Molecular line survey of "The Rotten Egg"

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Goals

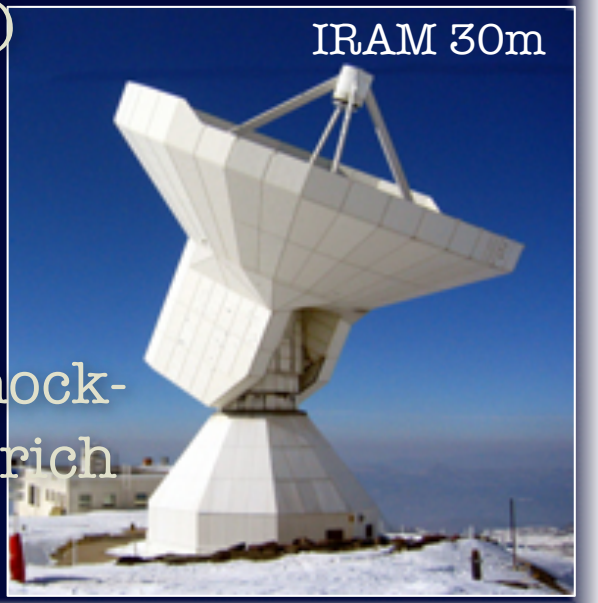
- Characterize the chemistry in CSEs around O-rich AGB stars (most chemistry studies on C-rich CSEs: IRC+10216 & CRL 618)
- Study non-equilibrium, shock-induced chemistry.

Methods

- **Molecular line survey:** IRAM 30m/EMIR (80-350GHz) & HSO/HIFI (480-1245 GHz)
- Two targets:

  IK Tau ('normal' Mira-type, O-rich AGB)

  OH231.8+4.2 (a.k.a "The Rotten Egg")= shock-accelerated, fast+bipolar flow & unusually rich chemistry



The 'bipolar' disorder of OH231.8+4.2

- Mira-type variable (P=700d)
- M6-9III
- $L \sim 10^4 L_\odot$, $T_{eff} \sim 2200K$
- $\dot{M} \approx 10^{-4}\ M_\odot/yr$
- SiO maser emission (+OH, H_2O)
- d~1500 pc

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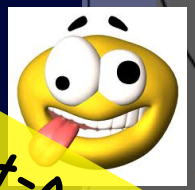
I'm an AGB star



I'm a post-AGB nebula

- Fast, Bipolar outflow

  $v_{exp} \sim 7$-30 km/s (core)

  $v_{exp} \sim 30$-400 km/s (axial flow)

  $\nabla v \sim 6.5$ km/s arcsec^{-1}
- Central core (torus), $V_{exp} \sim 7$- 35km/s

$M_{mol} \sim 1 M_\odot$, cool~10-35 K

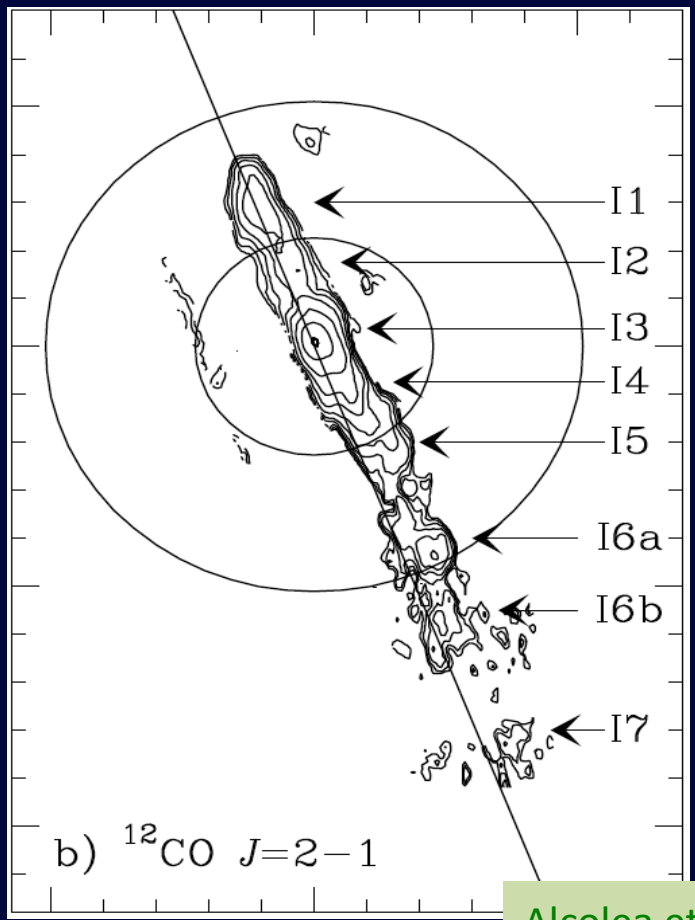
The 'bipolar' disorder of OH231.8+4.2

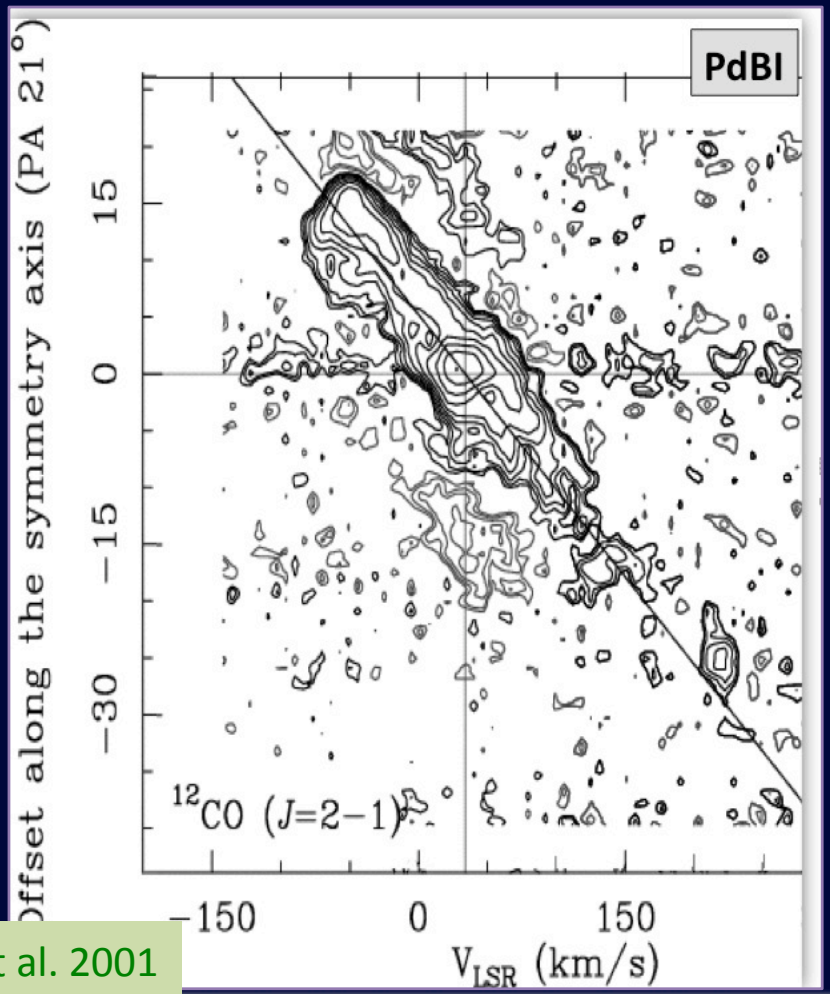
"Hubble-law" kinematics, $V \propto r$ (common in pPNs)

Sudden interaction betwen

jet+'AGB CSE'

1000yr ago, in ≲150yr





Alcolea et al. 2001

The ‘bipolar’ disorder of OH231.8+4.2

Atypical CHEMISTRY:

- CO, H_2O, OH, SiO, SO, SO_2,...

The 'bipolar' disorder of OH231.8+4.2

Atypical CHEMISTRY:

- CO, H_2O, OH, SiO, SO, SO_2,...

.... BUT ALSO

- C-, S-, and N-bearing species unexpected to be abundant in O-rich CSEs:

H_2S (Rotten Egg), HCO^+, HNC,
HNC, CS, NS, OCS, H_2CO, NH_3

(isotopologs ^{13}CO & $H^{13}CN$)

Morris et al. 1987
Linqdvist et al. 1990
Sánchez Contreras et al. 1997, 2000

shocks → endothermic reactions, molecule desorption from dust, grain destruction, dissociating molecules

IRAM 30m mm-line survey: OH231.8+4.2 & IKTau

- Single-pointed observations (HPBW≈29”–8”)
- EMIR receivers [79-350GHz]
- WILMA (2MHz≈1.7-7.5km/s), FTS (195kHz≈0.2-0.7km/s)
- Several runs: 2009, 2010, 2011 & 2013
- sensitive survey → rms[2MHz]=0.8-20 mK

Velilla et al., in prep.

Table 1. IRAM-30 m efficiencies and parameters of the EMIR receivers at representative frequencies.

Frequency (GHz)	Beam eff. (%)	Forward eff. (%)	HPBW (”)	S/T_a^* (Jy/K)
86	81	95	29	5.9
145	74	93	16	6.4
210	63	94	11	7.5
260	53	88	9	8.4
340	35	81	7.5	10.9

Notes. (#1) Frequency in GHz; (#2) Beam efficiency percentage; (#3) Forward efficiency percentage; (#4) Half Power Beam Width in arsec; (#5) Flux to antenna temperature conversion factor in Jansky per Kelvin.

Table 2. Relevant observational information.

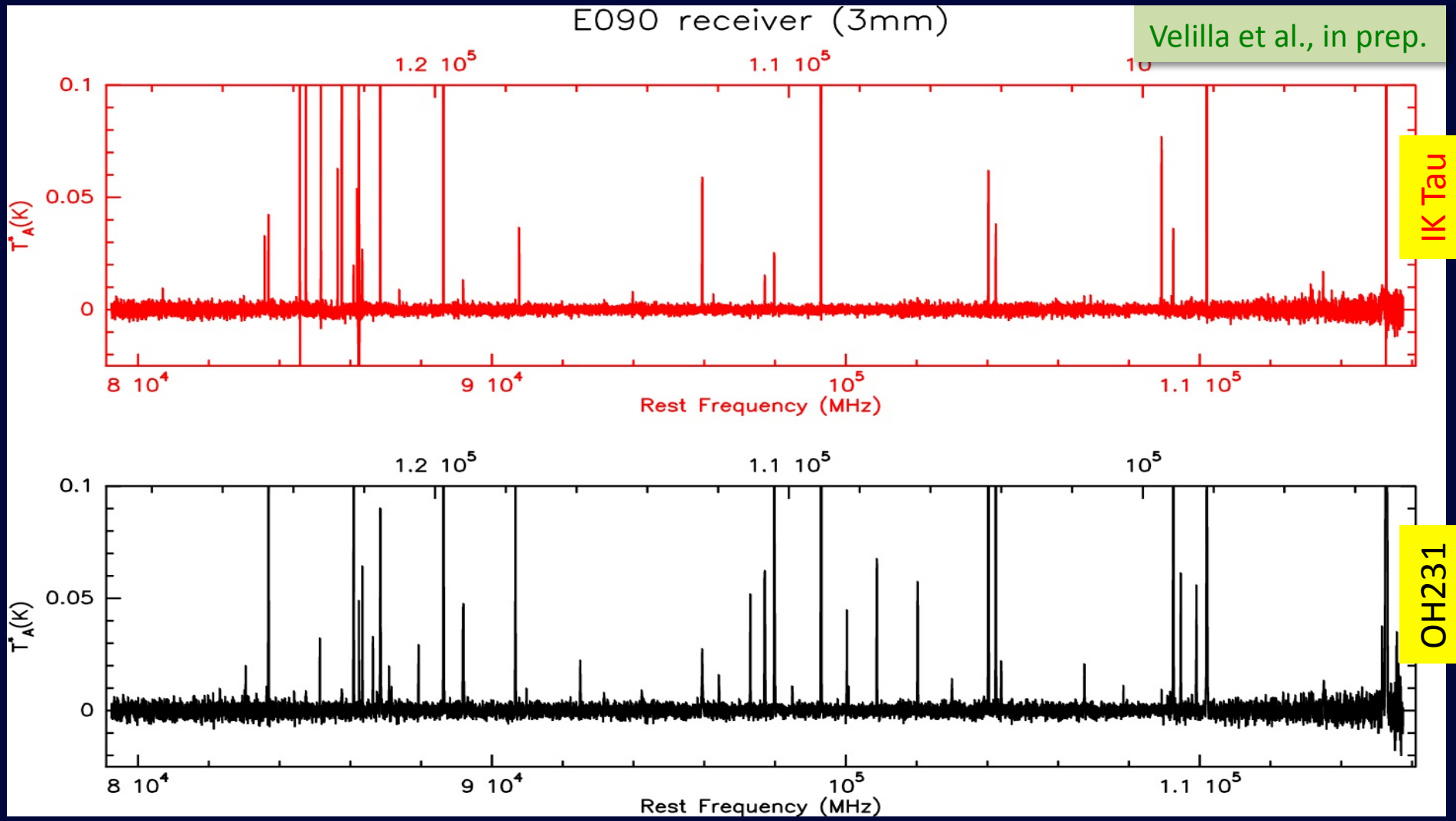
Band	Mode & IBW (GHz)	ν_{obs} (GHz)	RMS (mK)	Opacity
E090 (3mm)	DSB - 8	79.2 - 115.7	1 - 2	0.07 - 0.3
E150 (2mm)	SSB - 4	128.3 - 167.6	1 - 4	0.09 - 0.4
E230 (1mm)	DSB - 16	202.0 - 270.8	5 - 9	0.12 - 0.3
E330 (0.9mm)	DSB- 16	258.3 - 348.9	9 - 20	0.17 - 0.8

Notes. (#1) EMIR receiver band; (#2) Observing mode Single sideband or Dual sideband (SSB/DSB) and Instantaneous bandwith (IBW) in GHz; (#3) Observed frequency windows; (#4) Root Mean Square (rms) noise for a spectral resolution of $\Delta\nu$=2 MHz; (#5) Zenith atmospheric opacities at the observed frequency.

IRAM 30m mm-line survey: OH231.8+4.2 & IKTau

0.8mm-3mm: ~200 lines detected, few mK

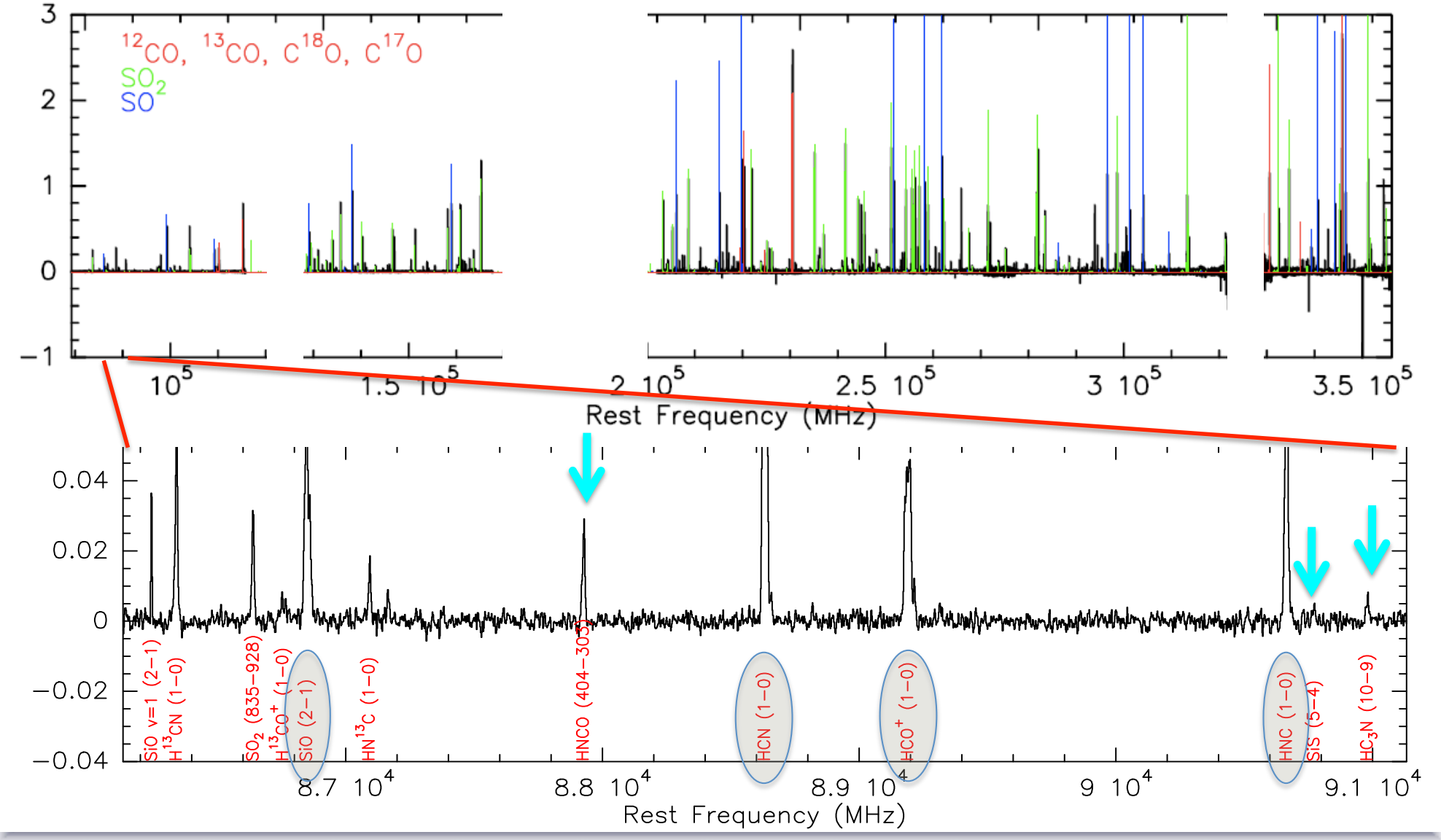
OH231 has a richer spectrum: CO, SO_2, SO, (+isotopologues) ...



IRAM 30m mm-line survey: OH231.8+4.2 & IKTau

OH231 spectrum dominated: CO, SO_2, SO, (+isotopologues) ...

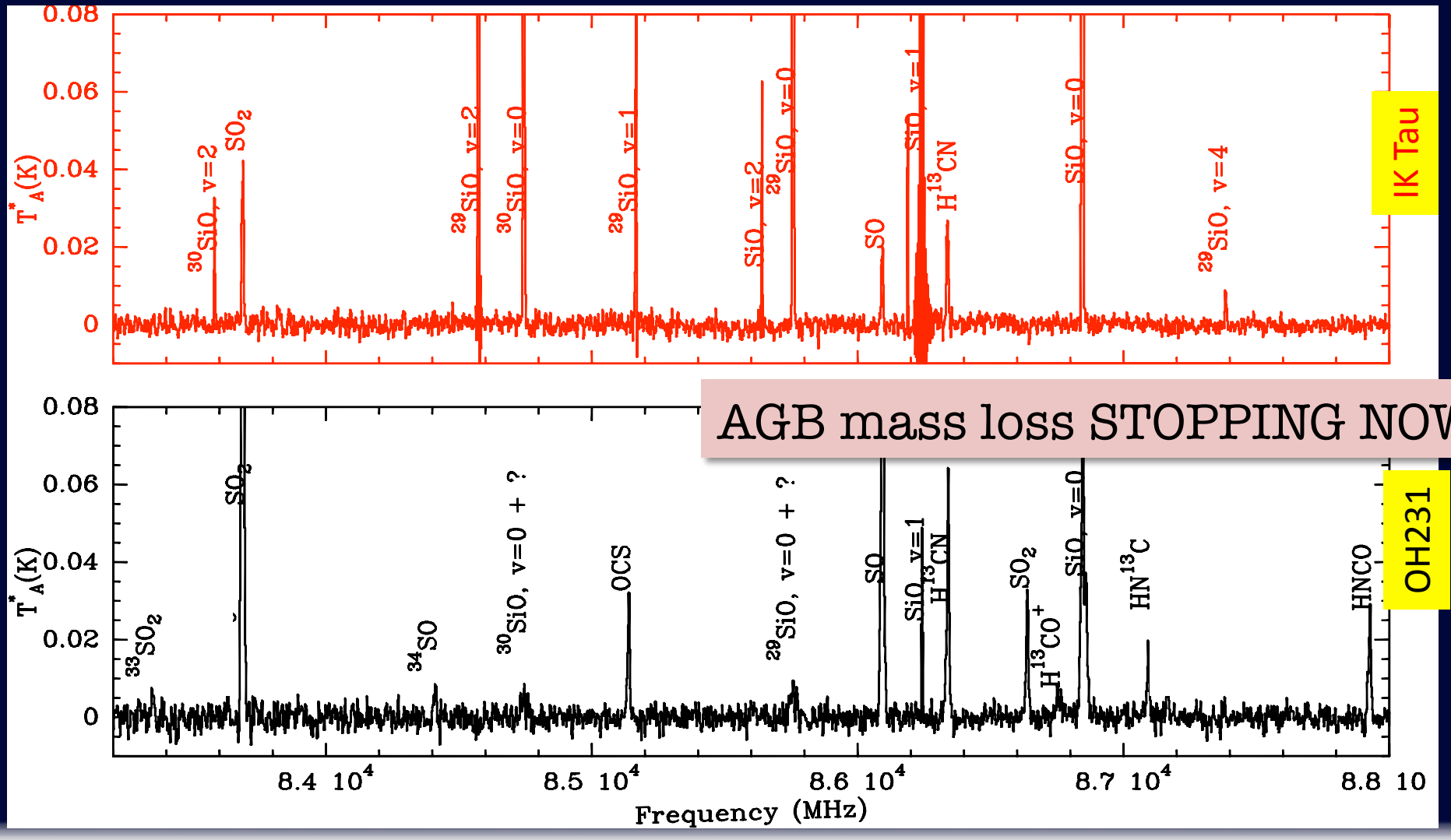
^{33}S, ^{34}S, ^{18}O, ^{17}O, ^{13}C, ^{29}Si, ^{30}Si



IRAM 30m mm-line survey: OH231.8+4.2 & IKTau

Lines present in IK Tau but NOT/weak in OH231.8: SiO, SiS, NaCl, PN, PO.. → inner envelope → growing inner hole

Progressive weakening of SiO masers in OH231.8 (in prep.) →



IRAM 30m mm-line survey: OH231.8+4.2 & IKTau

Lines present in OH231.8 but NOT/weak in IK Tau: SO, SO_2, OCS, HCO^+, H_2CO, HNCO, HNCS, HC_3N, CN, NO, SO^+, N_2H^+, H_3O^+...

discovered in this survey

IRAM 30m mm-line survey: OH231.8+4.2

HNCO, HNCS, HC_3N (Velilla et al., in prep.)

Molecule	$J_u - J_l$ $J^u_{K_u-k_u} - J^l_{K_l-k_l}$	ν_{rest} (MHz)	E_u (K)	A_{ul} s^{-1}
^{13}CO	1 – 0	110201.35399	5.3	6.336×10^{-8}
	2 – 1	220398.68356	15.9	6.082×10^{-7}
	3 – 2	330587.96441	31.7	2.199×10^{-6}
HNCO	$4_{0,4} - 3_{0,3}$	87925.237	10.5	9.025×10^{-6}
	$5_{0,5} - 4_{0,4}$	109905.749	15.8	1.802×10^{-5}
	$6_{1,6} - 5_{1,5}$	131394.230	65.3	3.006×10^{-5}
	$6_{0,6} - 5_{0,5}$	131885.734	22.2	3.163×10^{-5}
	$7_{1,7} - 6_{1,6}$	153291.935	72.7	4.863×10^{-5}
	$7_{0,7} - 6_{0,6}$	153865.086	29.5	5.078×10^{-5}
	$7_{1,6} - 6_{1,5}$	154414.765	72.9	4.971×10^{-5}
	$10_{0,10} - 9_{0,9}$	219798.274	58.0	1.510×10^{-4}
	$11_{1,11} - 10_{1,10}$	240875.727	112.6	1.957×10^{-4}
	$11_{0,11} - 10_{0,10}$	241774.032	69.6	2.019×10^{-4}
	$12_{0,12} - 11_{0,11}$	263748.625	82.3	2.630×10^{-4}
HNCO†	$13_{0,13} - 12_{0,12}$	285721.951	96.0	3.355×10^{-4}
	$14_{0,14} - 13_{0,13}$	307693.905	110.8	4.200×10^{-4}
HNCS	$8_{0,8} - 7_{0,7}$	93830.07049	20.3	1.217×10^{-5}
	$9_{0,9} - 8_{0,8}$	105558.07582	25.3	1.744×10^{-5}
	$11_{0,11} - 10_{0,10}$	129013.25917	37.2	3.215×10^{-5}
	$12_{0,12} - 11_{0,11}$	140740.37808	43.9	4.189×10^{-5}
	$13_{0,13} - 12_{0,12}$	152467.14243	51.2	5.342×10^{-5}
	$14_{0,14} - 13_{0,13}$	164193.52268	59.1	6.690×10^{-5}
HC_3N	9 – 8	81881.46210	19.6	4.215×10^{-5}
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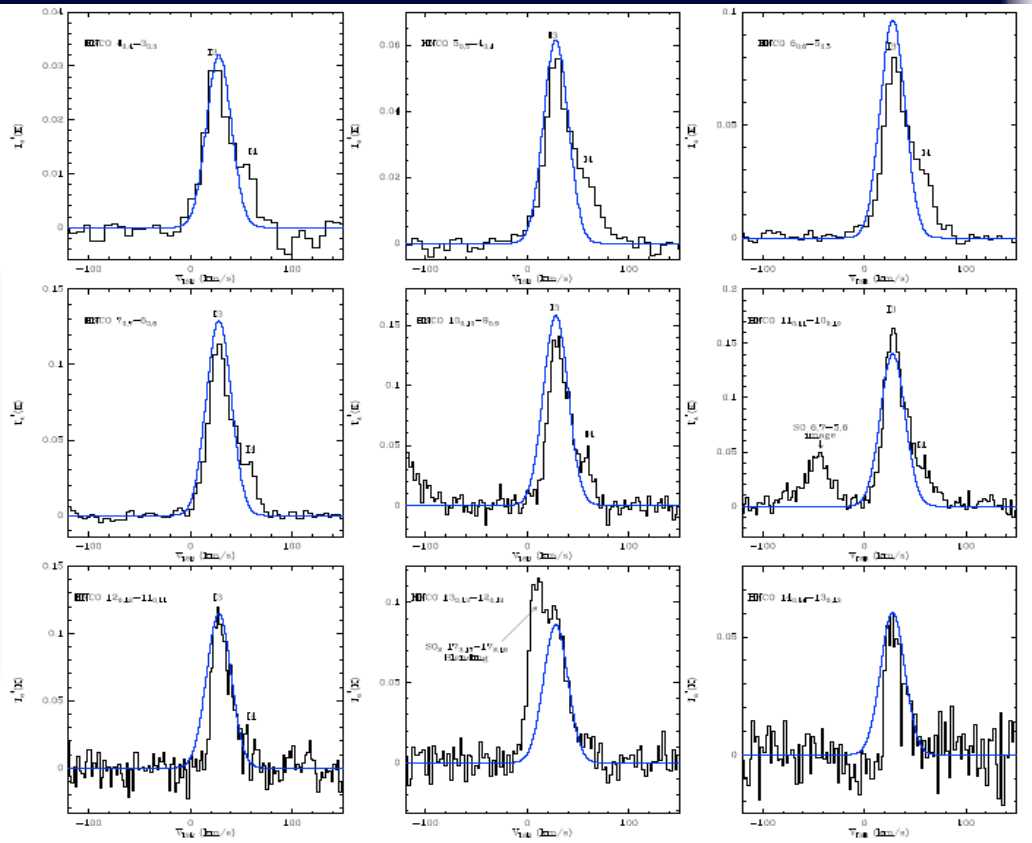

FWHM~20km/s → central core (I3) wing, v_{lsr}=60km/s → base of the SOUTH lobe (I4)

IRAM 30m mm-line survey: OH231.8+4.2

HNCO, **HNCS,** HC_3N= Velilla et al., in prep.

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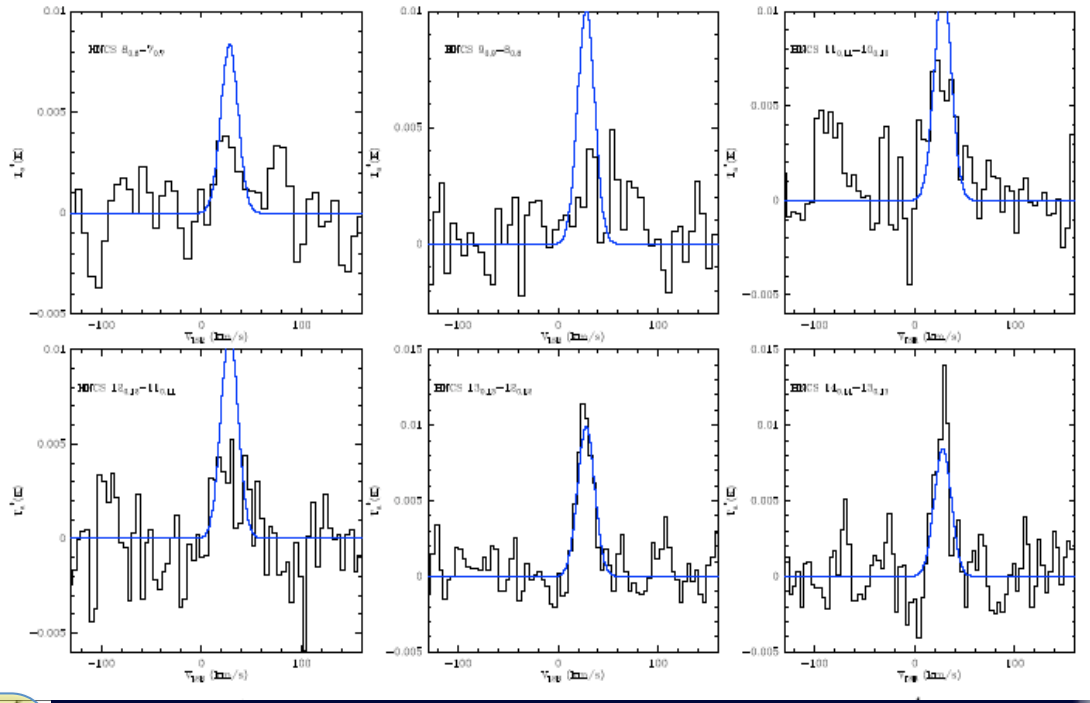

FWHM~20km/s → central core (I3)
weak wings? (low S/N)

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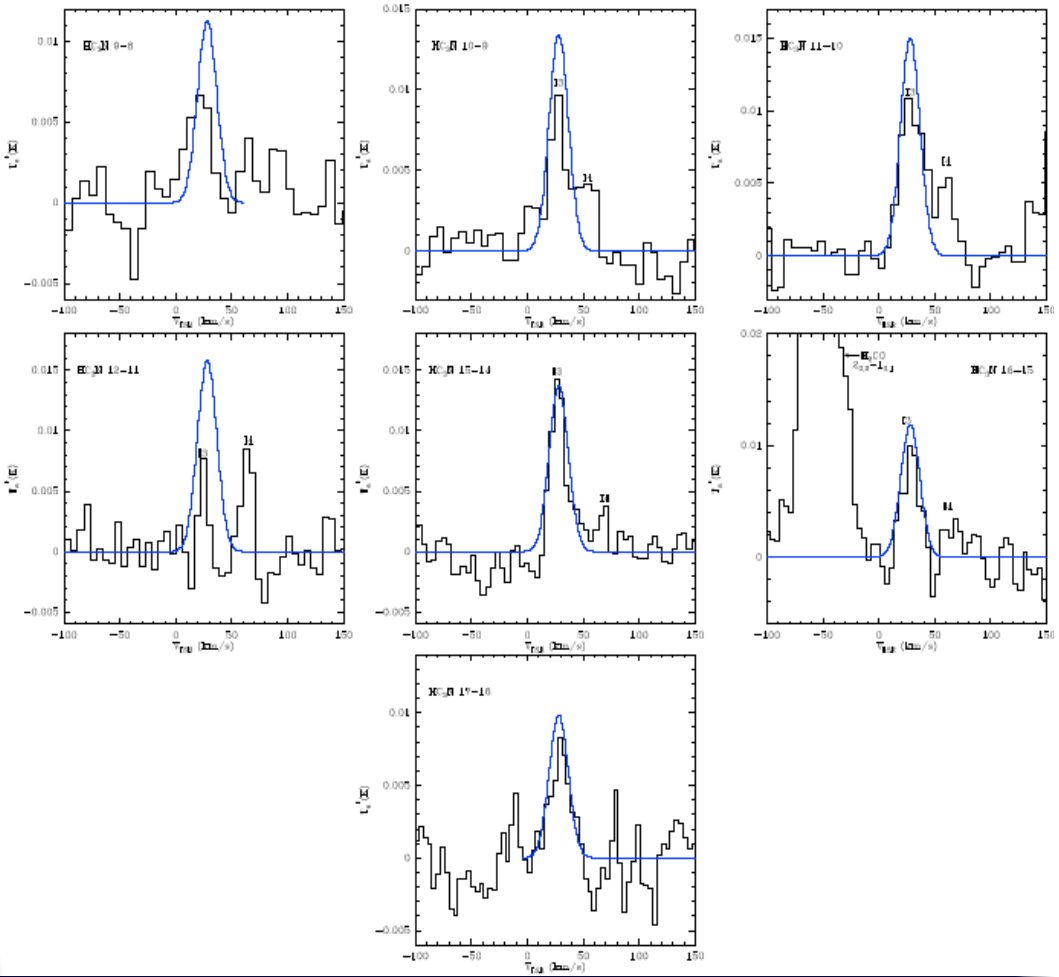
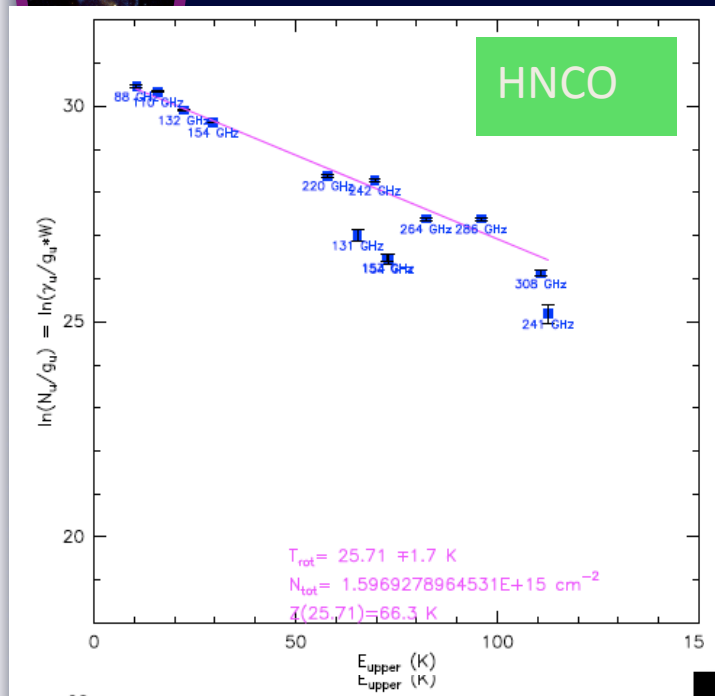
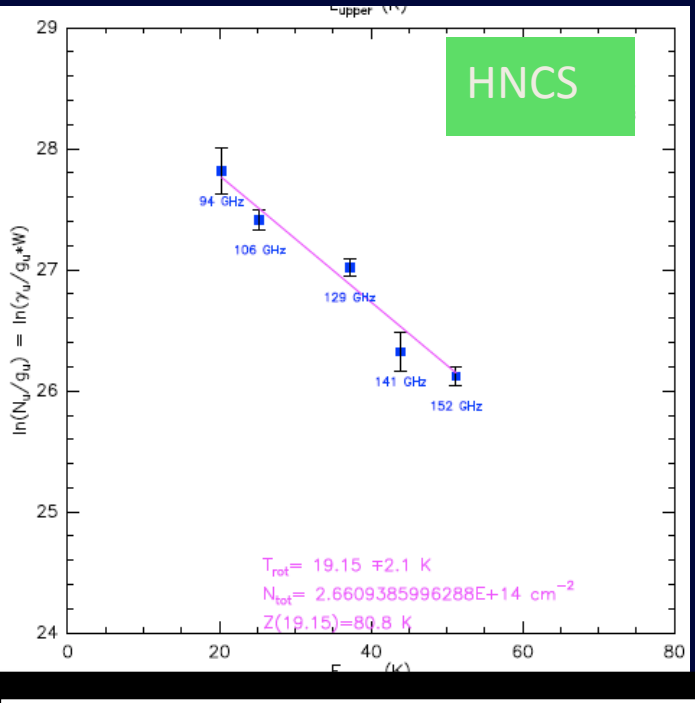


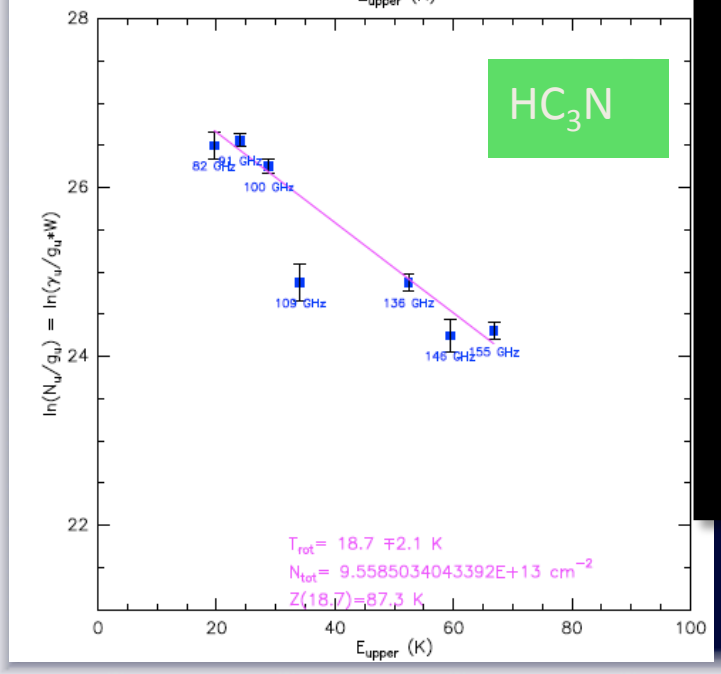
FWHM~20km/s → core (I3)

v_{lsr}=60km/s base of the SOUTH lobe (I4)

IRAM 30m mm-line survey: OH231.8+4.2







RDA (LTE,τ<1):

beam-avergared

N, T_{rot} → X

(MOL) w.r.t.

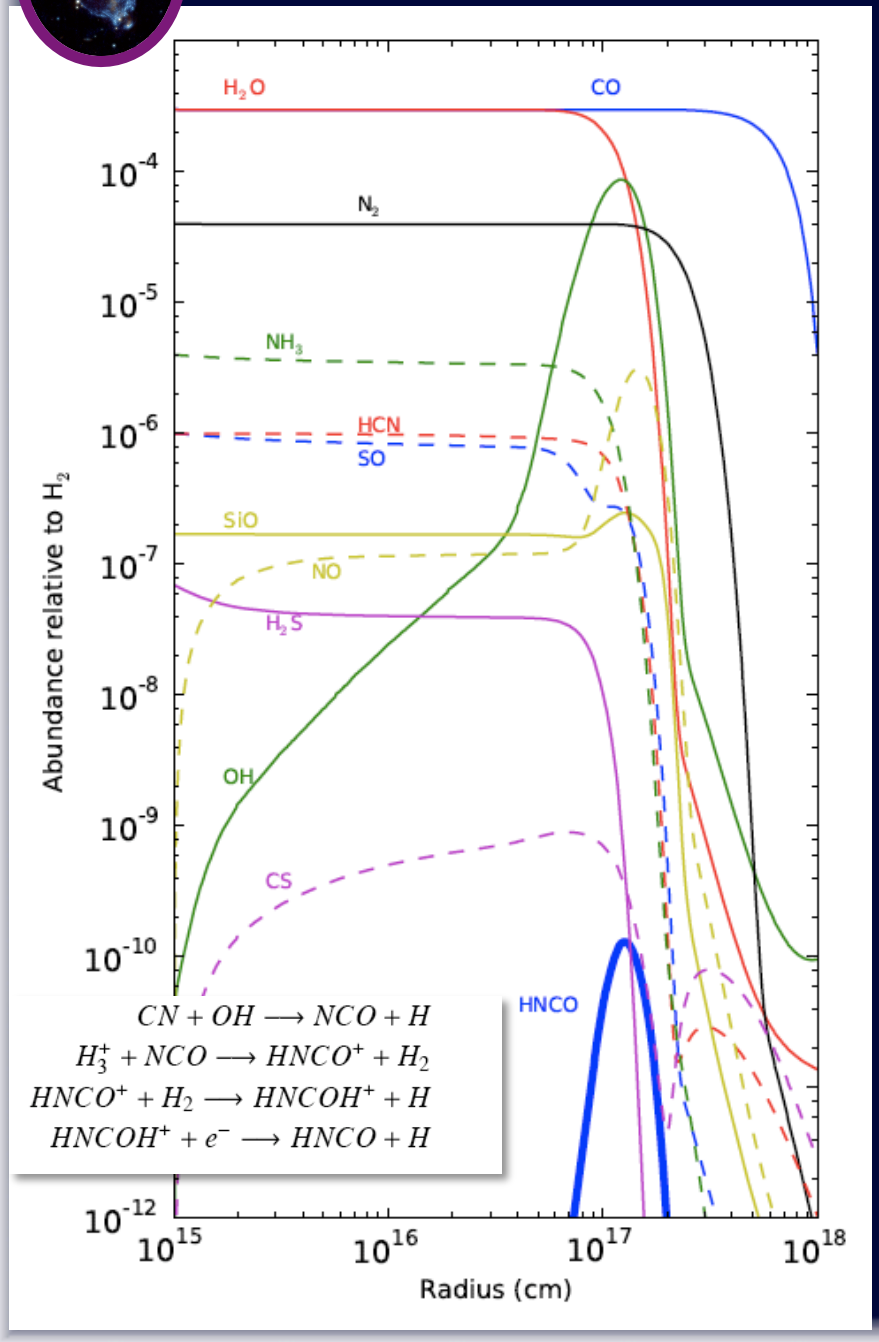
$^{13}CO \approx 5x10^{-5}$

$n(H_2)$~>10^6-$10^{[4-5]}$cm^{-3}

Molecule	ds (arcsec)	N (cm^{-2})	T_{rot} (K)	X
		(*i*) LTE RESULTS		
^{13}CO	4× 8	6.7(1.9)×10^{17}	10 (1)	5×10^{-5}
HNCO	3× 5	1.6(0.2)×10^{15}	26 (2)	1×10^{-7}
HNCS	3× 5	2.6(0.7)×10^{14}	18 (2)	2×10^{-8}
HC_3N	3× 5	1.1(0.3)×10^{14}	17 (2)	8×10^{-9}

X(HCN)≈X(HNC) ≈10^{-8}

IRAM 30m mm-line survey: OH231.8+4.2



Chemical kinetics model (Agúndez et al 2007): gas-phase + UV-chemistry

HNCO, HNCS, and HC_3N abundances by factor >100

Other astronomical environments:

- **HNCO:** SgrB2, Taurus, shocked outflow L1157 (X_{HNCO}≈9.6e-8)
- **HNCS:** SgrB2, TMC-1 (X_{HNCS}≈10^{-11})
- **HC_3N**: SgrB2, Or… (X_{HC3N}≈10^{-6})

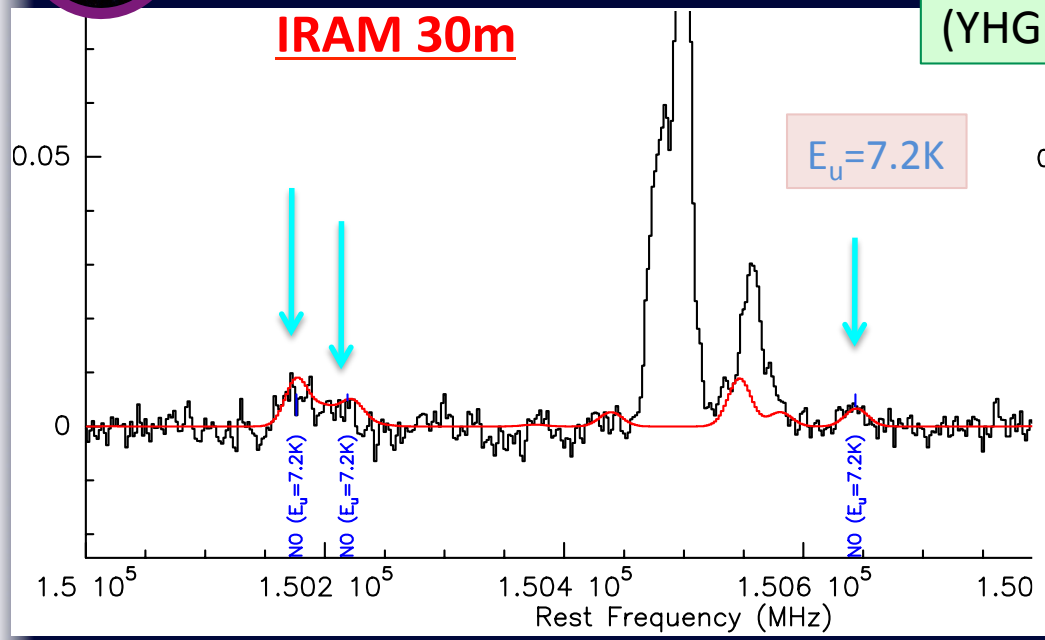
what is different? shocks

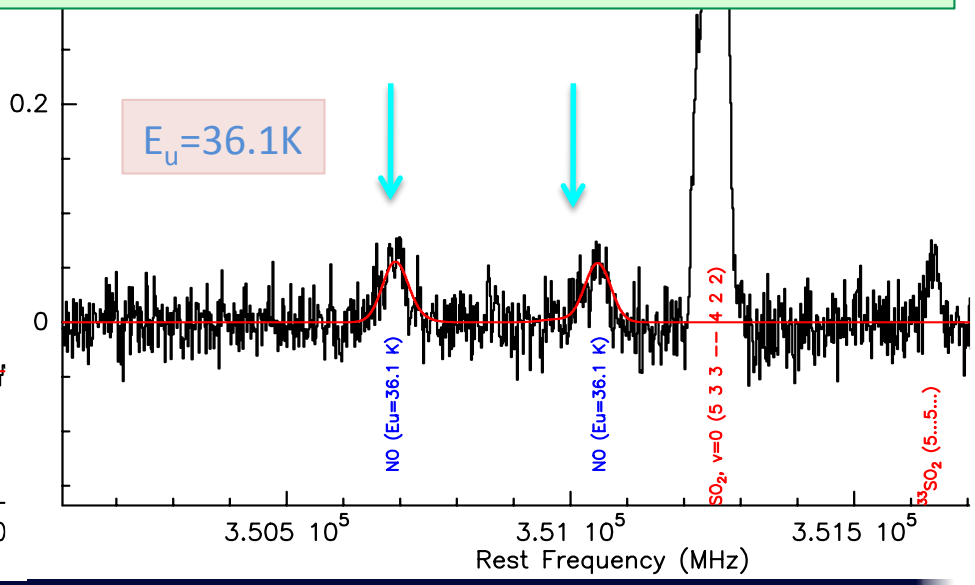
Non detected (O-rich CSE):
IK Tau <10^{-9}-10^{-10}
(VY CMa, IRC+10420)

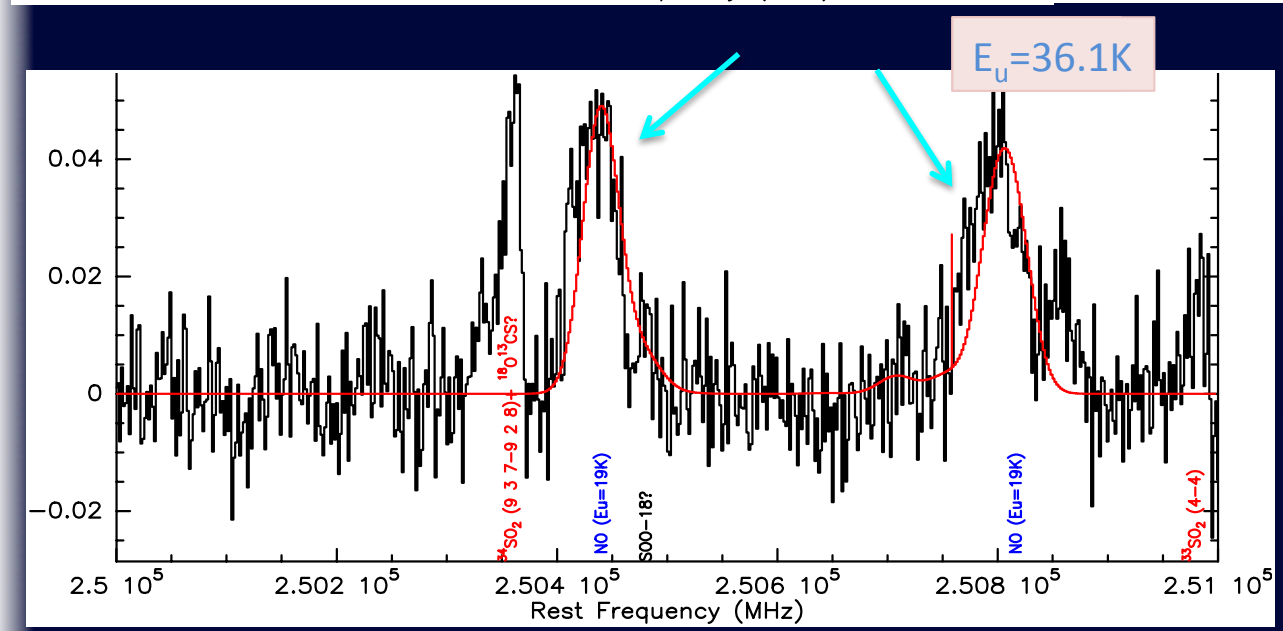
New detections in OH231.8+4.2: NO

first detection in an **AGB** CSE (Velilla et al., in prep)
(YHG IRC+10420 G. Quintana-Lacaci 2013)

IRAM 30m







NO broad → FWHM=55km/s

preliminary ETL:

N(NO)~8x10^{15} cm-2

T$_{rot}$~15 K

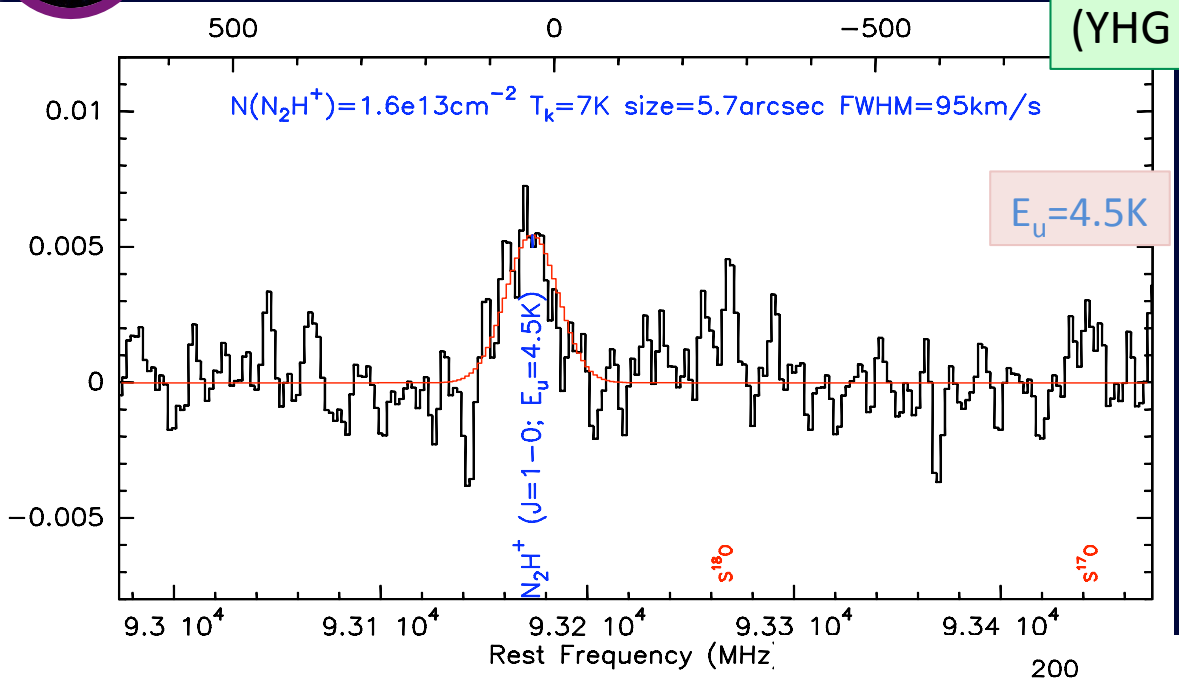
X(NO)≈1.3x10^{-6}

X(SO)≈X(SO$_2$) ≈10^{-6}

New detections in OH231.8+4.2: N_2H^+

first detection in an **AGB** CSE
(YHG IRC+10420, G. Quintana-Lacaci 2013)

IRAM 30m

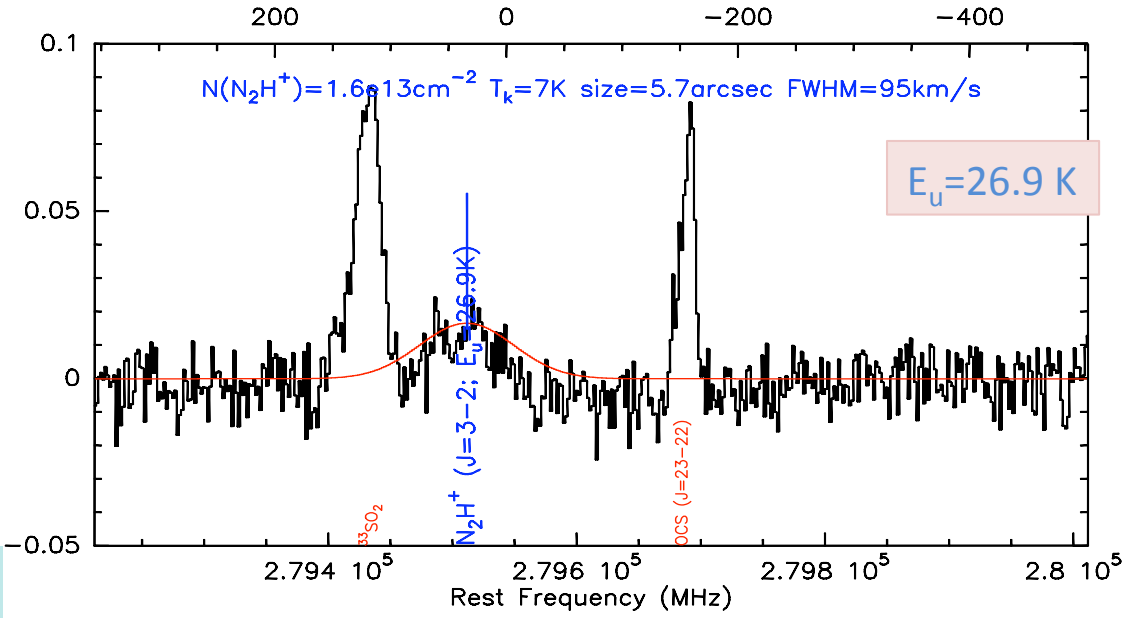


E_u=4.5K

N_2H^+ broad → FWHM=90km/s

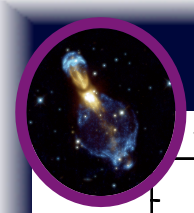
preliminary ETL:
$N(N_2H^+)$~1.6x10^{13} cm-2
T_{rot}~5-10 K
$X(N_2H^+)$≈3x10^{-9}

N_2H^+ probably enhanced in the fast flow (+hyperfine splitting)

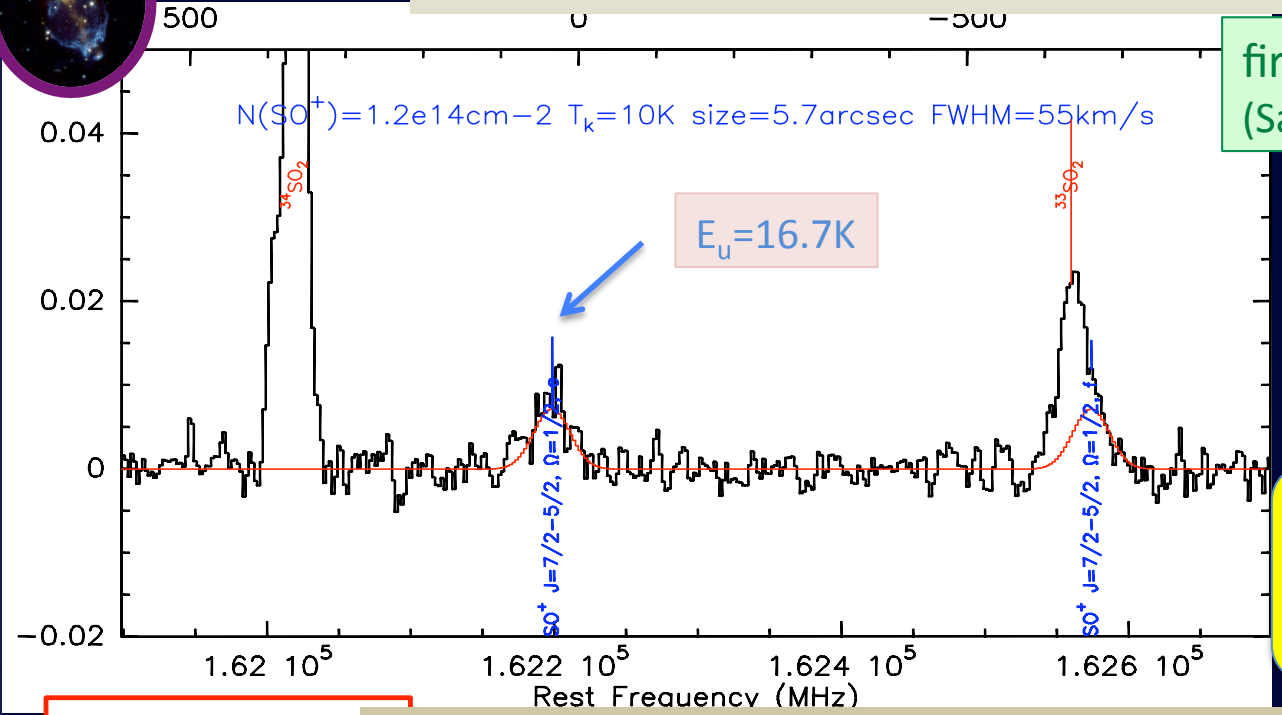


E_u=26.9 K

(Sánchez Contreras et al., in prep)



New detections in OH231.8+4.2: SO+



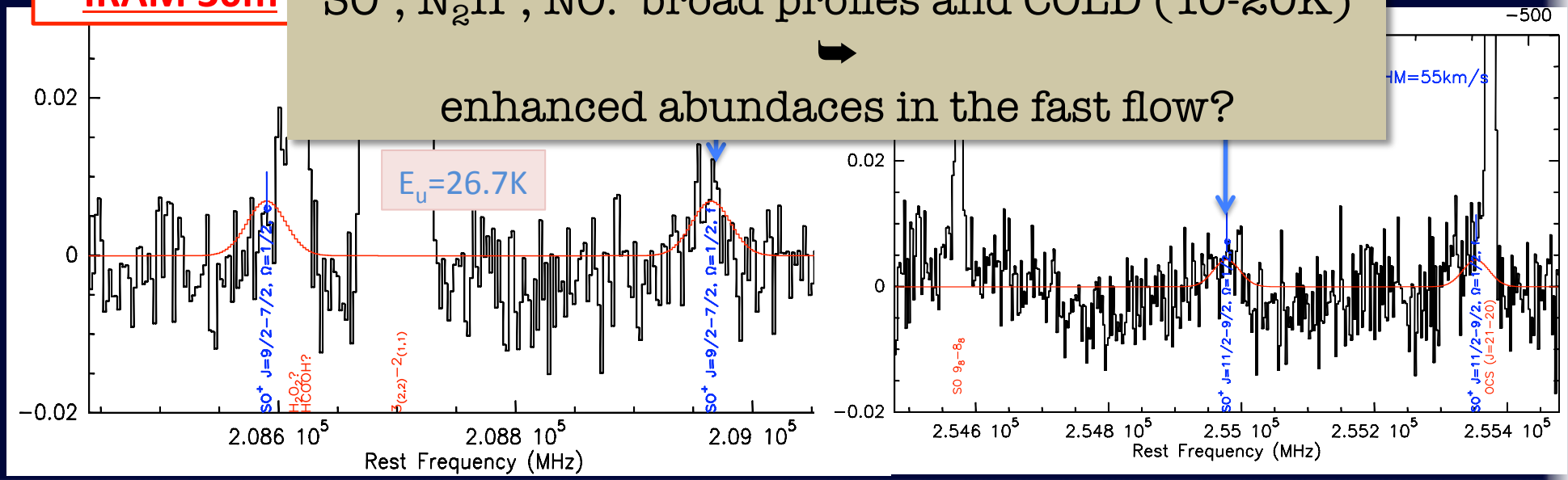
first detection in an **AGB** CSE
(Sánchez Contreras et al., in prep)

SO⁺ broad profile:
FWHM~55km/s
~100km/s-wide wings
→ shocked outflow

preliminary ETL:
$N(SO^+)\sim10^{14}cm^{-2}$ and **COOL ~10K**
$X(SO^+)\sim2x10^{-8}$ ~X(SO)/100

IRAM 30m

SO^+, N_2H^+, NO: broad profiles and COLD (10-20K)
➥
enhanced abundaces in the fast flow?



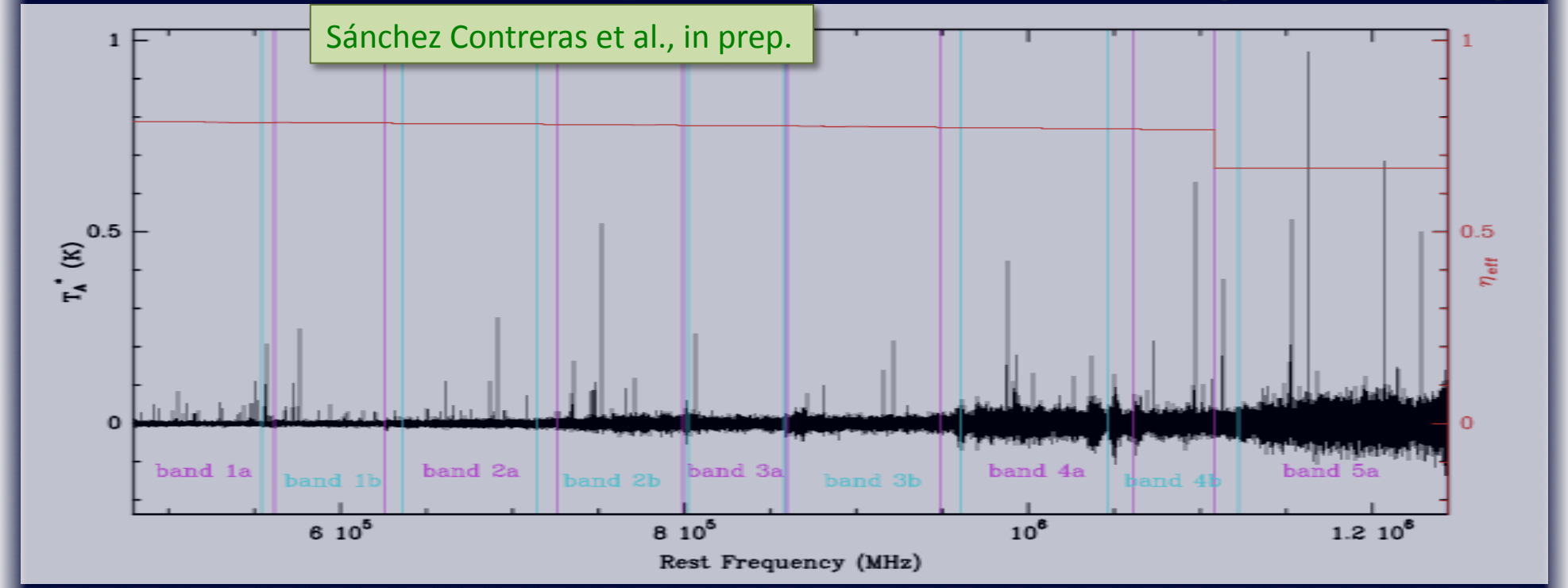
HSO/HIFI line survey: OH231.8+4.2

- 760 GHz, ~600 transitions (80% identified)
- No new species discovered: CO, SO, SO_2, H_2S, H_2O dominate
- Rotational ladders → physical and chemical properties

^{12}CO, ^{13}CO, $C^{18}O$, **H_2O, $H_2{}^{18}O$, $H_2{}^{17}O$** (30 transitions, 3 vibrationally excited), SO, SO_2, H_2S, CS, HCN, HNC, HCO^+, SiO, SiS, NS (+isotopologues)

- Sensitive to warmer regions + spectral resolution (slow vs. fast)

Sánchez Contreras et al., in prep.

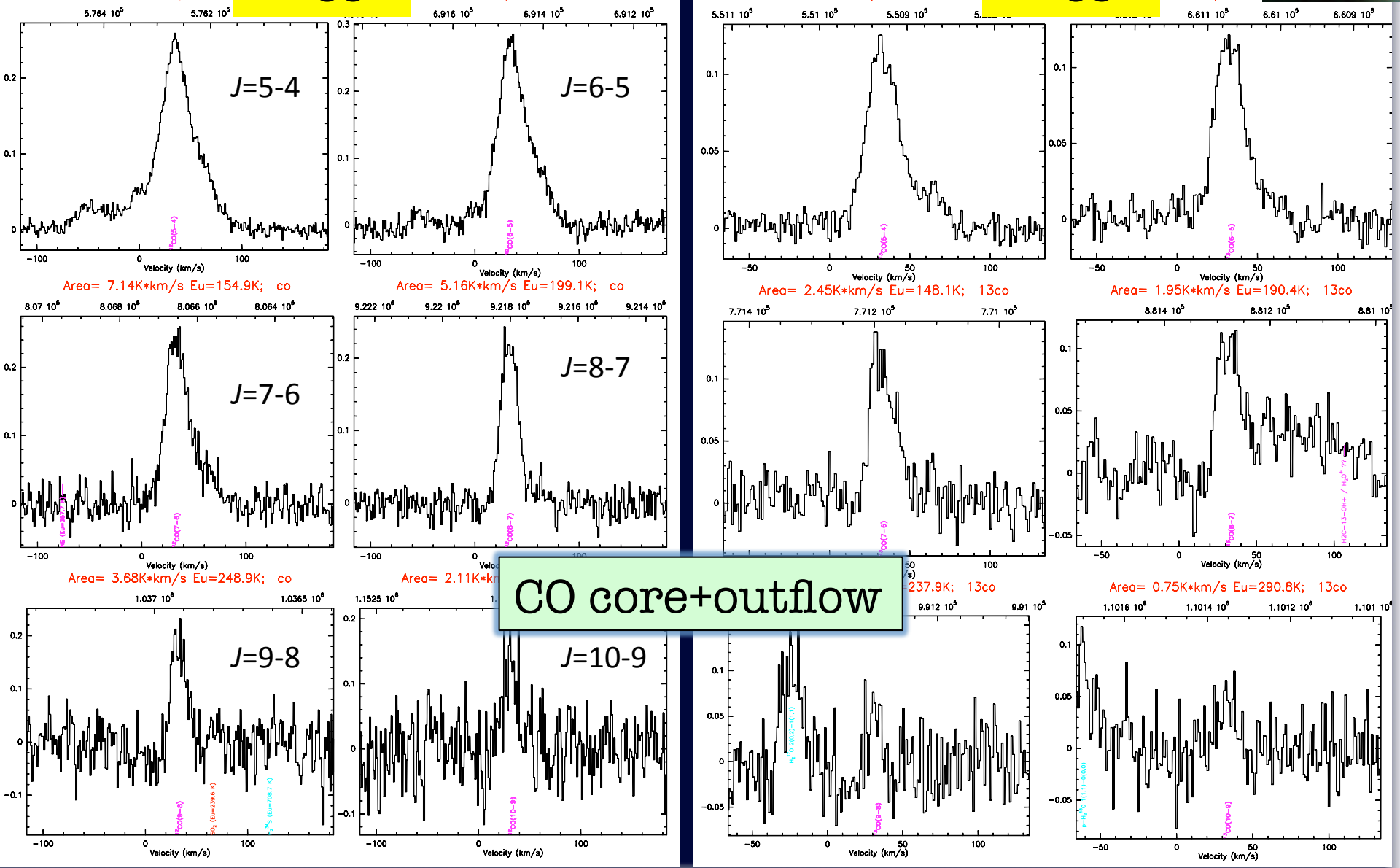


HSO/HIFI line survey: OH231.8+4.2

Results: Line profiles

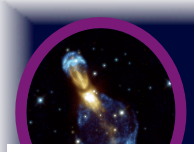
^{12}CO

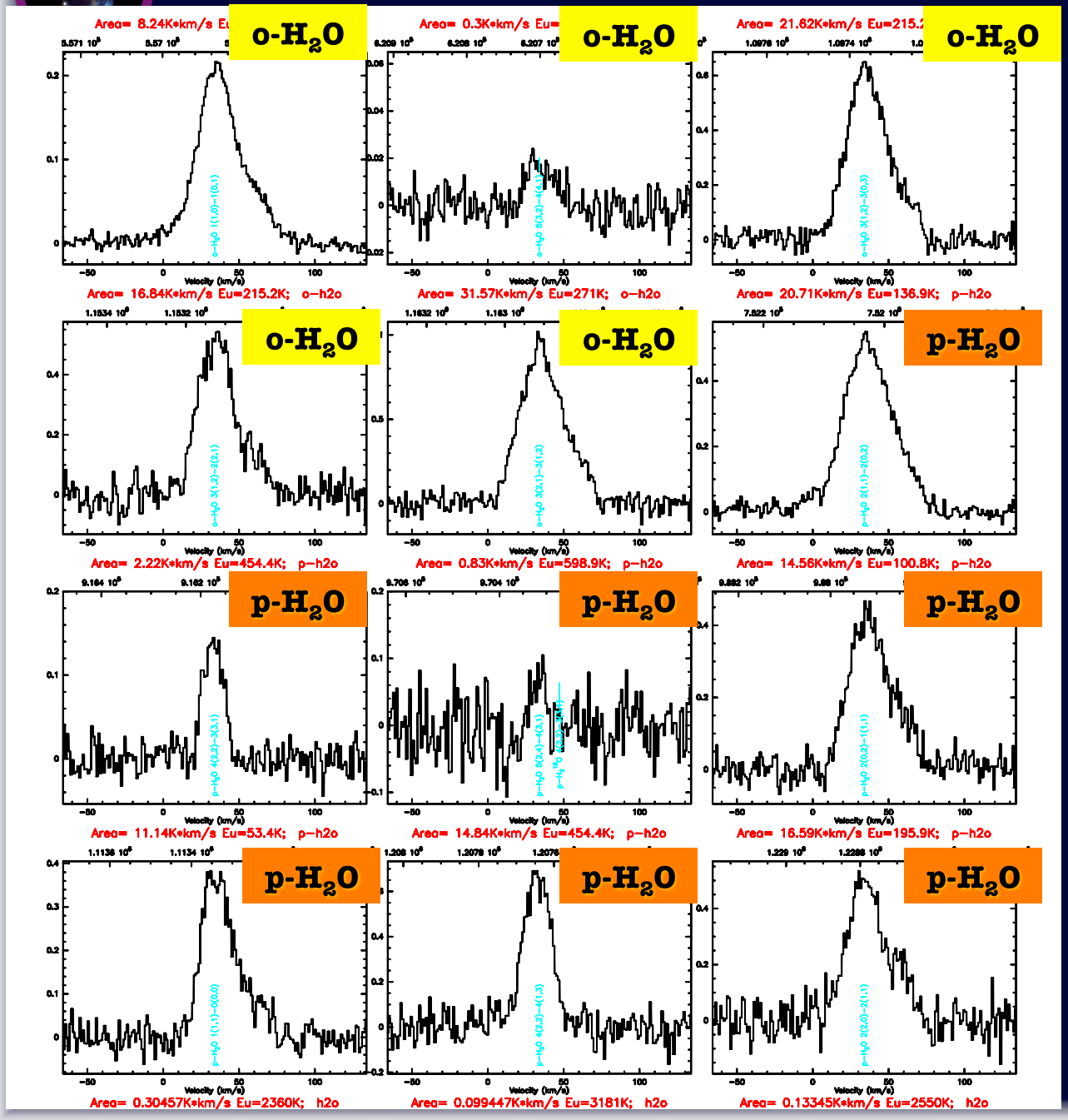
^{13}CO



CO core+outflow

HSO/HIFI line survey: OH231.8+4.2





Line profiles

H_2O, $H_2{}^{18}O$, $H_2{}^{17}O$

- E_u=26-698K (v=0)
- E_u=2-3x10^3K (v_2=1)

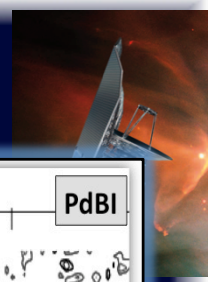
v=0

core~10-40 km/s

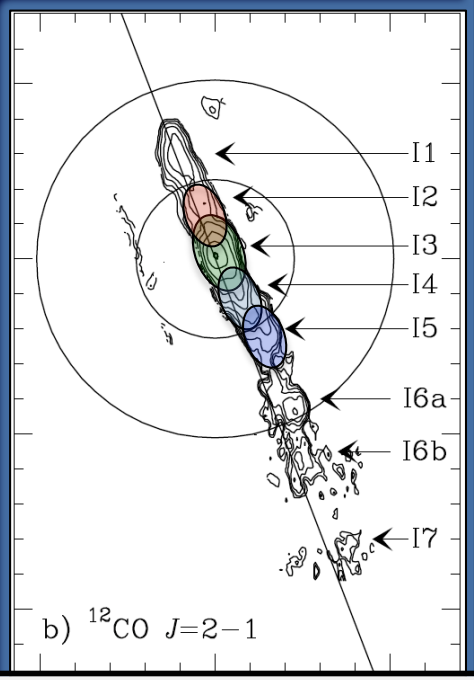
wings~100 km/s

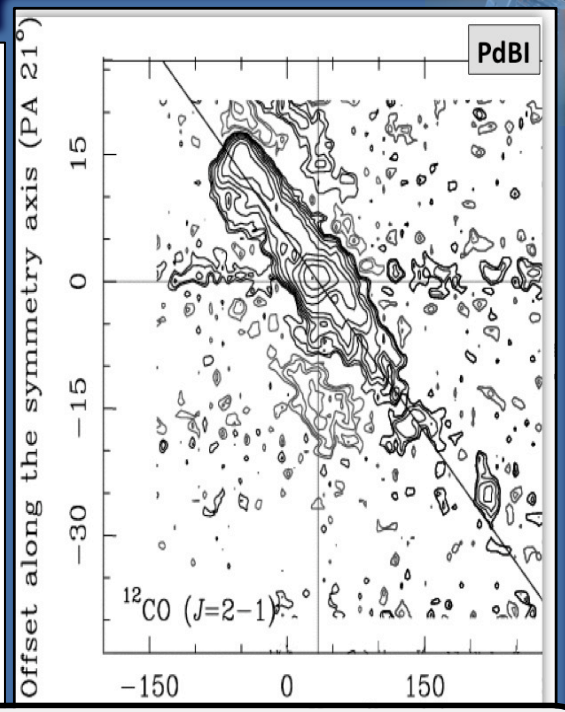
→ similar to CO profile

HSO/HIFI line survey: OH231.8+4.2



H_2O & CO similar spatio-kinematic structure





H_2O traces warm (>200K)

CO traces cool (10-30K)

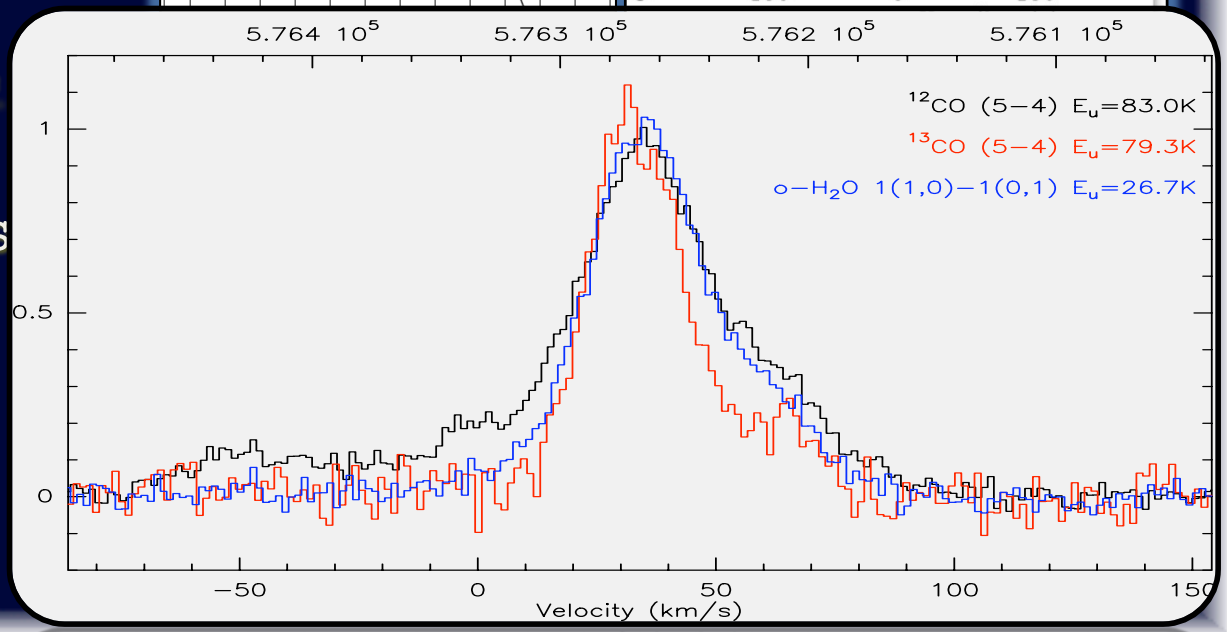
OUTFLOW=WARM+COOL

→

∇T ACCROSS the lobe walls

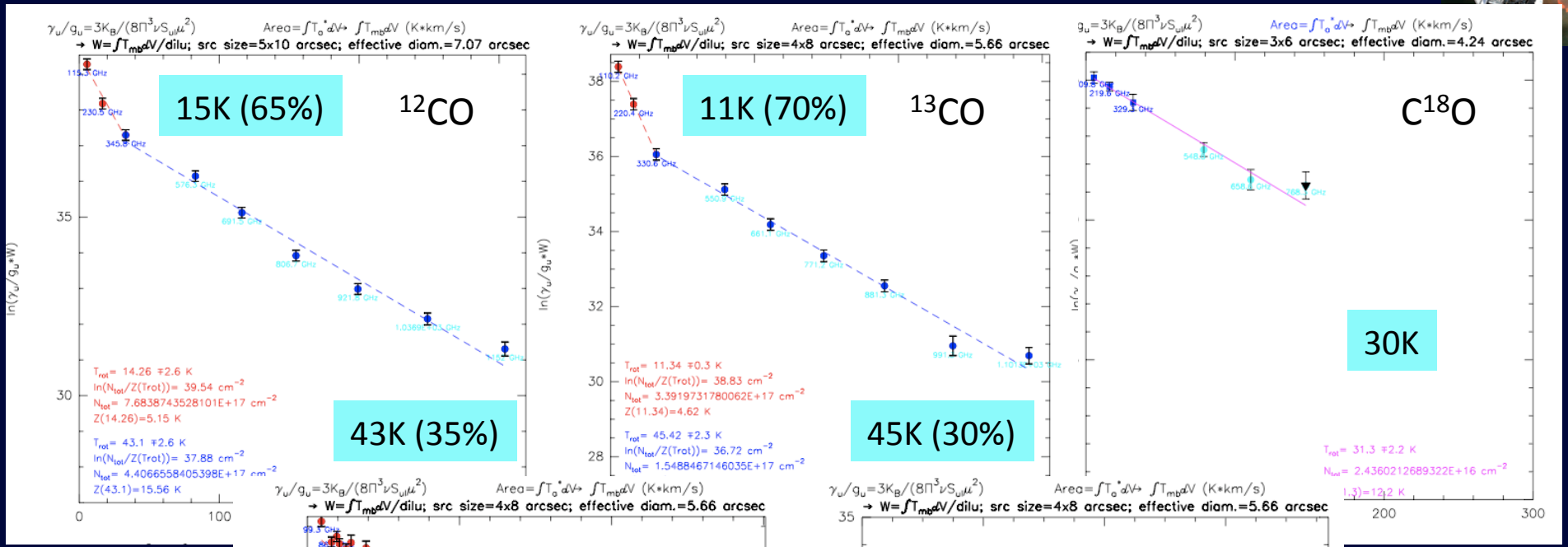
CO=outer walls

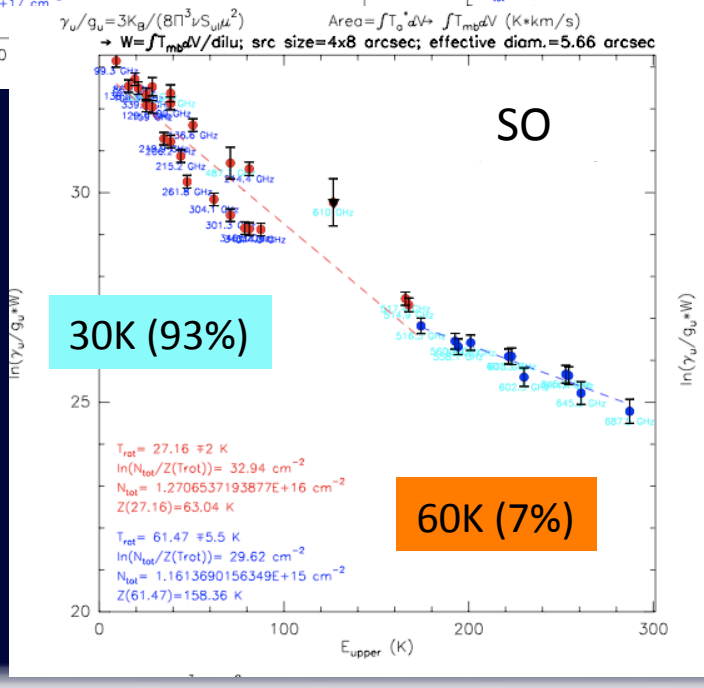
H_2O=inner walls

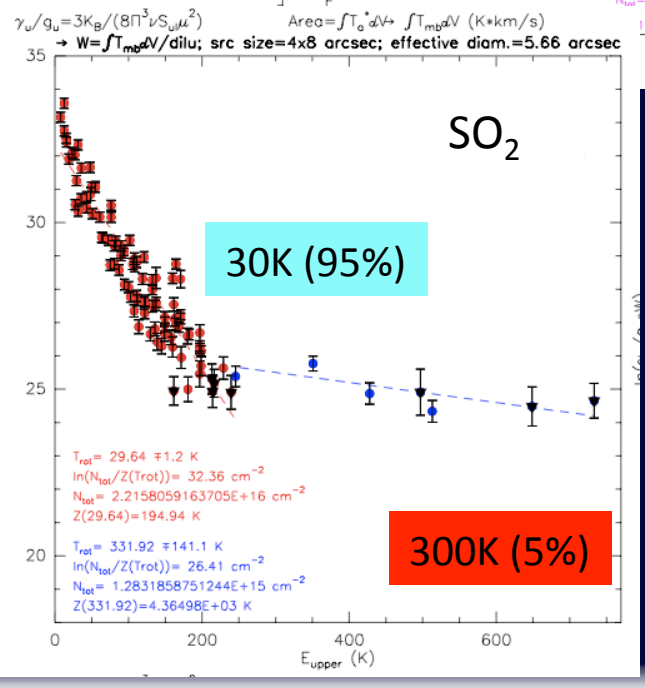


HSO/HIFI line survey: OH231.8+4.2

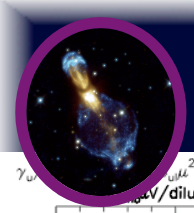
Results: Rotational diagrams (+ IRAM 30m data)

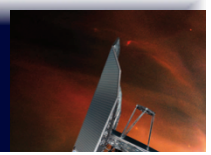


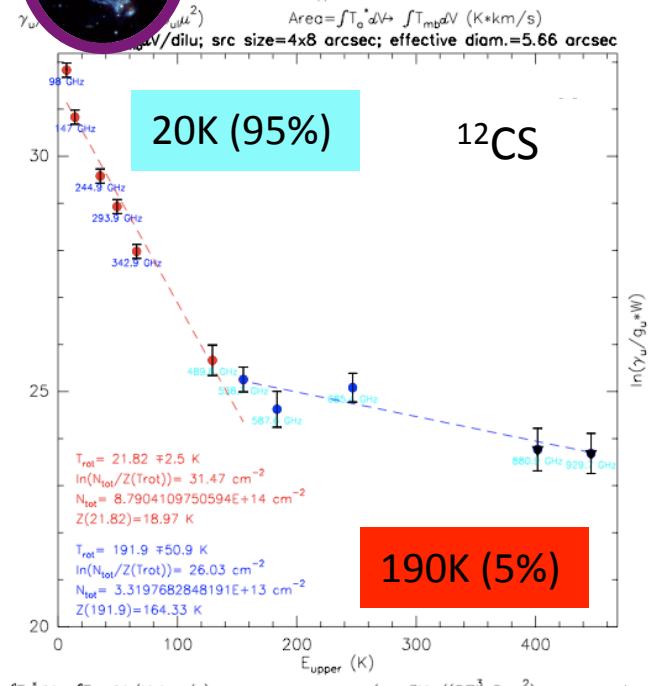


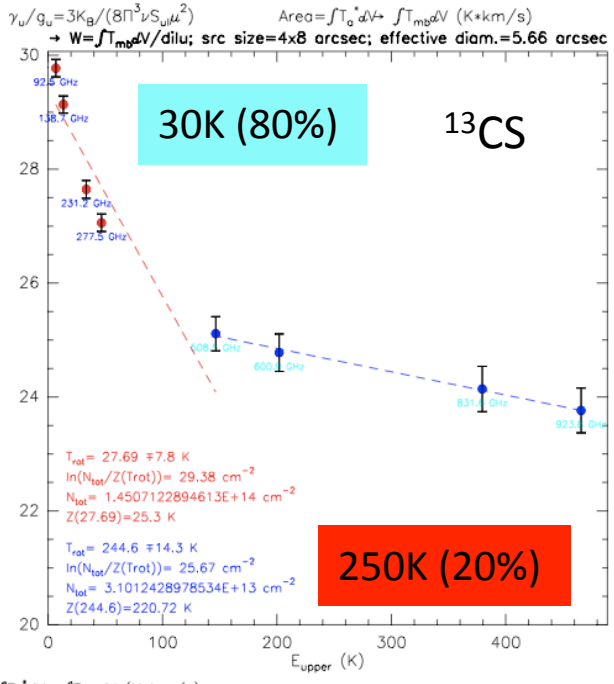


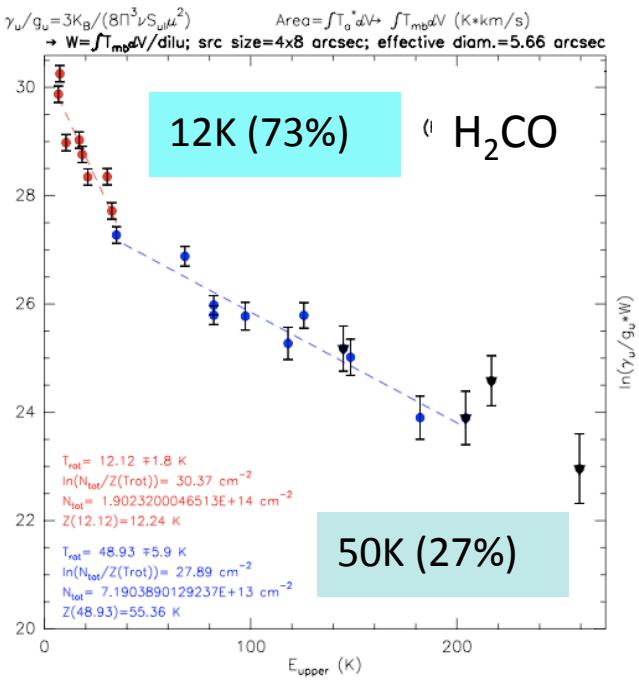
HSO/HIFI line survey: OH231.8+4.2

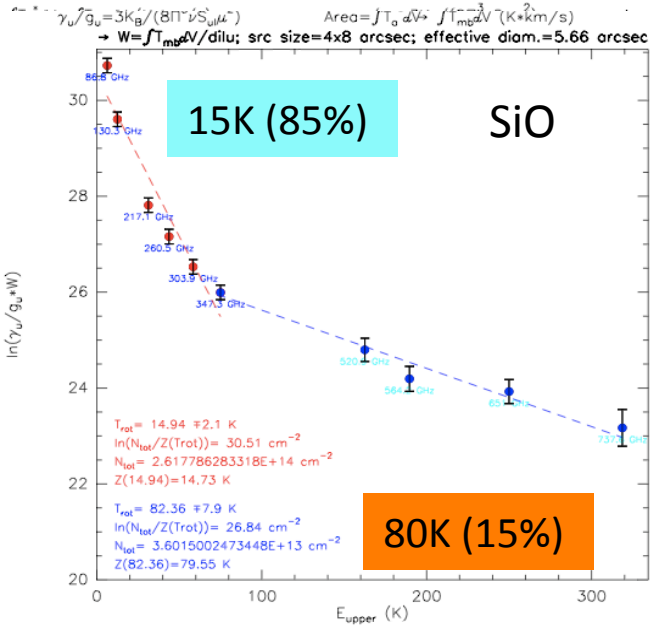


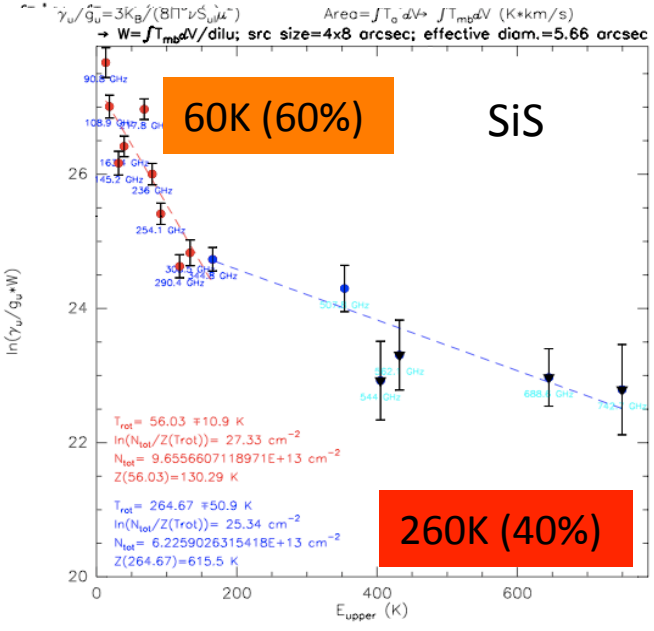


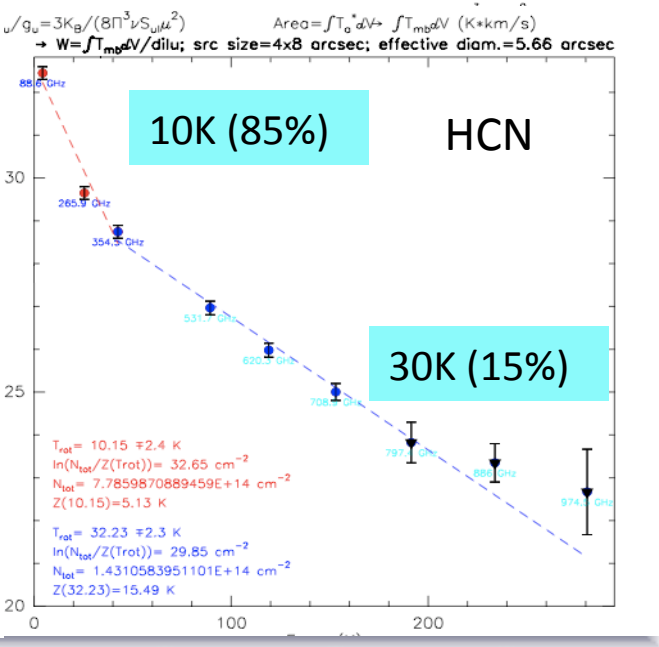


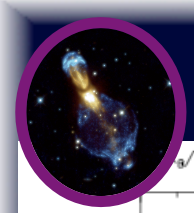




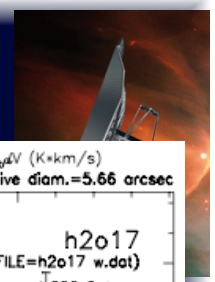


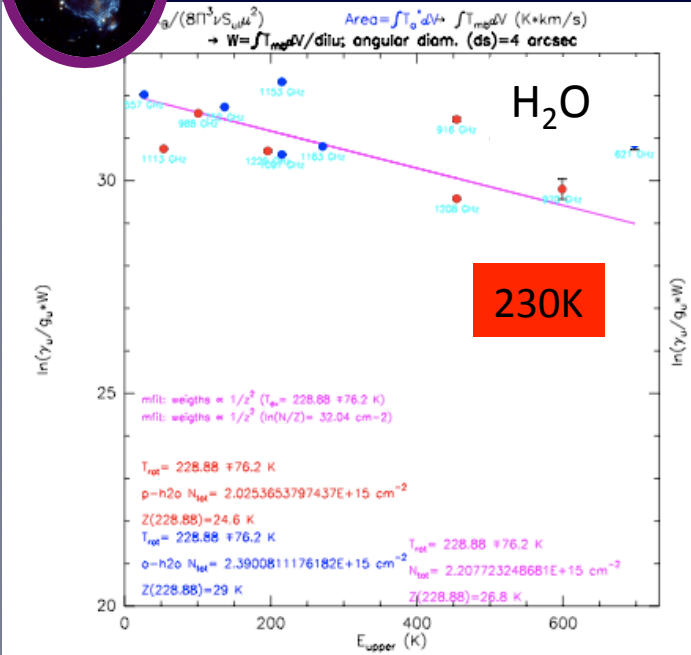


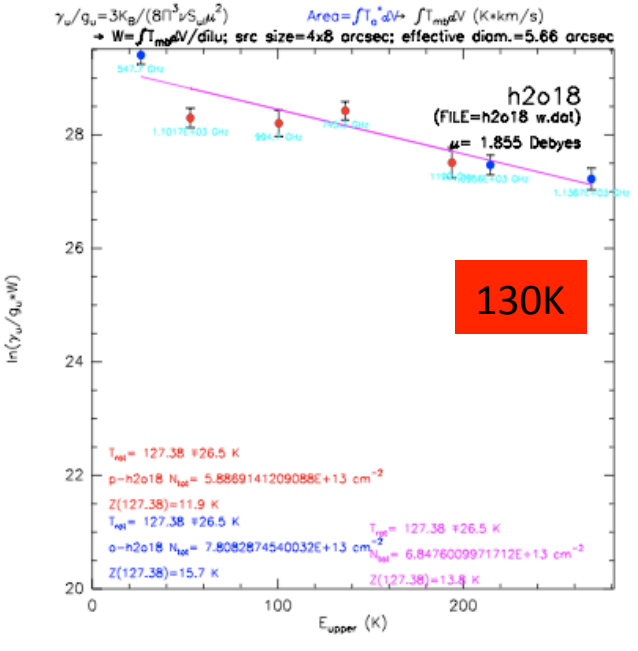


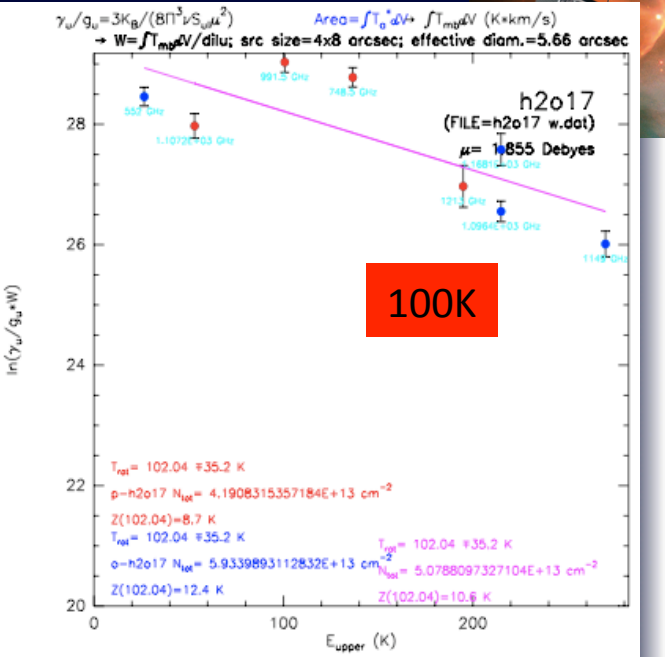


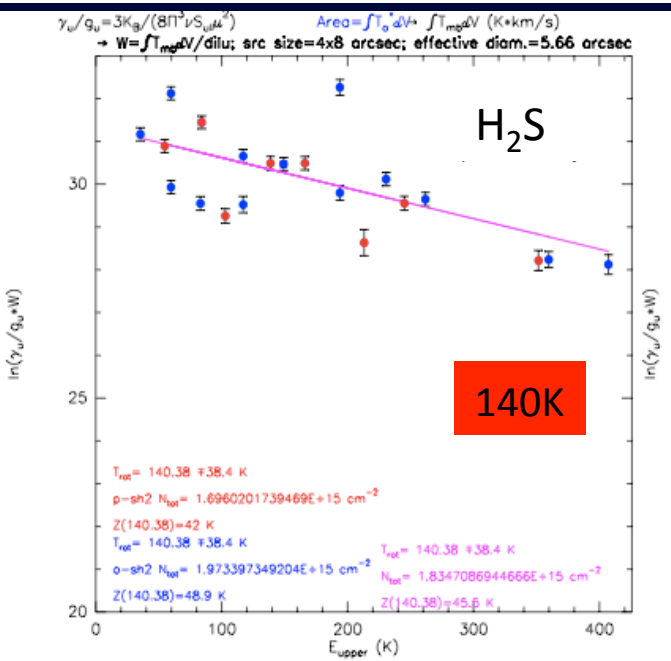
HSO/HIFI line survey: OH231.8+4.2

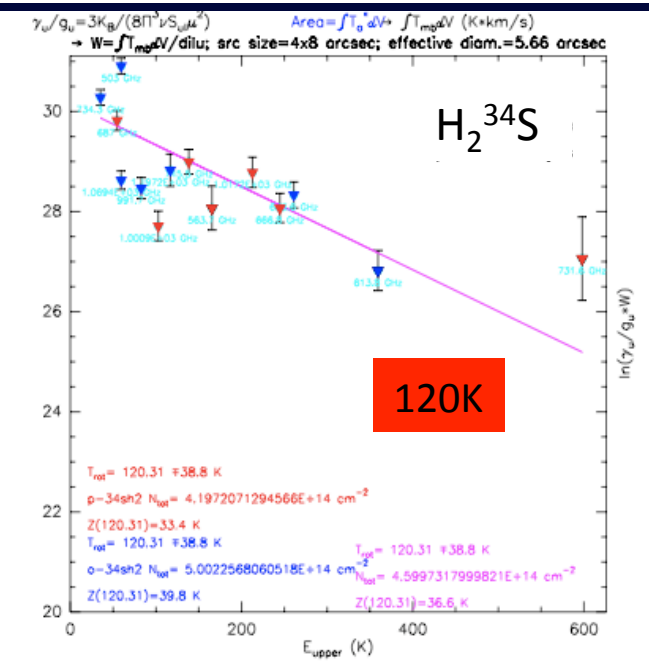


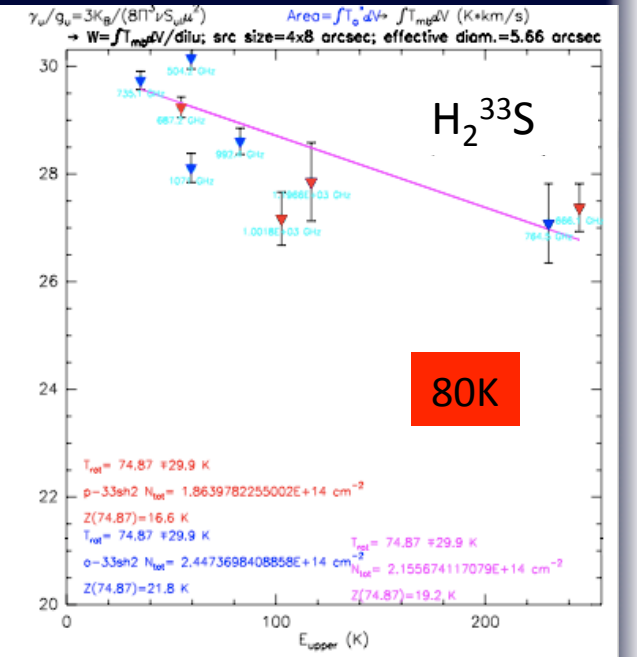




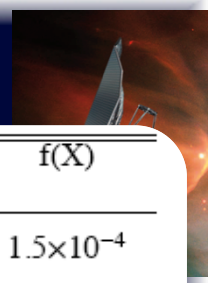








HSO/HIFI line survey: OH231.8+4.2



Results: Rotational diagrams

- N_{tot}, X for all molecules

  non-LTE, radiative tranfs. in progress

  o/p ratio ≈1 (?) in progress...

  isotopic ratios (C, S, O, Si) in progress...

- Temperature stratification

COLD	~10-50 K	CO, CS, SiO, HCN, HNC, HCO^+, NH_3, H_2CO, SO^+, N_2H^+, OCS, NS, NO
WARM	>50-100K	SO, SiO, SiS, H_2CO
HOT	>100-200K	H_2O, H_2S, H_3O^+, SO_2, CS, SiO (maser), SiS, NS

∇T not only at the CORE but also accross the LOBE walls!

Species	$\theta \times \theta$ (")×(")	N_{tot} (cm^{-2})	T_{rot} (K)	f(X)
^{12}CO	5×10	≳7.7(2.0)×10^{17}	14 (3)	1.5×10^{-4}
	5×10	4.4(1.0)×10^{17}	43 (3)	
^{13}CO	4×8	3.4(0.2)×10^{17}	11 (1)	5×10^{-5}
	4×8	1.6(0.3)×10^{17}	45 (2)	
$C^{18}O$	4×8	1.4(0.2)×10^{16}	31 (2)	2×10^{-6}
SO_2	4×8	2.2(0.3)×10^{16}	29 (1)	3×10^{-6}
	4×8	1.3(0.7)×10^{15}	330 (140)	
SO	4×8	1.3(0.3)×10^{16}	27 (2)	2×10^{-6}
	4×8	1.2(0.4)×10^{15}	61 (5)	
NH_3	4×8	≳7.0(4.0)×10^{14}	21 (4)	≳3×10^{-7}
CS	4×8	8.8(0.3)×10^{14}	21 (2)	1.0×10^{-7}
	4×8	3.3(1.2)×10^{13}	190 (50)	
HCN	4×8	7.8(0.50)×10^{14}	10 (2)	≳2×10^{-8}
	4×8	1.4(0.04)×10^{14}	32 (2)	
HCO^+	4×8	3.0(0.5)×10^{14}	14 (1)	5×10^{-8}
HNC	4×8	2.6(1.7)×10^{14}	24 (5)	4×10^{-8}
SiO	4×8	2.6(0.1)×10^{14}	14 (2)	4×10^{-8}
	4×8	3.6(0.7)×10^{13}	82 (8)	
SiS	4×8	9.7(3.0)×10^{13}	60 (11)	3×10^{-8}
	4×8	6.2(1.6)×10^{13}	260 (50)	
H_2CO	4×8	1.9(0.05)×10^{14}	12 (2)	2.5×10^{-8}
	4×8	7.2(1.70)×10^{13}	48 (6)	
$^{13}CS^{\dagger}$	4×8	1.5(0.07)×10^{14}	27 (8)	2.5×10^{-8}
	4×8	3.1(0.2)×10^{13}	244 (14)	
H_2O^*	4×8	>1.2(0.3)×10^{15}	230 (70)	>2×10^{-7}
$H_2{}^{18}O^*$	4×8	7.0(1.8)×10^{13}	130 (30)	>1.3×10^{-8}
$H_2{}^{17}O^*$	4×8	5.1(2.1)×10^{13}	100 (35)	≳1.0×10^{-8}
H_2S^*	4×8	≳1.8(0.7)×10^{15}	140 (40)	≳3×10^{-7}
$H_2{}^{34}S^*$	4× 8	4.6(1.7)×10^{14}	120 (40)	8.0×10^{-8}
$H_2{}^{33}S^*$	4×8	2.2(0.9)×10^{14}	75 (30)	4.0×10^{-8}
NS	4×8	9.8(4.0)×10^{13}	170 (50)	2×10^{-8}

Molecular Inventory in OH231.8+4.2

2 atoms	3 atoms	4 atoms	5 atoms
^{12}CO, ^{13}CO, $C^{18}O$, $C^{17}O$	SO_2, $^{33}SO_2$, $^{34}SO2$, $SO^{18}O$, $SO^{17}O$	H_2CO, $H_2{}^{13}CO$	HC_3N
SO, ^{33}SO, ^{34}SO, $S^{18}O$, $S^{17}O$	HCN, $H^{13}CN$	HNCO	
CS, ^{13}CS, $C^{34}S$, $C^{33}S$	HNC, $HN^{13}C$	HNCS	
NS, $N^{33}S$, $N^{34}S$	HCO^+, $H^{13}CO^+$	NH_3	
CN, ^{13}CN	H_2S, $H_2{}^{33}S$, $H_2{}^{34}S$	H_3O^+	
SiO, ^{29}SiO, ^{30}SiO	OCS, $O^{13}CS$		
SiS	H_2O, $H_2{}^{18}O$, $H_2{}^{17}O$		
NO	N_2H^+		
SO+			

17 → 51 species

Line lidentification NOT finished
20% features remaining...

Summary

- Molecular Line survey of –rich CSE OH231.8: IRAM 30m + HSO
- ~1000 GHz explored mm/fIR, ~800 lines detected
- Line identification ~80%: 17 → 51 species
- Lack of/weak em. from the INNER layers →$\dot{M}_{AGB}$ STOPPING
- OH231's chemistry unparalleled amongst O-rich AGB & post-AGB →non-equilibrium molecule reformation in the shocked outflow
- New detections: HNCO, HNCS, HC_3N, NO, N_2H^+, SO^+, CN, SiS, H_3O^+ … NOT EXPLAINED chemical kinetics models
- Many transitions of H_2O, CO, SO_2, SO, H_2S, etc → physical and chemical properties, molecular abundances
- Temperature comps.: 10-50, 50-100, >100 K (accross lobe walls)

Thank you for your attention