A. Wootten 7/22/83

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- Glassgold Huggins & Schucking 1982 Ann NY Acad Sci Vol 395

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- Riegler and Blandford 1982 AIP Conf Proc #83

Masers

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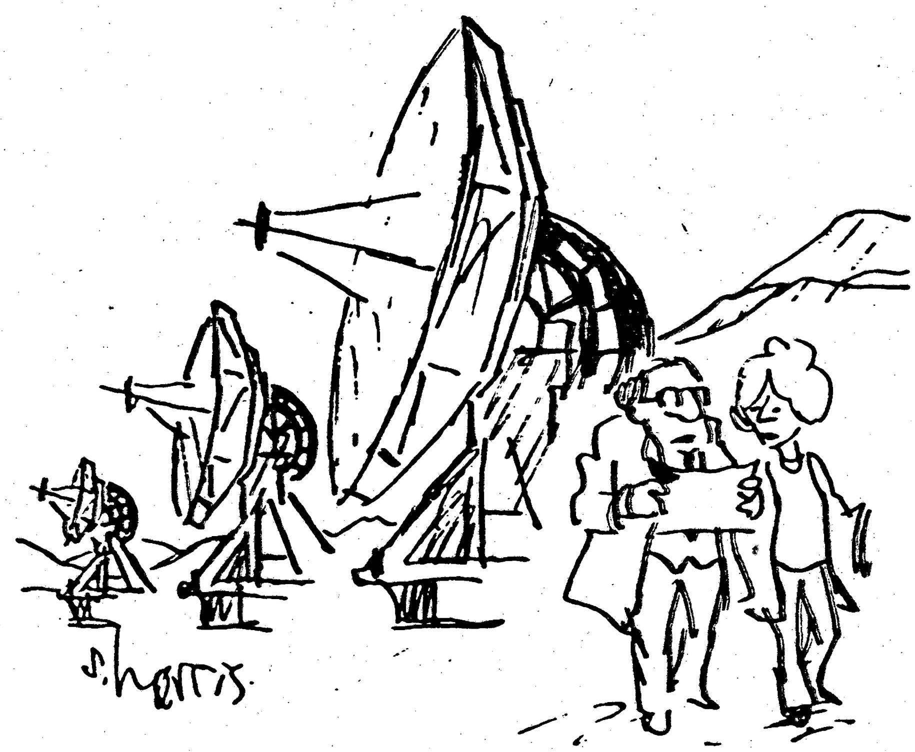


"We've discovered a massive dust and gas cloud which is either the beginning of a new star or just a hell of a lot of dust and gas."

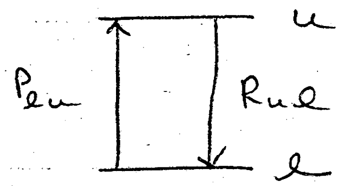
~~WHICH MOLECULES~~

THE CAST

H_2	UBIQUITOUS BUT INVISIBLE
CO	SCARCER BUT STRONG
CI	THE VEILED TEMPTRESS
HCO^+	THE ION CONNECTION (MAGNETIC FIELDS)
CS	DENSITY TRACER
H_2CO	THE CENTIMETER CONNECTION
HC_3N	DENSITY, CHEMISTRY
NH_3	THE SPOILER
H_2O CH OH	THE IMPOSSIBLE DREAM

GENERAL CONSIDERATIONS: OPTICALLY THIN

TWO LEVEL MOLECULE



Molecule in state ℓ must be able to get to state u

1) COLLISIONS
2) RADIATIVE ABSORPTION / EMISSION

i.e. RATE UP must exceed rate down

$$P_{\ell u} > R_{u\ell} \approx A_{u\ell} n_u \quad \text{transitions/sec}$$

net up collisions

$$P_{\ell u} - P_{u\ell} = n_H (n_\ell C_{\ell u} - n_u C_{u\ell})$$

$C_{\ell u}$ excitation rate coefficient

$C_{u\ell}$ deexcitation rate coefficient

$C \sim \sigma v$ avgd over Maxwellian at T_K

Principle of detailed balance

$$C_{\ell u} = C_{u\ell} (g_u/g_\ell) e^{-(E_u - E_\ell)/kT_K}$$

For net up to balance net down

$$T_K > (E_u - E_\ell)/k$$

$$n_H > A_{u\ell} / \langle\sigma v\rangle_{u\ell}$$

MOLECULE	T_K	n_H	$\nu_{u\ell}$	
H_2	500 K	$\sim 10^3$	28 μm	Q'pole
CO	5.5 K	$\sim 10^3$	115 GHz	
HCO^+	4.2 K	$\sim 3 \times 10^5$	89 GHz	
CS	2.2 K	8×10^4	49 GHz	
H_2CO	6.4 K	1.3×10^6	140 GHz	
HC_3N	1 K	$\sim 10^4$	18 GHz	
	26 K	3×10^7	573 GHz	
NH_3	1 K	1.5×10^3	24 GHz	
OH	120 K	$\sim 10^9$	119 μm	

RADIATION

$$P_{lu} - P_{ul} = U_{lu}(n_l B_{lu} - n_u B_{ul})$$

B_{ul} stimulated emission coefficient

U_{lu} local radiation energy density from external source

Star, dust

$$U_{lu} = \frac{8\pi h\nu^3}{c^3} \frac{W}{e^{h\nu/kT_c} - 1} (1 - e^{-\tau_c})$$

T_c = color temperature

τ_c = opacity

W = dilution factor $\propto \frac{1}{r^2}$

Condition $$\frac{W(1-e^{-\tau_c})}{e^{h\nu/kT_c} - 1} > 1$$

⇒ molecules must see BB rad field with $T > \frac{h\nu}{k}$

CASES: VIBRATIONAL LEVELS OF HC_3N near IrC2 in BN/KL.

MASSIVE CIRCUMSTELLAR SHELLS.

CONCLUDE: COLLISIONAL EXCITATION NORMAL

⇒ DENSITIES, TEMPERATURES OF LOCAL GAS

HIGH OPTICAL DEPTH

MANY RADIATIVE DECAYS $u \to l$

some may be reabsorbed, exciting molecule, UNTIL ESCAPE THERMALIZED

DEFINE <u>NET</u> RAD DECAY

NO BACKGROUND

$$R_{ul} - R_{lu} = n_u A_{ul} \beta$$

spontaneous decay rate is multiplied by an escape probability β

FOR SPHERICAL REGION WITH CONSTANT VELOCITY GRADIENT dV/dR

$v \propto r$

$$\beta = \frac{1}{\tau}(1 - e^{-\tau})$$

$\simeq 1$ $\qquad \tau \ll 1$

$\simeq \frac{1}{\tau}$ $\qquad \tau \gg 1$

$$\tau \sim \frac{c^3}{8\pi\nu^3} \frac{g_u A_{ul}}{dV/dr} \left(\frac{n_l}{g_l} - \frac{n_u}{g_u}\right)$$

Then collisional pump requirement

$$n_H > \frac{8\pi \nu^3}{c^3} \frac{dv}{dr} \Big/ n_e \langle \sigma v \rangle_{ue}$$

or X = molecular abundance $\quad f_e = \frac{n_e}{n_{TOT}}$

$$n_H > \left[\frac{8\pi \nu^3}{c^3} \frac{dV}{dr} \Big/ (X f_e \langle \sigma v \rangle_{ue}) \right]^{1/2}$$

$\therefore$ A does not matter; X does!

Why? Large line strength ⇒ more rapid spontaneous decay
BUT EXACTLY COMPENSATED BY LARGE τ, GREATER PHOTON TRAPPING

RADIATIVE EXCITATION $\tau > 1$ – no change!
since net decay rate decreased by β.
prob of external photons reaching molecule decreased by β.

TEMPERATURE OF MOLECULAR CLOUDS

1. CO OPTICALLY THICK, EXTENDED

$T_R = T_{ex}$

THERMALIZED

$T_{ex} = T_K$

THEN for CO $J=1\to 0$

$$T_K = \frac{5.5}{\ln\left(1 + \frac{5.55}{T_A/\eta_p + 0.83}\right)}$$

~10K

→ 100K

PROBLEMS: 1) $n > 500$ FOR THERMALIZATION
OUTER REGIONS POOR THERMOMETER
2) WHERE IS CO $\tau \sim 1$ PHOTOSPHERE? WHAT ARE WE MEASURING T OF?
SELF-REVERSALS

OTHER GAS TEMPERATURE PROBES - THE SYMMETRIC TOPS

2. NH_3 OPTICAL DEPTH KNOWN FROM hfs
SIMPLE EXCITATION MODEL ⇒ >2 LINES
J,K 1,1 & 2,2 inversion doublets
⇒ populations in these lines

$$T_R = -41.5 \Big/ \ln\left(\frac{3}{5}\frac{n(2,2)}{n(1,1)}\right) \simeq T_K$$

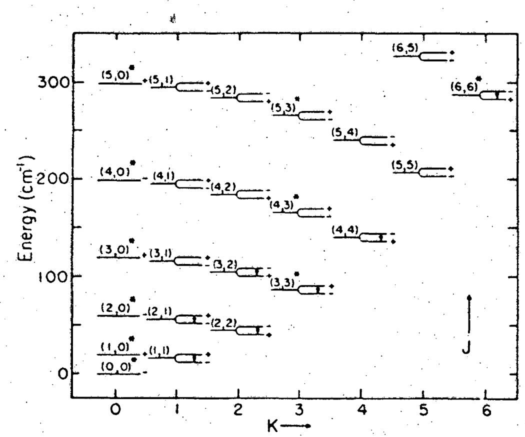
(T_R = $T_{ROTATIONAL}$)

ASSETS: 1) SOURCE NEED NOT BE EXTENDED
2) IN PRINCIPLE, MEASURES T IN DENSER REGI[ONS]

PROBLEMS 1) (2,2) STATE TOO HIGH FOR COLD CLOUDS
2) WEAK LINES, SEVERAL TRANSITIONS NEEDED
3) RADIATIVE TRANSFER EFFECTS

3. OTHER THERMOMETERS OF GAS T_K
SYMMETRIC TOP MOLECULES CH_3CN CH_3C_2H CH_3C_3N
ALL $\Delta K = 0$ LINES OF $\Delta J = 1$ TRANSITION CLOSE TOGETHER
⇒ T_{EX} FROM ONE OBSERVATION
CUMMINS ET AL ApJ <u>266</u>, 331

DUST TEMPERATURE



... 3. Rotational energy levels for NH_3 in its ground vibrational state (Morris *et al.*, 1973, ... permission of The University of Chicago Press). Ortho levels are marked by asterisks. ... splittings have been expanded by a factor of 10.

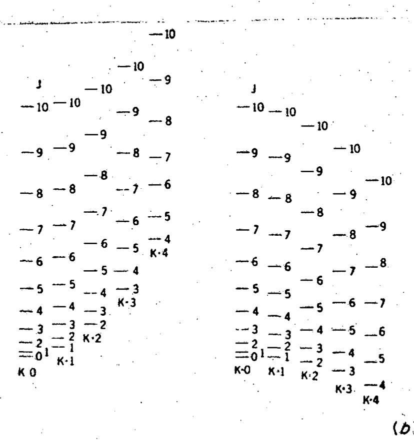
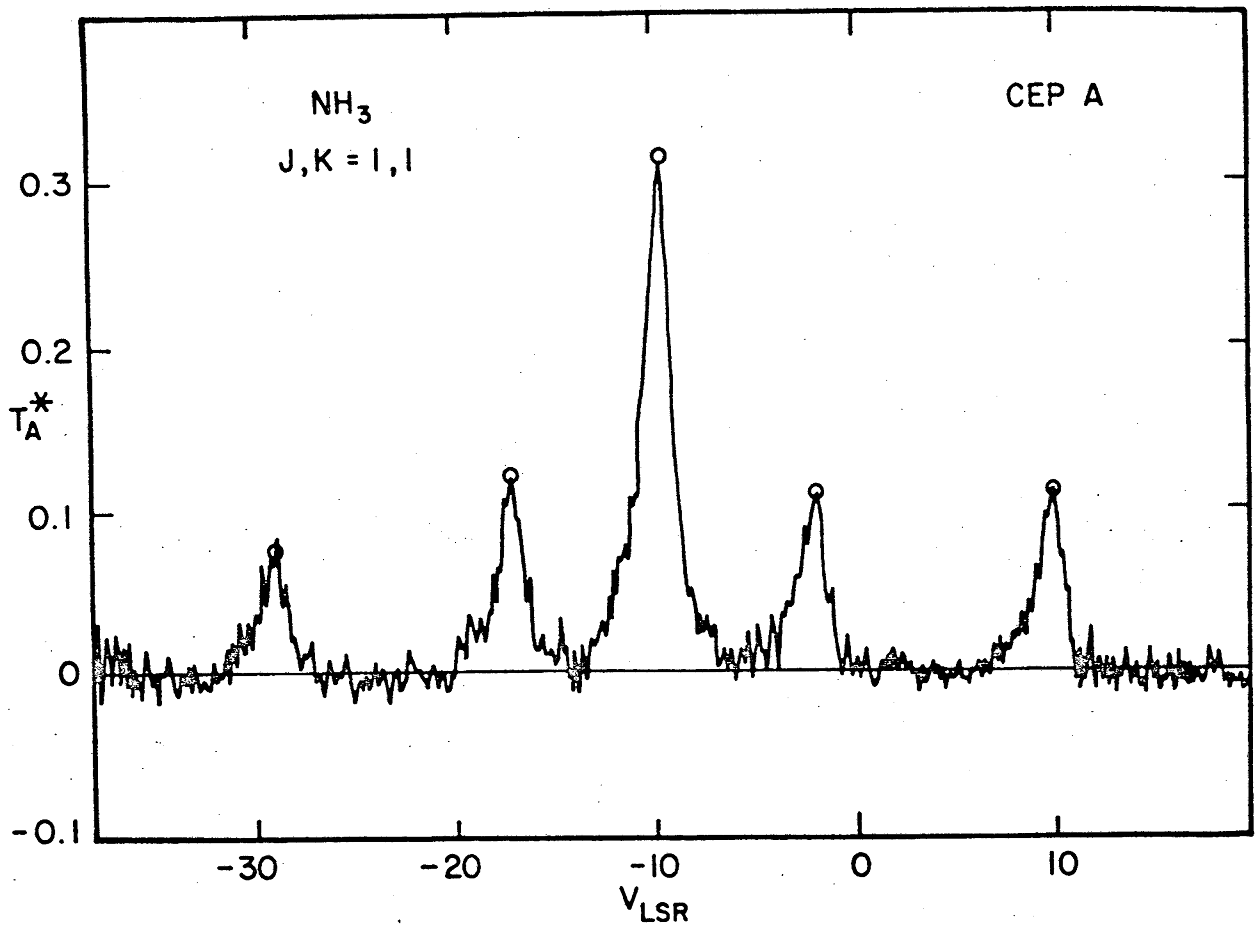
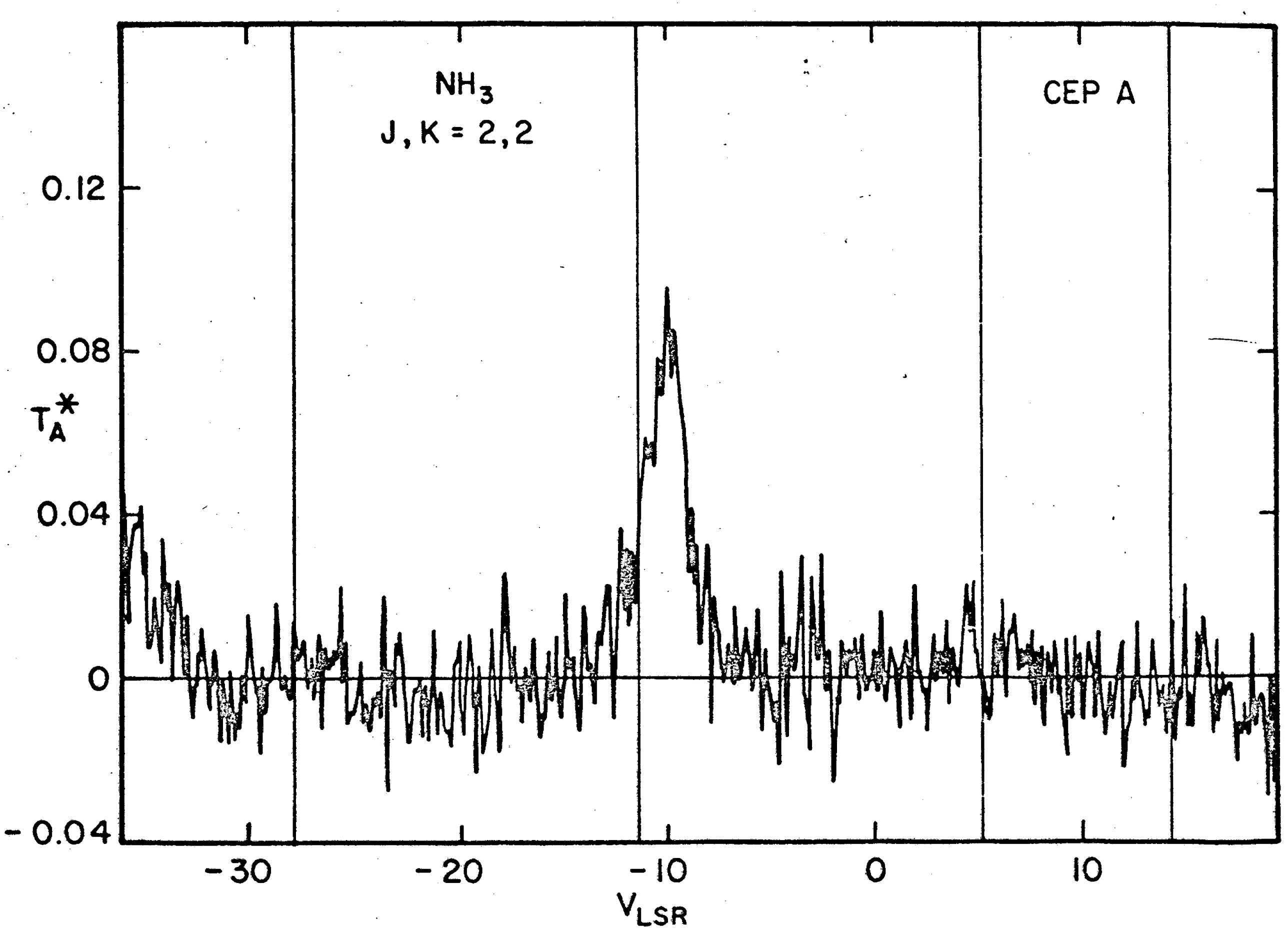
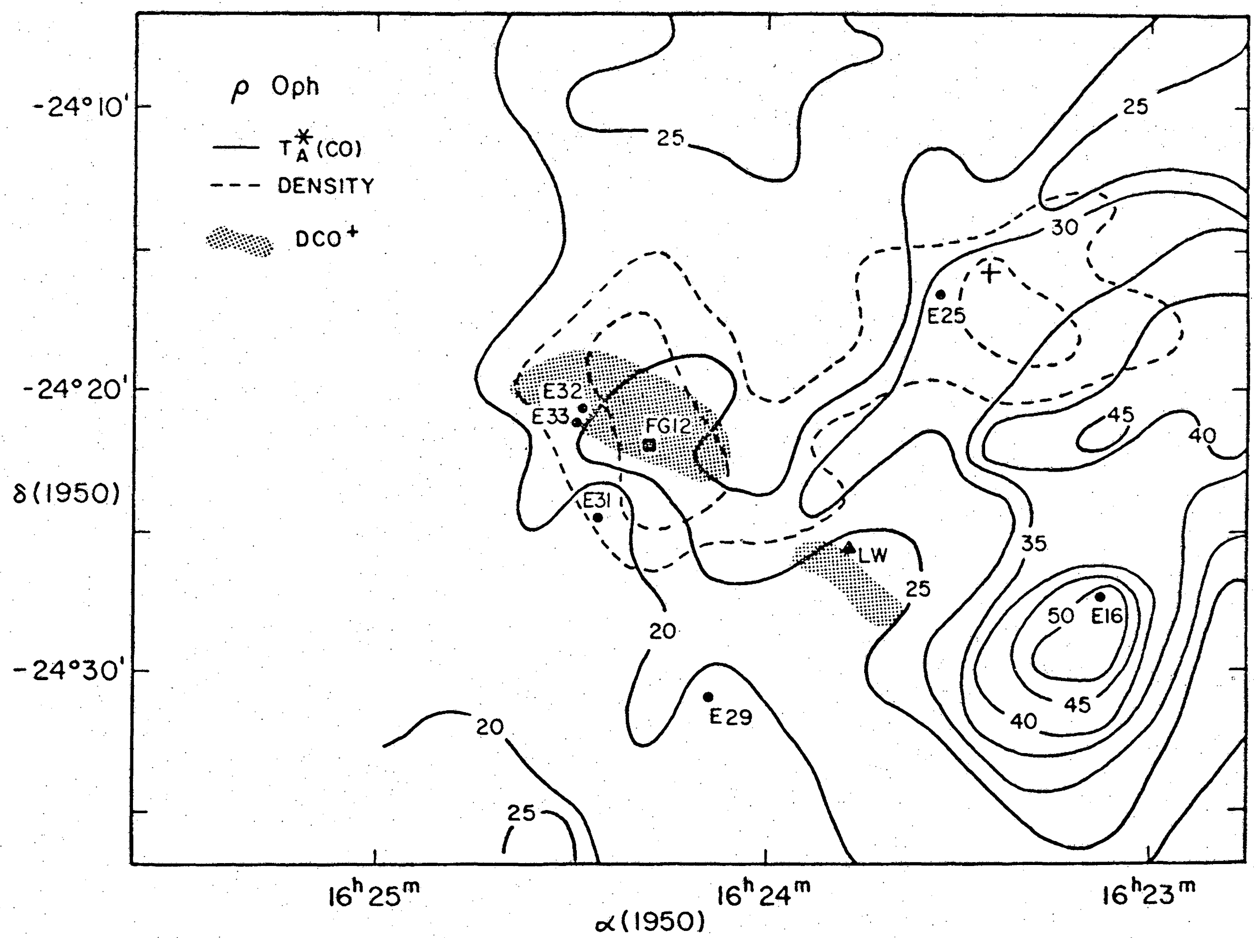


Fig. 3-2. Energy levels of typical symmetric-top molecules. (*a*) prolate; (*b*) oblate symmetric top.


NH3
J,K = 1,1
CEP A
0.3
0.2
0.1
0
-0.1
T_A^*
-30
-20
-10
0
10
V_{LSR}


NH3
J,K = 2,2
CEP A
0.12
0.08
0.04
0
-0.04
T_A^*
-30
-20
-10
0
10
V_{LSR}



ρ Oph
T*A (CO)
DENSITY
DCO+
-24°10'
-24°20'
-24°30'
δ(1950)
16h25m
16h24m
16h23m
α(1950)
25
30
35
40
45
50
20
E25
E32
E33
FG12
E31
LW
E16
E29

FIGURE 11

DENSITY OF MOLECULAR CLOUDS

ONE LINE 1. COLUMN DENSITY OF A SIMPLE LINEAR ROTOR — $^1\Sigma$ X (CO, CS, SiO, SiS

$E(v,J) = B_v J(J+1) - D_v J^2(J+1)^2 + \ldots$ $\Delta J = \pm 1$

EMISSION LINE INTENSITY — LEVELS i (upper), j (lower); QUANTUM # J+1, J

$$I = \frac{h\nu_{ij}}{4\pi} A_{ij} N_i$$

where

$$A_{ij} = 1.16\times10^{-38}\, \nu_{ij}^3 \mu^2 \left(\frac{J+1}{2J+3}\right)$$

§1.4 TS (μ in Debye (10^{-18} esu))

μ = Electric DIPOLE MOMENT OF MOLECULE
= .11 (CO)
= 3.72 (HC_3N)

In the Rayleigh-Jeans regime

$$I = \frac{2kT_A\Delta\nu}{\lambda^2} = 2kT_A \Delta V \frac{\nu^3}{c^3}$$

Using $\lambda^2 = c^2/\nu^2$ $\Delta V = \Delta\nu \frac{c}{\nu}$

So

$$T_A = \frac{hc^3 A_{ij} N_i}{8\pi k \Delta V \nu^2}$$

or

$$N_i = \frac{8\pi k \Delta V \nu^2 T_A}{hc^3 A_{ij}}$$

FOR LTE $T_{ex} = T_K$

$$\frac{N_j}{N_{TOT}} = \frac{\ldots}{Q_{ROT}} (2J+1) e^{-E_j/kT_x}$$

$$Q_{ROT} \approx \int_0^\infty (2J+1) e^{-E_j/kT_x} dJ = \frac{2kT_x}{h\nu_{10}}$$

and for other levels

$$\frac{N_i}{N_j} = \frac{g_i}{g_j} \exp\left(-\frac{h\nu_{ij}}{kT_{ex}}\right)$$

$$N_{TOT}(J+1\to J) = \frac{7\times10^{33}\,\Delta V(\text{km/s})\, T_x T_A\, e^{E_{J+1}/kT_x}}{\nu_{ij}\,\nu_{10}\,(J+1)\,\mu(D)^2} \quad \sim 10^{13}\ \text{cm}^{-2}\ (\text{CO } 1\to0)$$

$= nL \Rightarrow n = \frac{N_{TOT}}{L}$ mean density $\sim 10^3\ \text{cm}^{-3}$

or

$X\, n(H_2) L$ $X = \frac{N_{TOT}}{n(H_2)L}$ where $X = \frac{n(\text{mol})}{n(H_2)}$ abundance $\sim 10^{-8}$ CO

or

$m(H_2) = N_{TOT} A/X \cdot m(H_2)$ $\sim 1\, M_\odot$ @ 1 kpc

DENSITY OF MOLECULAR CLOUDS

2. MORE THAN ONE LINE $\tau < 1$

Usual CASE: $J+1 \to J$ 3 mm
$J+2 \to J+1$ 1.5 mm

Then

$$T_A(J+2, J+1)/T_A(J+1, J) = 4 \exp(-11/T_X)$$

$\simeq .1$ $T_X \sim T_{BGD}$

$\simeq 3.6$ $T_X \sim T_K \sim 100$ K.

∴ MULTI-TRANSITIONAL STUDIES IN "HOT" CLOUDS.

LARGE VELOCITY GRADIENT MODELS (LVG)

MICROTURBULENT MODELS
- SIMPLE SLAB
- LEUNG

MONTE CARLO MODELS

MANY MODELS OF SINGLE POINTS AT CLOUD CORES

MULTITRANSITIONAL MULTIPOINT MODELS

H_2CO ρ Oph, RCrA } COREN + WOOTEN 15 July ApJ

CS S140, NGC2024, M17 } SNELL, MUNDY, EVANS IN PRESS

MODERATE SUCCESS –
1. PREDICTIVE POWER
2. CLUMPINESS
   - n ~ constant
   - N falls off

(f=1 ⇒ large cloud mass fraction incor

PROBLEMS $\tau > 1$ FOREGROUND MATERIAL
LVG unrealistic

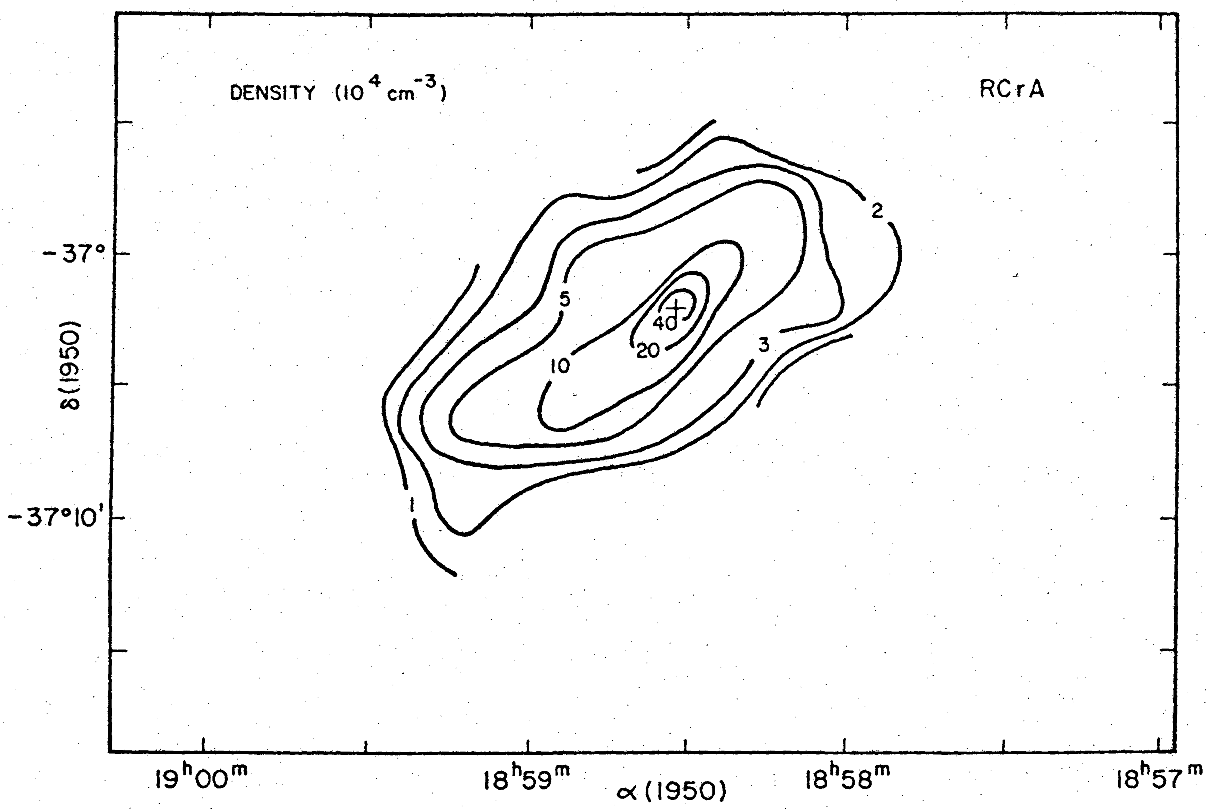


FIGURE 15

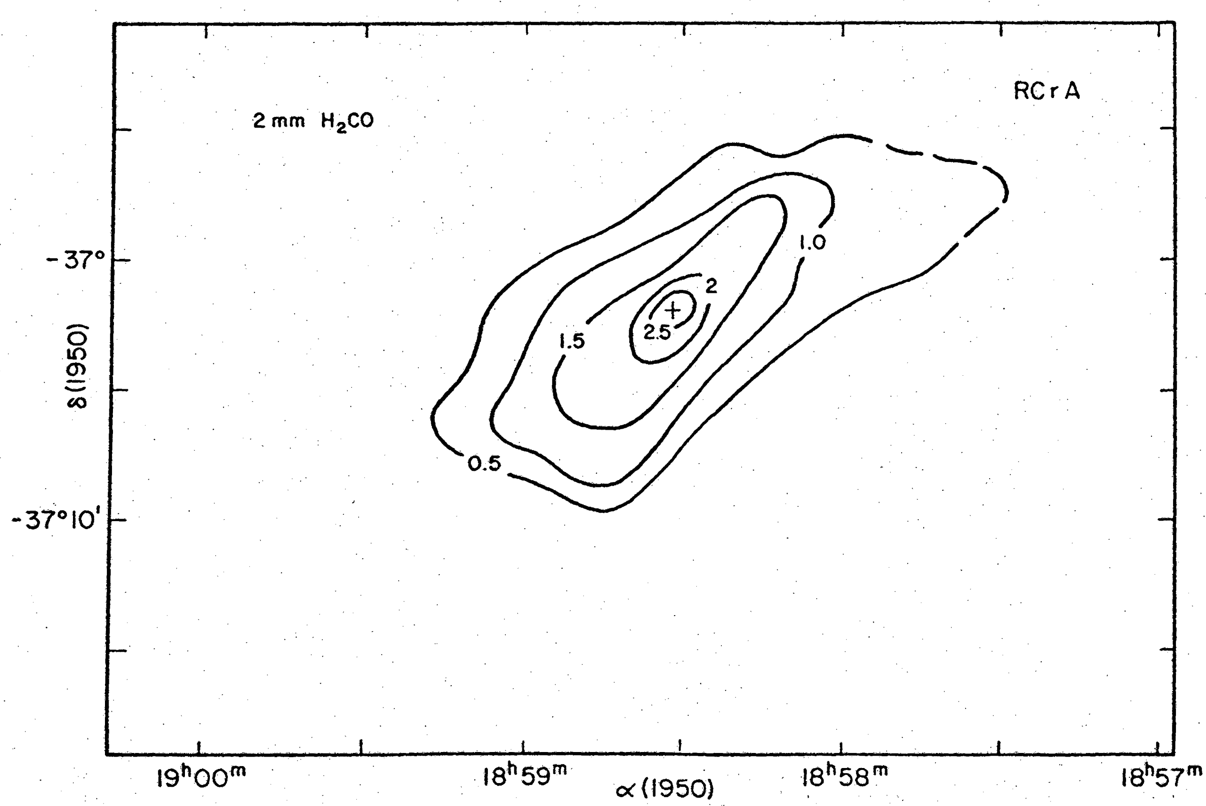


FIGURE 12

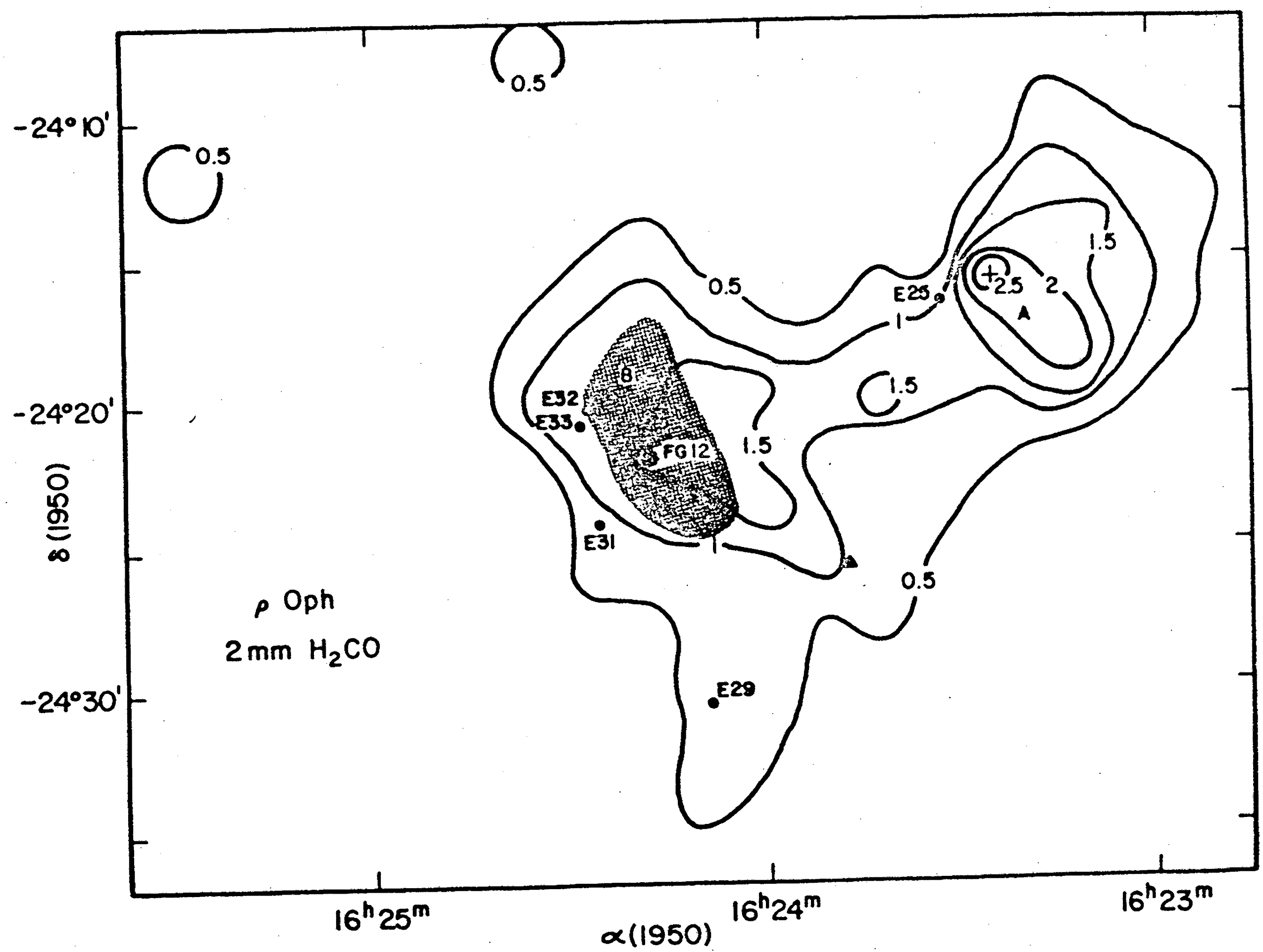


FIGURE 1

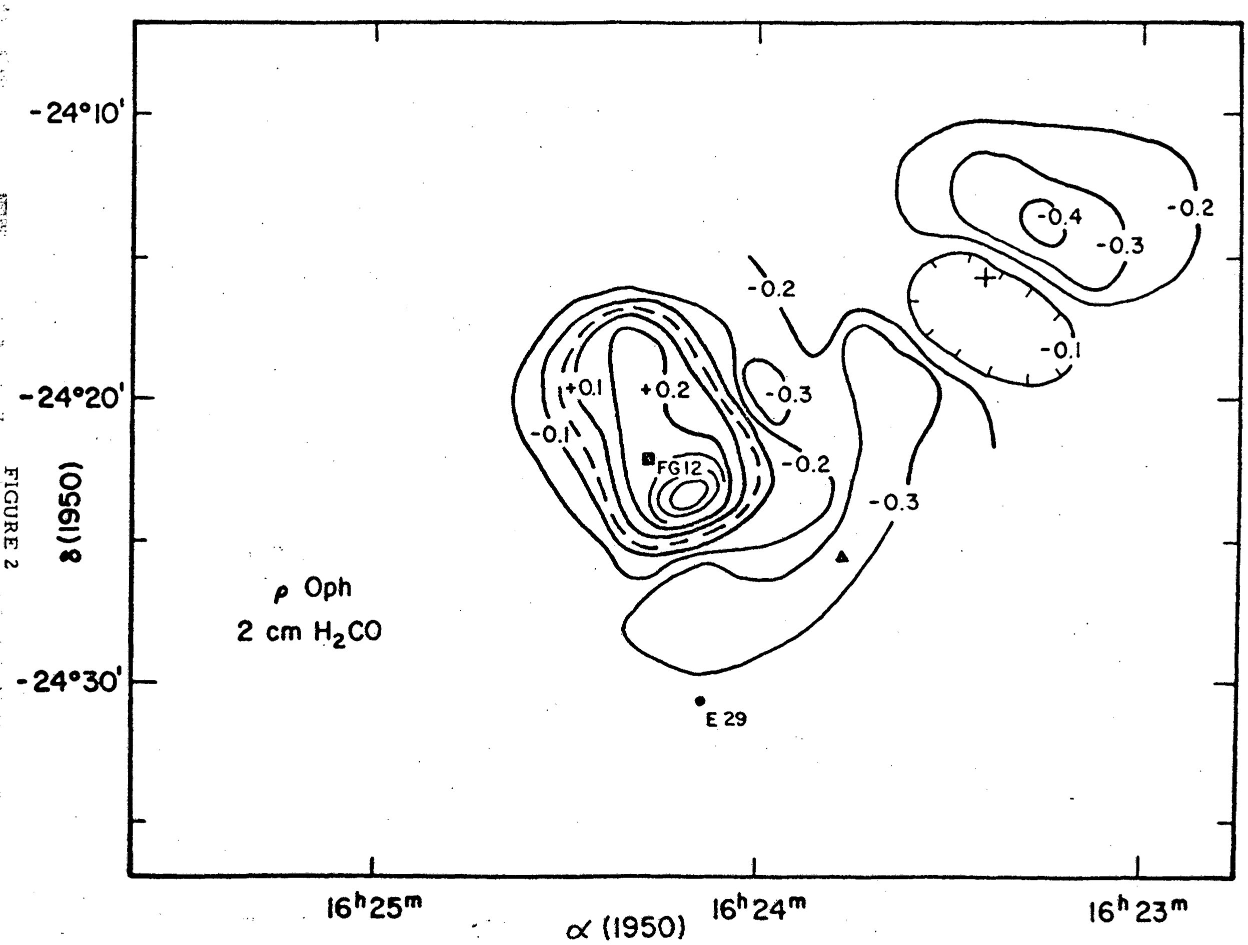


FIGURE 2

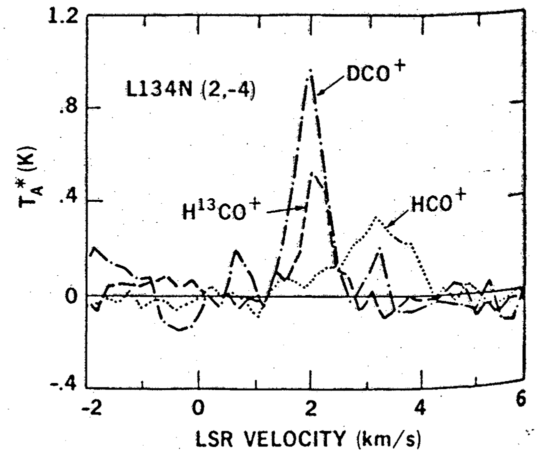


FIG. 3.—Spectra for HCO^+, $H^{13}CO^+$, and DCO^+ at the position (2′, −4′) in L134N (see Fig. 2 for the reference position). Hardly any HCO^+ emission is evident at v_{LSR} = 2.0 km s^{-1}, where both $H^{13}CO^+$ and DCO^+ peak.

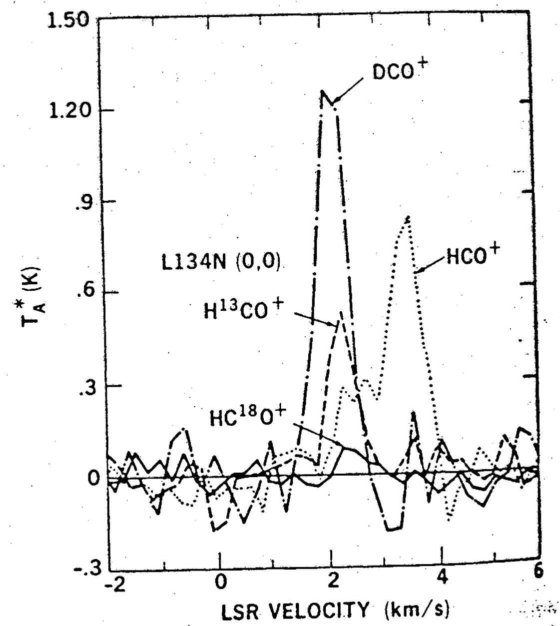


FIG. 2.—Spectra for the HCO^+ isotopes at the central position (0, 0) in L134N. This position has the (1950) coordinates α = $15^h51^m30^s$, $\delta = -2°43'31''$, and v_{LSR} = 2.5 km s^{-1}. The peak in T_A^* for HCO^+ occurs at v_{LSR} = 3.5 km s^{-1}, while those for both $H^{13}CO^+$ and $HC^{18}O^+$ are at 2.4 km s^{-1}, and the DCO^+ emission peaks at 2.0 km s^{-1}.

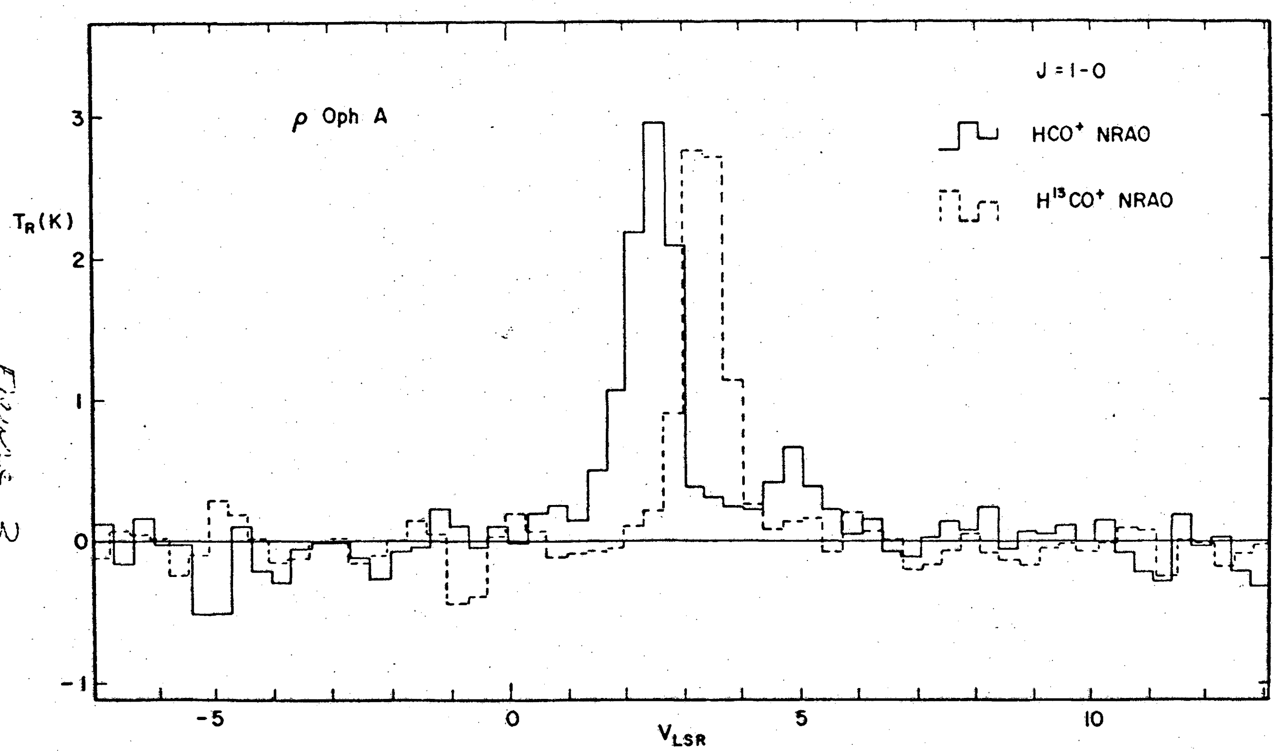


Figure 3

ABUNDANCES OF MOLECULES

1. COMPARE COLUMN DENSITIES

   ASSUME SAME T_{ex}, SAME SPATIAL REGION

2. MODEL EXCITATION, DERIVE FROM MODELS

   APPARENT X DECREASE WITH n INCREASE

   DIFFICULTY: $\tau < 1$

   MOLECULES DEPLETE ONTO GRAINS?

   OPTICAL EVIDENCE

   IR BANDS:

   95% OF NH_3 IN BN/KL ON GRAINS (KNACKE)

   H_2CO

   CO (RATHER SURPRISING) MCGREGOR ET AL 16TH ESLAB SYMPOSIUM p51.

$\Rightarrow$ ASSUMPTION OF CONSTANT $X(^{13}CO) \Rightarrow$ MASS UNDERESTIMATE

ABUNDANCES OF UNOBSERVABLE CONSTITUENTS

H_2 - MASS FROM ^{13}CO, ^{12}CO

e important for magnetic field INFORMATION

A LITTLE CHEMISTRY

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

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

$$H_3^+ + CO \rightarrow HCO^+ + H_2$$

$$H_3^+ + HD \rightarrow H_2D^+ + H_2 + \Delta E$$

$$H_2D^+ + CO \rightarrow DCO^+ + H_2$$

FOR LOW ENOUGH T $(T \ll \Delta E/k)$ $\frac{H_2D^+}{H_3^+} \gg \frac{HD}{H_2}$

NO SPECTRUM FOR H_2D^+ KNOWN

$\Rightarrow$ OBSERVE DCO^+ WOOTTEN ET AL. ApJ 255, 160; GUÉLIN ET AL A+A 107, 107.

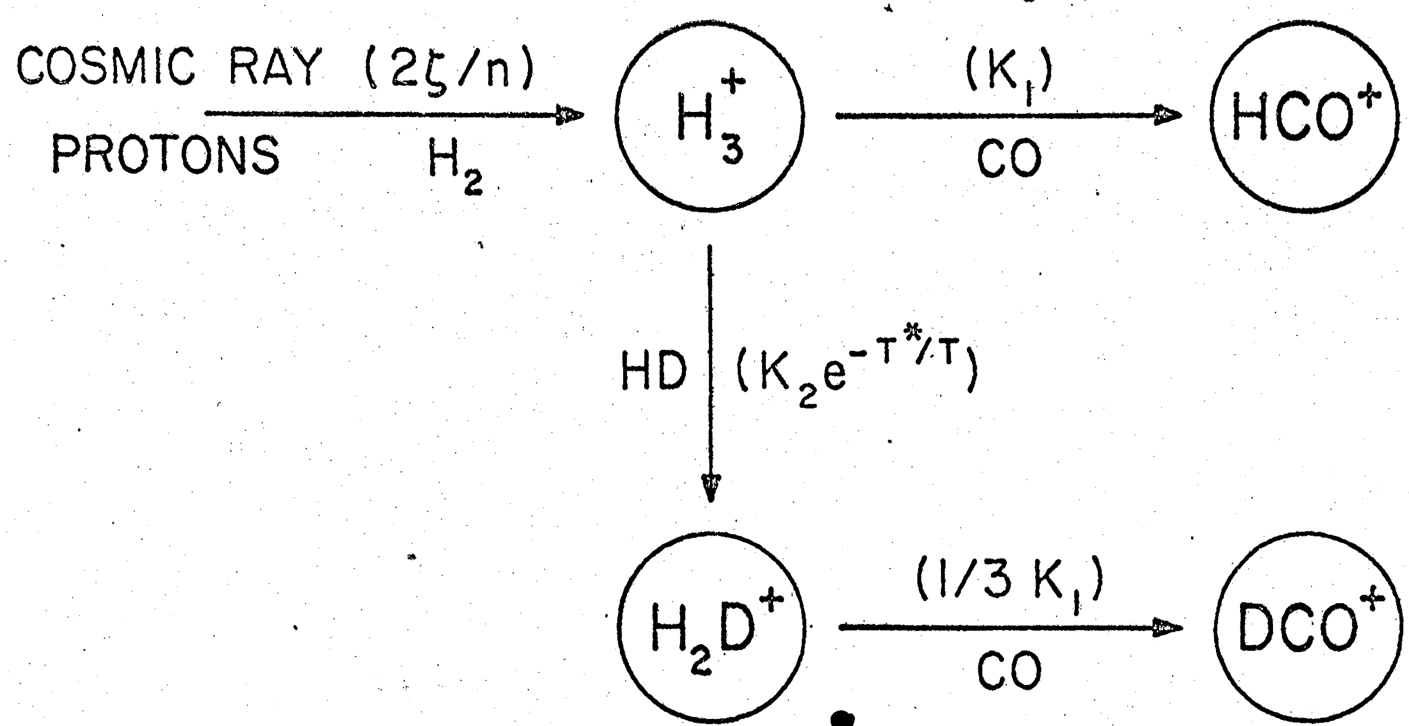
$$R = \frac{X(DCO^+)}{X(HCO^+)} \lesssim \frac{6\times10^{-9}}{X(e) + 7.4\times10^{-4}\exp(-\Delta E/kT) + 7\times10^{-4}[X(CO) + X(N_2) + 3X(H_2O) + \ldots]}$$

$\Rightarrow$ limits on $X(e)$ $X(CO)$ $X(N_2)$

$R \gtrsim 10^3 \frac{D}{H}$ $\quad$ * $X(e) \lesssim 10^{-7}$ $\quad$ metals depleted by atleast 40x

COLD CLOUDS

DCO^+ UNOBSERVABLE IN WARM CLOUDS



$$R = \frac{x(DCO^+)}{x(HCO^+)} \leq \frac{6 \times 10^{-9}}{X(e) + 7.4 \times 10^{-4} \exp(-\Delta E/kT) + 7 \times 10^{-4}\left[x(CO) + x(N_2) + \ldots\right]}$$

$$\frac{x(H^{13}CO^+)}{X(^{13}CO)} = \frac{\left[2\zeta / n(H_2)\right] K}{(\beta x_e + \delta)(\beta' x_e + \delta')} \Rightarrow x_e \leq \left(\frac{2\zeta K}{\beta\beta' Z}\right)^{1/2}$$

$X(HCO^+) \sim 10^{-8}$ ⇒ +ive CHARGE RESIDES IN HCO^+

$$\frac{X(H^{13}CO^+)}{X(^{13}CO)} = \frac{[2\zeta/n(H_2)]K}{(\beta x_e + \delta)(\beta' x_e + \delta')}$$

$$x_e \leq \left(\frac{2\zeta K}{\beta\beta' Z}\right)^{1/2}$$

K rate coefficient for HCO^+
β_1 e recombo H_3^+
β e recombo HCO^+
$\delta = \Sigma k_i x_i$ H_3^+ destruy
$\delta' = \Sigma k_i' x_i$ HCO^+ destruy

$x_e \lesssim 6 \times 10^{-8}$ WARM CLOUDS WOOTTEN ET AL
ApJ 234, 876, & 255, 160.

IF CHARGE RESIDES ~~ON~~ IN GAS ALONE, B-FIELD NOT TIED TO GAS
GRAINS COMPLICATE PICTURE

L134N, B5 : CORE OF CLOUD ROTATES IN OPPOSITE SENSE TO THE PERIPHERY!
FROZEN IN BFIELD TRANSFERS ANGULAR MOMENTUM OUTWARD, EXTERNAL MEDIUM EXERTS RESTORING TORQUE, REVERSING ROTATION SENSE OF CLOUD CORE
CLARK & JOHNSON 1981 ApJ 247, 104
YOUNG ET AL. 1981 ApJ 251, L81.

SUMMARY	GIANT CLOUDS	WARM CLOUD CORES	DARK CLOUDS
M	$10^4 - 5\times10^6 M_\odot$	$\sim \frac{1}{2} M_{CLOUD}$ ($<10^3 M_\odot$)	$<100 M_\odot$
T	15 K	30 K	10 K
r	~90 pc	~0.5 pc	1.1 pc
$\langle n \rangle$	few 100	$5\times10^4 \rightarrow 10^6$	$10^3 \rightarrow$ few $\times 10^4 - 10^5$

DYNAMICS

LINEWIDTHS > THERMAL (few km/s as opposed to ~ .2 km/s)

SCALE OF MOTIONS?

MICROTURBULENCE SCALES LESS THAN 1 MEAN FREE PATH

MESO TURBULENCE EQUAL TO

MACROTURBULENCE LARGER THAN

(COLLAPSE, ROTATION, EXPANSION)

MICROTURBULENCE ⇒ CHARACTERISTICALLY SELF REVERSED PROFILES

ORIGINALLY RULED OUT BY SCARCITY OF THESE IN CO

QUITE COMMON IN OTHER MOLECULES

ALSO CO T-PROFILE NOW THOUGHT TO RISE OUTWARD.

DARK CLOUDS - MYERS FINDS $\Delta V - \Delta R$ RELATION

HIGH EXCITATION LINES SMALLER REGION & LINEWIDTH

SLIGHTLY TURBULENT OR THERMAL CORE

ROTATION; EXPANSION & BIPOLAR FLOWS

EXTREMELY COMMON FLOWS NEAR FORMED STARS

BIPOLARITY - CHARACTERISTICS FROM CO BALLY & LADA 265, 824

SIZE ~ .3pc (i.e. must be within 1kpc)

$M \sim 0.3 - 100 M_\odot$ $E \sim 10^{46-47}$ ergs

$V \sim 10-50$ km/s $P \lesssim 200 M_\odot$ km/s

$\tau \sim \frac{R}{V} \sim 10^4$ yr

CANNOT BE DRIVEN BY RAD PRESSURE

MECHANICAL ORIGIN OF UNKNOWN NATURE

COLLIMATING AGENT UNKNOWN

HIGH FORMATION RATE: $\gtrsim 3 \times 10^{-4}$ yr^{-1} kpc^{-2}

$\gtrsim 0.1$ yr^{-1} for Galaxy $< R_\odot$

TOTAL ✱ FORMATION RATE: 1-10 $M_\odot$ yr^{-1}

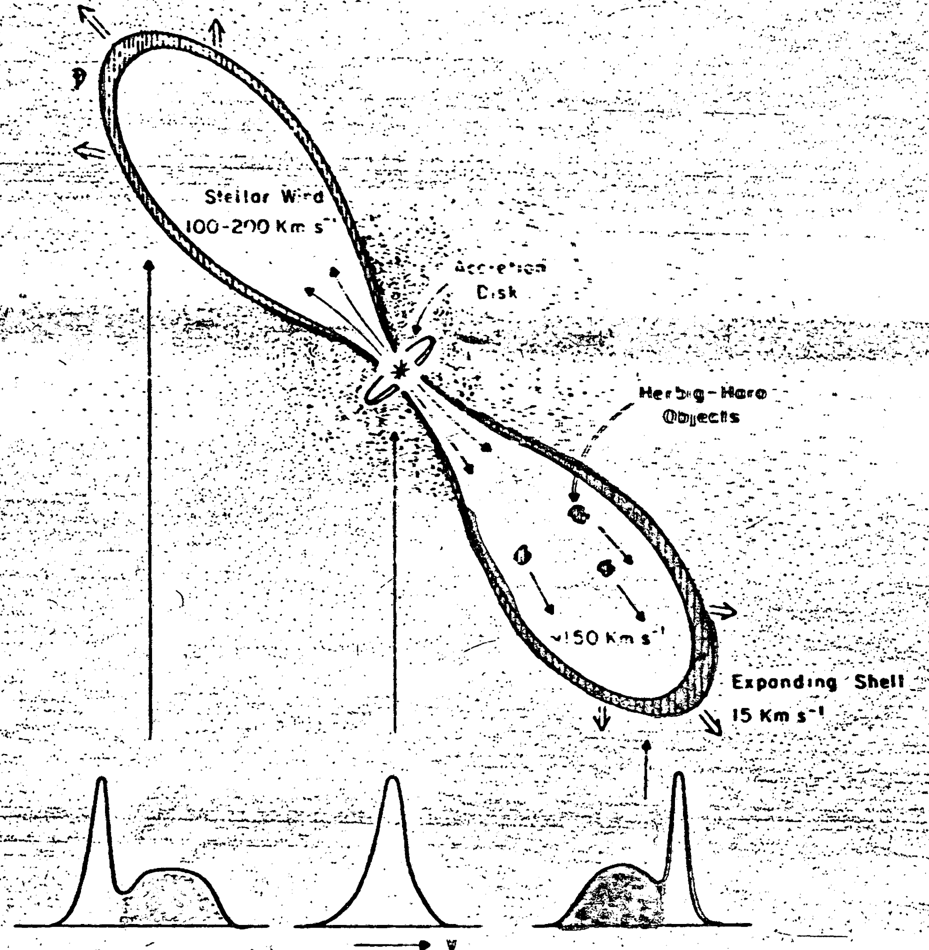


FIG. 5.—A schematic picture of the stellar wind driven shock model for L1551, indicating the CO line profiles which would be expected at different positions across the source. The Herbig-Haro objects are not necessarily located inside the shell; because of their high velocities, they may have been ejected through the shell and into the surrounding medium.