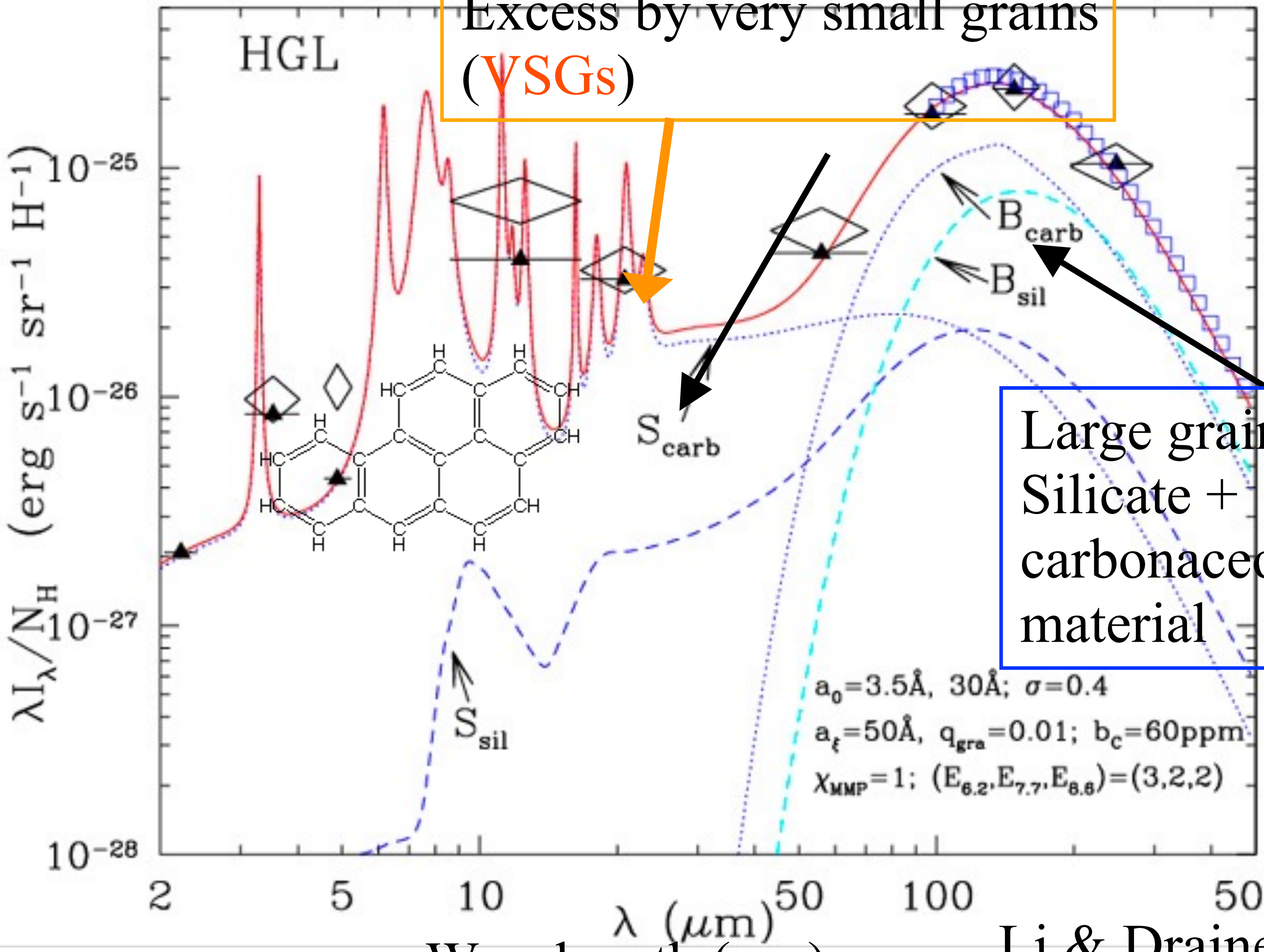
Scicluna & Siebenmorgen (2015)





The “effective” extinction curve (attenuation curve) depends on the clumpiness.

Infrared Emission of Dust



Excess by very small grains (VSGs)

Large grains (LGs)
Silicate + carbonaceous material

Intensity

Wavelength (µm)

Li & Draine (2001)

Effects of UV Radiation

H II Region

$$\dot{N}_{\rm Lyc} = \frac{4\pi}{3} R_{\rm S}^3 \overset{n_e n_p}{n^2} \beta_{\rm B}$$

Number of Lyman continuum (> 13.6 eV) photons emitted per time.

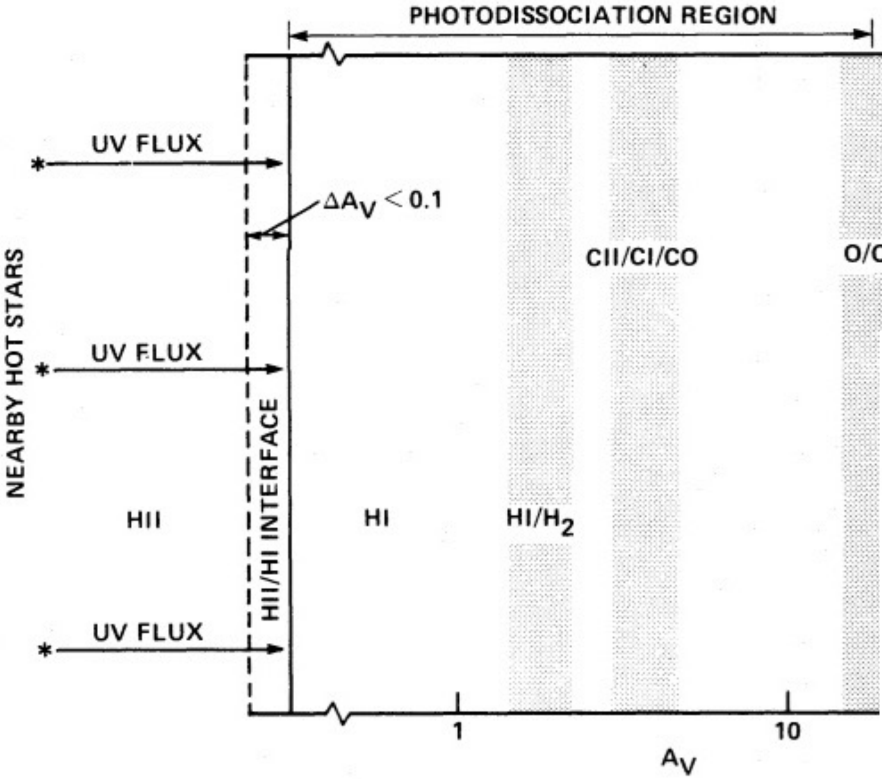
Case B: Lyman series/continuum (transitions down to *n* = 1) are optically thick. Recombination rate to *n* >= 2 levels contributes to the loss of ionizing photons.

$R_{\rm S}$: Strömgren radius

$$R_{\rm S} \simeq 1.2 \left(\frac{n}{10^3\ {\rm cm}^{-3}}\right)^{-2/3} \left(\frac{\dot{N}_{\rm Lyc}}{5\times10^{49}\ {\rm s}^{-1}}\right)^{1/3}\ {\rm pc}$$

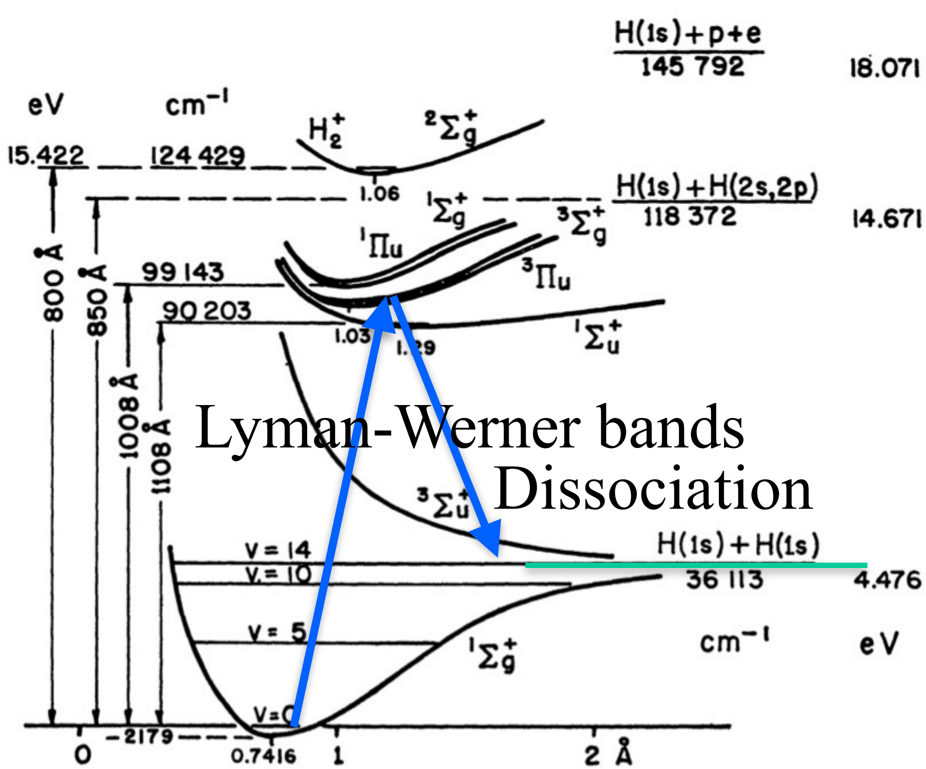
Orion Nebula (HST)

Photodissociation Region (PDR)



Tielens & Hollenbach (1985)

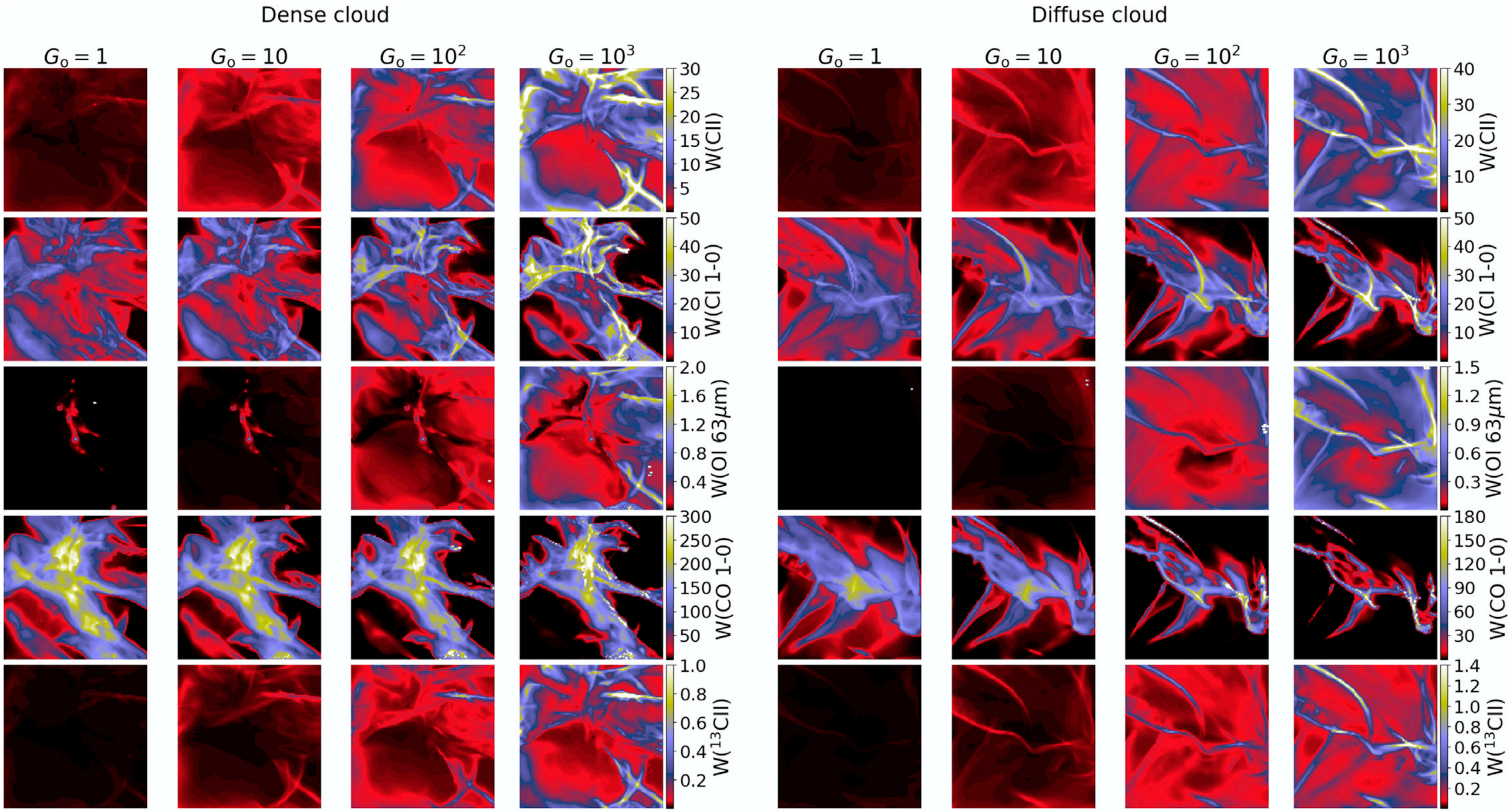
Field et al. (1966)



Lyman-Werner bands

Dissociation

Abundant Line Emissions from PDRs



Bisbas et al. (2021)

3. Multi-Phase ISM

McKee & Ostriker (1977)

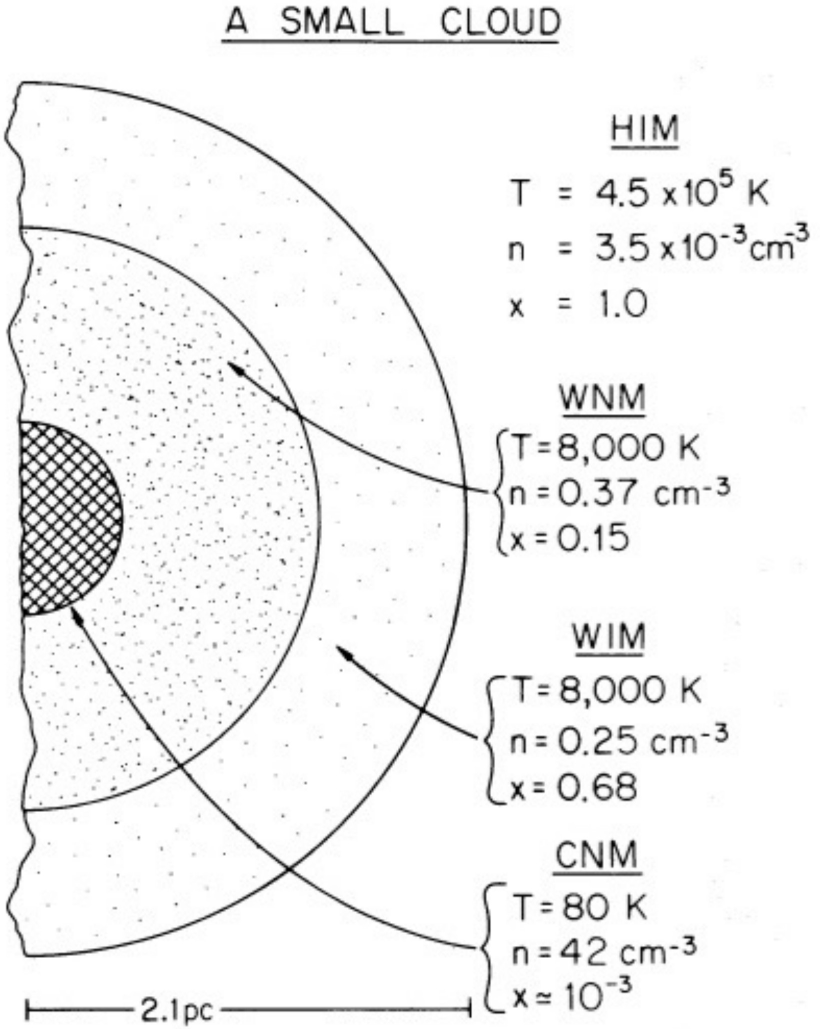


FIG. 1

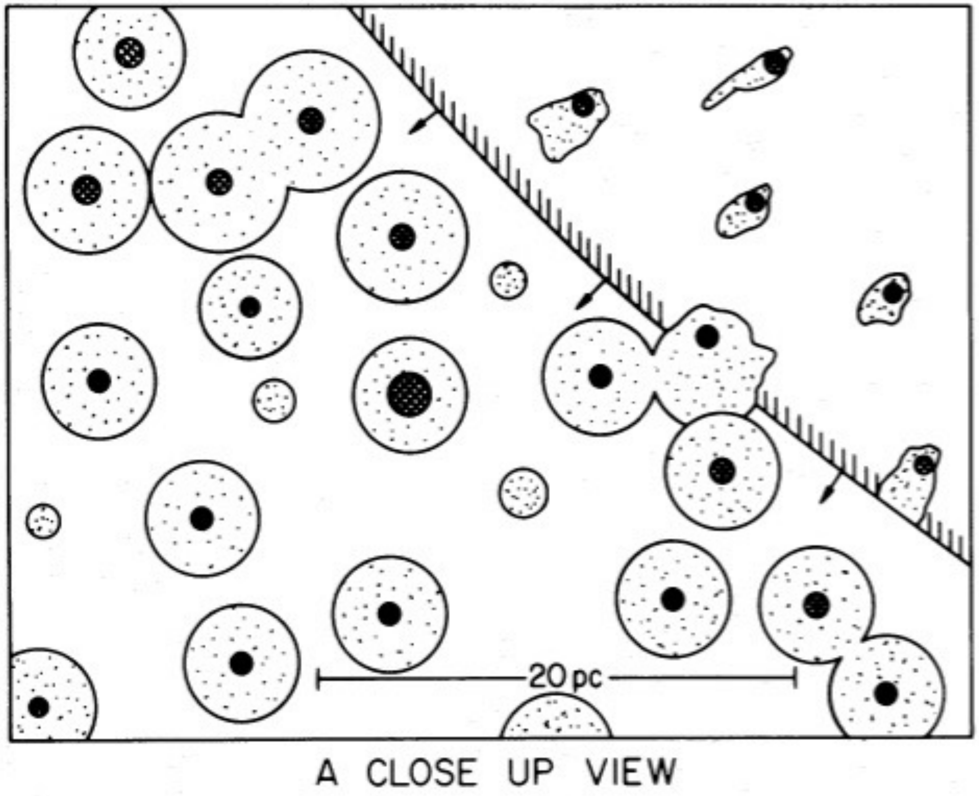
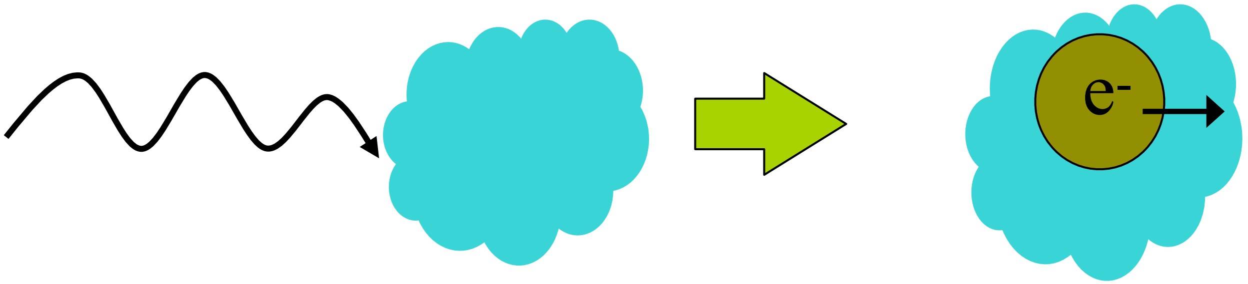


FIG. 2

Heating

Formation of free electrons by radiation causes heating (energy transfer from radiation to gas).

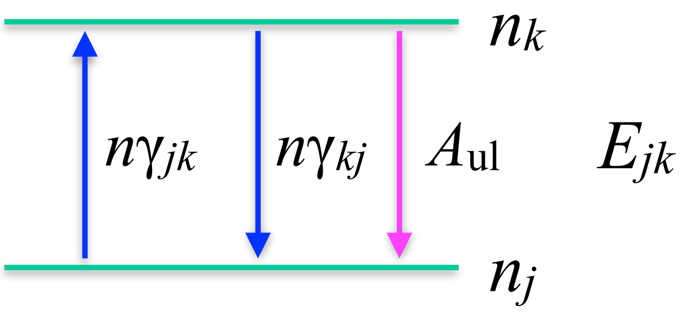


Major heating mechanisms:

Photoionization ($H + \gamma \rightarrow H^+ + e^-$)

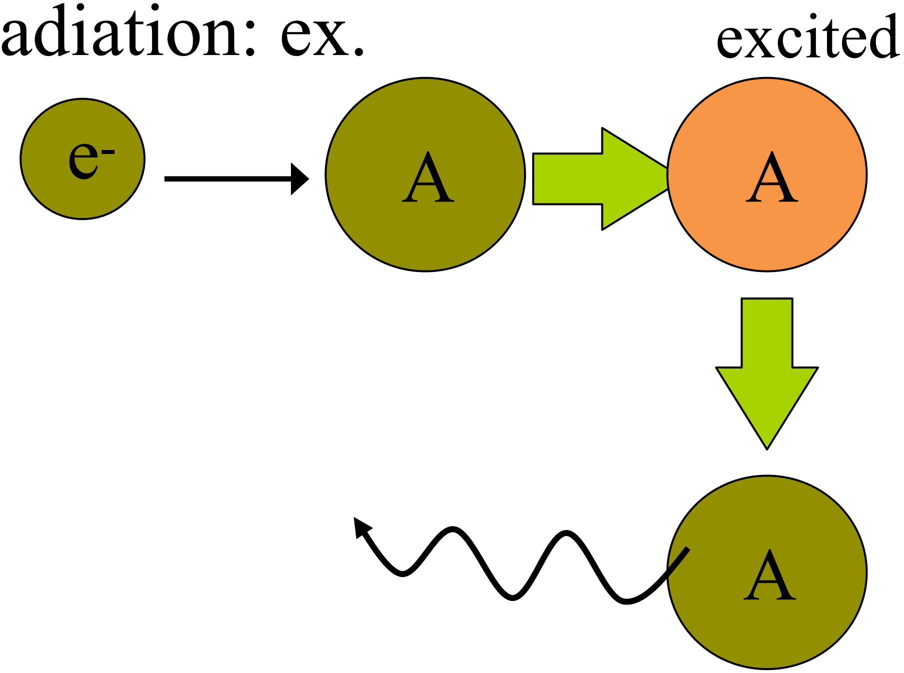
Photoelectric emission ($\text{dust} + \gamma \rightarrow \text{dust}^+ + e^-$)

Cooling



n: number density of colliding species

Thermal energy is converted into radiation: ex.

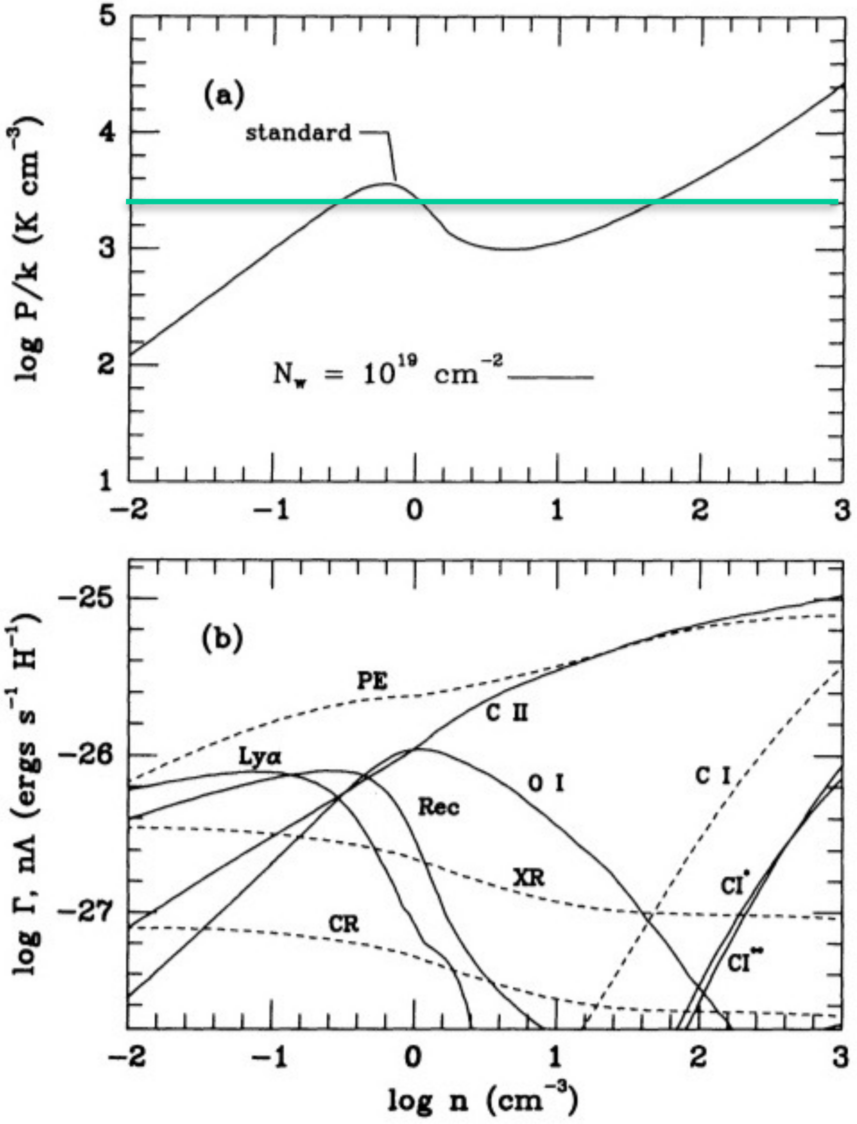


$$\Lambda = n \sum_{j<k} E_{jk}(n_j \gamma_{jk} - n_k \gamma_{kj})$$

Two-Phase Model of Neutral Medium

Wolfire et al. (1995)

Field et al. (1969)



Thermal equilibrium:

$\Lambda \quad = \quad \Gamma$

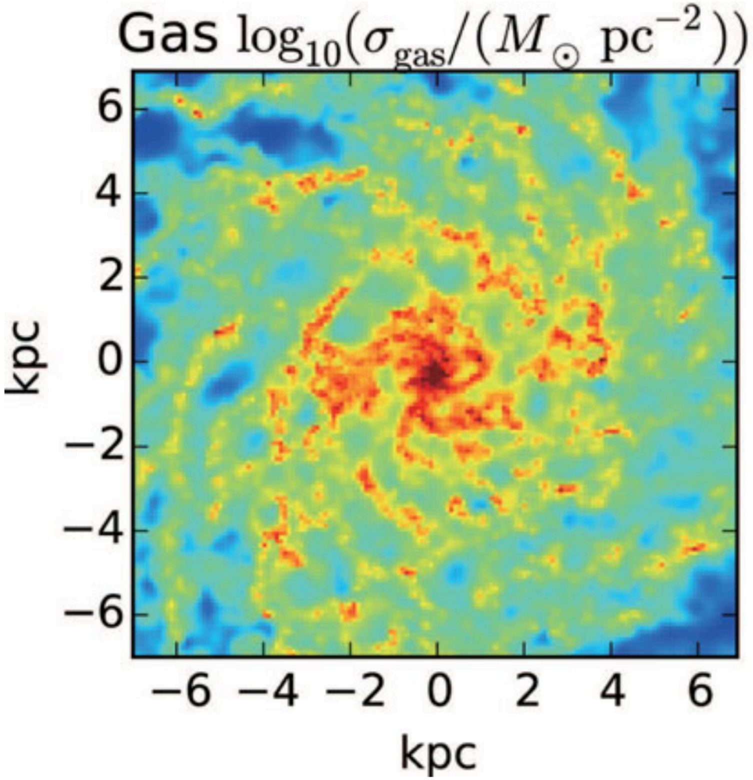
(cooling) = (heating)

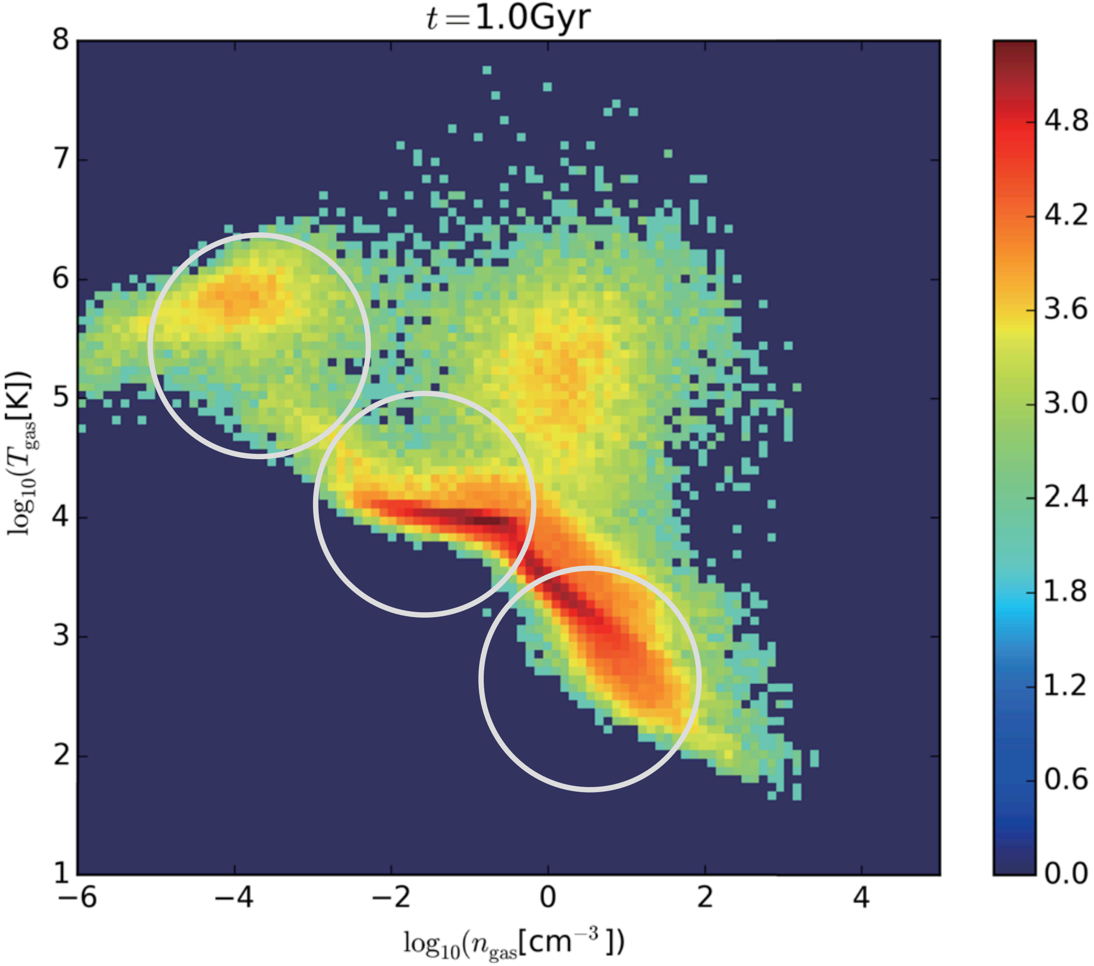
Lyα line cooling ~ Photoelectric heating at low density ($T \sim 10^4$ K)

C II line cooling ~ Photoelectric heating at high density ($T \sim 100$ K)

ISM Structures in Simulation

Aoyama, Hirashita, et al. (2017)





Realistic structures are more dynamic, but we still see some characteristic features in the phase diagram.

Molecular Clouds

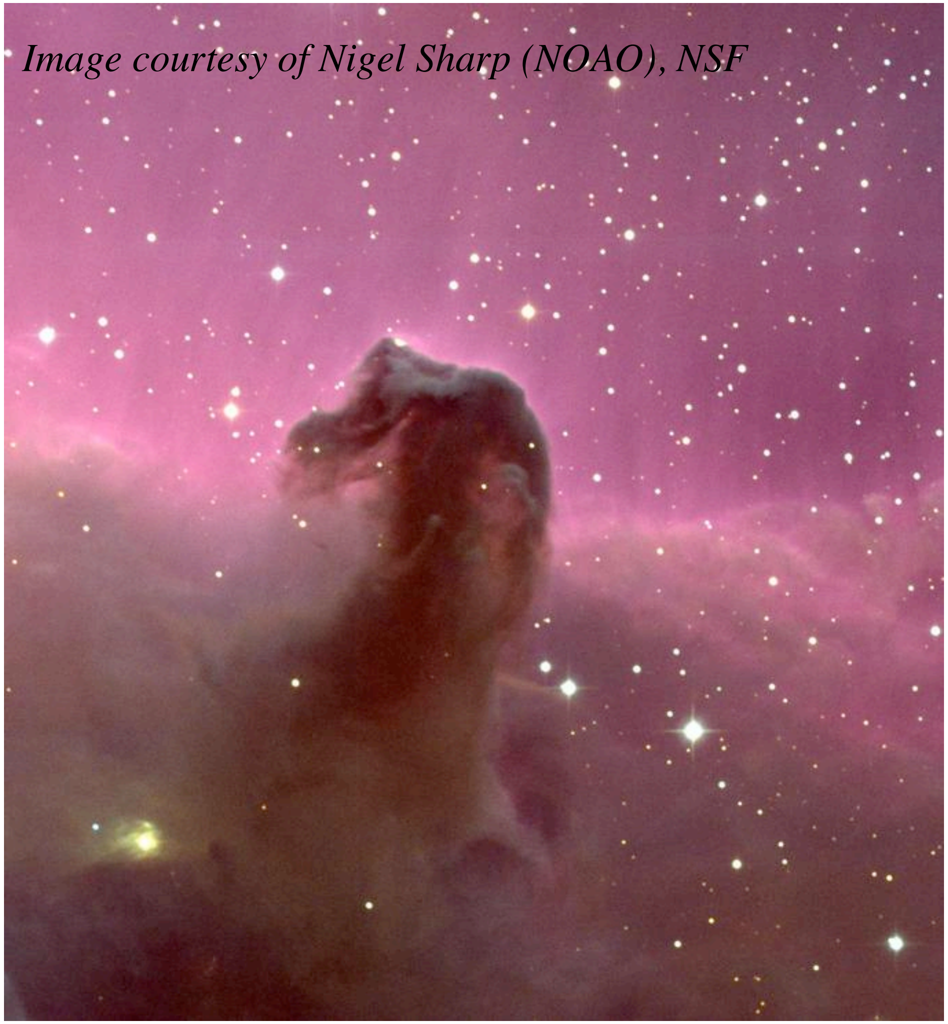
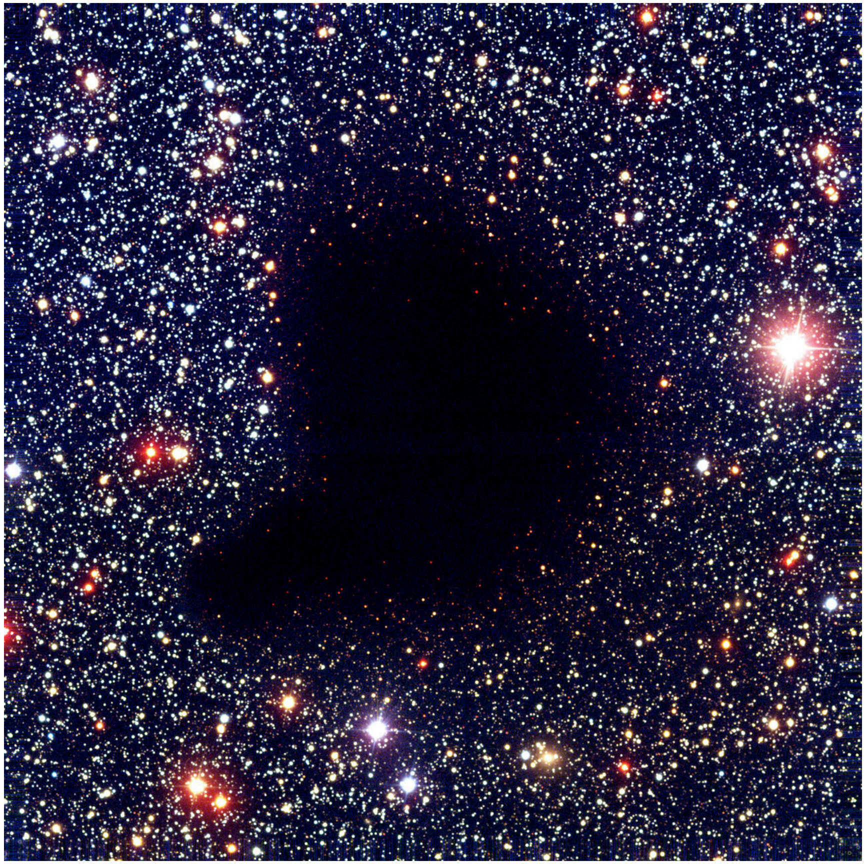
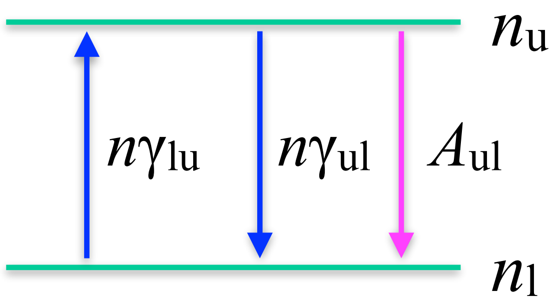


Image courtesy of Nigel Sharp (NOAO), NSF


ESO

See Yueh-Ning's talk for the processes leading to star formation.

Various Tracers and Critical Density



n: number density of colliding species

Statistical equilibrium:

$$n_\mathrm{l} n\gamma_\mathrm{lu} = n_\mathrm{u} n\gamma_\mathrm{ul} + n_\mathrm{u} A_\mathrm{ul}$$

$$\gamma_\mathrm{lu} = (g_\mathrm{u}/g_\mathrm{l})\gamma_\mathrm{ul}\ \exp(-E_\mathrm{ul}/k_\mathrm{B}T)$$

$$\frac{n_\mathrm{u}}{n_\mathrm{l}} = \frac{g_\mathrm{u}/g_\mathrm{l}\ \exp(-E_\mathrm{ul}/k_\mathrm{B}T)}{1 + n_\mathrm{cr}/n} \qquad n_\mathrm{cr} \equiv \frac{A_\mathrm{ul}}{\gamma_\mathrm{ul}}$$

Critical density

Critical density ~ Typical density which the line is suitable for tracing.

Critical densities at 10 K:

CO(1-0): 4×10^3 cm^{-3}, CO(3-2): 7×10^4 cm^{-3}

HCO$^+$(1-0): 2×10^5 cm^{-3}, HCO$^+$(3-2) : 3×10^6 cm^{-3}

HCN(1-0): 2×10^6 cm^{-3}, HCN(3-2): 6×10^7 cm^{-3}

4. Dynamical Processes

See Hung-Yi’s talk for hydrodynamic equations.

Characteristic Scales

Free-fall time: gravitational contraction

$t_{\mathrm{ff}} \sim 1/(G\rho)^{1/2}$

Crossing time: hydrodynamic effects

$t_{\mathrm{cr}} \sim L/v \quad v = c_{\mathrm{s}} = (\gamma P/\rho)^{1/2} \propto T^{1/2}$ (for sound wave)

$v = v_{\mathrm{A}} = (B^2/4\pi\rho)^{1/2}$ (for Alfvén wave)

Cooling time: gas cooling

$t_{\mathrm{cool}} \sim k_{\mathrm{B}}T/n\Lambda$

Jeans length/mass (typical size/mass for gravitationally bound structures)

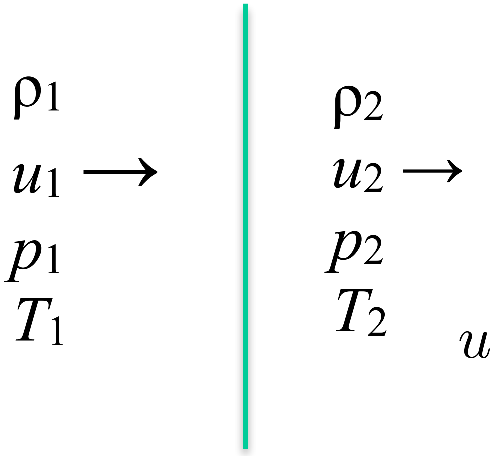
$\lambda_{\mathrm{J}} \sim c_{\mathrm{s}}\, t_{\mathrm{ff}} \propto (T/\rho)^{1/2}$

$M_{\mathrm{J}} \sim \rho\lambda_{\mathrm{J}}^3 \propto T^{3/2}/\rho^{1/2}$

Estimate these quantities for the objects you like.

Shocks

Conservation laws in hydrodynamic equations:



$$\rho_1 u_1 = \rho_2 u_2$$

$$p_1 + \rho_1 u_1^2 = p_2 + \rho_2 u_2^2$$

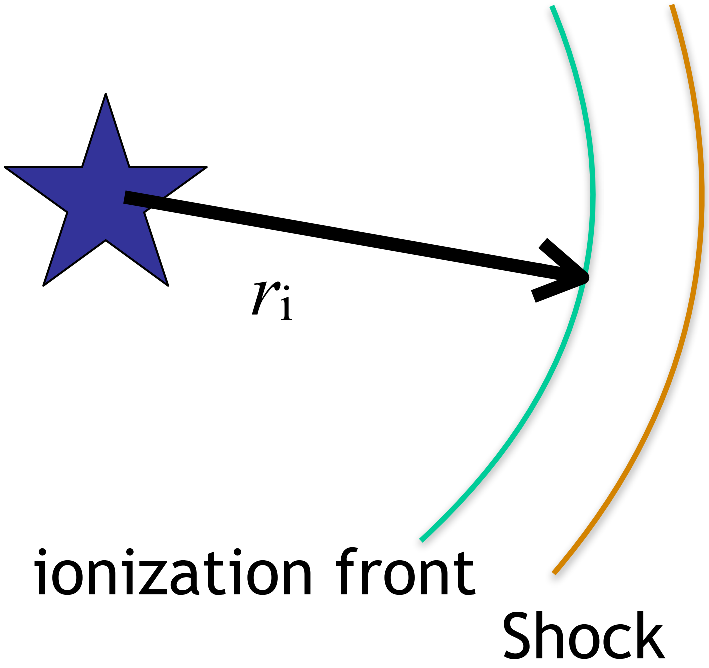
$$u_2\left(\frac{1}{2}\rho_2 u_2^2 + \mathcal{U}_2\right) - u_1\left(\frac{1}{2}\rho_1 u_1^2 + \mathcal{U}_1\right) = u_1 p_1 - u_2 p_2$$

$$\mathcal{U} = \frac{1}{1-\gamma} p$$

$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma+1}\mathcal{M}^2 - \frac{\gamma-1}{\gamma+1} \qquad \frac{u_2}{u_1} = \frac{\rho_1}{\rho_2} = \frac{2}{\gamma+1}\frac{1}{\mathcal{M}^2} + \frac{\gamma-1}{\gamma+1}$$

$$\mathcal{M}^2 \equiv \frac{\rho_1 u_1^2}{\gamma p_1} = \frac{u_1^2}{C_1^2}$$ Mach number

Expansion of H II Region



Conservation laws at the ionization front and shock front

Constant ionization photon luminosity ($\rho_{II} \propto r_i^{-3/2}$; see Strömgren radius)

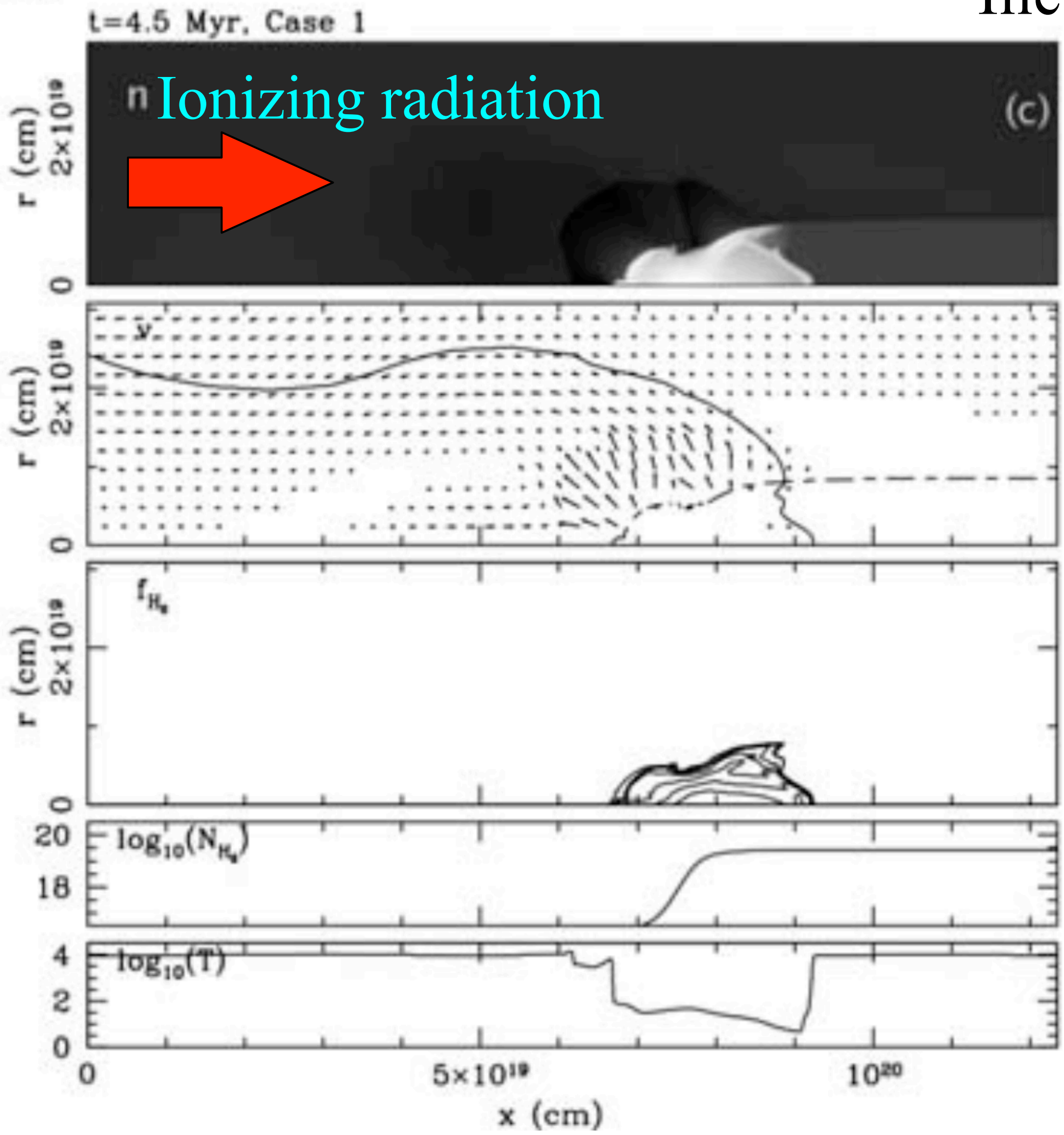
$$\frac{r_i}{r_{i0}} = \left(1 + \frac{7}{4}\frac{C_{II}t}{r_{i0}}\right)^{4/7}$$

C_{II} : Sound speed in the H II region

r_{i0}: initial radius of H II region (under $\rho_{II} = \rho_I$)

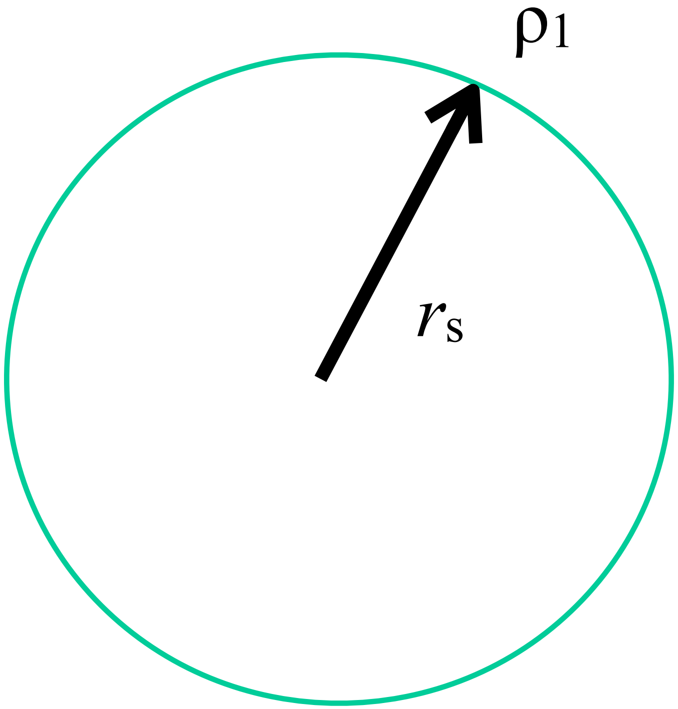
External Ionizing Radiation

Iliev, Hirashita, Ferrara (2006)



Ionizing photons incident on a cloud could cause compression, inducing star formation, or evaporation, suppressing star formation.

Supernova Blast Wave



Based on the pressure inside the SN remnant (described by E and r_s), and assuming a strong shock, we obtain the relation V_s and r_s (under a given ρ_1.

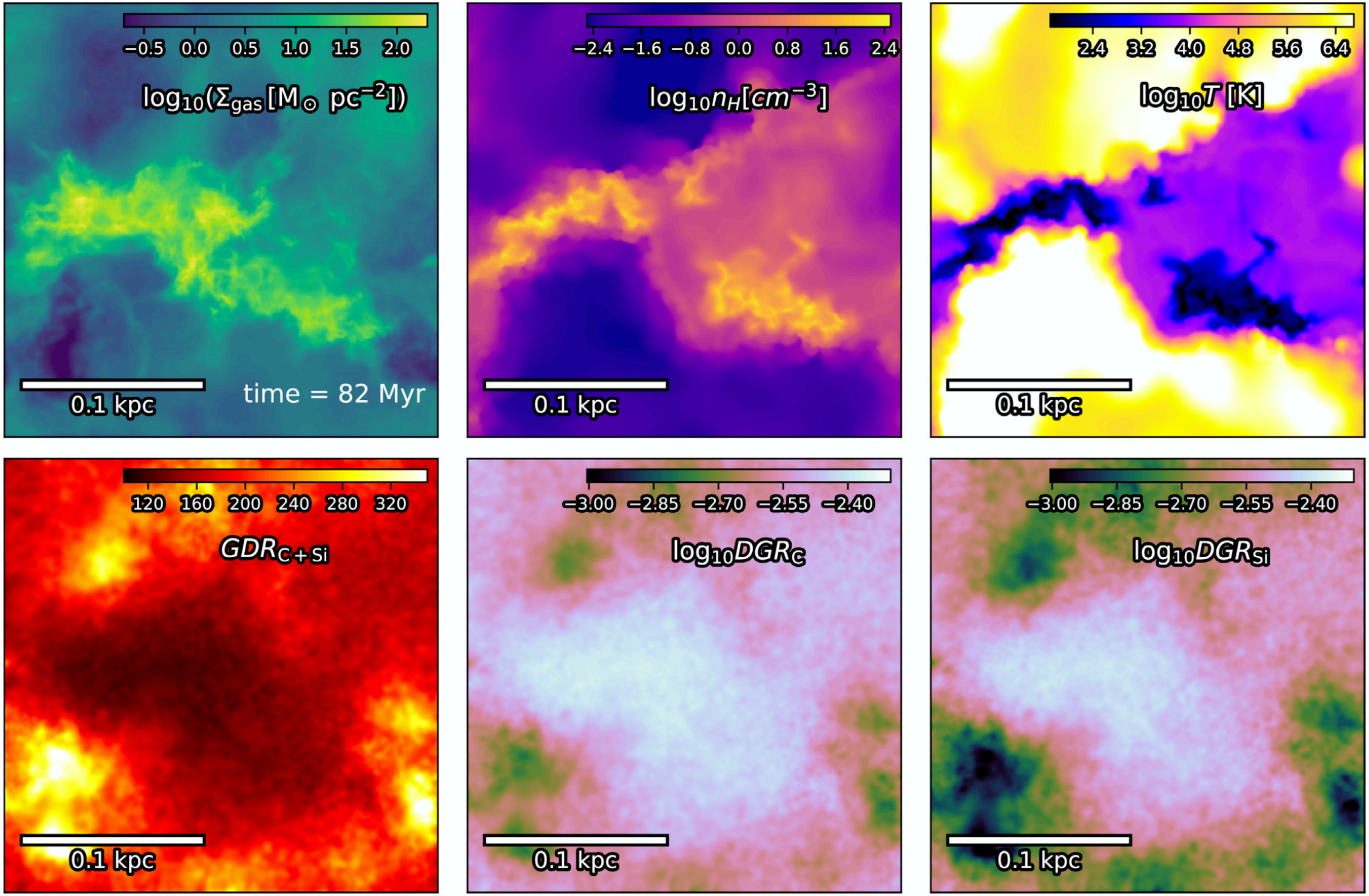
$$r_s \sim (E/\rho_1)^{1/5} t^{2/5}$$

Sedov solution

See Yen-Chen's talk for SN explosion.

Supernovae and Dust Destruction

Hu et al. (2019)



5. Summary

Overviewed the following processes in the ISM:

(1) Radiation transfer.
(2) Ionization and dissociation.
(3) Heating and cooling.
(4) Multi-phase ISM.
(5) Dynamical processes (hydrodynamic treatment of the ISM).

Further Reading

- Spitzer, L. 1978, “Physical Processes in the Interstellar Medium”
- Tielens, A. G. G. M. 2005, “The Physics and Chemistry of the Interstellar Medium”