THE INTERSTELLAR MEDIUM: V
Molecular clouds

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OUTLINE

- Background.
- Interesting atomic lines: The [C I] 609/370-μm lines.
- Molecular transitions: electronic, rotational, vibrational...
- Molecular hydrogen: The electronic Lyman and Werner bands.
- Conditions in diffuse clouds.

Background

- HI-21cm studies: Estimates of N_{HI}, T_K, T_S, $B_{\parallel}$, scale height.
  External galaxies: Mass, spatial distribution, velocity field,

- Collisional & radiative excitation / de-excitation: (2-level atom)
  $$(n_1/n_0) = [n_c k_{01} + n_\gamma (g_1/g_0) A_{10}] / [n_c k_{10} + (1 + n_\gamma) A_{10}]$$

- Critical density: $n_{crit,u} = [\Sigma_{l<u} (1 + n_\gamma) A_{ul}] / [\Sigma_{l<u} k_{ul}]$
  If $n_c \gg n_{crit,u}$ ⇨ $T_X = T_K$; if $n_c \ll n_{crit,u}$ ⇨ $T_X = T_R$.

- [CII]-158μm line: "Forbidden" transition; $A_{10} \sim 2.4 \times 10^{-6}$ s^{-1}.

- $n_{crit} \sim 3000$ $cm^{-3} \gg$ Number density in diffuse clouds ⇨ $T_X \ll T_K$!

- Collisional excitation, radiative de-excitation ⇨ Radiative losses!

- [CII]-158μm line most important cooling route in diffuse gas!
  ~ 0.5% of a galaxy's luminosity! Very important line for ALMA !

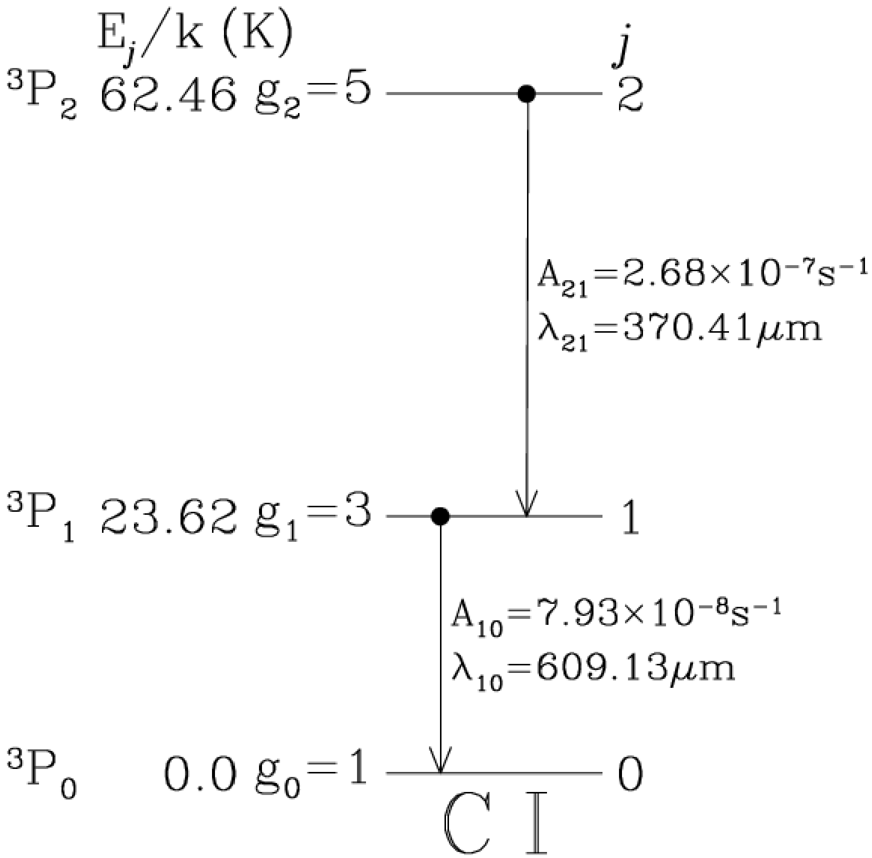
Three Level Atoms: CI

- Three level system: More complex!

- $(dn_2/dt) = R_{02}n_0 + R_{12}n_1 - (R_{20} + R_{21})n_2$
  $(dn_1/dt) = R_{01}n_0 + R_{21}n_2 - (R_{10} + R_{12})n_1$

- E.g. $R_{10} = C_{10} + (1 + n_{\gamma,10})A_{10}$;
  $R_{01} = (g_1/g_0)[C_{10}e^{-E_{10}/kT} + n_{\gamma,10}A_{10}]$...

- In steady state, $(dn_2/dt) = (dn_1/dt) = 0$.



(Draine 2011)

- $(n_1/n_0) = (R_{01}R_{20} + R_{01}R_{21} + R_{21}R_{02})/(R_{10}R_{20} + R_{10}R_{21} + R_{12}R_{20})$
  $(n_2/n_0) = (R_{02}R_{10} + R_{02}R_{12} + R_{12}R_{01})/(R_{10}R_{20} + R_{10}R_{21} + R_{12}R_{20})$.

Three Level Atoms: CI

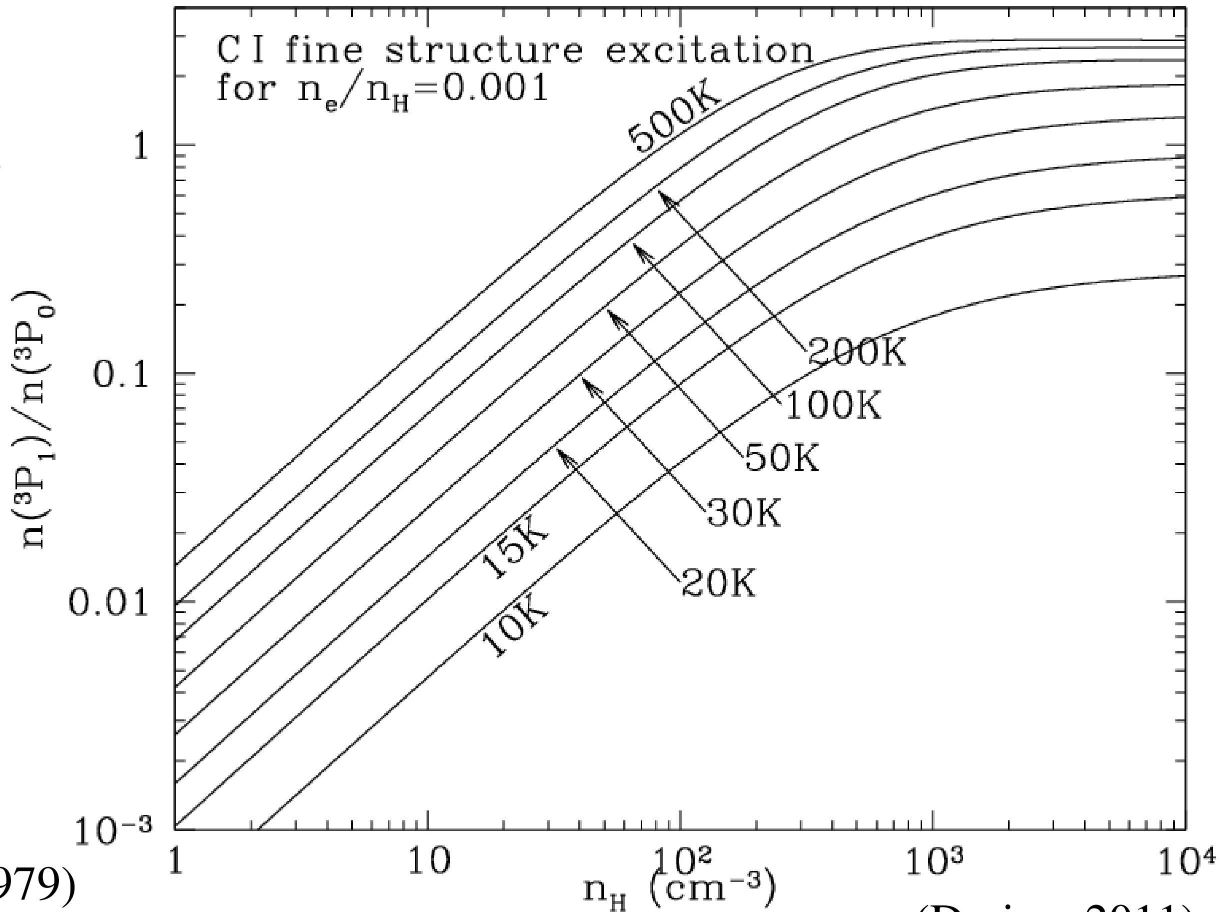
- $n_{crit} \sim 700\ cm^{-3}$ ($T_K \sim 100$ K) ; $n_{crit} \sim 150\ cm^{-3}$ ($T_K \sim 5000$ K).
  Densities in diffuse ISM much lower than critical density!

- Since $n < n_{crit}$, the level populations depend on n & T_K !

- Level populations obtained from strengths of UV lines to higher excited states.

- Three levels ⇨ Solve for density and temperature!
  ⇨ Infer thermal pressure!

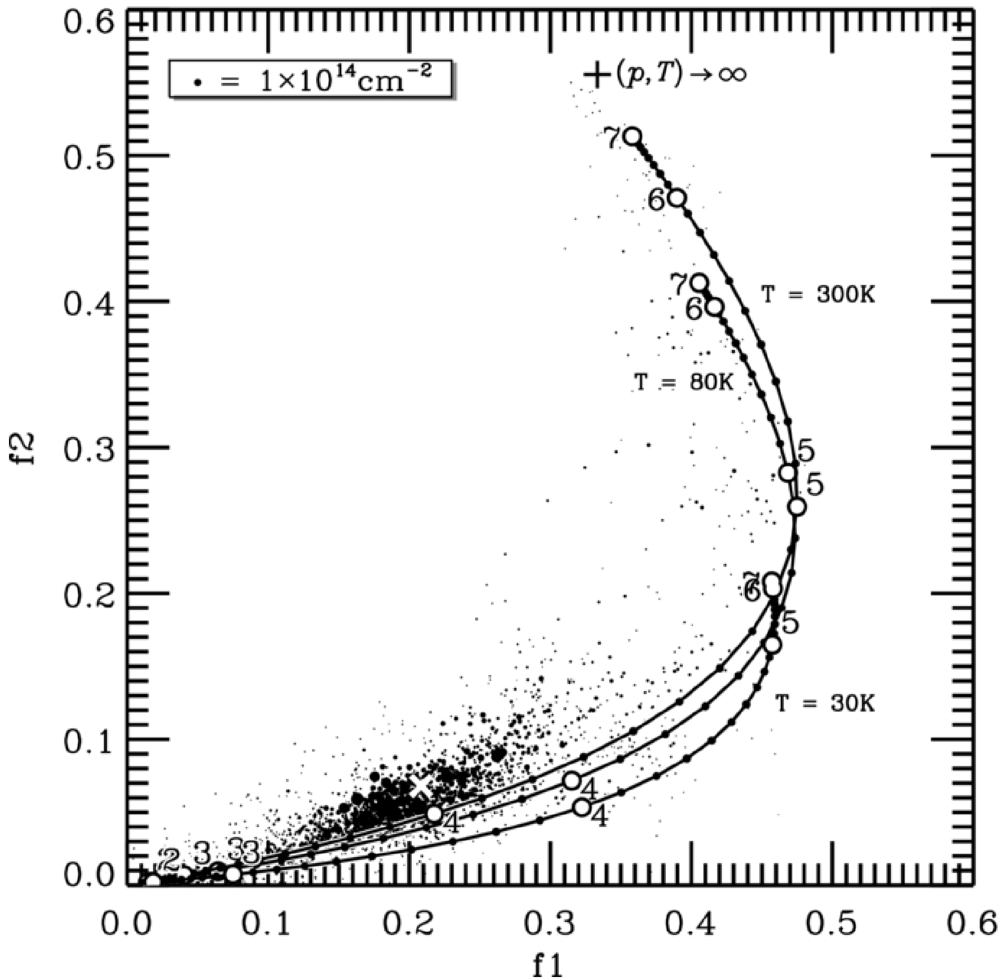
(Jenkins & Shaya 1979)

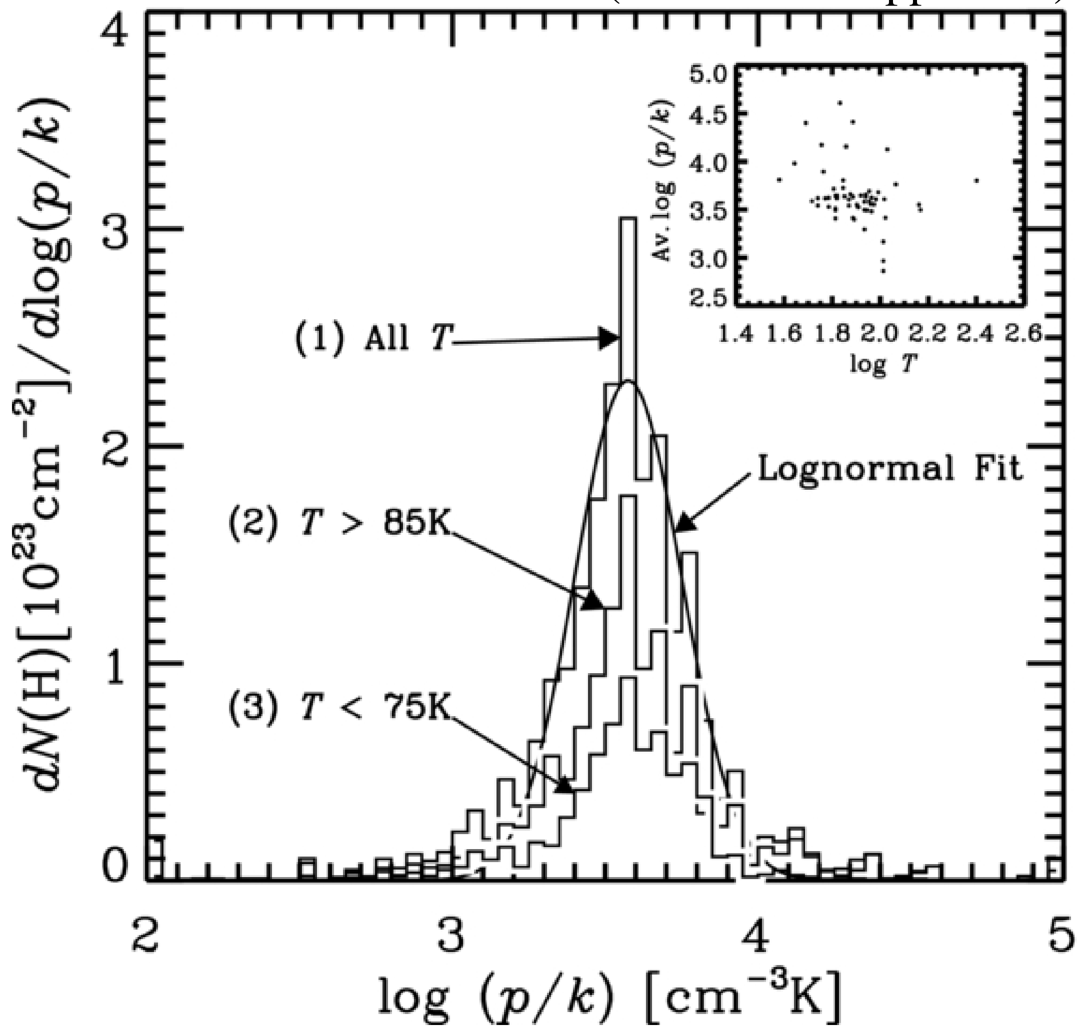


(Draine 2011)

THREE LEVEL ATOMS: CI

(Jenkins & Tripp 2011)





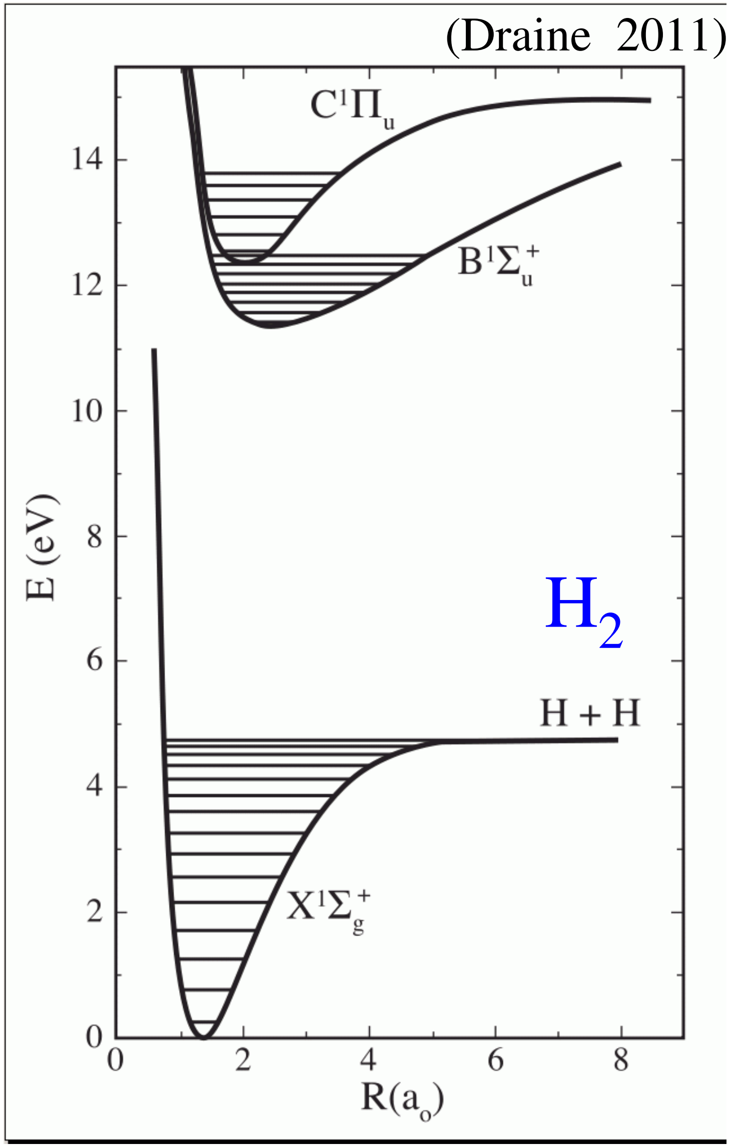
- Most points lie above and to the left of the curves!

  ⇨ Two pressures, 3800 cm^{-3} K and > 10^4 cm^{-3} K ???

(Jenkins & Tripp 2011)

Molecular Lines: Vibration

- Diatomic molecules: Stretch along the line joining the nuclei.



- Vibration: Assume fixed internuclear separation, solve for electron ψ_q & E_q. For slow nuclear motion, ψ_q & E_q will change adiabatically.
  ⇨ Nuclear motion under effective potential $V_q(r_n) = E_q(r_n) + (Z_1Z_2e^2/r_n)$.

- Near minimum r_0, $V_q(r) = V_0 + (1/2)k(r-r_0)^2$
  Harmonic oscillator: $\omega_0 = (k/m_r)^{1/2}$.

- Vibrational modes: $E = h\nu_0\,(v + 1/2)$
  Low mass ⇨ High vibration frequency (e.g. H_2: 2.1μm).

Molecular Lines: Rotation

- Diatomic molecules: Rotate around axis ⊥ to molecular axis.

- Classical kinetic energy of a rigid rotor = $(J\hbar)^2/2I$,
  where $I = m_r r_0^2$ is the moment of inertia.

  ⇨ Quantum mechanical rotational energy = $J(J+1)\hbar^2/2m_r r_0^2$.

- Total vibration-rotation energy in electronic state *q*:

$$E_q = V_q(r_0) + h\nu_0 (v + ½) + B_v J(J+1)$$

  with $\nu_0 = (\omega_0/2\pi) = (1/2\pi)(k/m_r)^{1/2}$ & $B_v = \hbar^2/2m_r r_0^2$.

  Vibration lines, v → v-1: $h\nu_0$; Rotation lines J → J-1: $2B_v J$

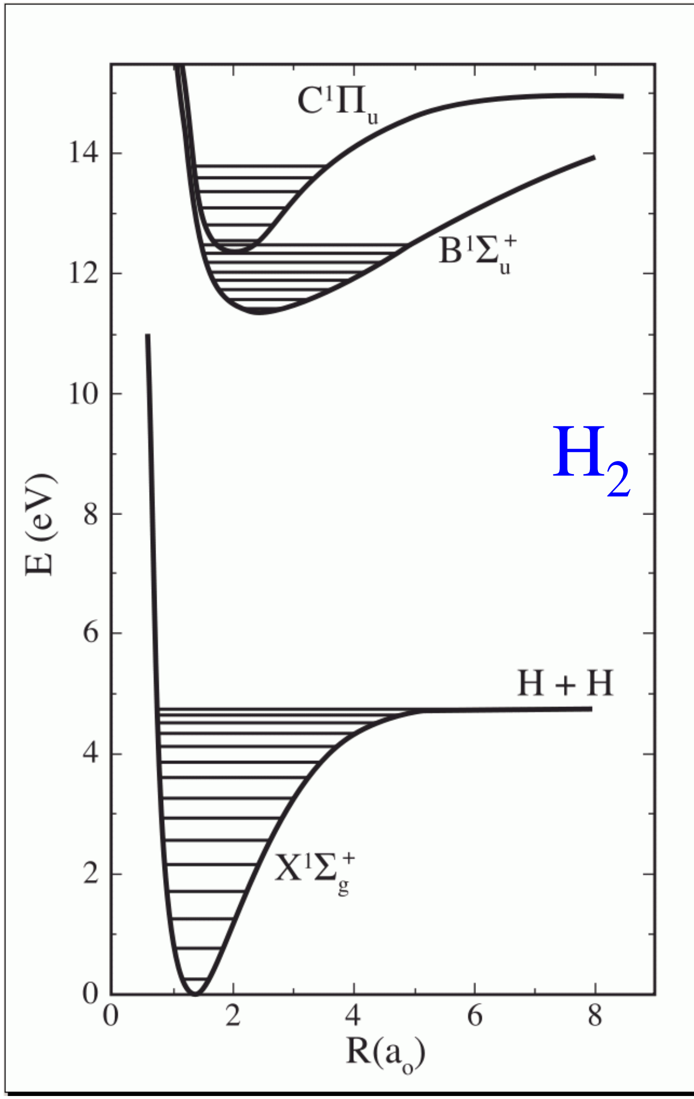
- None of the above is *exact*!!! Not a quadratic potential, nor a rigid rotor; I depends on vibrational & rotational levels.

- *All* molecules have rotation/vibration states, besides electronic states.

Wavelengths & Selection Rules

(Draine 2011)

- Electronic transitions : UV or optical.
  Pure vibrational transitions : Mid-IR.
  Pure rotational transitions : Radio – far-IR.



- Rotational : (1) Permanent dipole moment.
  (2) $\Delta J = \pm 1$.

- Vibrational: (1) $\Delta v = \pm 1$.
  (2) $\Delta J = \pm 1$ (for Σ states).

- Electronic : Complex; rules different for different symmetries.

- Homonuclear molecules (e.g. H_2): No permanent dipole moment!
  ⇨ Rotational and vibrational transitions "forbidden".

MOLECULAR HYDROGEN, H_2

- "para-H_2": (S=0, J=0,2,4,...) & "ortho-H_2" (S=1, J=1,3,5,...). $\Delta J = \pm 2$.

- Symmetric molecule ⇨ No permanent electric dipole moment!
  ⇨ Rotational and vibrational transitions "forbidden".

- Electric quadrupole rotation/vibration lines: Low Einstein A's!

- Low mass ⇨ High vibration, rotation frequency (~ 2.1, 28 μm).
  ⇨ Upper states only excited at high temperatures ($T_* \sim$ 510 K)
  ⇨ No detectable emission from normal molecular clouds!

- Electronic lines: Only direct tracer of H_2 in molecular clouds!
  Typically detected in absorption against stars/quasars.

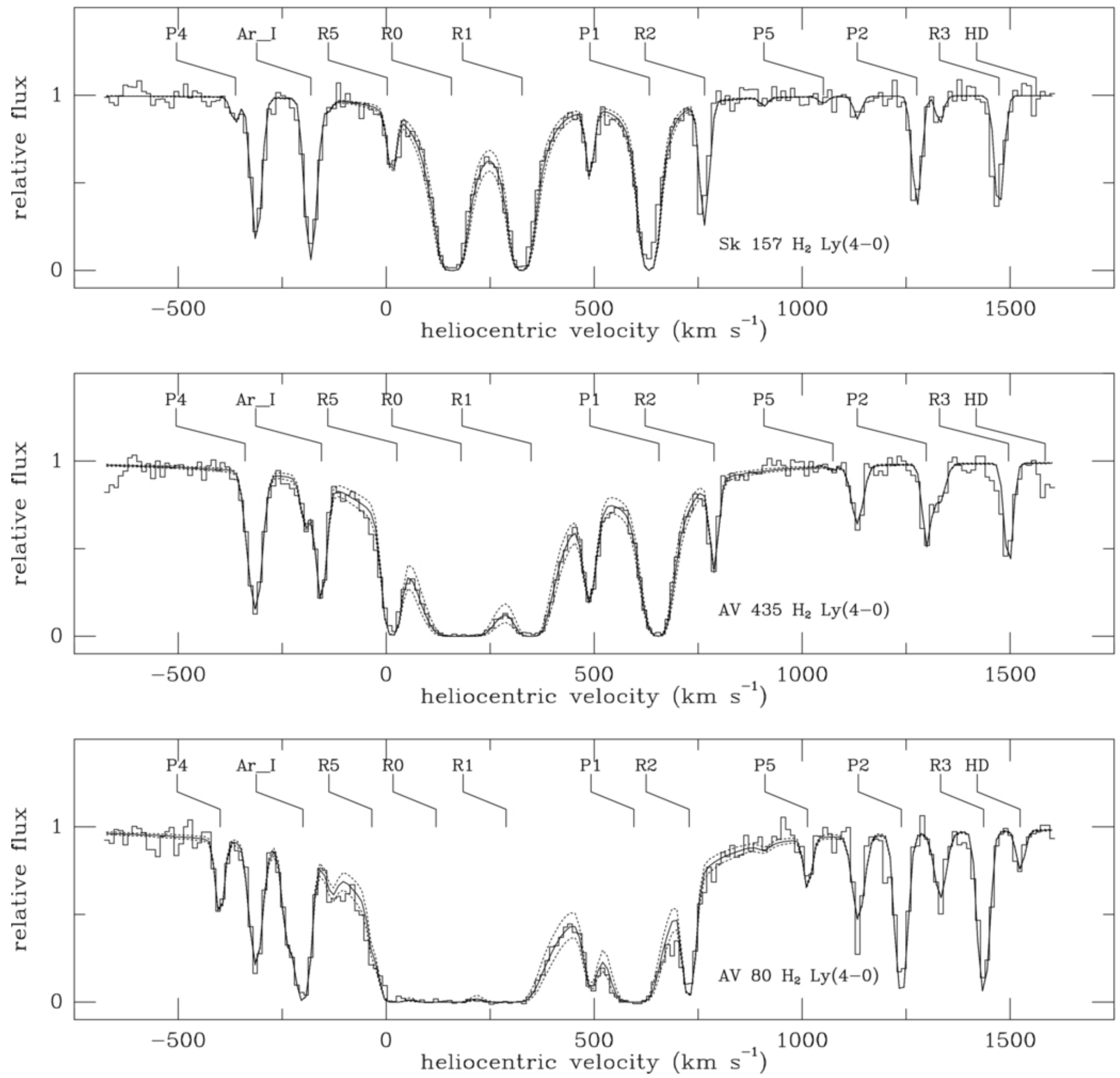
- But... Far-UV wavelengths ($\lambda < 1110$ Å) ⇨ Only detectable on diffuse sightlines without much dust extinction (i.e. low N_{HI}).

MOLECULAR HYDROGEN, H_2

- Lyman ($\lambda < 1110$ Å) and Werner bands: $\lambda < 1021$ Å.
  - ⇨ Mostly studies with the *Copernicus* and *FUSE* satellites.

(e.g. Savage et al. 1977; Rachford et al. 2009)

H_2 in the LMC/SMC



(Welty et al. 2012)

Molecular Hydrogen, H_2

- Lyman/Werner absorption studies ⇨ Level populations in ro-vibrational levels of ground electronic state & total N_{H_2}.

- J=1 and J=0 levels thermalized by collisions ⇨ $T_{ROT} = T_K$!
  ⇨ $T_K \sim 77$ K in cold diffuse gas.
  (Savage et al. 1977)

- Correlation between total H column density ($N_H = N_{HI} + 2N_{H_2}$) and "reddening" $E_{B-V} = A_B - A_V$ (B: 4405 Å; V: 5470 Å).

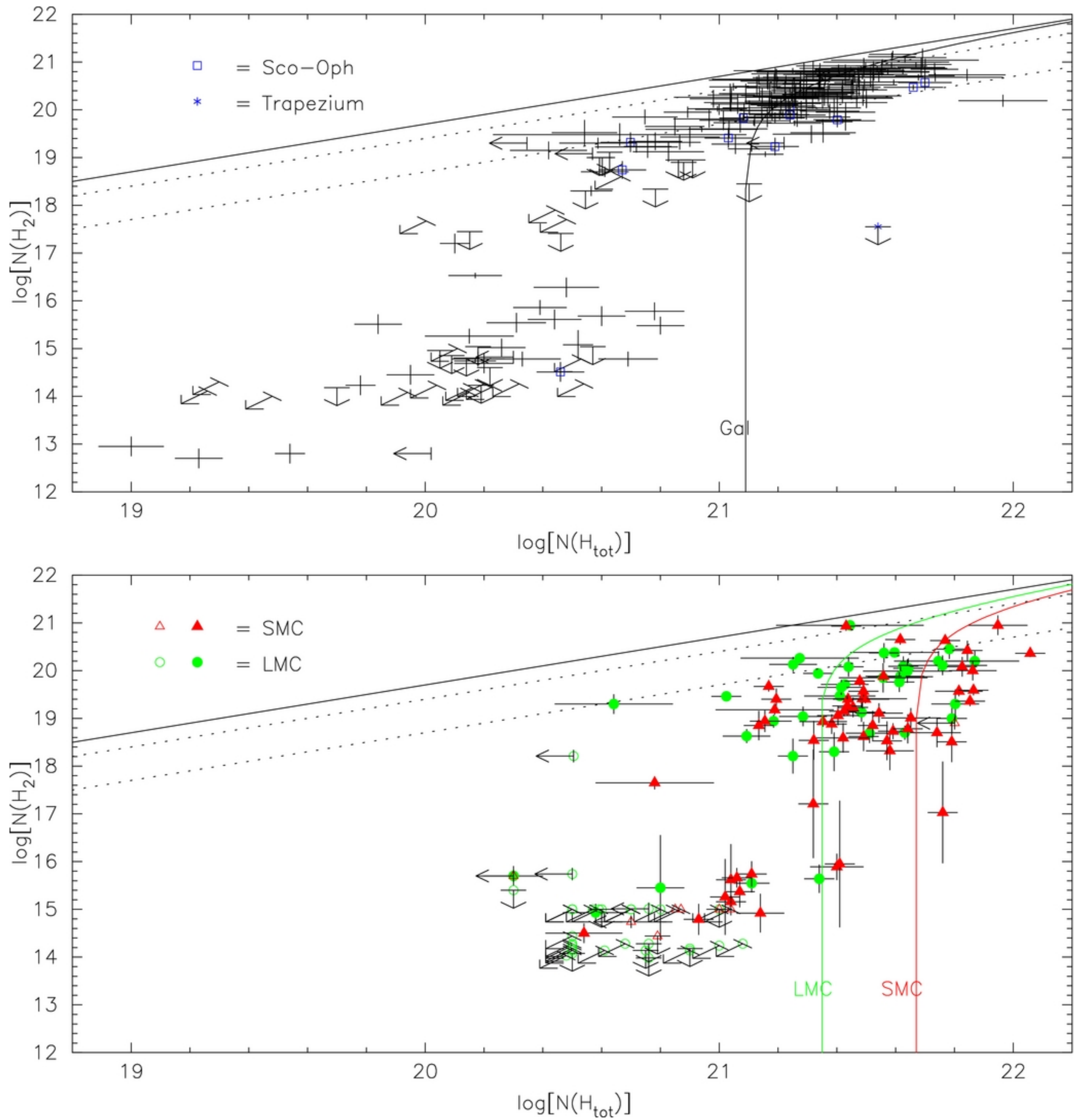
$$N_H = 5.8 \times 10^{21} E_{B-V} \ \mathrm{cm^{-2}\ mag^{-1}}.$$

(Bohlin et al. 1978; Rachford et al. 2009)

- Constant higher by a factor of ~ 3 (LMC) and ~ 5 (SMC), similar to metallicity factors in LMC and SMC.
  (Welty et al. 2012)

MOLECULAR HYDROGEN, H_2

- Metallicity-dependent N_{HI} threshold for H_2 formation.



(Welty et al. 2012)

Diffuse Clouds: Properties

- Multi-phase medium: CNM with $T_K \sim 70$ K and high density.
  WNM with $T_K > 1000$ K and low density.
- Extended far beyond the stars in normal galaxies.
  Scale heights of ~ 75 pc (CNM) and ~ 220 pc (WNM).
- $T_S \sim T_K$ in the CNM; $T_S < T_K$ in the WNM.
- Magnetic field strengths of ~ 5 μG in the CNM.
- Pressures of ~ 3800 cm^{-3} K, from CI absorption. But...
- Important coolant: [CII]-158μm line.
- Cold phase formation at $N_{HI} \sim 2 \times 10^{20}$ cm^{-2} in the Galaxy.
  H_2 formation at $N_{HI} \sim 6 \times 10^{20}$ cm^{-2}.
  Metallicity-dependent threshold! Higher threshold in LMC/SMC !