DENSITOMETRY AND THERMOMETRY OF STARBURST GALAXIES

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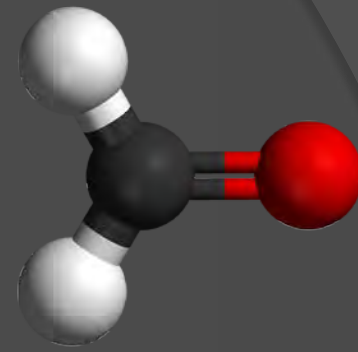
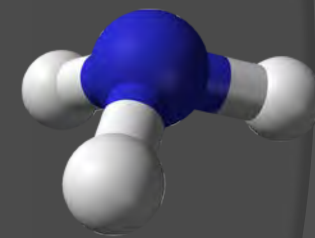
The Tools

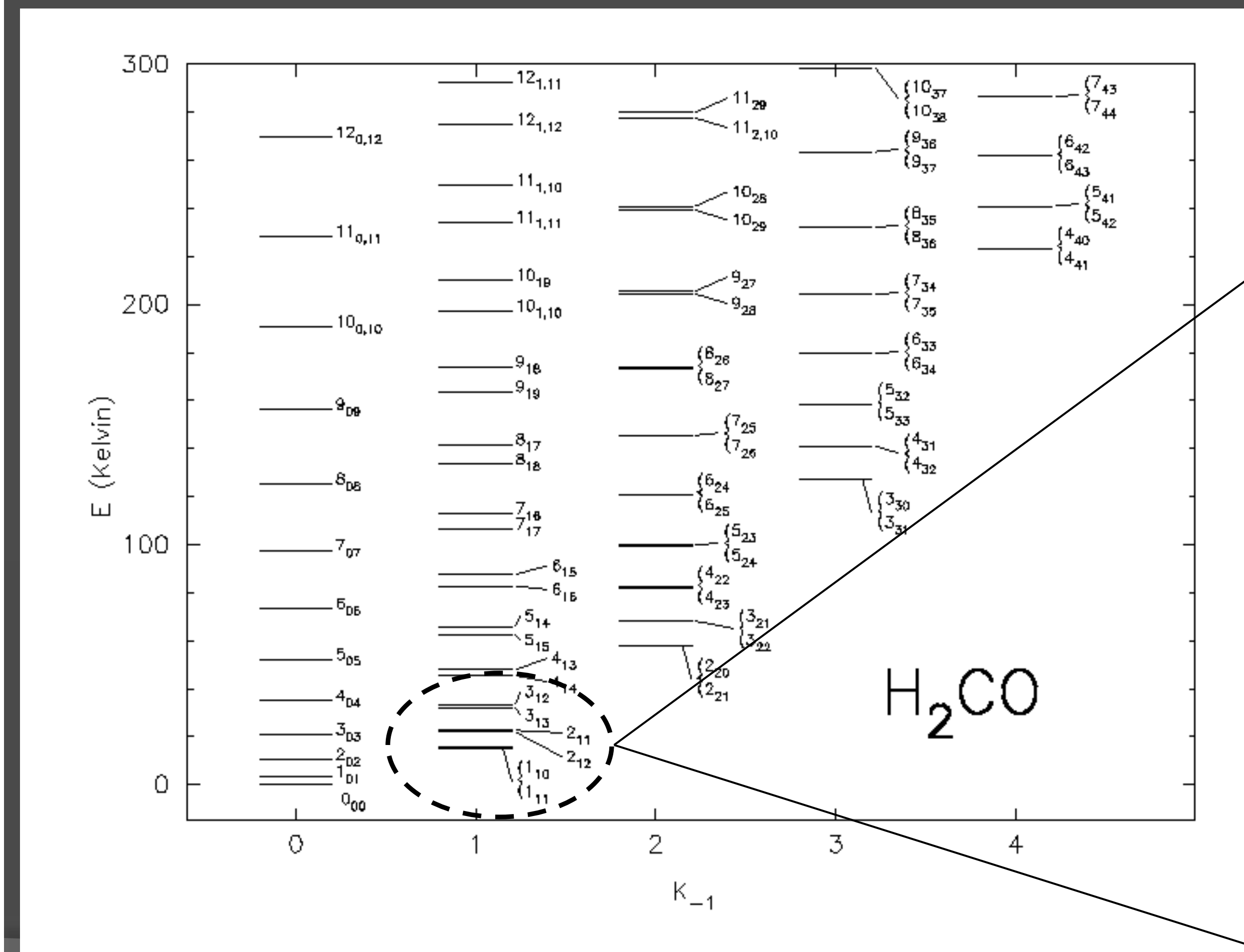


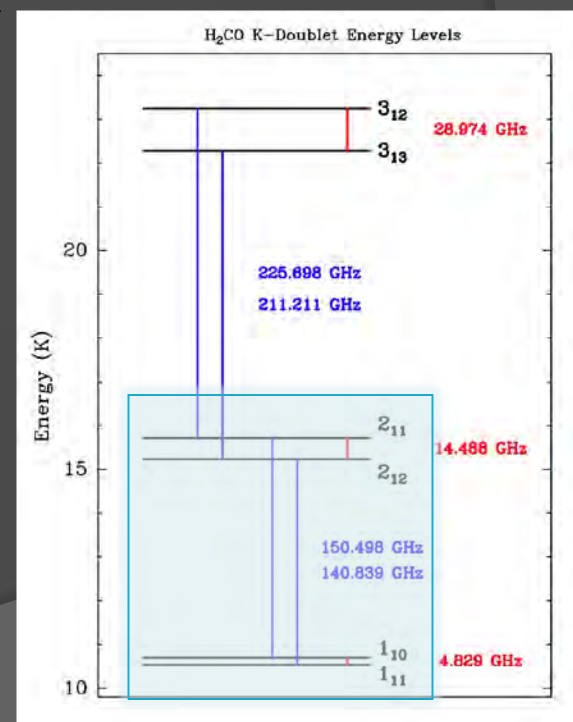
- Densitometry
  - Formaldehyde (H_2CO)
  - Slightly asymmetric rotor molecule (κ = -0.96)
  - K-doublet energy level splitting
- Thermometry
  - Ammonia (NH_3)
  - Symmetric rotor molecule
  - Rotation-inversion energy level splitting

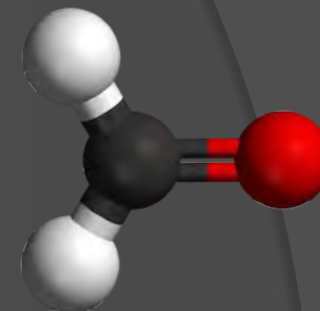


- LVG model to fit multi-transition measurements from both molecules

H_2CO Energy Level Structure

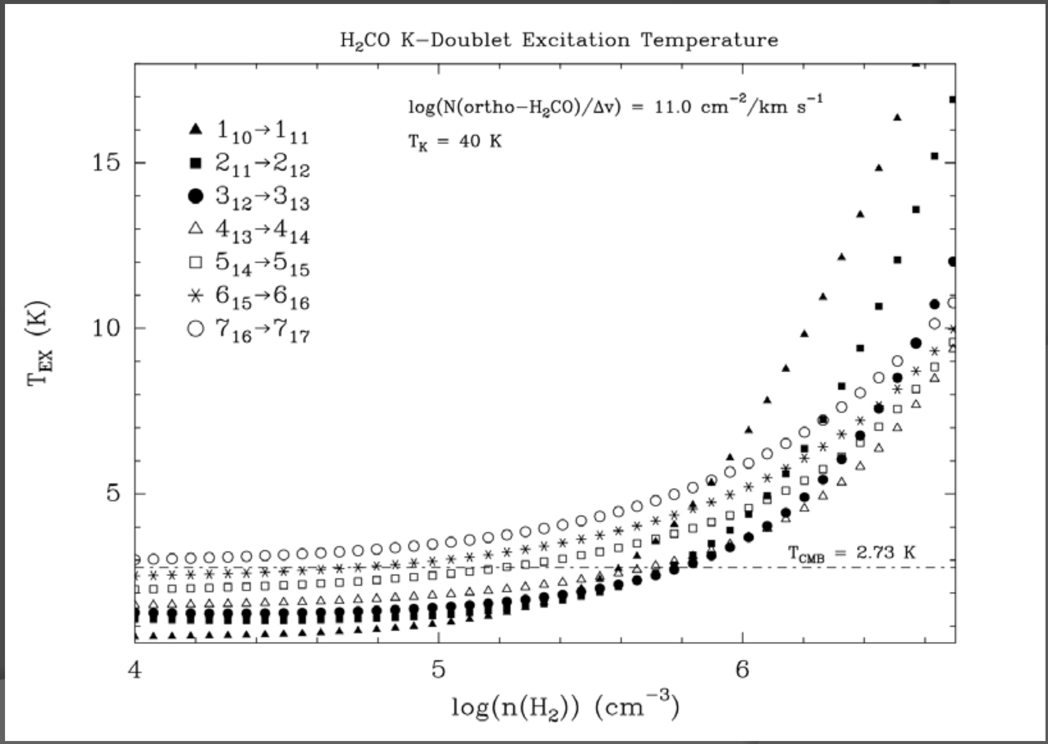




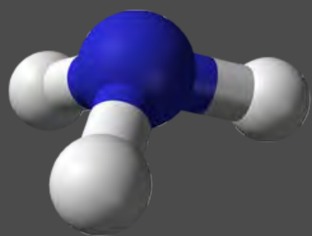


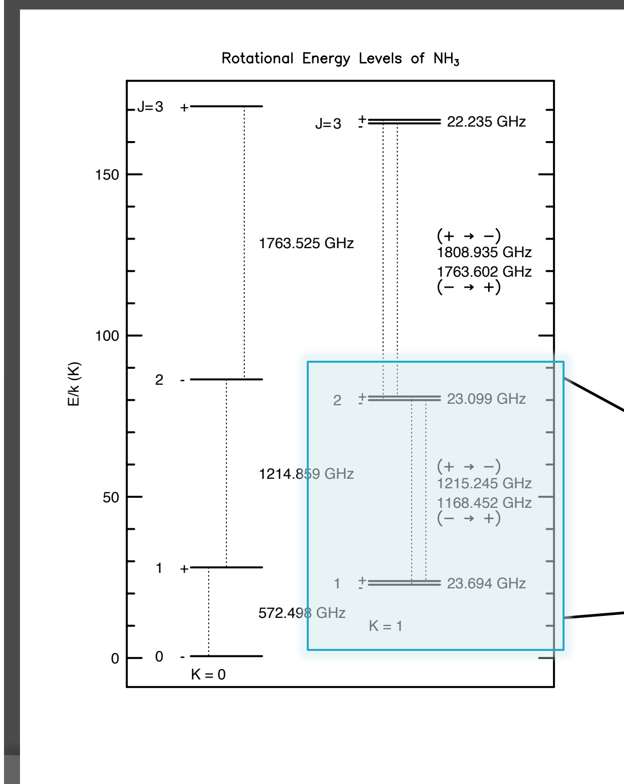
K-Doublet Excitation

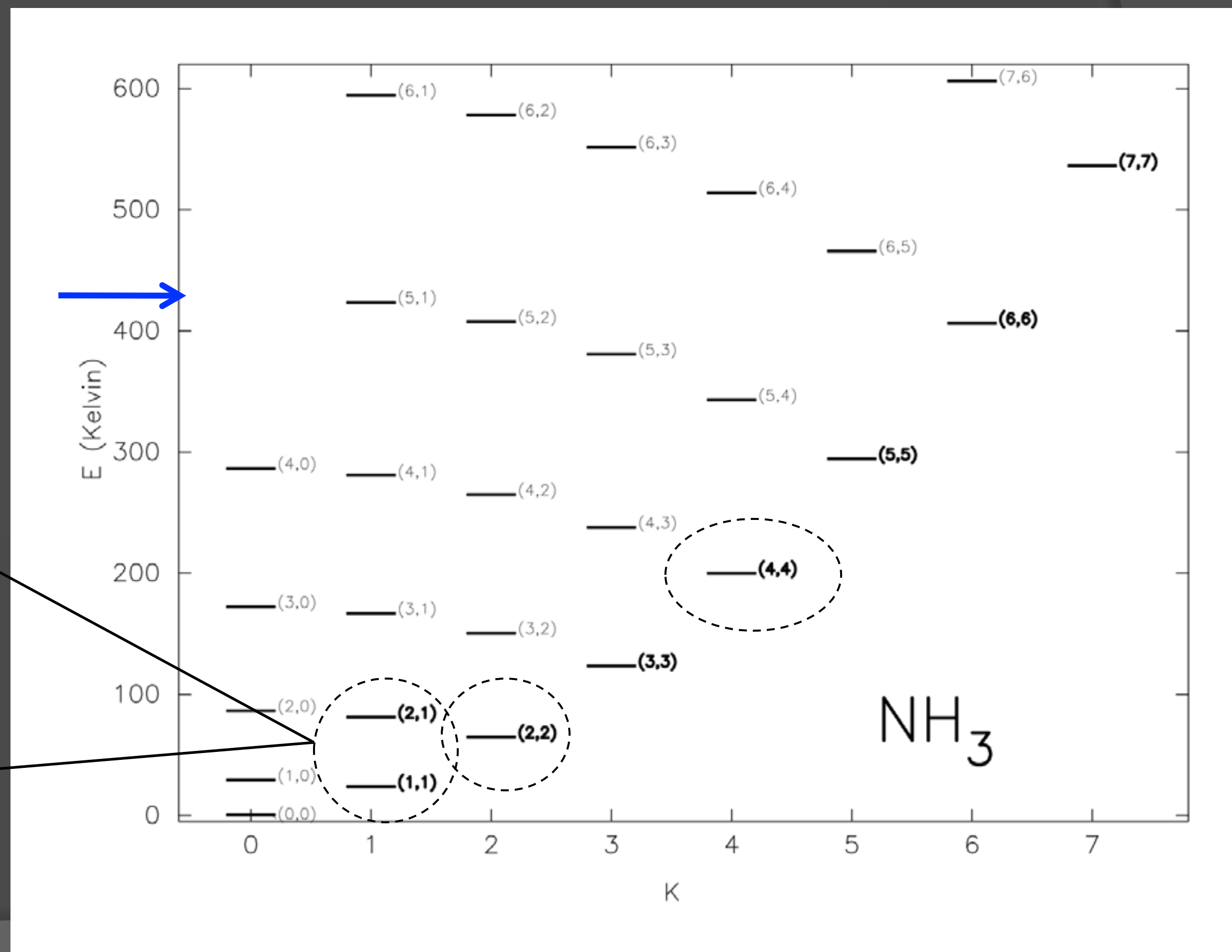
- In-plane collisions with H_2 produce an excess of molecules in the 1_{11} and 2_{12} (lower) energy states at low densities.
- High densities quench this collisional cooling process.
- $n(H_2) < 10^{5.6}$ cm^{-3} → K-Doublet absorption
- $n(H_2) \geq 10^{5.6}$ cm^{-3} → K-Doublet emission



NH_3 Energy Level Structure







H_2CO and NH_3 in Starburst Galaxies

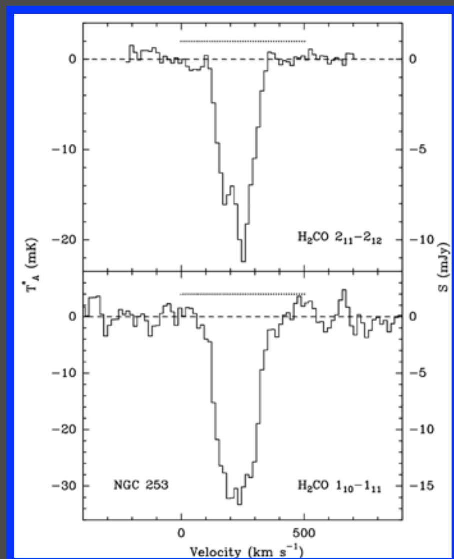
- Selection criteria:
  - Dec (J2000) > -40 deg
  - L(60μm) > 50 Jy and/or
  - Bright HCN and CO emission
- H_2CO
  - Green Bank Telescope (θ_b = 51 and 153 arcsec)
  - 26 of 56 galaxies detected in at least one H_2CO transition
  - 1_{10}-1_{11} emission/absorption = 6/19
  - 2_{11}-2_{12} emission/absorption = 0/13
  - 17 of 26 detections are new extragalactic discoveries of H_2CO
- NH_3
  - GBT (θ_b = 30 arcsec)
  - 12 of 19 galaxies detected in at least one NH_3 transition
  - NH_3 emission/absorption = 7/5
  - 4 of 12 detections new discoveries of extragalactic NH_3

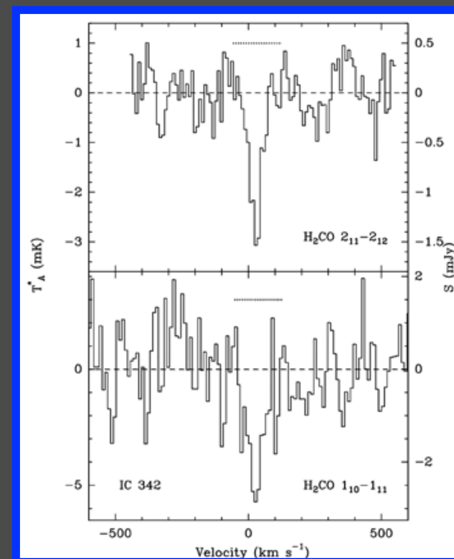
Table 1. Starburst Galaxy Survey List

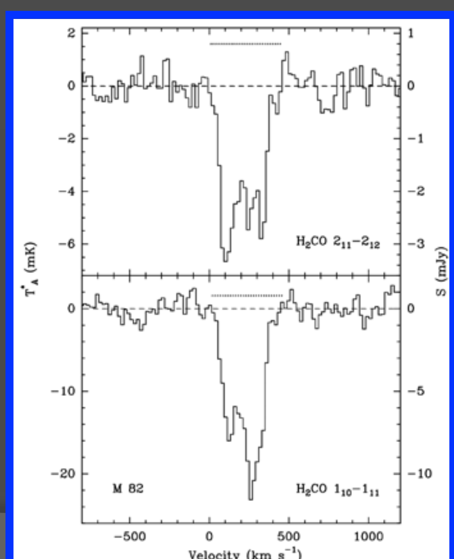
Source	α (J2000)	δ (J2000)	v_{hel}[a] (km s^{-1})	D_L[b] (Mpc)	T_{dust}[c] (K)	Classification[d]
NGC 55	00:14:54.5	−39:11:19	129	1.7	···	SB(s)m: edge-on
NGC 224	00:42:44.8	+41:16:13	−300	0.8	···	SA(s)b LINER
NGC 253	00:47:33.1	−25:17:18	251	2.5	34	SAB(s)c
IC 1623	01:07:47.2	−17:30:25	6028	81.0	39	···
NGC 520	01:24:35.3	+03:47:37	2281	30.4	38	Pec, Pair, Sbrst
NGC 598	01:33:54.0	+30:40:07	−179	0.9	···	SA(s)cd
NGC 660	01:43:01.7	+13:38:36	856	14.0	37	SB(s)a:pec, HII LINER
IR 01418+1651	01:44:30.5	+17:06:09	8101	110.0	···	LIRG
NGC 695	01:51:14.9	+22:34:57	9769	134.0	34	SO pec:LIRG
Mrk 1027	02:14:05.6	+05:10:24	9061	120.5	37	I:LIRG
NGC 891	02:22:33.4	+42:20:57	529	8.6	28	SA(s)b?:sp
NGC 925	02:27:16.9	+33:34:35	553	9.9	···	SAB(s)d
NGC 1022	02:38:32.7	−06:40:39	1503	18.5	39	SB(s)a
NGC 1055	02:41:45.2	+00:26:35	996	15.0	29	SBb:sp:Sy2 LINER
Maffei 2	02:41:55.1	+59:36:15	−17	3.1	···	SAB(rs)bc
NGC 1068	02:42:40.7	−00:00:48	1136	13.7	40	SA(rs)b:Sy1/2
UGC 02369	02:54:01.8	+14:58:15	9262	125.2	···	DBL
NGC 1144	02:55:12.2	−00:11:01	8750	118.5	32	S pec
NGC 1365	03:33:36.4	−36:08:25	1652	17.9	32	SBb(s)b
IR 03359+1523	03:38:47.1	+15:32:53	10507	145.6	···	LIRG
IC 342	03:46:49.7	+68:05:45	31	3.7	30	SAB(rs)cd
NGC 1614	04:33:59.8	−08:34:44	4847	64.2	46	SB(s)c:pec
VIIZw31	05:16:46.4	+79:40:13	16290	222.5	34	···
NGC 2146	06:18:37.7	+78:21:25	918	16.5	38	SB(s)ab:pec
NGC 2623	08:38:24.1	+25:45:17	5535	102.0	···	LIRG
Arp 55	09:15:55.1	+44:19:55	11957	159.4	36	Pair
NGC 2903	09:32:10.1	+21:30:02	556	6.2	29	SB(s)d
UGC 5101	09:35:51.6	+61:21:11	11810	157.5	36	Sy1.5, LINER
M 82	09:55:52.2	+69:40:47	203	3.5	45	I0,Sbrst
NGC 3079	10:01:57.8	+55:40:47	1150	16.2	32	SB(s)c, LINER
IR 10173+0828	10:19:59.9	+08:13:34	14716	196.2	···	Sbrst
NGC 3227	10:23:30.7	+19:52:46	1111	20.8	···	SAB(s):pec
NGC 3627	11:20:15.0	+12:59:30	727	10.2	30	SAB(s)b:LINER
NGC 3628	11:20:17.2	+13:35:20	847	9.6	30	Sb:pec:sp
NGC 3690	11:28:32.2	+58:33:44	3121	43.9	···	Merger
NGC 4631	12:42:08.0	+32:32:29	606	7.3	30	SB(s)d
NGC 4736	12:50:53.0	+41:07:14	308	5.1	···	SA(r)ab:Sy2:LINER
Mrk 231	12:56:14.2	+56:52:25	12642	175.1	···	SA(rs)c:pec
NGC 5005	13:10:56.2	+37:03:33	946	18.1	28	SAB(rs)bc
IC 860	13:15:04.1	+24:37:01	3866	51.5	···	Sa, Sbrst
NGC 5194	13:29:52.7	+47:11:43	463	7.7	···	SA(s)bc:pec
M 83	13:37:00.9	−29:51:57	518	3.7	31	SAB(s)c
Mrk 273	13:44:42.1	+55:53:13	11324	156.7	48	LINER
NGC 5457	14:03:12.6	+54:20:57	241	7.0	···	SAB(rs)cd
IR 15107+0724	15:13:13.1	+07:13:27	3897	52.0	···	Sbrst
Arp 220	15:34:57.1	+23:30:11	5434	72.5	44	Pair, Sbrst
NGC 6240	16:52:59.0	+02:24:02	7339	97.9	41	I0:pec, LINER, Sy2
IR 17208-0014	17:23:21.9	−00:17:00	12834	177.1	46	ULIRG
IR 17468+1320	17:49:06.7	+13:19:54	4881	65.1	···	Sbrst
NGC 6701	18:43:12.4	+60:39:12	3950	57.2	32	SB(s)a
NGC 6921	20:28:28.8	+25:43:24	4399	62.3	34	SA(r)0/a
NGC 6946	20:34:52.3	+60:09:14	48	5.5	30	SAB(rs)cd
IC 5179	22:16:09.1	−36:50:37	3447	44.2	33	SA(rs)bc
NGC 7331	22:37:04.1	+34:24:56	821	14.2	28	SA(s)b;LINER
NGC 7479	23:04:56.6	+12:19:22	2385	32.4	36	SB(s)c;LINER
IR 23365+3604	23:39:01.3	+36:21:09	19330	267.5	45	SBa:pec;LINER
Mrk 331	23:51:26.7	+20:35:10	5422	78.1	41	LIRG

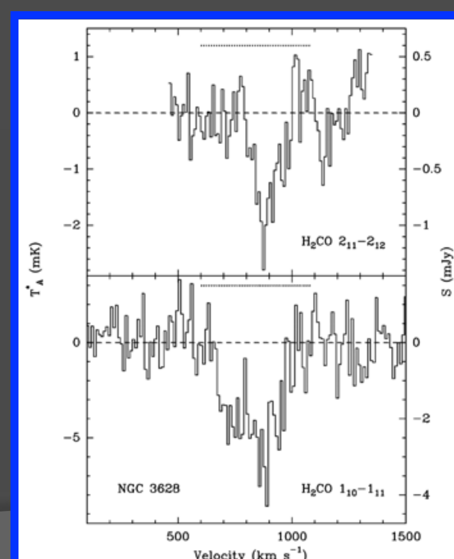
H_2CO in Starburst Galaxies

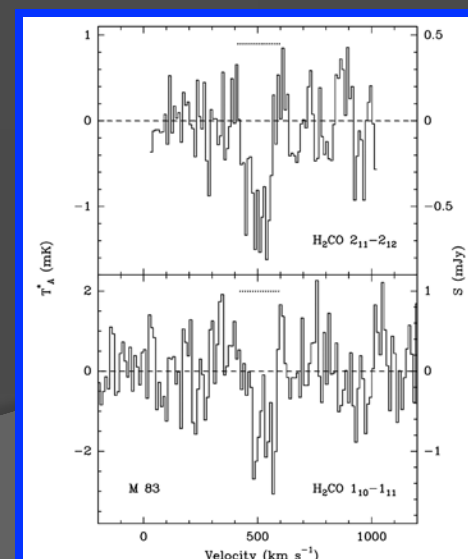
1_{10}-1_{11} absorption and 2_{11}-2_{12} absorption





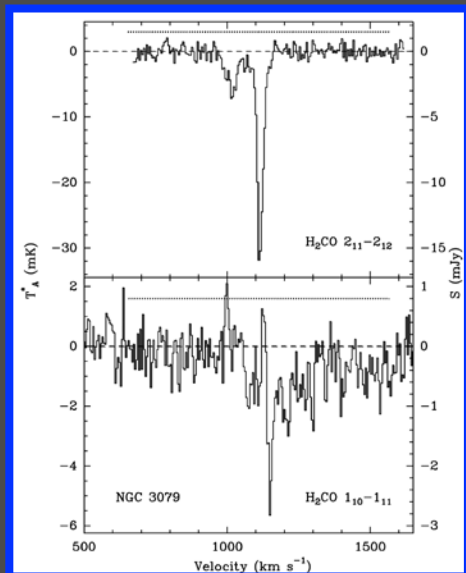


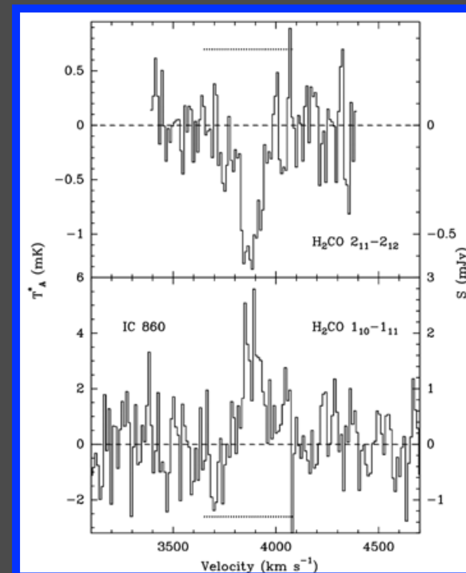


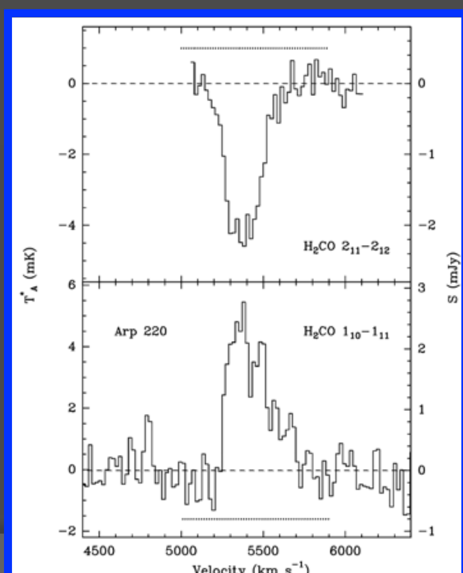


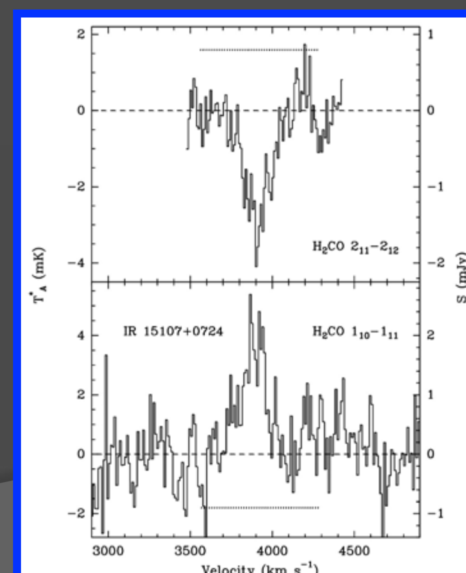
H_2CO in Starburst Galaxies

1_{10}-1_{11} emission and 2_{11}-2_{12} absorption

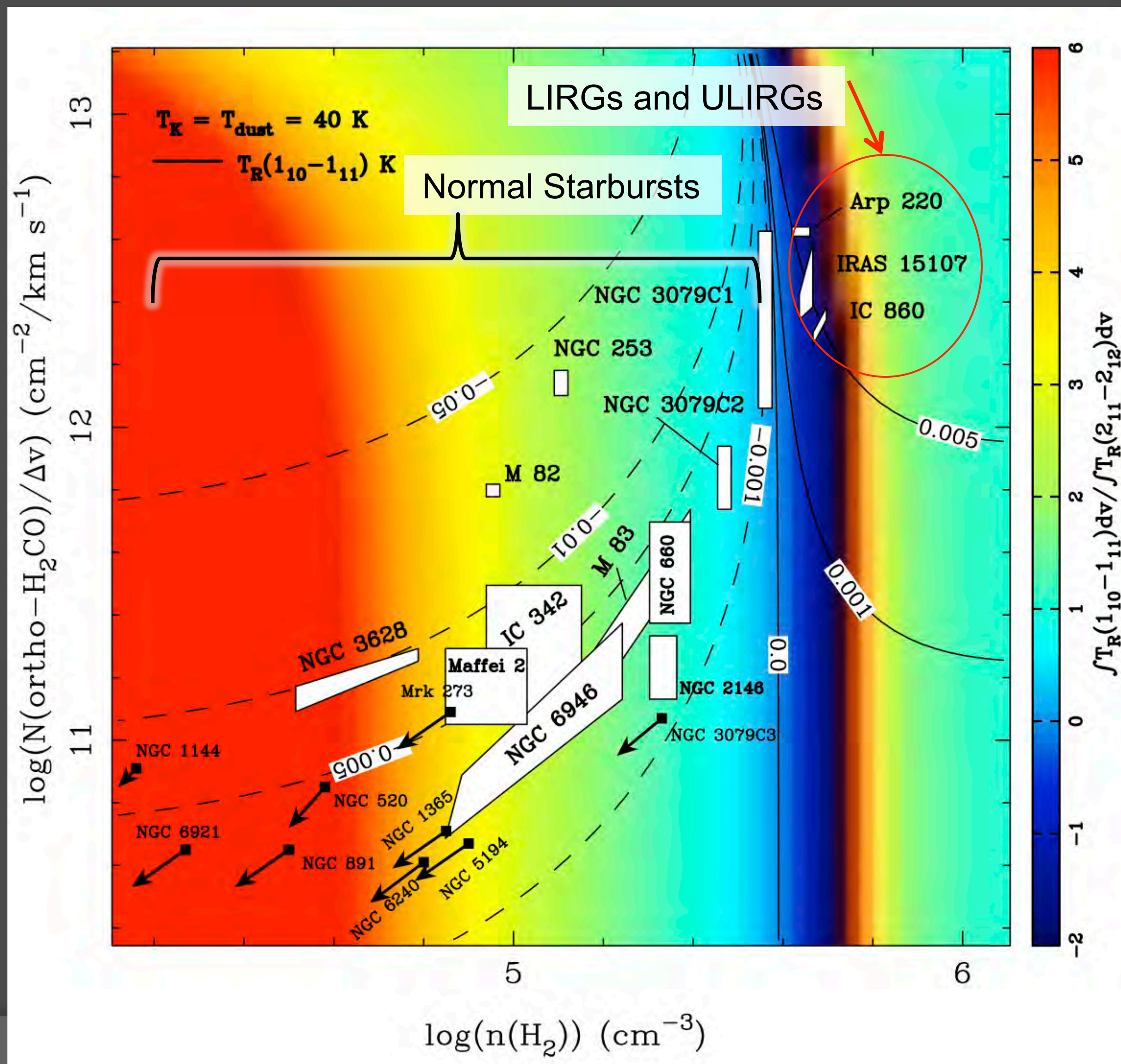




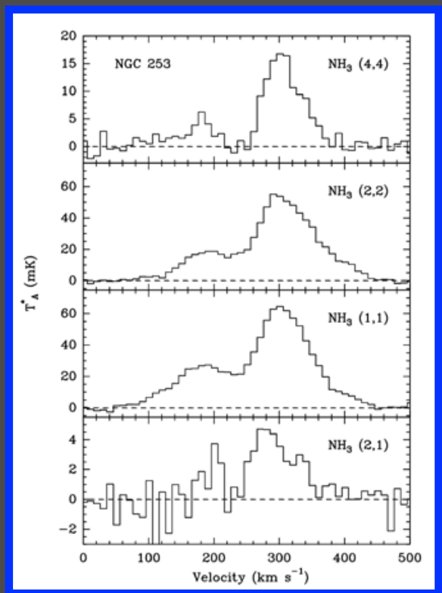


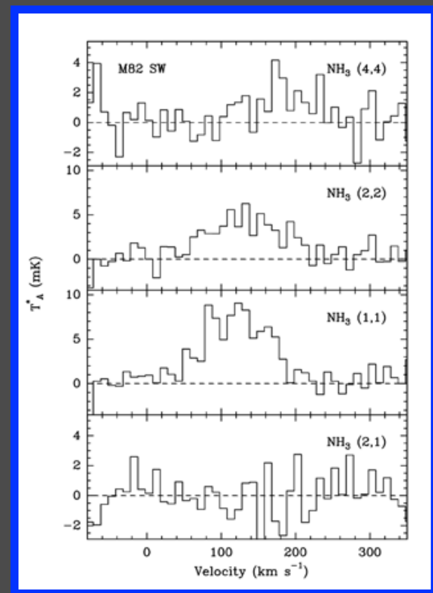


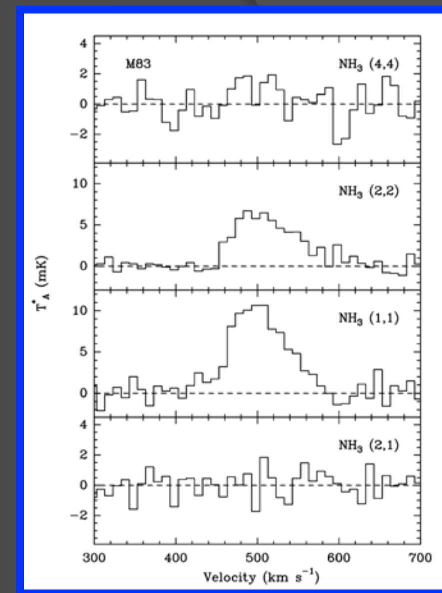
Starburst Galaxy Densitometry

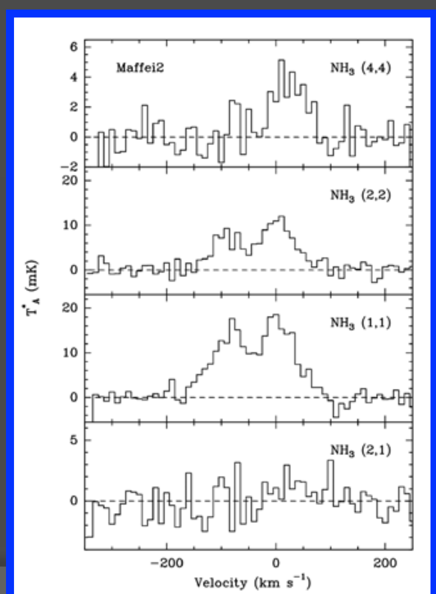


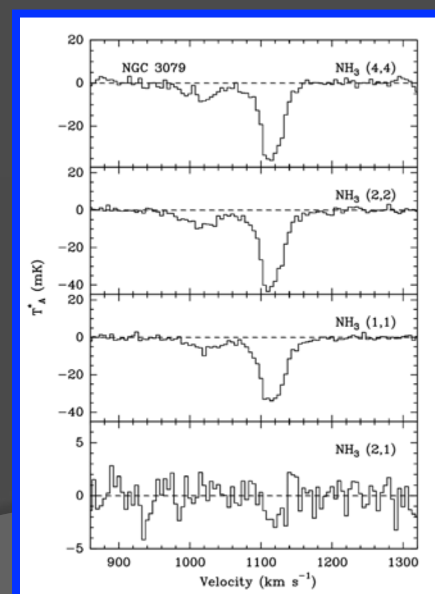
NH_3 in Starburst Galaxies



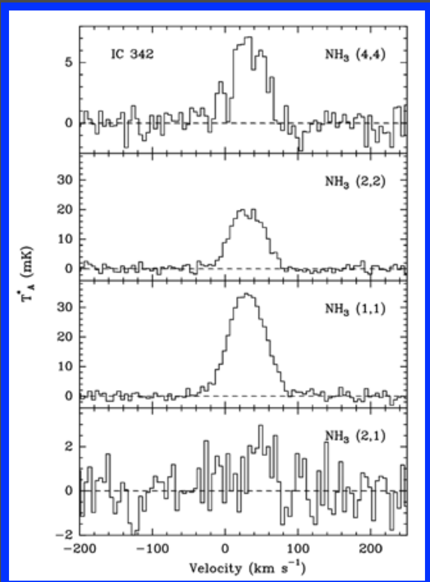


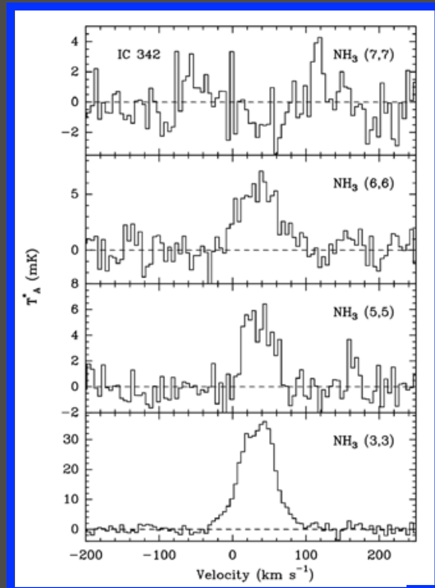


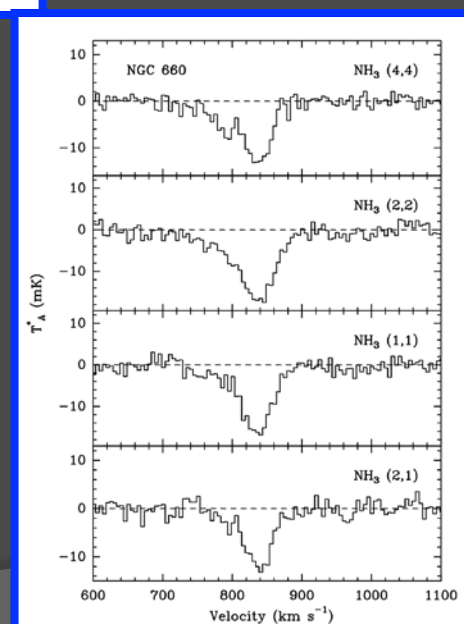


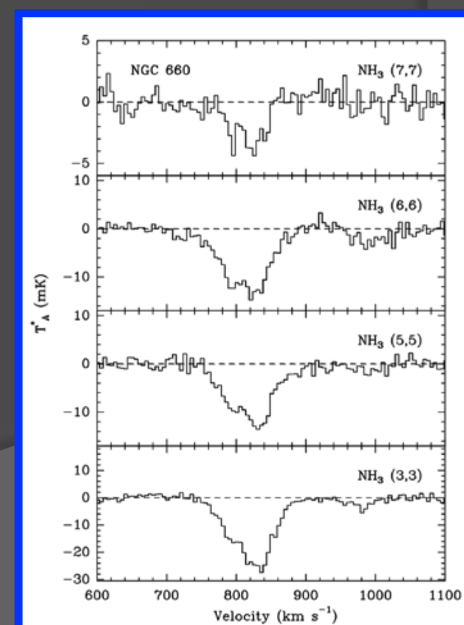


(More) NH_3 in Starburst Galaxies









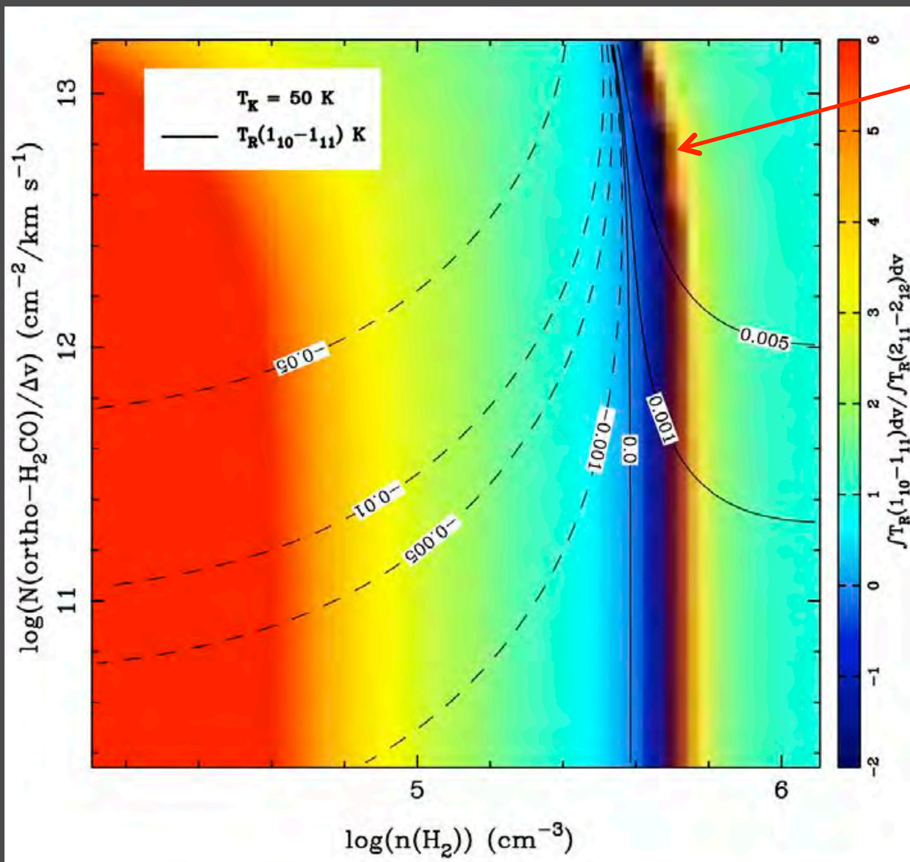
Thermometry

- NH_3 (1,1), (2,2) and (4,4) measurements toward all galaxies.
- NH_3 (3,3), (5,5), (6,6), and (7,7) toward IC342 and NGC660.
- Multiple temperature components noted in several galaxies.
- Most galaxies have kinetic temperatures significantly larger than their measured dust temperatures.
- Evidence for mechanical or CR heating.

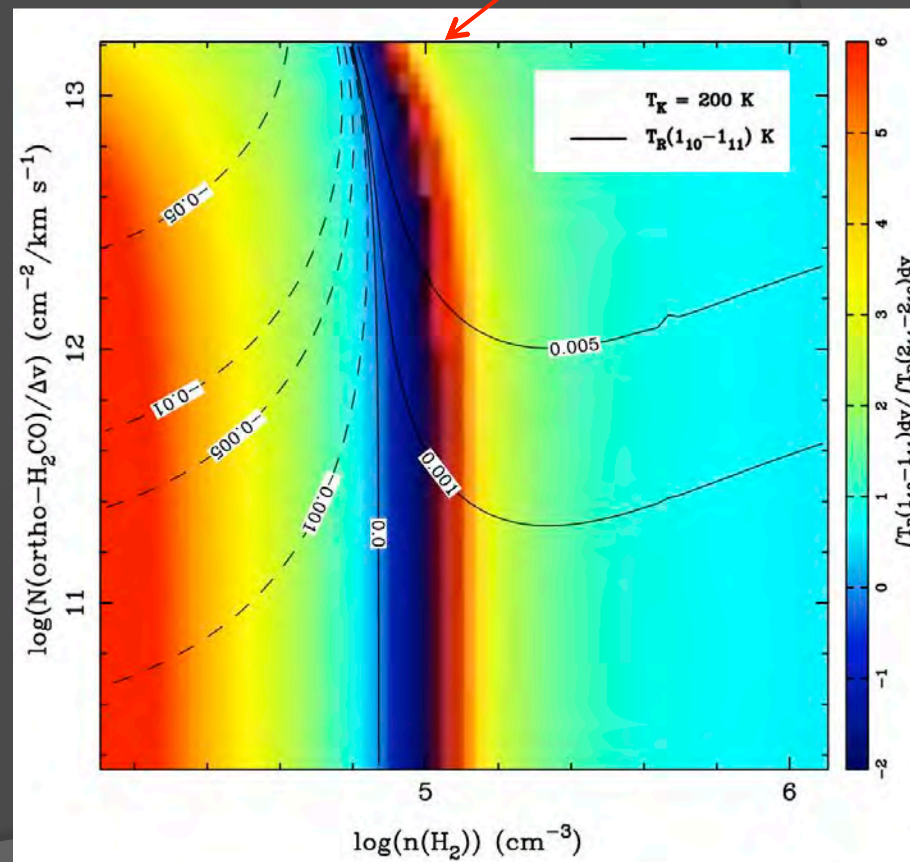
Source	T_{dust} (K)	T_K (K)
NGC 253	34	77 ± 14
NGC 253 NE	...	42 ± 5 / 69 ± 10
NGC 253 SW	...	69 ± 2
NGC 660	37	215 ± 65
NGC 660 G1	...	> 145
NGC 660 G2	...	$\simeq 150$
NGC 660 G3	...	230 ± 50
NGC 660 G4	...	180 ± 30
NGC 891	28	< 30
Maffei 2 G1/G2	40[a]	32 ± 5 / 110 ± 20
NGC 1365	32	50 ± 11
NGC 1365 G1	...	86 ± 26
NGC 1365 G2	...	29 ± 6
IC 342	30	~ 150
IC 342 G1	...	$24 \pm 7/115 \pm 17/> 140$
IC 342 G2	...	$75 \pm 14/> 185$
M 82 SW	45	58 ± 19
NGC 3079 G1/G2	32	both > 270
IC 860	40[d]	200 ± 40
M 83	31	56 ± 15
Arp 220	44	> 180
NGC 6946	30	42 ± 7
NGC 6946 G1	...	26 ± 3
NGC 6946 G2	...	71 ± 20

[a]Assumed value.

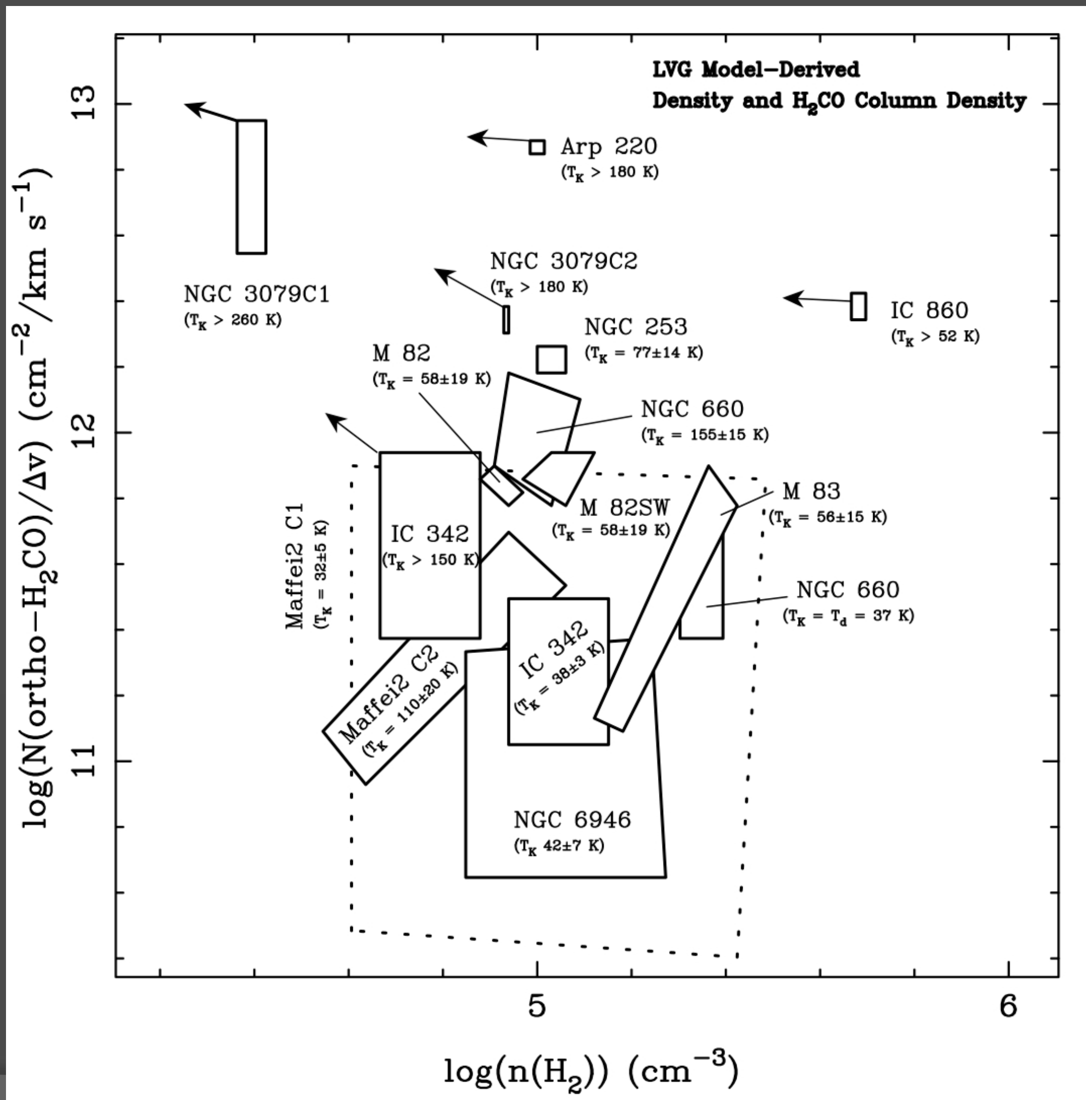
Densitometry With Thermometry



Note how absorption/emission transition density shifts from high to low density as temperature increases



Densitometry With Thermometry



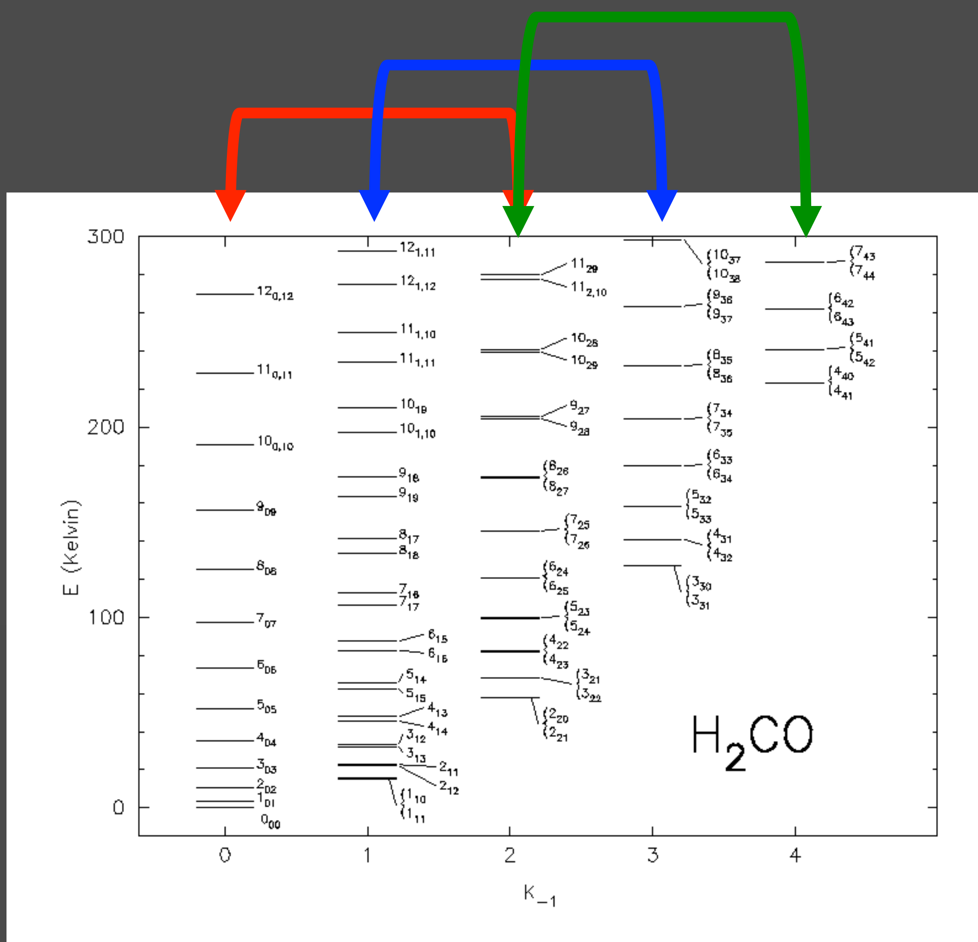
T_K derived from NH_3

Average starburst galaxy density now in range $10^{4.5}$ to $10^{5.5}$ cm^{-3}

Conclusions

- H_2CO is a very sensitive tracer of physical conditions in both galactic and extragalactic star formation environments.
- First *measurements* of the mean density in starburst galaxies.
- Measurements of the kinetic temperature critical to proper interpretation of densitometry.
- Mean density roughly the same ($10^{4.5}$ – $10^{5.5}$ cm^{-3}) in all starburst galaxies measured. This implies that the Schmidt-Kennicutt relation between L_{IR} and M_{dense}:
  - Is a measure of the dense gas mass reservoir available to form stars.
  - Has nothing to do with a higher average density driving the star formation process in the most luminous starburst galaxies.

Studies of H_2CO with CCAT



- λ = 150 to 350 μm
- High-Excitation ΔJ=1 Transitions
  - J = 13-12 at 965 GHz
  - $E_u \cong 370$ K
- Inter-Ladder Transitions
  - K=2 to K=0: 150-300 μm
  - K=3 to K=1: 100-150 μm
  - K=4 to K=2: 80-100 μm
  - $S_{ij} \cong 0.001$ to 0.01

"What spectral lines are most important for mapping?"

What molecules are most important for imaging physical conditions?

Mangum & Wootten 1993, ApJS, 89, 123