Processes in Formation + Destruction of Molecules in ISM

H + other elements ($>10^3$ less abundant)

low density → binary gas-phase reactions (except H_2)

usually only exothermic reactions (release energy) - but endothermic may be important at $T \gtrsim$ few$\times 10^2$ K

define rate co-efficient K_{AB} such that

$$R = K_{AB}\, n(A)\, n(B) \quad \text{cm}^{-3}\,\text{s}^{-1}$$

1. Radiative association

$$A + B \rightleftarrows AB^* \longrightarrow AB + h\nu$$

eg $H + H^+ \rightarrow H_2^+ + h\nu$

→ can lead to H_3^+, H_2 via charge transfer

$$\underset{\substack{\uparrow \\ \text{mean collision rate}}}{K \approx \langle \sigma v \rangle} P \;\longleftarrow\; \overset{\text{probability stabilizing transition}}{A_{ul}\,\delta t \approx A_{ul}\frac{d}{v}}$$

- rate coefficient typically small compared to other processes ($\sim 10^{-16} - 10^{-18}$)
- if one of reactants is a molecule, probability increased (increased degrees of freedom) $k \sim 10^{-9}$

2. Ion - Molecule Reactions

$$A^+ + BC \rightarrow AB^+ + C$$

- dominates interstellar chemistry

important process is cosmic ray ionization of H_2, then

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

H_3^+ important component in formation of many species

$k \sim 10^{-9}$, little variation with temperature

ionization by cosmic rays is driving mechanism (rate ~ $5 \times 10^{-17} n(H_2)$ cm^{-3} s^{-1} in diffuse clouds)

$$H_2 + CR \rightarrow H^+ + H + e$$

$$\rightarrow H_2^+ + e$$

$$\rightarrow H + H$$

$$\rightarrow H^+ + H^-$$

3. Neutral - Neutral Reactions

$$A + BC \rightarrow AB + C$$

- typically not important → large potential barriers ~ $\exp(-E_{th}/kT_K)$ → can become important in high temperature regimes
- if no potential barriers $k \sim 10^{-11}$

4. Charge Transfer

$$A + B^+ \rightarrow A^+ + B$$

- very important, can initiate crucial chemical sequences

$$O + H^+ \rightarrow O^+ + H$$

is especially important reaction

5. Photodissociation

$$AB + h\nu \rightarrow A + B$$

- most rapid destruction route wherever UV photons present $k \sim 10^{-9}$ in ambient ISM UV field

2 main types of process
- continuous photodissociation
- photodissociation through lines

- most molecules destroyed by cont. p.d.
- CO, H_2 destroyed by line p.d.
  → self-shielding can be very effective

6. Dissociative Recombination

$AB^+ + e \rightarrow A + B$

- most important destruction route for ions
- $k \sim 10^{-6} - 10^{-7}$

apparently $H_3^+ + e \rightarrow H_2 + H$

$\rightarrow H + H + H$

does not occur rapidly

7. Negative ion processes

$A + e \rightarrow A^- + h\nu$

$A^- + h\nu \rightarrow A + e$

processes involving negative ions usually very rapid

ie $A^- + B^+ \rightarrow A + B$ $k \sim 10^{-6}$

$A^- + B \rightarrow AB + e$ $k \sim 10^{-9}$

The Important Case of H_2

must form on surfaces of dust grains (radiative association very unlikely; 3-body collisions also)

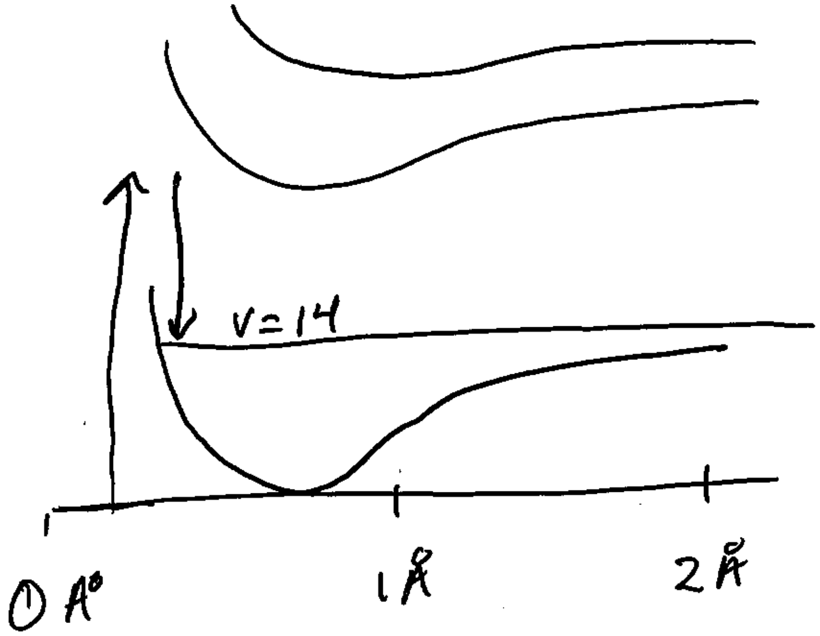
rate coefficient for H_2 formation

$$R = 0.5 \langle \sigma_g v \rangle S(T_g)$$
$$\simeq 6 \times 10^{-17} (T_k/300)^{1/2} S(T_g) \quad \mathrm{cm^3\ s^{-1}}$$

$\langle \sigma_g v \rangle \rightarrow$ mean collision rate of grains with H atoms

$S(T_g) \rightarrow$ sticking probability, $\sim 0.1 - 1.0$

destroyed by photo-dissociation
→ absorbs photon → excited state
→ spontaneous decay to unbound ($v \geq 14$) vibrational level of ground electronic state

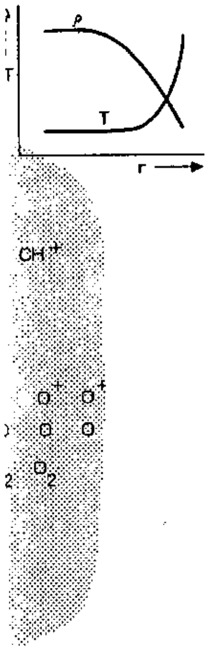


→ line absorption process
∴ self-shielding is important

$\frac{n_{H_2}}{n_{HI}}$ increases rapidly + non-linearly with cloud thickness

→ H_2 builds up very rapidly once you get $\tau \sim 1$ in lines

→ H_2 can have very low abundance ($\lesssim 1\%$) in shielding layers of cloud



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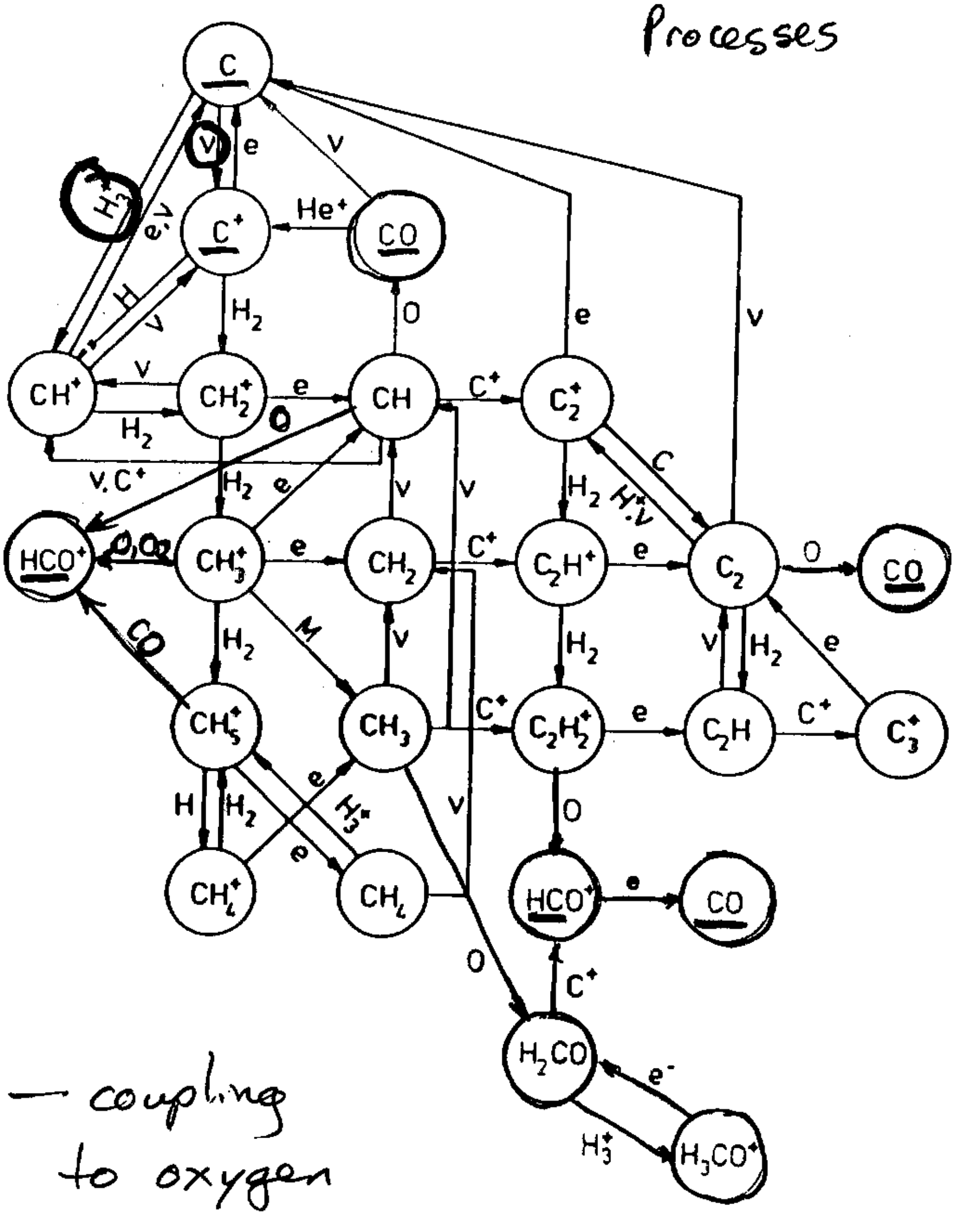
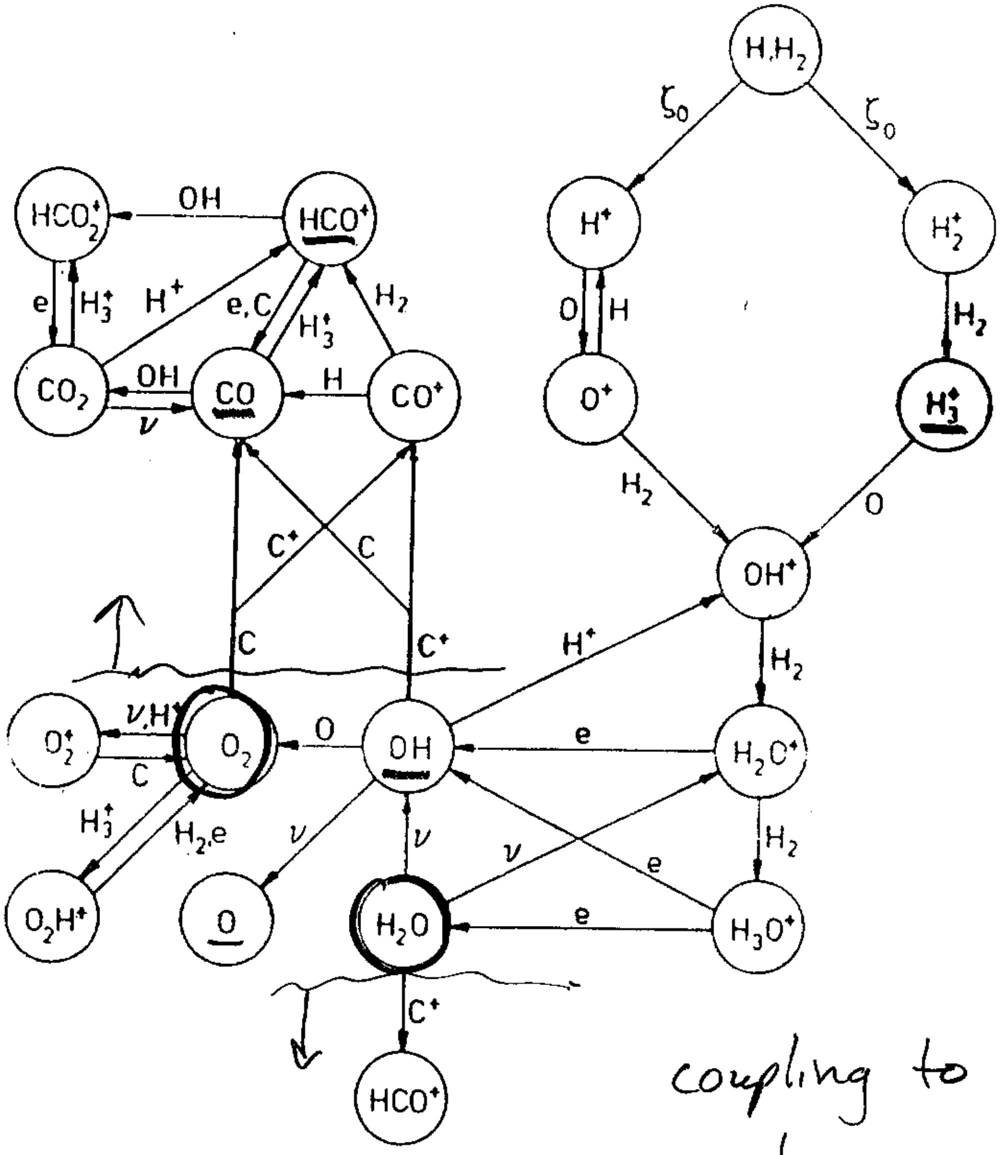


Figure 4. A simplified version of carbon chemistry and its coupling with oxygen chemistry.

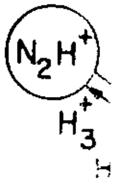
— coupling to oxygen

OXYGEN



coupling to carbon

Figure 5. A simplified version of oxygen chemistry and its coupling with carbon chemistry.



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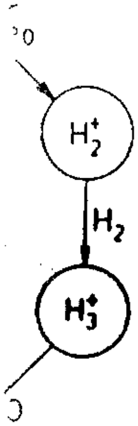

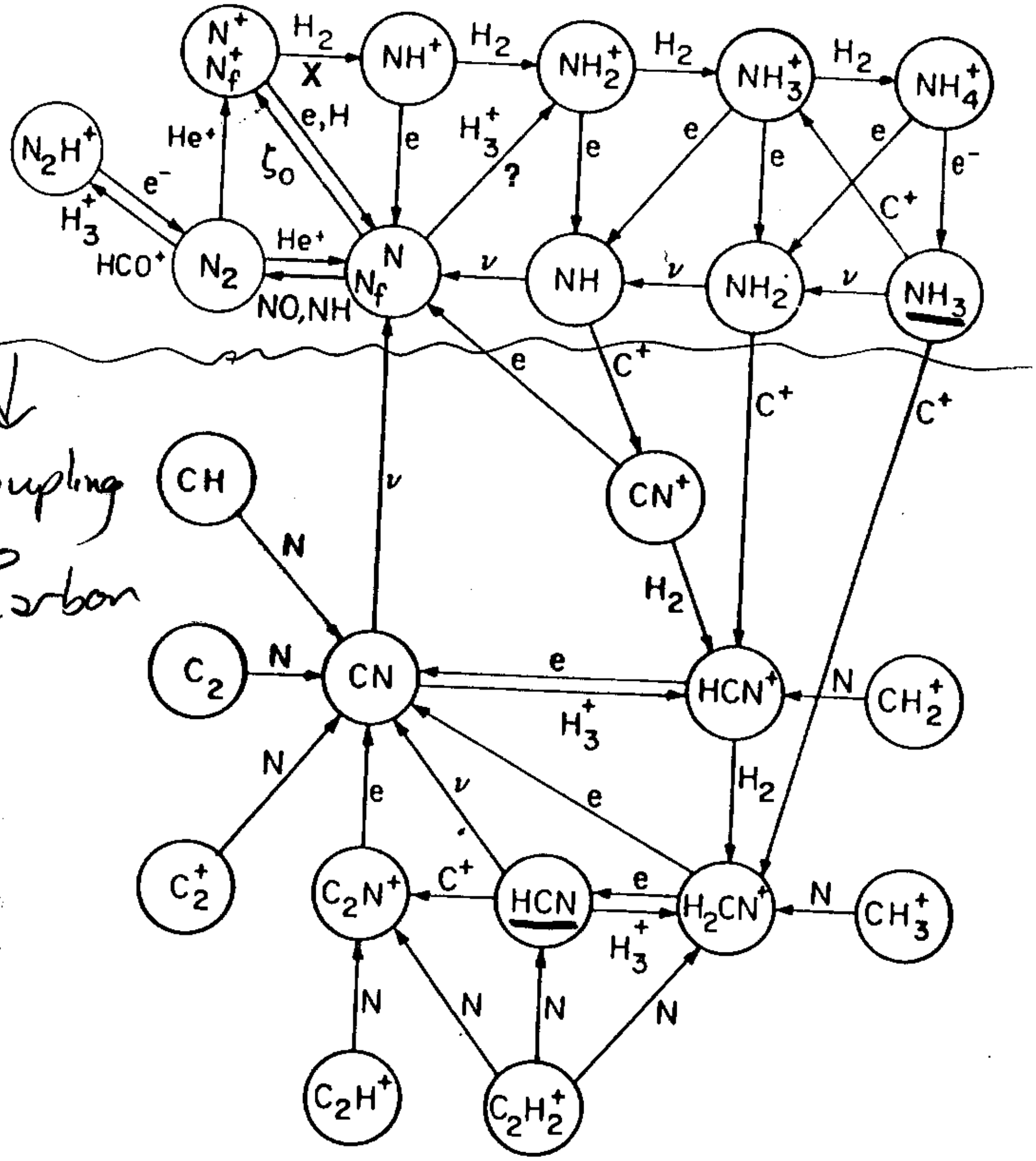

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Figure 6. A simplified version of nitrogen chemistry and its coupling with carbon chemistry.

(29)

Molecular Cloud Cores

Definition (Myers): subregion of a molecular cloud with $n \gtrsim 10^4$ cm^{-3}

molecular clouds usually mapped in ^{12}CO $J=1-0$
→ $\log n = 2.5-4$

molecular cores mapped in high-density tracers
NH_3, CS, $C^{18}O$, HC_3N

Caution: different molecules may trace things like density, temperature, column density slightly differently (plus could have abundance variations!)

cores are ~10-100x smaller than clouds

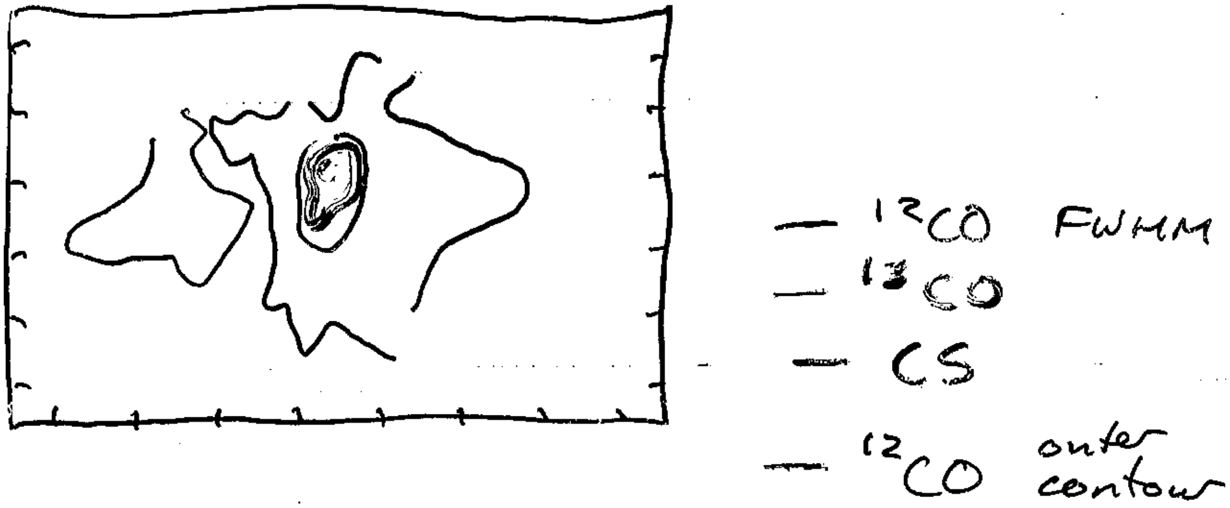
- may be visible as optical obscuration in nearby clouds
- size of a core is sensitive to which molecule you use
- only a relatively small fraction of the mass in a molecular cloud is in the form of cores

Cloud Core Properties (Myers PPII)

	Low Mass	High Mass
0_{FWHM}	.05-.2 pc	.1-3
log n	4-5	4-6
T	9-12 K	30-100
ΔV	.2-.4 km/s	1-3
M	.3-10 $M_\odot$	$10-10^3$
log τ_{ff}	5-5.3	4.3-5.3
Nearby Stars	T Tauri	OB

(all properties from NH_3 data)

Map of S252 molecular cloud



Low-Mass Cores

- in nearby dark clouds, typically have high optical obscuration
- Example is TMC-2 : FWHM ~ 0.1 pc , $\bar{n} \sim 3\times10^4$

  → ~1 $M_\odot$ of gas

  $T_K \sim 10\,K$, FWHM velocity ~ 0.3 km/s

  → $V_{turb} \sim \frac{1}{2} V_{therm}$

  Subsonic turbulence

  $\tau_{ff} \sim 2\times10^5\,yr$, comparable to ages of T Tauri stars

$$\left.\begin{array}{l}\text{- many have low luminosity } (\lesssim 10 L_\odot) \text{ infrared sources} \\ \text{- some show bi-polar outflows}\end{array}\right\} \text{star formation}$$

Massive Cores

- larger (in all properties) than low-mass cores, found near young stars, compact HII regions, etc
- greater range in properties than low-mass cores
- found at larger distances (> 1 kpc), so harder to resolve
- also, don't know much about low mass cores in same clouds!
- have highly supersonic turbulence
- IR sources are luminous ($\sim 10^4 L_\odot$)
- are sufficiently numerous in a cloud + move near virial speeds, that may undergo frequent collisions with each other
  - → depending on geometry it can inhibit or promote collapse
- more energetic outflows + more luminous stars means cores likely to be destroyed by star formation

Shapes of Cores

Myers et al. 1991 ApJ

NH_3, CS, $C^{18}O$ maps of low mass cores in dark clouds (size ~ 0.1 pc)

→ size in 3 transitions is different

→ similar elongation (axis ratios ~ 0.5-0.6)

→ similar orientation of long axis

→ all 3 lines sample same volume of gas, located in elongated core

not spherically symmetric → isolated core model supported by random motions not valid (also not due to rotation → don't see velocity gradients)

if cores are prolate, true axial ratio ~ 0.4-0.5

if oblate, " " " < 0.1 - 0.3

→ more likely to be prolate (less severely flattened/elongated) - also some are inside long filaments

average axial ratio same for cores with and without stars → core elongation preceeds star formation (is not produced by star formation)

Rotation in Dense Cores

Goodman et al., 1993, ApJ, 406, 528

Initial angular momentum of core is important for

- final angular momentum of star + disk
- support of core
- potential for fragmentation

⇒ estimate solid body rotation by least-squares fitting to velocity map in NH_3

⇒ shows up as a velocity gradient

Gradients from 0.3 - 2.5 km/s/pc

⇒ oriented randomly with respect to core major axis → core elongation not caused by rotation

Ratio of rotational to gravitational energy

$\beta < 0.18$, typically < 0.05

⇒ low β inhibits fragmentation due to <u>rotational</u> instabilities

(gravitational or magnetic instabilities could drive fragmentation)

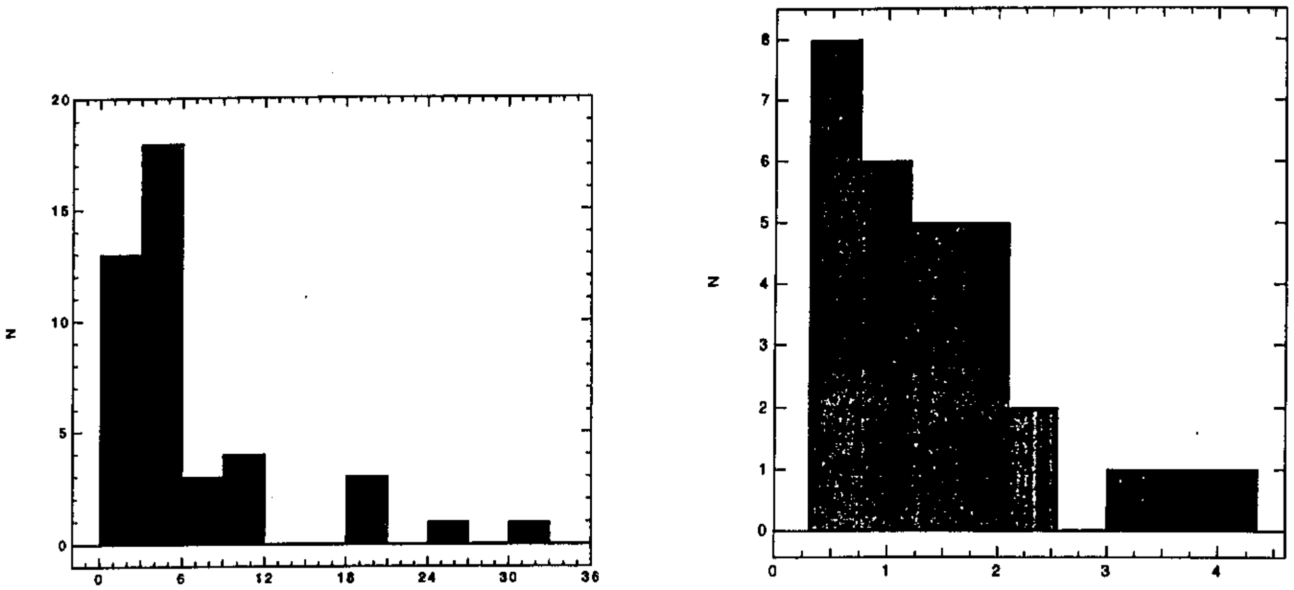


FIG. 1*a* FIG. 1*b*

FIG. 1.—Distributions of (*a*) gradient significance and (*b*) magnitude ([*b*] and all figures to follow only include gradient with $\mathcal{G}/\sigma_{\mathcal{G}} \geq 3$).

"a good" rotation gradient ⇒

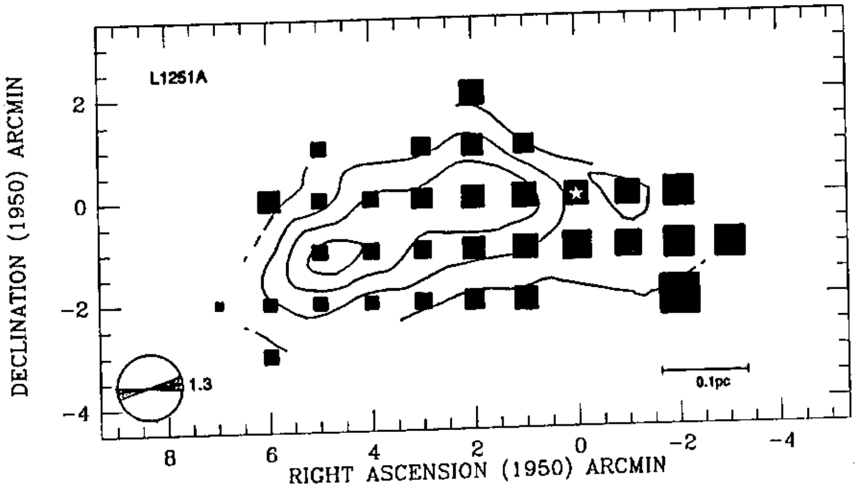


FIG. 3*a*

FIG. 3.—Filled squares of varying size represent the LSR velocity of the peak of the fitted NH_3 $(J, K) = (1, 1)$ line profile at each position, and contours map the peak antenna temperature. The linear size of a filled square is proportional to v_{LSR} at its position. The small circle with an arrow indicates the velocity gradient fitted to the NH_3 data (arrowhead points toward increasing v_{LSR}), and the shading around the arrow indicates the 1 σ error in the fit which determined the gradient. (A cross in the circle means that no significant gradient could be fitted.) Stars show the position of *IRAS* sources thought to be young stellar objects associated with these cores. The core names, (0, 0) map positions $(\alpha_{1950}, \delta_{1950})$, velocity ranges, and contour levels are as follows: (*a*) L1251A: $(22^h29^m03^s.2, 74°58'51'')$, $(-3.46, -4.65$ km s$^{-1})$, (0.15, 0.35, 0.55, 0.75 K); (*b*) B35: $(05^h41^m45^s.3, 09°07'40'')$, $(11.28, 12.59$ km s$^{-1})$, (0.15, 0.20, 0.25, 0.30 K); (*c*) L158: $(16^h44^m33^s.7, -13°52'03'')$, $(3.76, 4.16$ km s$^{-1})$, (0.2, 0.3, 0.4, 0.5 K); (*d*) L1527: $(04^h36^m49^s.3, 25°57'16'')$, $(5.80, 6.39$ km s$^{-1})$, (0.20, 0.35, 0.50 K).