Reference Books

① Spitzer, "Physical Processes in the Interstellar Medium"

→ older book but very complete in what it does

→ where my notes follow a text book, this is it

② Stahler & Palla "The Formation of Stars"

→ new book, about 8-10 chapters relevant to this module

→ Ralph may use this next semester for Star Formation module

③ Tielens, "Physics and Chemistry of the Interstellar Medium"

→ new book, much more chemistry than the others

→ has an "errata" page

The diffuse (atomic) ISM

Introductory material:

Spitzer Chapters 1, 3, 6 (Stahler & Palla Chapter 2 (maybe Ch. 1))

Fundametal papers (theory)

Field, 1965, ApJ, 142, 531 (First 5-10 pages)

* Field, Goldsmith, & Habing 1969, ApJ, 155, L149

Cox & Smith, 1974, ApJ, 189, L105

McKee & Ostriker, 1977, ApJ, 218, 148

* paper for in-class presentation

~~on Tuesday, Sept~~

Observational Overview of the ISM

(excluding molecular clouds)

(Stahler & Palla ch1) Spitzer Ch. 1

1. Neutral Gas (HI)

- Galaxy contains $\sim 5 \times 10^9\ M_\odot$ of HI
  (similar amount of H_2)
- mean volume density $n(HI) \sim 1$ atom/cm^3
- effective thickness $2H$ of layer

$$2H \simeq 250 \text{ pc near Sun}$$

Neutral gas occurs in "clouds"
(see data later)

- dispersion in radial velocities ~ 6 km/s
- radial velocities v_r up to 50 km/s and more
- some clouds observed ~ 750 pc above the plane

- Kinetic temperatures (of gas within clouds)

$\sim 50-150^\circ K$ $\quad \overline{T_c} = 80^\circ K$

There exists a second component of neutral HI with

$n(HI) = .05 - 0.2\ cm^{-3}$

$T \gtrsim 6000^\circ K$

more uniform distribution

A 4 Phase Diffuse Medium

- Cold Neutral Medium (CNM)
  $T \sim 80^\circ K$
- Warm Neutral Medium (WNM)
  $T \lesssim 8000^\circ K$
- Warm Ionized Medium (WIM)
  $T \sim 8000^\circ K$
  ISM mass fraction $\sim 1\%$
- Hot Ionized Medium (HIM)
  $T \sim 10^6 K$
  ISM mass fraction $\sim 0.1\%$

2. Dust and Gas

- dust particles $\lesssim 1\mu m$ in neutral cloud
- dust grains absorb and scatter light → shorter wavelengths most affected

Colour excess $E(B-V)$ → difference in B-V magnitude of an obscured star and an unreddened star of same spectral type

$E(B-V)$ correlates well with HI column density $N_H = \int n_H \, dL$ cm^{-2}

ie Bohlin, Savage, & Drake 1978

$$\frac{\text{Gas Mass (including He)}}{\text{Dust Mass}} \simeq 160$$

"Typical" HI cloud is ~10pc
"large" HI cloud is ~70pc } $n \sim 20\ cm^{-3}$

Also evidence for large HI envelopes around molecular clouds $\gtrsim 100$ pc

Chemical Composition of the Gas

- determined from absorption line measurements (especially in UV)

→ different from "cosmic" composition (Sun, stars, meteorites) (see Spitzer Table 1.1)

Cosmic abundance $= 12 + \log(N_x/N_H)$

Depletion $= \log(N_x/N_H)_{Oph} - \log(N_x/N_H)_{cosmic}$

- Results for line of sight towards ξ Oph
  - $\frac{3}{4}$ of C, N, O have condensed out
  - all but a few % of Fe, Ca, Al

⇒ "missing atoms" are in dust grains

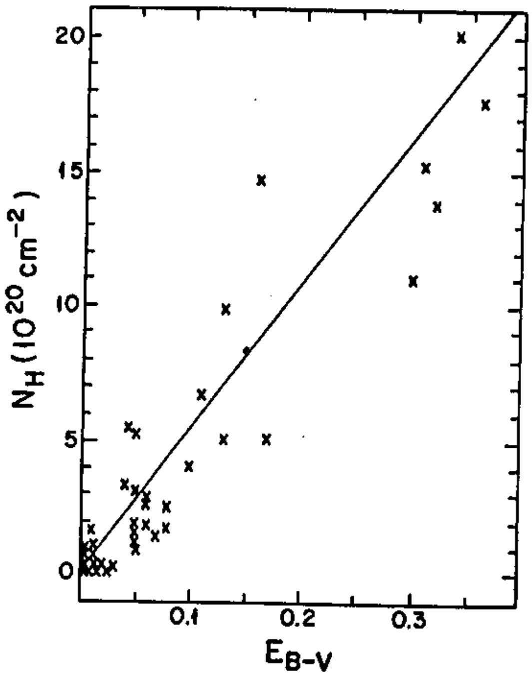


Figure 1.1 Correlation of N_H with E_{B-V}. The column density of H atoms per cm^2 in the line of sight to various stars is plotted against the color excess E_{B-V}, which measures the total amount of dust in each line of sight. Each plotted point, taken from ref. [32] of Chapter 3, represents a sum of N(H I) found from $L\alpha$ absorption and $2N(H_2)$ from the H_2 molecular lines; N(H II), the column density of ionized H, is ignored.

Table 1.1. Cosmic Composition Compared with That of Interstellar Gas

Element X	He	Li	C	N	O	Ne	Na
Cosmic Abundances*	11.0	3.2	8.6	8.0	8.8	7.6	6.3
Depletion,† ζ Oph		−1.5	−0.7	−0.7	−0.6		−0.9
Element X	**Mg**	**Al**	**Si**	**P**	**S**	**Ca**	**Fe**
Cosmic Abundances*	7.5	6.4	7.5	5.4	7.2	6.4	7.4
Depletion,† ζ Oph	−1.5	−3.3	−1.6	−1.1	−0.3	−3.7	−2.0

*Cosmic abundance values: $12 + (\log N_X/N_H)_{\text{cosmic}}$.

†Depletion: $(\log N_X/N_H)_{\zeta\ \text{Oph}} - (\log N_X/N_H)_{\text{cosmic}}$.

From Spitzer

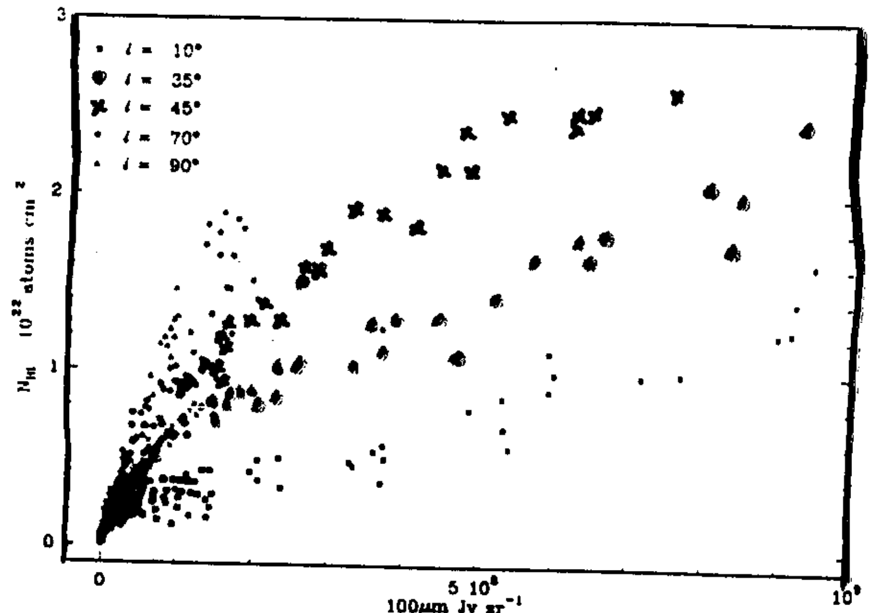


Fig. 35. Scatter diagram showing the correlation on a point-by-point basis between the intensities of dust emission at 100 μm and the total column density of HI. Strips at constant longitude, extending over the latitude range ($-60° < b < 60°$), and 0°.5 wide in longitude, were taken to illustrate global variations in the correlation characteristics with position in the Galaxy

- most far-IR emission is thermal emission of warm grains heated by general interstellar radiation field
- Good correlation of 100μm and HI column
  - Flattening at high intensities
  - (i) → 100μm allways optically thin BUT HI profiles show $\tau_{HI} \gtrsim 1$
    → lines of sight to Galactic Centre have lots of gas (some molecular)
  - (ii) Presence of molecular clouds
  - (iii) Interstellar radiation field → more O+B stars towards Galactic Center

3. Ionized Gas

Photoionization

- O + B stars are strong sources of U.V photons
  - → $\lambda < 912$ Å ($E > 13.6$ eV) ionizes surrounding gas
    - → HII regions
- density of electron gas
  - measure n_e from line ratios, $\langle n_e^2 \rangle$ from line intensities
  - $n_e \sim 2 \times 10^4$ cm^{-3} near <u>center</u> of Trapezium
  - $\sqrt{\langle n_e^2 \rangle} \sim \frac{1}{6} n_e$ → gas is clumpy
- kinetic temperature 7000 - 10,000 K
  $\bar{T} \sim 8000$ K

→ there is also diffuse $H\alpha$ emission
- → Diffuse Ionized Gas   i.e Hoopes & Walterbos 200
- → ionization: field O stars, leaky HII regions, shocks?

Collisional Ionization

- shocks heat ISM to 10^6 K
  - driven by winds (>1000 km/s) or supernova
- collisions between atoms & electrons
  - ionize species (H, He, metals)
  - generate X-rays (observed in SNRs)

Supernova remnants (SNRs)

Cygnus loop - nonthermal radio emission
- filaments & clouds moving at 300 km/s
- 17,000 years old

Cas A - 6000 km/s

Crab (1054) - nonthermal X-rays (older remnants have thermal X-rays)

$T \lesssim$ few $\times 10^6$ K (from O VI absorption lines towards O & B stars)

$T \gtrsim 2\times10^5$ K (from absence of S IV, Si IV, N V)

"Coronal" gas less hot than X-ray emitting gas produced by supernova → fills most of volume between clouds

4. Magnetic Fields and Cosmic Rays

Measurement of Faraday Rotation gives $\langle n_e B_{\parallel} \rangle$ in line of sight to a pulsar

Linearly polarized wave → express as sum of 2 circularly polarized waves

→ in magnetized plasma, these have different phase velocities

⇒ rotates plane of polarization of linearly polarized wave by

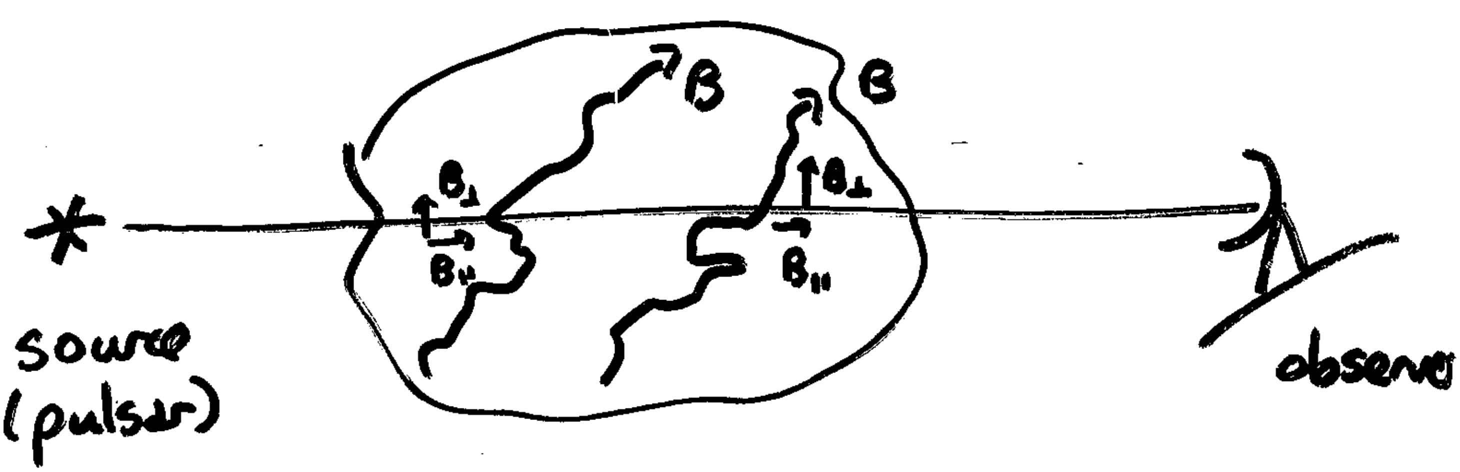
$$\psi = R_m \lambda_m^2 \quad \text{where}$$

$$R_m = 8.1 \times 10^5 \int n_e B_{\parallel} \, dL \quad m^{-2}$$

note typo in spitzer units

n_e in cm^{-3}, $B_{\parallel}$ in Gauss, λ in m

R_m is the Rotation Measure



Measure $\langle n_e \rangle$ from dispersion towards pulsar → $\langle B_{\parallel} \rangle \sim 2 \times 10^{-6}$ Gauss

In HI clouds, can measure Zeeman splitting
→ in ground state, splitting of 21 cm line

$$\Delta \nu_B = \frac{eB}{2\pi m_e c} = 2.8 \times 10^6 B_{\parallel} \text{ (Hz)}$$

↑ Gauss

→ $\langle B_{\parallel} \rangle_{HI} \sim$ up to 7×10^{-5} Gauss

Effects of Magnetic Fields

(1) Grain Alignment → polarization of light in passing through dusty magnetic gas

(2) Pressure → $B^2/8\pi$ from magnetic field is significant for ISM dynamics

(3) Shocks → much <u>lower</u> compression of gas compared to pure hydrodynamic shocks

(4) Synchrotron radiation → produced by particles with energies $10^9 - 10^{12}$ eV spiralling in 10^{-5} Gauss

Cosmic Rays

- most of energetic particles (Cosmic rays) are <u>protons</u> (outnumber electrons by 100 times at 10^9 eV)
- relative abundances of elements somewhat different from cosmic

$$\frac{\text{Fast H}}{\text{Fast He}} \sim 7 \qquad \frac{\text{Fast He}}{\text{Fast metals}} \sim 10$$

(from Longair: "High Energy Astrophysics")

Total energy density $U_R \simeq 1.3 \times 10^{-12}$ erg/cm^3

Isotropic up to very high energies

Collisions with ISM gas produce γ-rays → important for calibration of CO → H_2 conversion in molecular clouds

5. Galactic Distribution

Best to look at external galaxies for global view ie M31, M33; more distant spirals

- O stars & HII regions dominate spiral arms (but also found outside)
- neutral H also traces spiral arms
- CO clouds are sometimes embedded in giant HI clouds (Milky Way, M31)

→ CO & HI clouds separated in M51

In our Galaxy, HII regions trace arms

- spectral type of O star → absolute magnitude
- E(B-V) → amount of extinction

⇒ distance

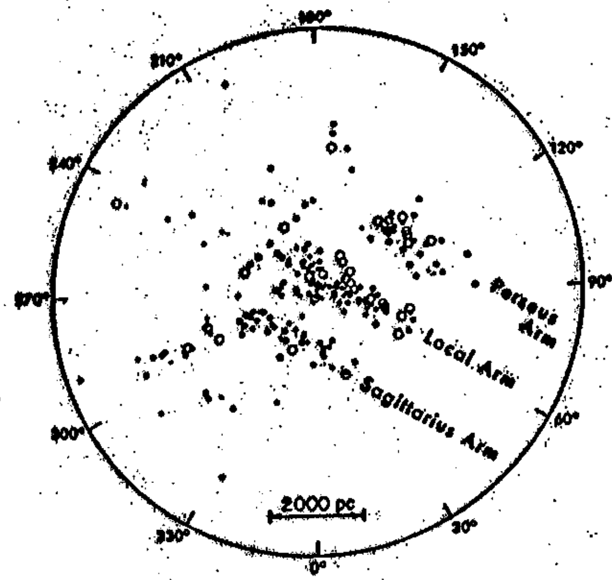
3 spiral arms within 3 kpc

(i) Local Arm

(ii) Perseus Arm (2 kpc further out

(iii) Sagittarius Arm (" " " ")

Milky Way Spiral Arms



(Spitzer)

Figure 1.8 Spiral arm tracers near the Sun [14]. The locations of young stars, gas and dust, which are mostly confined to spiral arms, are shown projected on the galactic plane for distances within about 5000 pc from the Sun. The large open and large filled circles represent O-B0 associations and clusters, while Bpe and bright Cepheids are indicated by small open and small filled circles, respectively. H II regions and dark clouds are represented by large filled circles with central holes and by plus signs. The galactic center is by definition in the direction $l=0$.

Galactic HI distributions

- largest clouds: $M \sim 10^7 M_\odot$, $n \sim 10\ cm^{-3}$ $R \sim 100\ pc$
  trace spiral arms (like HII regions, CO)
- diffuse HI emission features (Kulkarni & Heiles 1988)
  - shells around hot X-ray gas (nearby)
  - also filaments, supershells
    (4×10^{53} ergs or ~400 supernovae),
    worms + chimneys (vertical to plane)
- kinematics
  - most gas $V_{lsr} < 40$ km/s
  - some high velocity gas at high latitudes
    → up to -500 km/s

Canadian Galactic Plane Survey

① Normandeau et al. 1997 ApJS

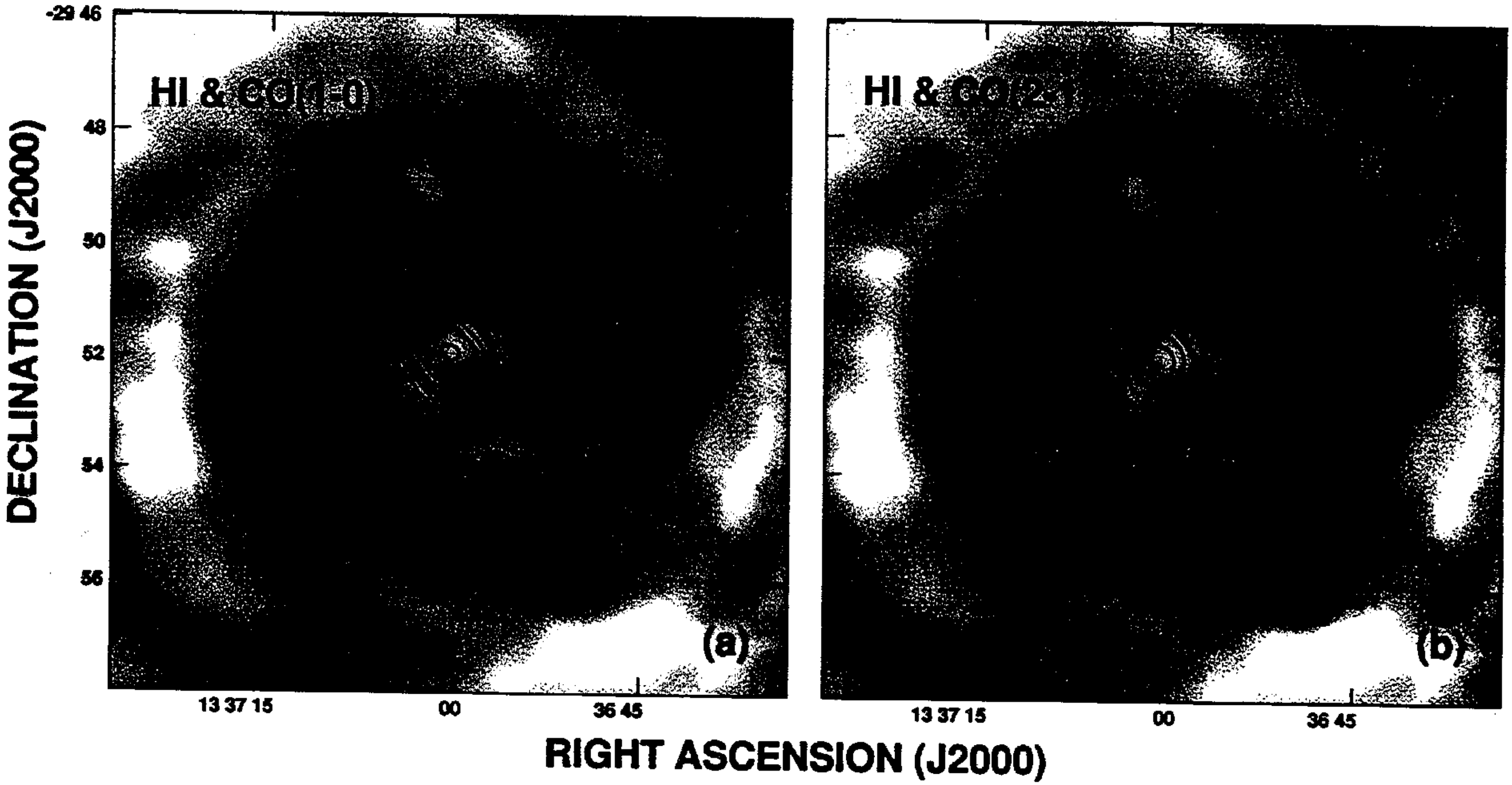
- channel at -26.09 km/s shows
  HI ~~skel~~ shell in lower right corner

- channel at −39.28 shows
  a chimney (blow out) in upper center

② Taylor et al. 2003 AJ

- Figure 10 compares HI
  CO
  IRAS (infrared)
  21 cm (ionized)

M83: Crosthwaite et al. 2002, AJ



CO → contours
HI → greyscale

M51: Aalto et al. 1999

(molecular) CO : contours
(ionized) Hα : red
(dust) Optical : background
HI - not shown