Neutral Gas

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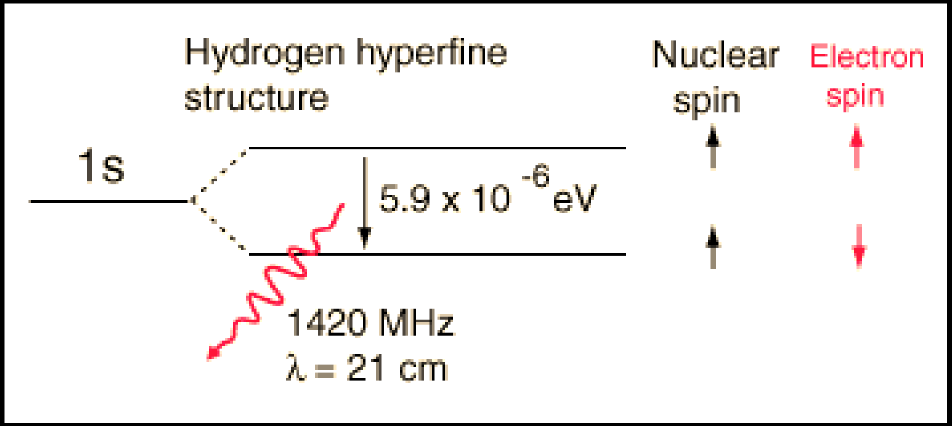
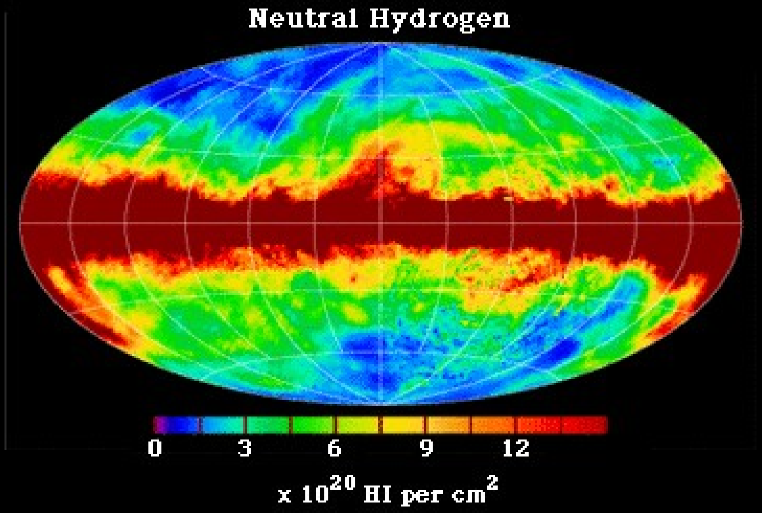
Observations

- 21 cm lines.
  - Emission.





Observations

- 21 cm lines.
  - Emission.
  - Absorption

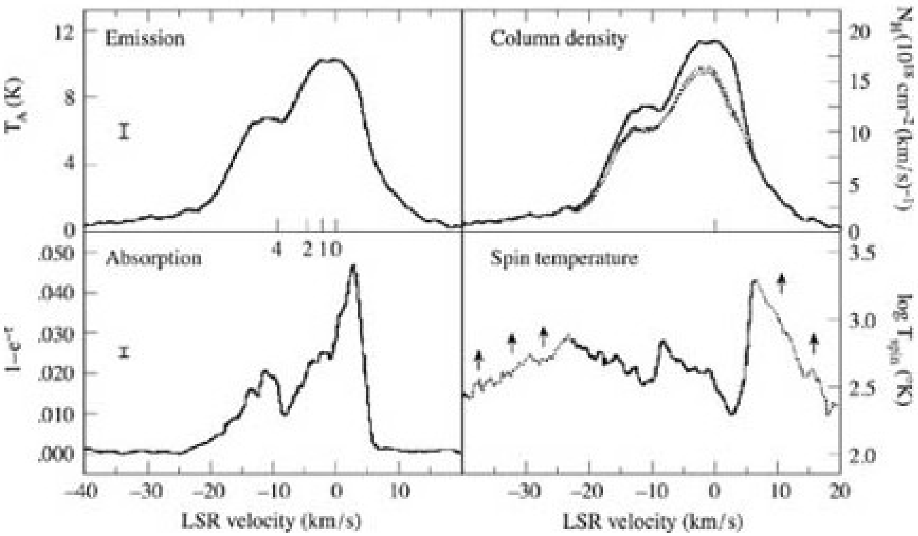


Figure 29.1 Left panels: Observed H I emission (off the quasar 3C48) and absorption (toward 3C48, at $\ell = 134°$, $b = -28.7°$). Lower right: spin temperature $T_{spin}(v)$ as a function of LSR velocity. Tick marks labeled 0, 1, 2, and 4 on abscissa of left panels show the LSR velocity expected for gas at a distance of 0,1,2,4 kpc (for an assumed Galactic rotation curve). Upper right: $dN(\mathrm{H\ I})/dv$ for different assumptions regarding the relative (foreground/background) locations of cold absorbing gas and warm gas seen only in emission. From Dickey et al. (1978).

Observations

- 21 cm lines.
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  - Absorption
- Velocity gives radial distribution.

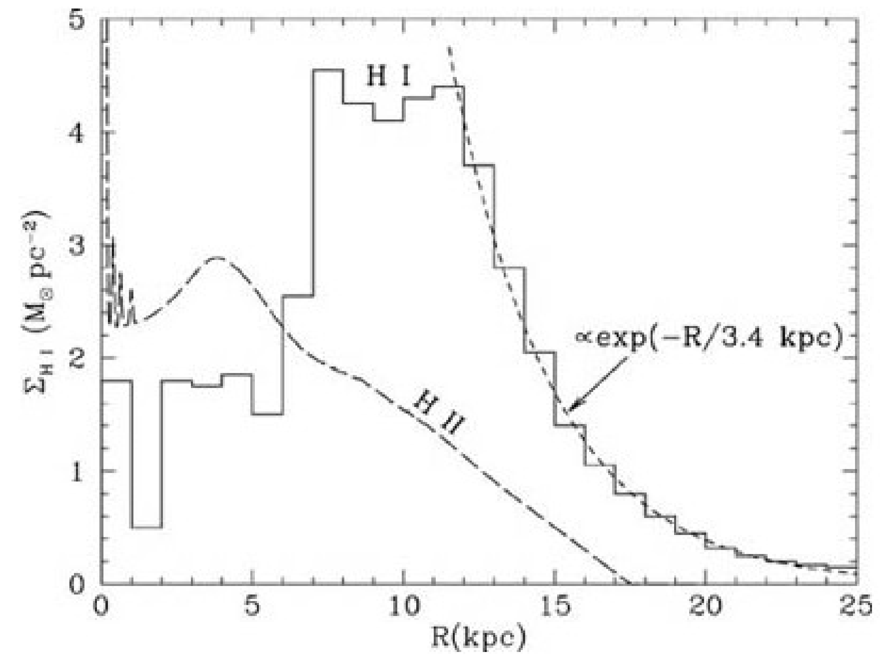
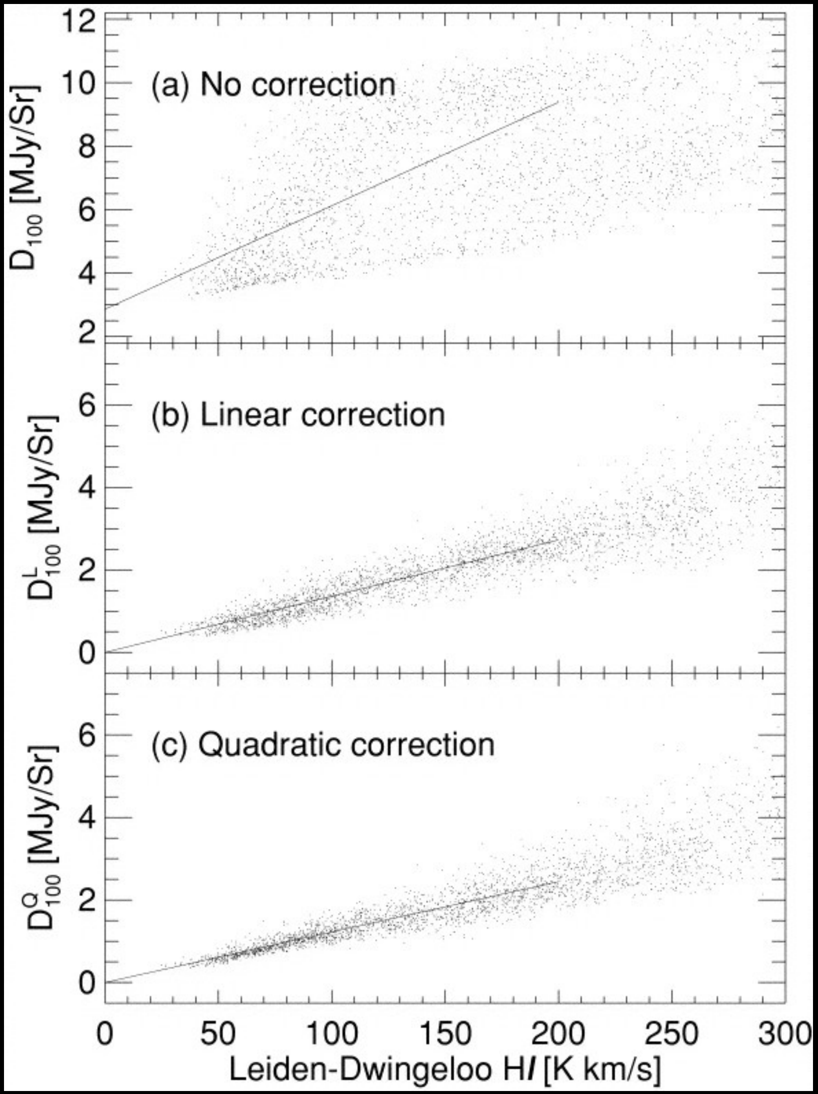


Figure 29.3 Radial distribution of H I from Nakanishi & Sofue (2003). At $R \gtrsim 11$ kpc, the H I surface density declines exponentially. Also shown is the radial distribution of H II from Figure 11.4

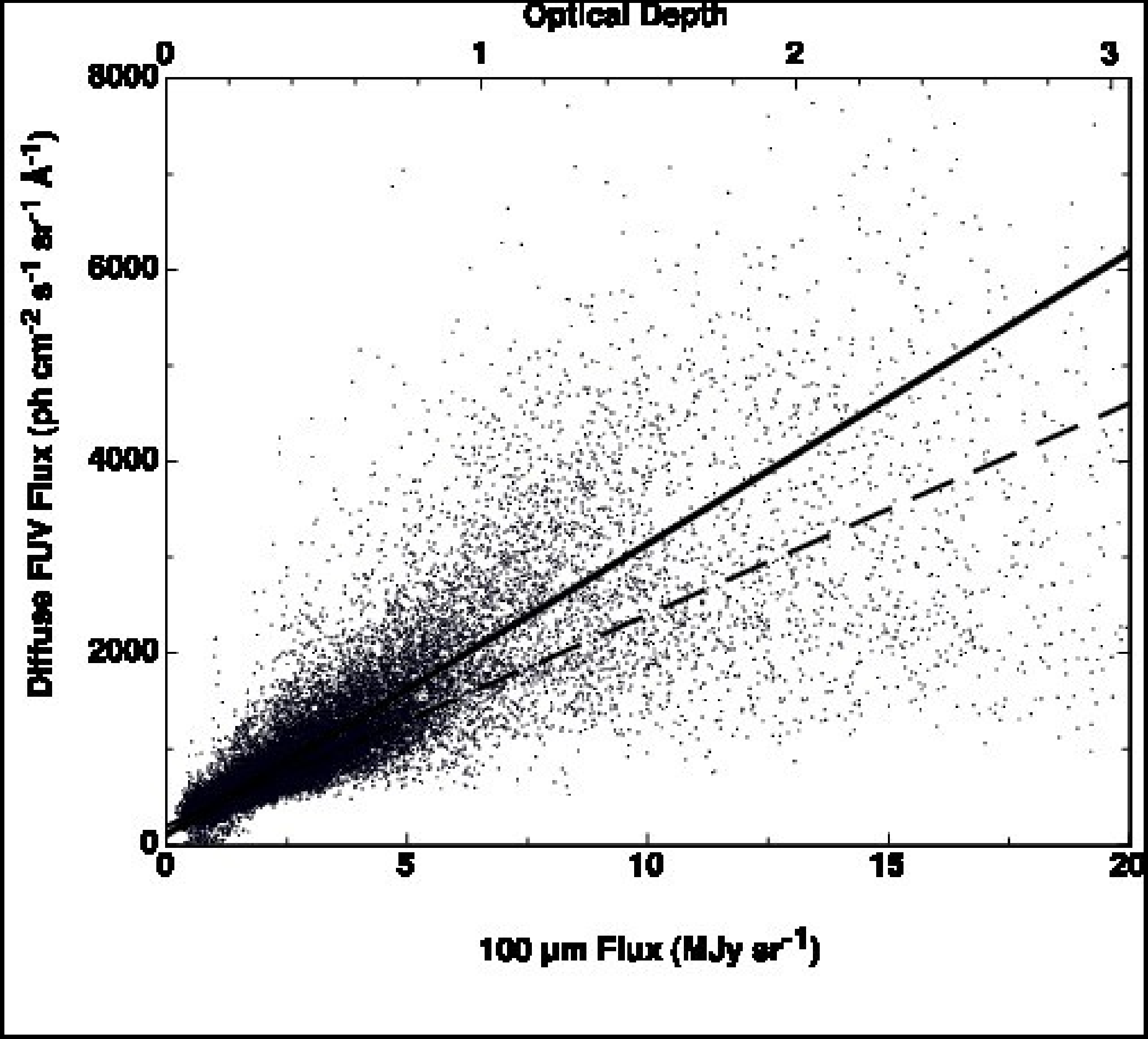
Observations

- 21 cm lines.
  - Emission.
  - Absorption
- Velocity gives radial distribution.
- Other measures:
  - Optical (absorption line) observations.
  - IR observations from dust.
- Absorption in Lyman lines.
- OI is a good tracer:
  - most of OI is in gas.
  - OI dominant species.
- IR correlated with 21 cm.

SFD 100 micron correlation



GALEX FUV-IR Correlation



Heating and Cooling

- Heating mechanisms:
- Photoionization.
- Gas by UV and X-rays.
- Dust by starlight.
- Cosmic rays.

Heating and Cooling

- Heating mechanisms:
- Photoionization.
- Shock heating.
- Dominant heating mechanism is photoionization of dust.
    - Mostly from small grains.
- Gas by UV and X-rays.
- Dust by starlight.
- Cosmic rays.

Observations of Molecular Gas

Cooling

- Cooling by line emission
- Lyα lines above 10,000 K
- Forbidden lines of CII and OI below 10,000 K.

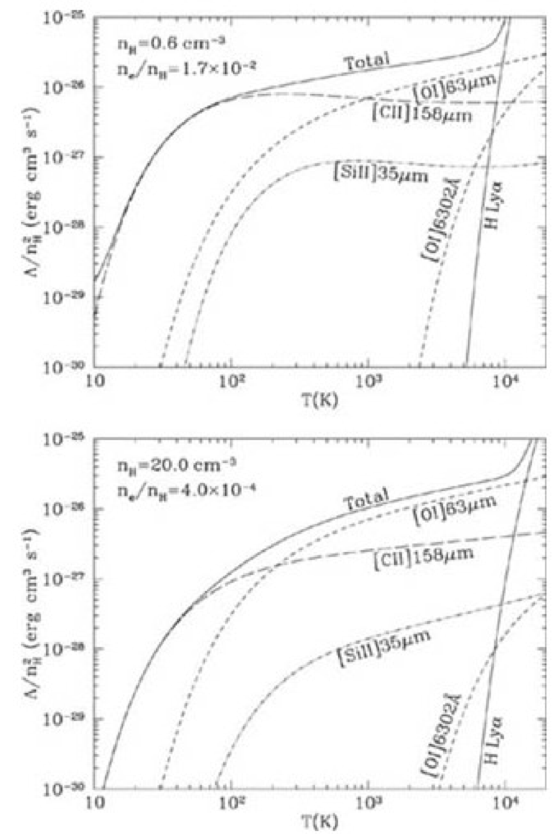


Figure 30.1 Cooling rate for neutral H I gas at temperatures $10 \lesssim T \lesssim 2 \times 10^4$ K for two fractional ionizations. For $T < 10^4$ K, the cooling is dominated by two fine structure lines: [C II]158 μm and [O I]63 μm.

Two Phase Model

- Field et al. (1969)
- Balance heating and cooling.
- Add pressure equilibrium.
- Only two stable phases:
    - WNM
    - CNM

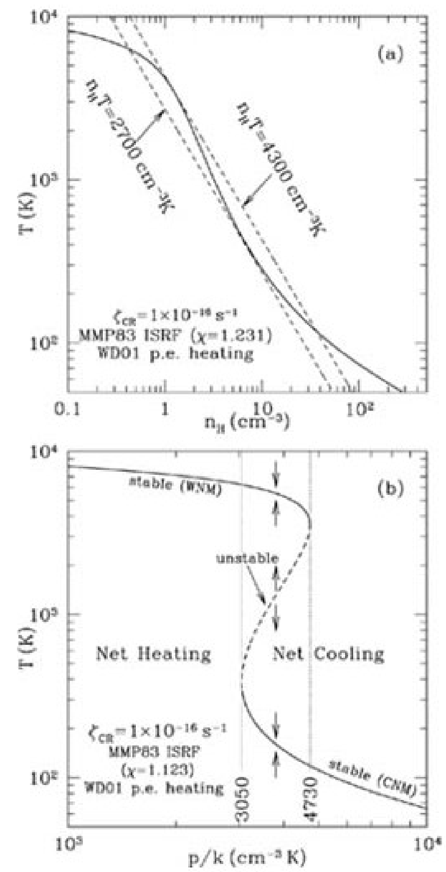


Figure 30.2 (a) Steady state temperature T as a function of density n_H, for gas heated by cosmic rays and photoelectric heating by dust grains. Two lines of constant $n_H T$ are shown. (b) Steady state temperature T as a function of thermal pressure p. For 3200 $\lesssim p/k$ 4400 cm^{-3} K there are three possible equilibria – a high-T WNM solution, a low-T CNM solution, and an intermediate temperature equilibrium that is thermally unstable.

Two Phase Model

- Field et al. (1969)
- Balance heating and cooling.
- Add pressure equilibrium.
- Only two stable phases:
  - WNM
  - CNM
- Line emission.

Table 30.1 Conditions at Stable Thermal Equilibria for $p/k = 3800\ \mathrm{cm^{-3}\ K}$

		CNM	WNM
T(K)		160.	5512
$n_{\mathrm{H}}(\mathrm{cm^{-3}})$		21.5	0.626
$n_e(\mathrm{cm^{-3}})$		0.00925	0.0116
n_e/n_{H}		0.00043	0.0185
$n(\mathrm{H^+})/n_{\mathrm{H}}$		0.000272	0.0167
$4\pi\nu j_\nu(\mathrm{dust}, 100\,\mu\mathrm{m})/n_{\mathrm{H}}$ $(10^{-26}\ \mathrm{erg\ s^{-1} H^{-1}})$		240.	240.
$4\pi j/n_{\mathrm{H}}$ $(10^{-26}\ \mathrm{erg\ s^{-1} H^{-1}})$:	[C II]158 μm	2.85	0.385
	[O I]63.2 μm	2.00	1.05
	[O I]145 μm	0.119	0.0875
	[O I]6302 Å	—	0.0317
	[Si II]34.8 μm	0.0341	0.0474
	[S II]6733 Å	—	0.100
	[S II]6718 Å	—	0.148
	[Fe II]5.34 μm	—	0.0216
	[Fe II]26.0 μm	0.00101	0.00904

Molecular Hydrogen

- How does one form H_2?

Molecular Hydrogen

- How does one form H_2?

- $H + H \rightarrow H_2 + h\nu$
- Symmetric so no electric dipole.
- Rate will be low.
- 3 body reaction unlikely.

Molecular Hydrogen

- How does one form H_2?
- Start with $H + e^- \rightarrow H^- + h\nu$
- $H^- + H \rightarrow H_2 + KE$
- Rate of formation is slow because H^- is easily destroyed.
- $H + H \rightarrow H_2 + h\nu$
- Rate $1.9 \times 10^{-16}\ T^{0.67}\ cm^3\ s^{-1}$
- Rate $1.9 \times 10^{-9}\ cm^3\ s^{-1}$

Molecular Hydrogen

- Grain catalysis.
- Rate dependent on grain surface area + cross section.

- H atom binds to grain surface.
    - Walks across surface.
- 2 atoms meet they combine.
    - Release 4.5eV.
    - Eject molecule

Molecular Hydrogen

- Grain catalysis.
- Rate dependent on grain surface area + cross section.

$$R_{\mathrm{gr}} = \frac{1}{2}\left(\frac{8kT}{\pi m_{\mathrm{H}}}\right)^{1/2} \langle \epsilon_{\mathrm{gr}} \rangle \Sigma_{\mathrm{gr}}$$

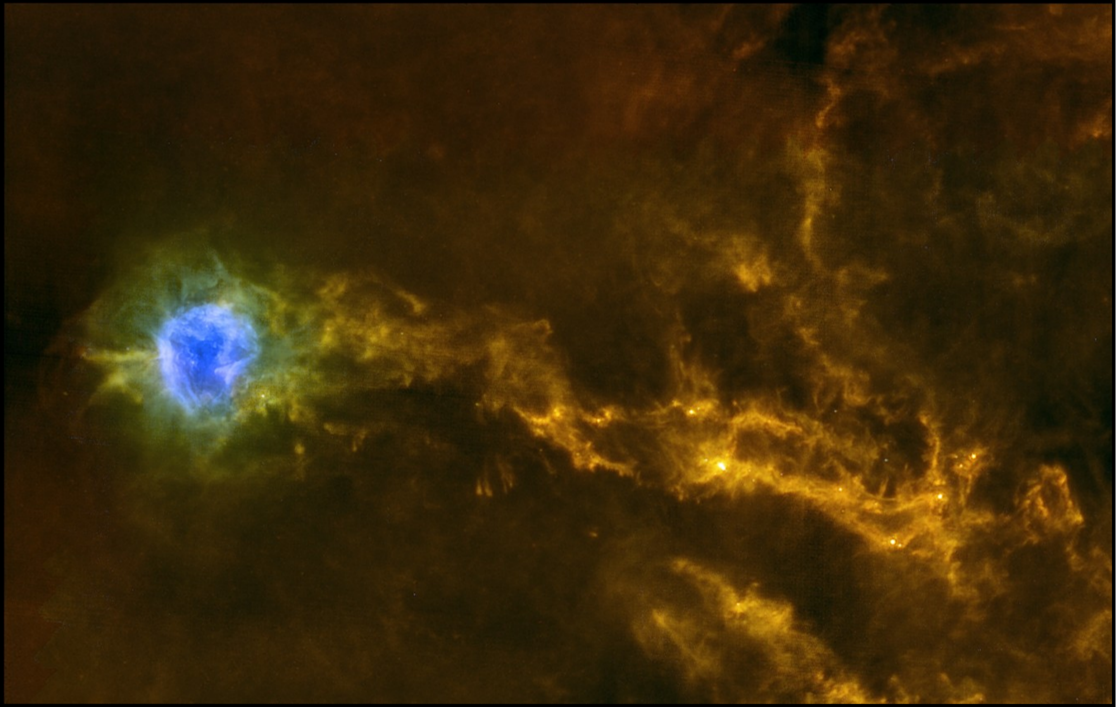
- where $\Sigma = \frac{1}{n_{\mathrm{H}}} \int da \frac{dn_{\mathrm{gr}}}{da} \pi a^2$
- and ε is the conversion efficiency of $H \rightarrow H_2$

Molecular Hydrogen

- Destroyed by photodissociation.
- As H density increases, self-shielding becomes important.
- Shielding due to extinction.
- In diffuse clouds the steady state level of H_2 is low.

Observations of Molecular Clouds

- Diffuse Clouds
  - $A_V < 1$
- Translucent Clouds
  - $A_V < 5$

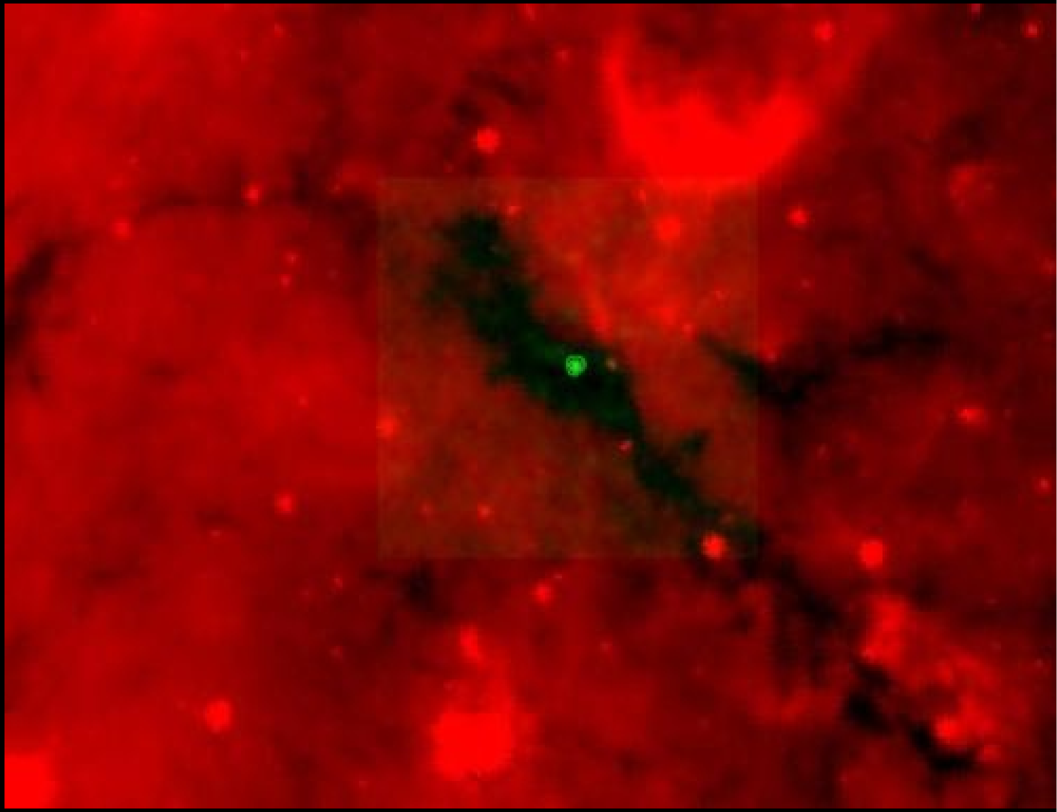


Observations of Molecular Clouds

- Diffuse Clouds
  - $A_V < 1$
- Translucent Clouds
  - $A_V < 5$
- Dark Clouds
  - $A_V < 20$
  - Self-gravitating.

Observations of Molecular Clouds

- Diffuse Clouds
  - $A_V < 1$
- Translucent Clouds
  - $A_V < 5$
- Dark Clouds
  - $A_V < 20$
  - Self-gravitating.
- IRDCs



Observations of Molecular Clouds

- Giant Molecular Clouds
  - Size > pc
  - Mass > 1000 $M_\odot$
- Complex
  - Size > 100 pc
  - Mass > 10^5 $M_\odot$

Mass Spectrum

- $dN/dM \propto M^{-1.5}$.

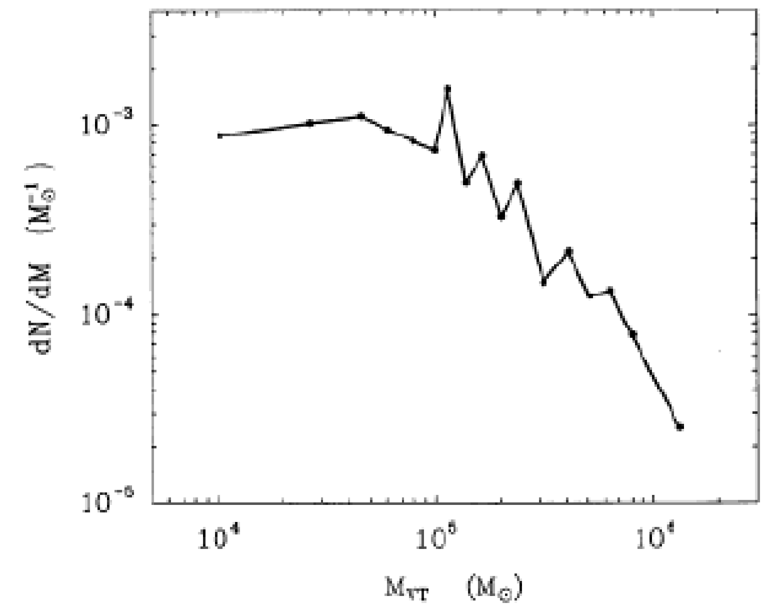


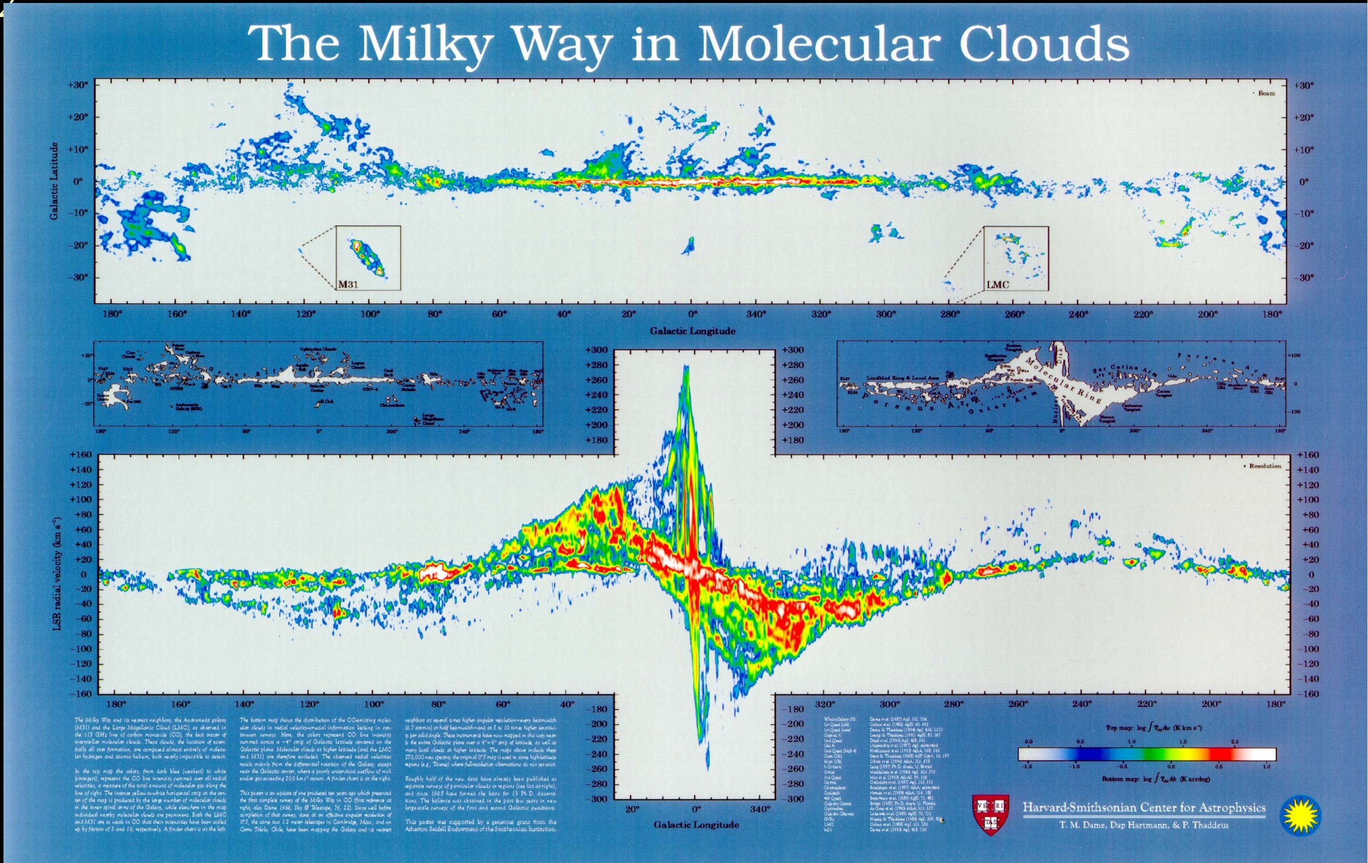
FIG. 3.—The molecular cloud mass spectrum dN/dM. A fit to the data above $M = 7 \times 10^4\ M_\odot$ gives $dN/dM \propto M^{-3/2}$. There are 15 clouds in each bin and the standard deviation is $\pm 24\%$. The turnover at low mass is due to undercounting of smaller clouds in the more distant parts of the galactic disk.

Star Counts

- Barnard 68.
- Extinction blocks stars in visible.
- Optical depth less in IR.

Emission Lines

- H_2 symmetric molecule so no lines.
- Observations of CO lines.
- $X_{CO} = 1.8 \times 10^{20}$ H_2 $cm^{-2}/K\ km\ s^{-1}$

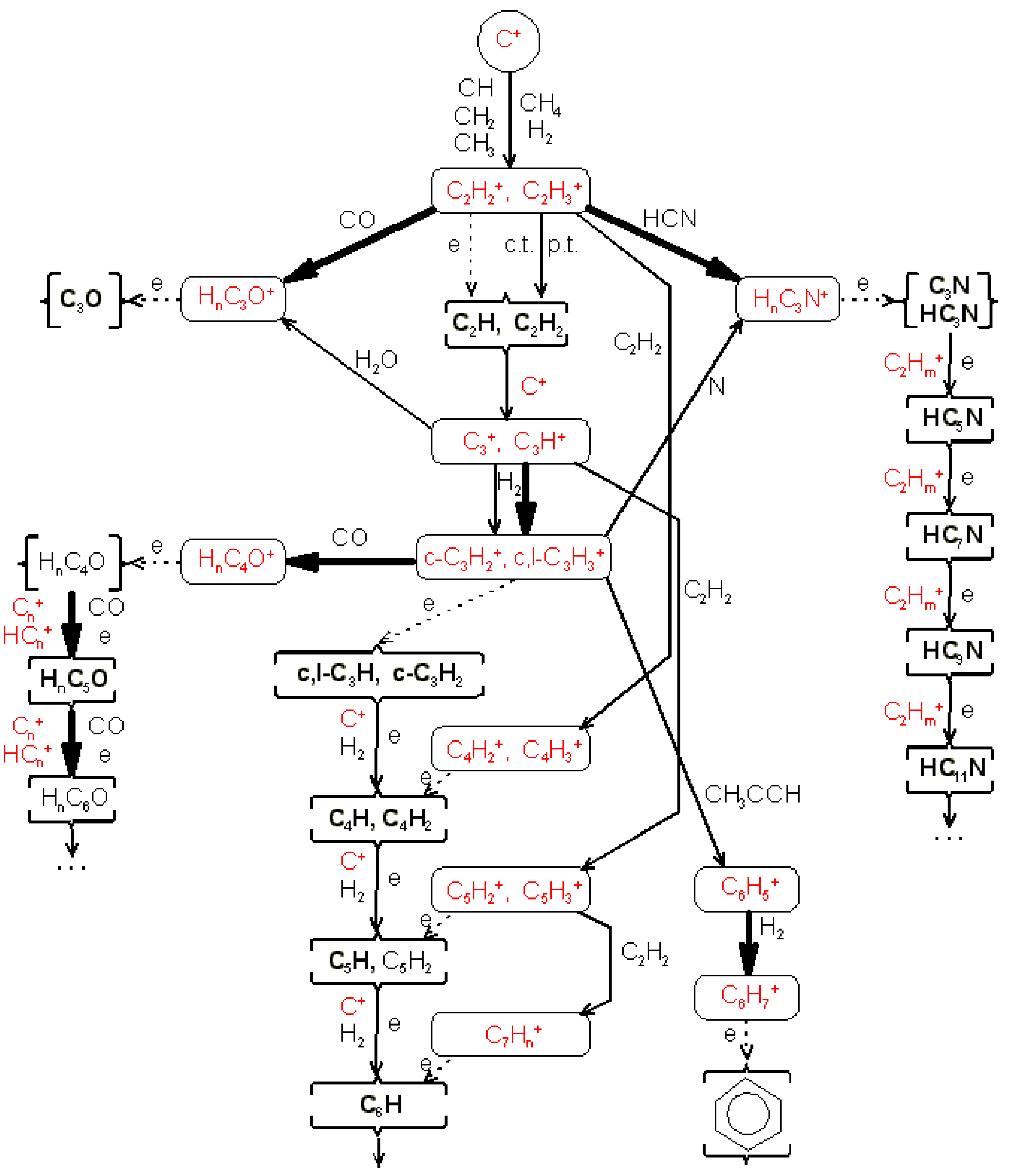


Chemistry

- Important processes:
- Photoionization:
  - H_2 cannot be photoionized because ionization energy is 15.43 eV
- Photodissociation:
  - Self-shielding important for many species
- Neutral-neutral exchange
  - $C + OH \rightarrow CO + H$
- Ion-neutral exchange
- Radiative association
- $A + B \rightarrow (AB)^* \rightarrow AB + h\nu$

Chemical Pathways

Some routes to the synthesis of carboxy, hydrocarbon and cyanopolyyne molecules in dense interstellar clouds



OUT OF THIS WORLD

A wealth of molecules is found in interstellar clouds

2 atoms

H_2, AlF, AlCl, C_2, CH, CH^+, CN, CO, CO^+, CP, CSi, HCl, KCl, NH, NO, NS, NaCl, OH, PN, SO, SO^+, SiN, SiO, SiS, CS, HF, SH, FeO

3 atoms

C_3, C_2H, C_2O, C_2S, CH_2, HCN, HCO, HCO^+, HCS^+, HOC^+, H_2O, H_2S, HNC, HNO, MgCN, MgNC, N_2H^+, N_2O, NaCN, OCS, SO_2, c-SiC_2, CO_2, NH_2, H_3^+, SiCN, AlNC

4 atoms

c-C_3H, l-C_3H, C_3N, C_3O, C_3S, C_2H_2, HCCN, $HCNH^+$, HNCO, HNCS, $HOCO^+$, H_2CO, H_2CN, H_2CS, H_3O^+, NH_3, SiC_3

5 atoms

C_5, C_4H, C_4Si, l-C_3H_2, c-C_3H_2, CH_2CN, CH_4, HC_3N, HC_2NC, HCOOH, H_2CHN, H_2C_2O, H_2NCN, HNC_3, SiH_4, H_2COH^+

6 atoms

C_5H, l-H_2C_4, C_2H_4, CH_3CN, CH_3NC, CH_3OH, CH_3SH, HC_3NH^+, HC_2CHO, NH_2CHO, C_5N

7 atoms

C_6H, CH_2CHCN, CH_3C_2H, HC_5N, $HCOCH_3$, NH_2CH_3, c-C_2H_4O, CH_2CHOH

8 atoms

CH_3C_3N, $HCOOCH_3$, CH_3COOH, C_7H, CH_2OHCHO

9 atoms

CH_3C_4H, CH_3CH_2CN, $[CH_3]_2O$, CH_3CH_2OH, HC_7N, C_8H

10 atoms

CH_3C_5N, $[CH_3]_2CO$, NH_2CH_2COOH

11 atoms

HC_9N

13 atoms

$HC_{11}N$

NOTE: Evidence suggests that much larger molecules such as polycyclic aromatic hydrocarbons and fullerenes are also present.

SOURCE: National Radio Astronomy Observatory