(Sub)-millimeter line-surveys of the high-mass star forming region G327.3-0.6

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HERSCHEL AND THE FORMATION OF STARS AND PLANETARY SYSTEMS

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Outline

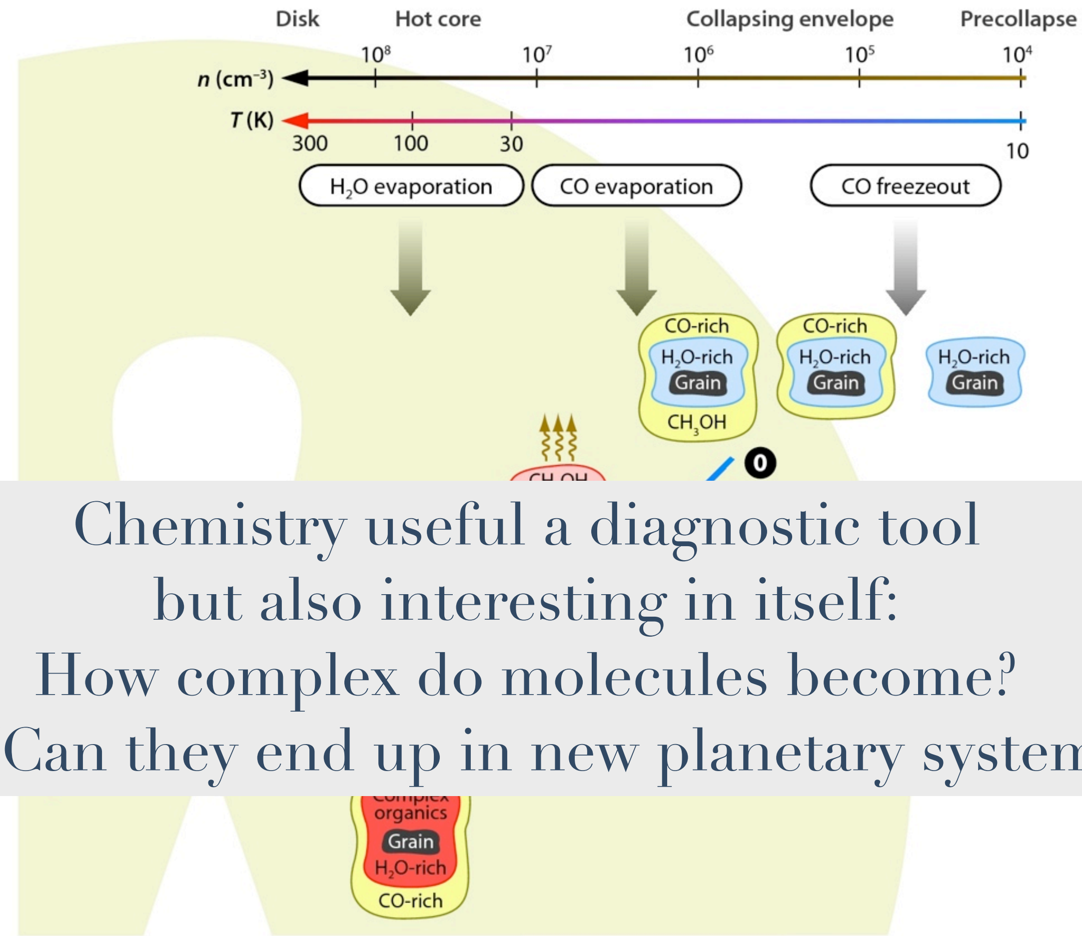
- Introduction: Molecules in star forming regions
- Unbiased (sub)millimeter line-survey of the high-mass star-forming region G327.3-0.6

2	3	4	5	6	7	8	9+
H_2	C_3	c-C_3H	C_5	C_5H	C_6H	CH_3C_3N	CH_3C_4H
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HCOOCH_3$	CH_3CH_2CN
AlCl	C_2O	C_3N	C_4Si	C_2H_4	CH_3C_2H	CH_3COOH	$(CH_3)_2O$
C_2	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	$HCOCH_3$	CH_2OHCHO	HC_7N
CH^+	HCN	C_2H_2	CH_2CN	CH_3OH	NH_2CH_3		C_8H
CN	HCO	CH_2D^+	CH_4	CH_3SH	c-C_2H_4O		CH_3C_5N
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	CH_2CHOH		$(CH_3)_2CO$
CO^+	HCS^+	$HCNH^+$	HC_3NC	HC_2CHO			NH_2CH_2COOH?
CP	H_2S	$HOCO^+$	H_2CHN	C_5N			HC_9N $HC_{11}N$
HCl	HNC	H_2CO	H_2C_2O				
KCl	HNO	H_2CN	H_2NCN				
NH	MgCN	H_2CS	HNC_3				
NO	MgNC	H_3O^+	SiH_4				
NS	N_2H^+	NH_3	H_2COH^+				
NaCl	N_2O	SiC_3					
OH	NaCN						
PN	OCS						
SO	SO_2						
SO^+	c-SiC_2						
SiN	CO_2						
SiO							

Currently ~150 species detected in space.

Overview chemistry during star formation

- Low temperatures: hydrogenation reactions of CO, O, N & C
- Intermediate temp: radical reactions in the ices
- High temp: gas phase reactions after evaporation



Chemistry useful a diagnostic tool
but also interesting in itself:
How complex do molecules become?
Do/Can they end up in new planetary systems?

Figure 14

Cartoon representation of the evolution of material from the prestellar core stage through the collapsing envelope (size ~0.05 pc) into a protoplanetary disk. The formation of zeroth- and first-generation organic molecules in the ices is indicated with 0 and 1, and the second-generation molecules in the hot-core/corino region when the envelope temperature reaches 100 K, and even strongly bound ices start to evaporate, are designated 2. The grains are typically 0.1 μm and are not drawn to scale. The temperature and density scale refer to the envelope, not to the disk (see also **Figure 4**). Once material enters the disk, it will rapidly move to the cold midplane where additional freeze-out and grain surface chemistry occur. All ices evaporate inside the (species-dependent) sublimation radius. For H_2O and trapped complex organic molecules, this "snow line" lies around a few astronomical units in a disk around a solar mass star. Figure by E. van Dishoeck & R. Visser.

Herbst & van Dishoeck, ARAA, 2009, 47, 427

Aim

Study the molecular composition of the surrounding material during the star formation process

Unbiased line-surveys:

- Large frequency coverage
- Low RMS
- Transitions of many different species (and isotopologues)
- Many transitions per species: excitation temperature, abundances, source sizes

The G327.3-0.6 star-forming region

- One of the chemically richest high-mass star-forming regions known (Gibb et al. 2000)
- Strong and narrow emission lines (~ 5 km s^{-1}: minimal line-confusion)

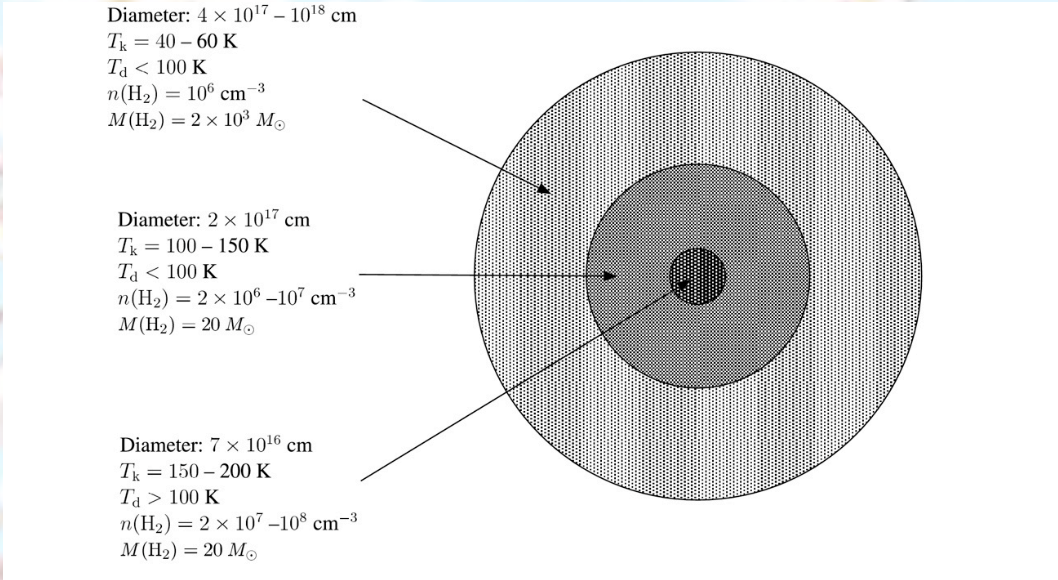
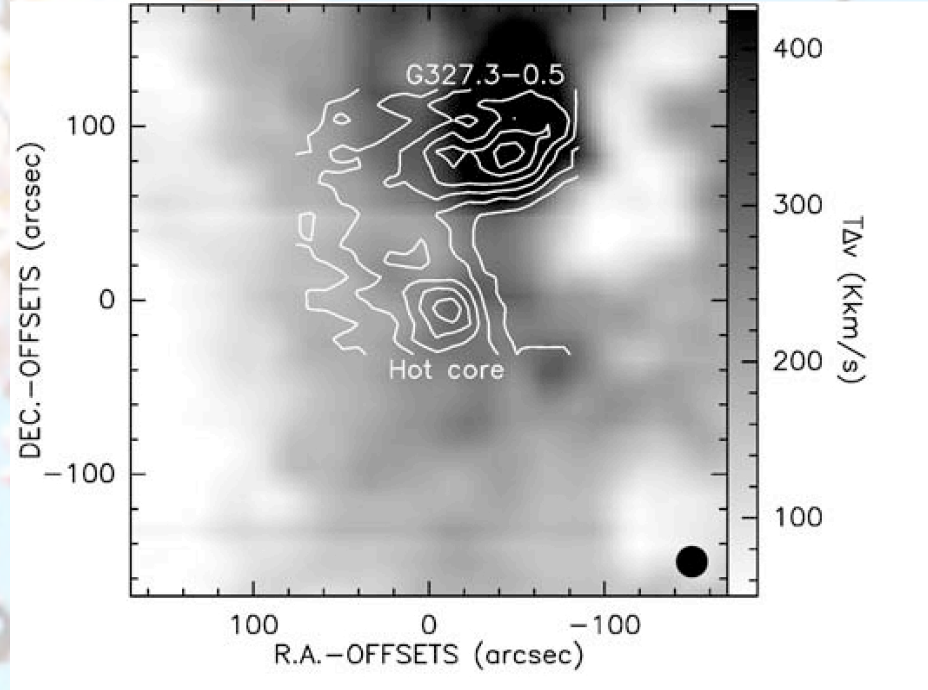


FIG. 1.—Physical structure of the hot core in G327.3 – 0.6, as derived by Bergman (1992) based on modeling of the CH_3CN and CH_3CCH emission

Gibb et al., ApJ, 2000, 545, 309

G327.3-0.6 continued....

- Luminosity: 0.5-1.5 x10^5 $L_\odot$
- Distance: 2.9 kpc
- Mass: ~500 $M_\odot$



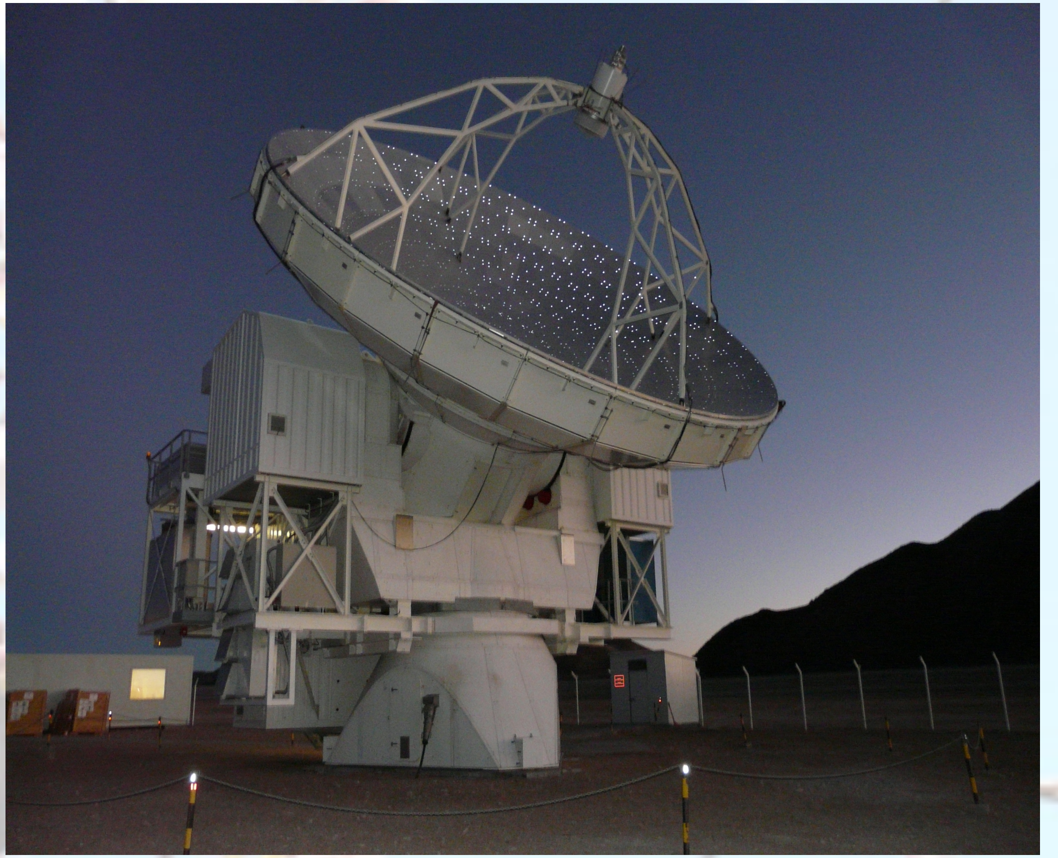
Wyrowski et al., A&A, 2008, 454, L91
Grayscale: ^{12}CO, contours: $C^{18}O$ (APEX)

Observations with the Atacama Pathfinder EXperiment (APEX)

APEX 1: 213 - 267.5 GHz

APEX 2: 270 - 315 & 335 - 362 GHz

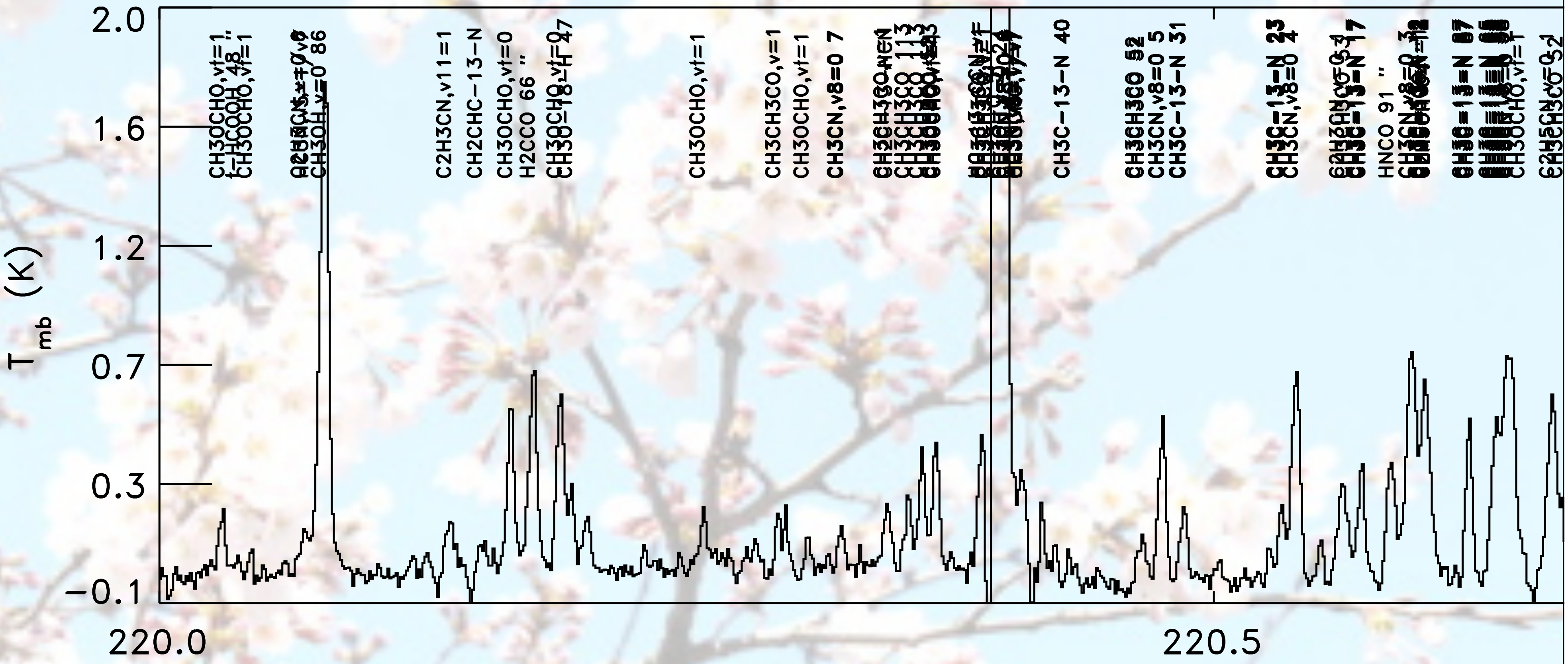
CHAMP+: 623 - 715 & 784 - 853 GHz



Data analysis

- Line-assignements: CDMS, JPL
- MyXCLASS package (Comito et al. 2005)
- Most molecules: 1/2 component fit, source size, T, column density, line width: hot core species ~2" with T~100-150 K
- 44 species detected, 52 isotopologues, 23 vibrationally excited species (e.g. HCN, HCO^+ to $(CH_3)_2CO$)
- ~60-70% of lines assigned ➡ 30+% U-lines

The incredible richness of G327.3-0.6



Overview detected species

- 1 atom: C
- 2-atoms: CN, SiO, SO, CS, NO, NS, CO
- 3-atoms: HCN, HNC, SO_2, H_2S, OCS, CCH, HCO^+, N_2H^+, HCS^+, HDO/$H_2{}^{18}O$, NH_2
- 4-atoms: HNCO, NH_2D, H_2CO, H_2CS
- 5-atoms: HC_3N, CH_2NH, H_2CCO, HCOOH, c-C_3H_2, l-C_3H_2
- 6-atoms: CH_3CN, CH_3NC, $HCONH_2$, CH_3SH, CH_3OH

Continued....

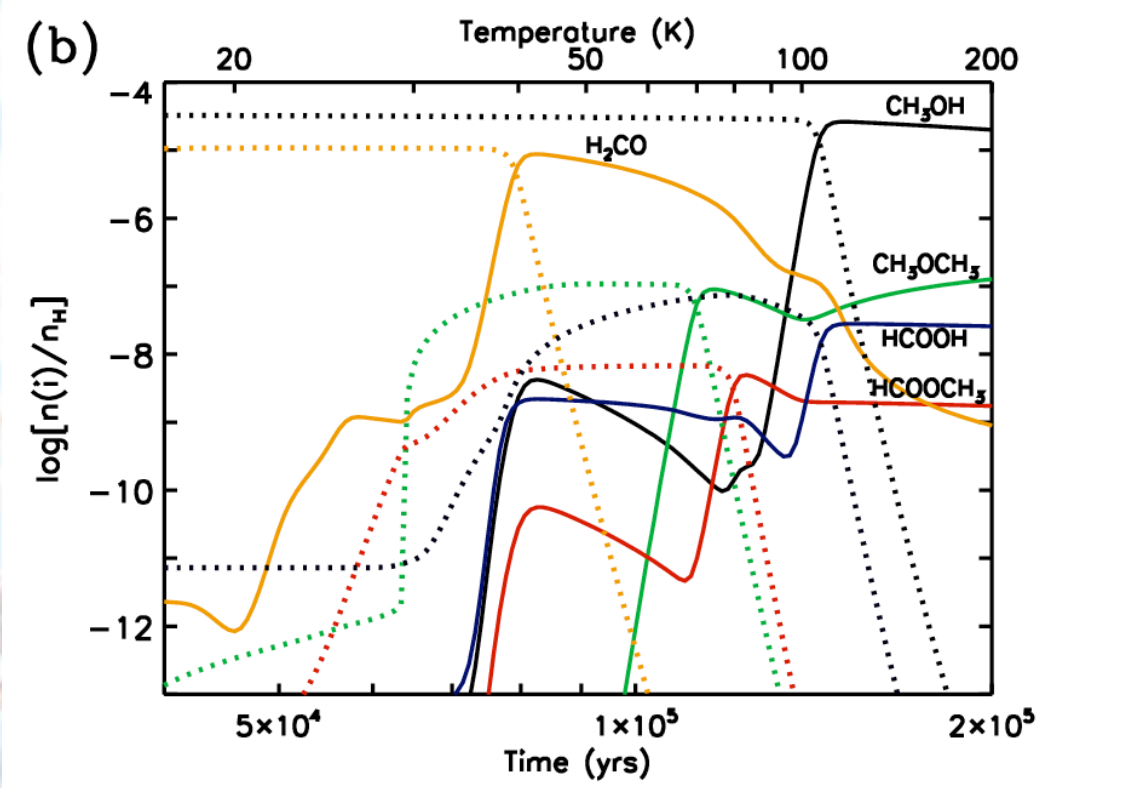
- 7-atoms: C_2H_3CN, CH_3CHO, CH_3NH_2, c-C_2H_4O, CH_3CCH
- 8-atoms: $HCOOCH_3$
- 9-atoms: C_2H_5CN, CH_3OCH_3, C_2H_5OH
- 10-atoms: CH_3CH_3CO

↓

Many hydrogen-rich organics indicative of hydrogenation processes on grain-surfaces!

Case study I: CH_3OCH_3

- CH_3OCH_3 is formed on the surfaces of icy grains at higher temperature 20-30 K
- It evaporates ~70 K and destroyed in the gas phase
- As CH_3OH evaporates it is formed in the gas phase



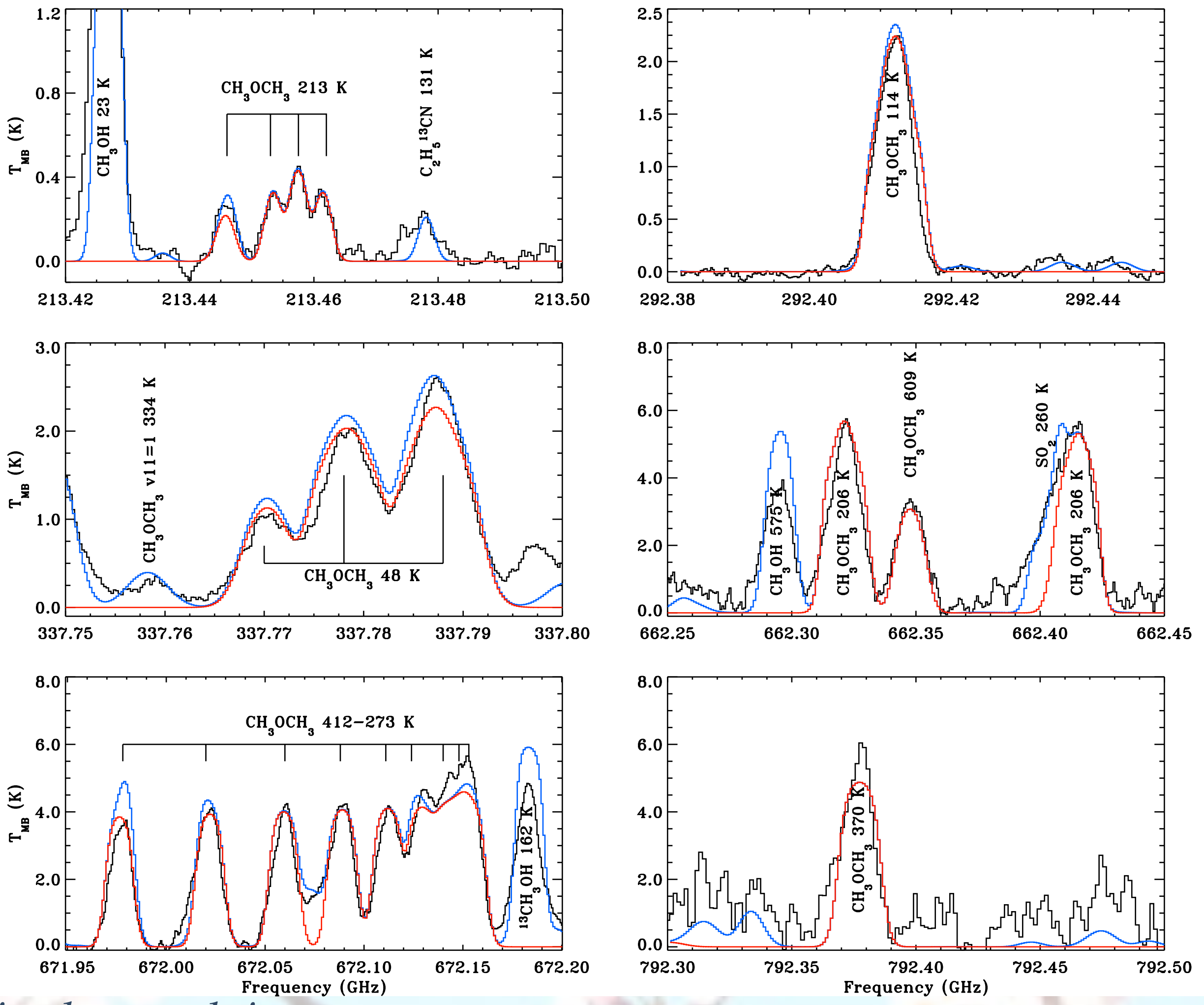
Is there observational evidence for the grain surface / gas phase formation scenario?

Garrod et al., ApJ, 2008, 682, 283

CH_3OCH_3 in G327.3-0.6

- Ground state:
  - ★ 251 unblended lines detected over whole freq range
- Torsionally excited (new lab data by Endres et al. in prep):
  - ★ v11=1 (288 K, infrared inactive): 102 unblended lines
  - ★ v15=1 (346 K, infrared active): 43 unblended lines

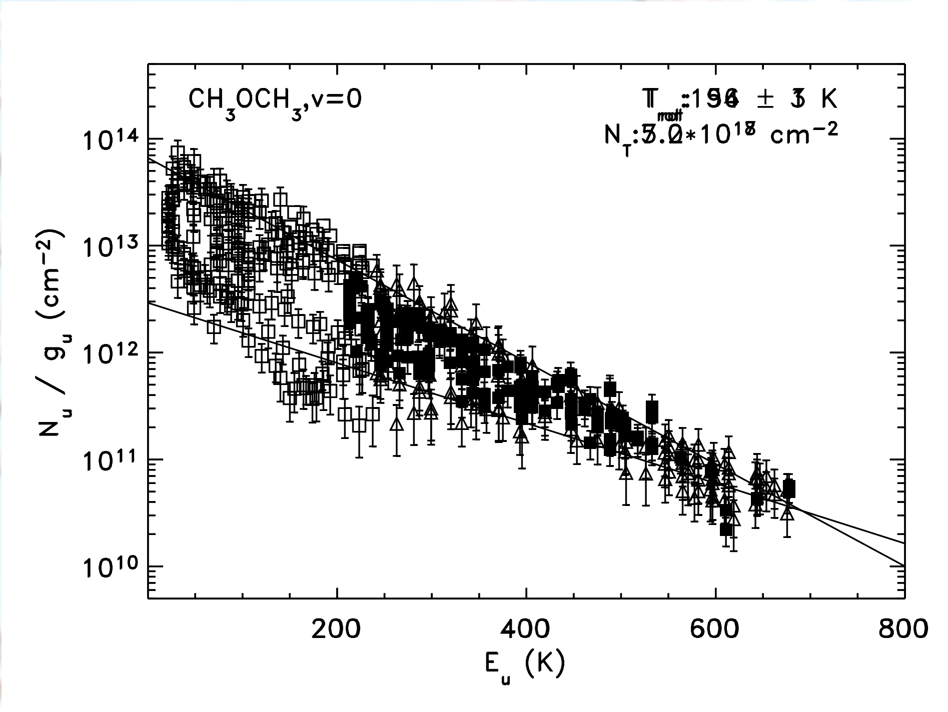
CH_3OCH_3 continued



Bisschop et al. in prep.

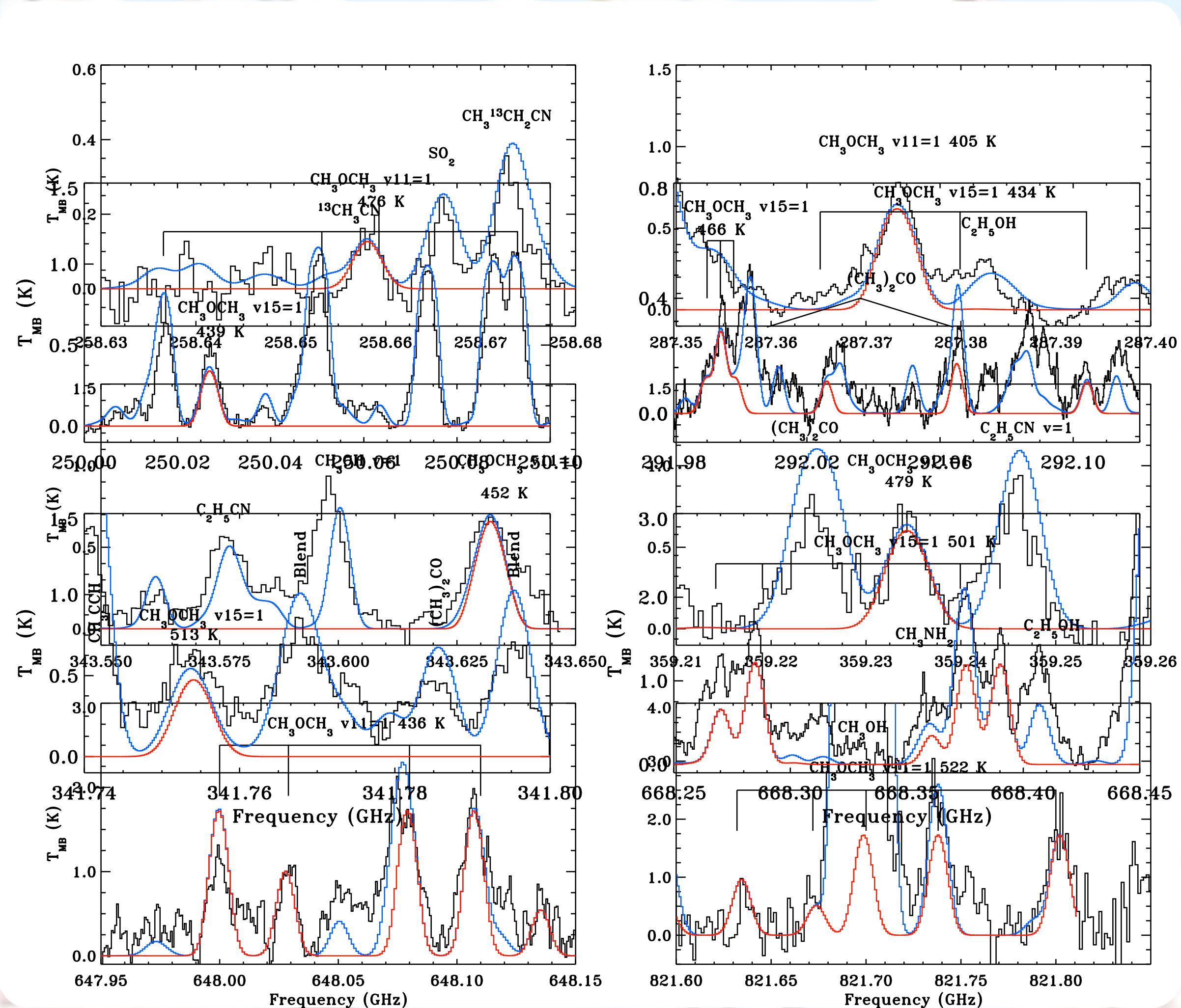
CH_3OCH_3 is detected in all atmospheric windows observed with transition spanning a large range in excitation energies

Excitation of CH_3OCH_3



- Comp 1: E_u> 200 K can be very well fit with a simple model with T~100 K and N~4.0x10^{18} cm^{-2} and a source size of 2.3″ (LTE)
- Comp 2: E_u< 200 K come from a region with a temperature of ~ 60 K and N~4.5x10^{16} cm^{-2} for 4.0″ (LTE??)

CH_3OCH_3 v_{11}=1 and v_{15}=1 detected for the first time!



- Recent lab. measurements by Endres et al. in prep.
- v_{11}= 1 detected in all bands
- v_{15}=1 detected at all but the highest frequencies
- Excitation well described by identical model to the ground state

Bisschop et al. in prep.

Summary CH_3OCH_3

- Main component of the ground state is tracing emission that has a temperature of 100 K
- A cooler more extended component is also present

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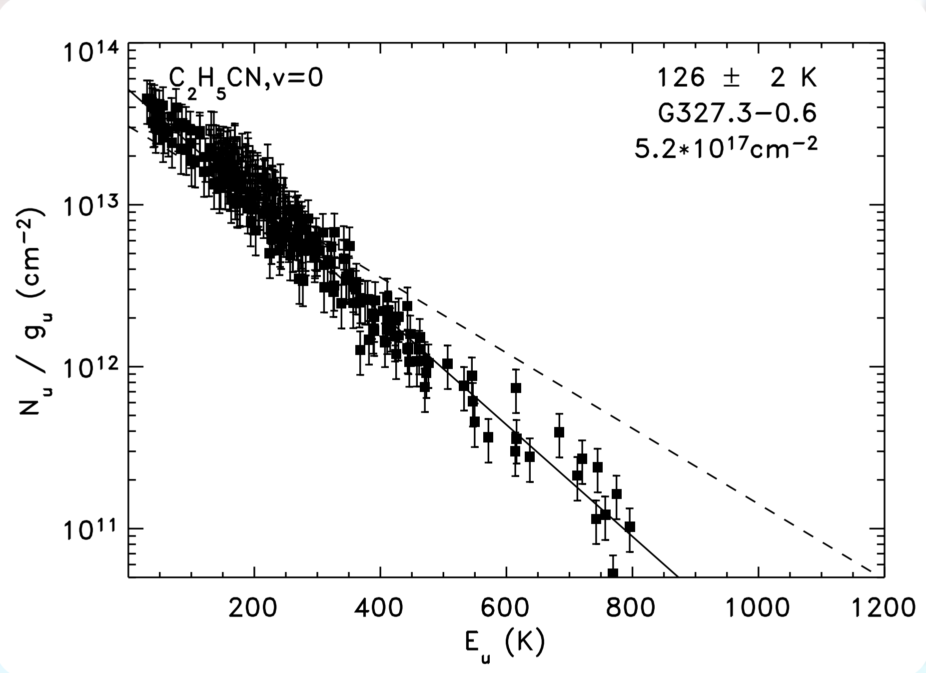
Two formation mechanisms/ (non)-LTE excitation effects?

Future work: modeling the CH_3OCH_3 with a more realisitic source model

Case study II: C_2H_5CN in G327.3-0.6

- Ground state:
  - ★ 324 unblended lines detected over whole freq range
- Vibrationally / torsionally excited v_{13}=1(298 K, CCN in-plane) & v_{21}=1 (303 K, torsion):
  - ★ 237 detected lines at low frequencies (no laboratory data above 500 GHz)
  - ★ Previously detected toward SgrB2(N) and W51 e2 *(Mehringer et al. 2004, Demyk et al 2008)*

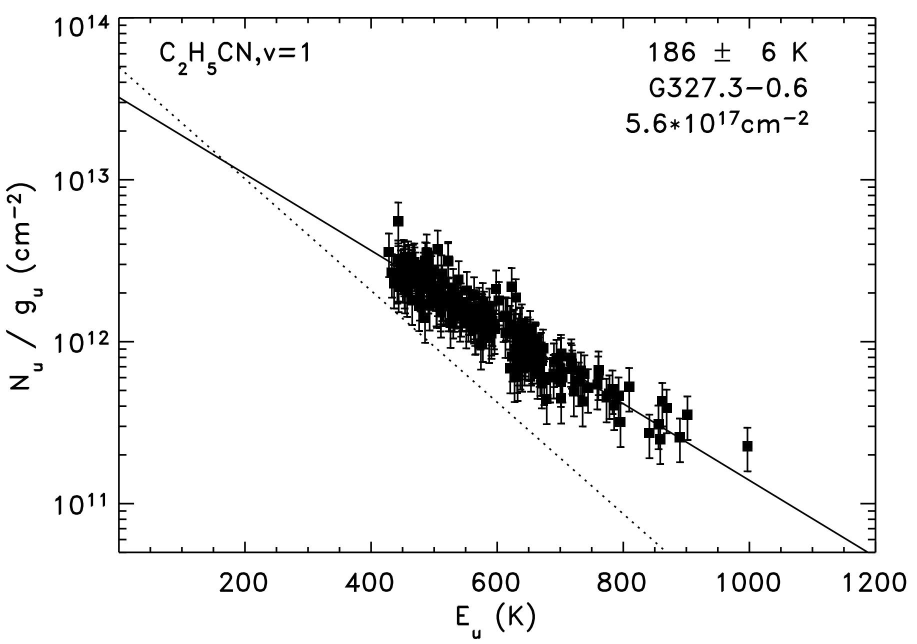
Example II: C_2H_5CN



v=0:

- Consistent with a single temperature and column density over a large excitation range
- Optically thick lines of all energies appear to probe the same source size of 2.3″
- ^{13}C isotopes are also detected and fit the same model

Vibrationally and torsionally excited C_2H_5CN, $v_{13}=1$ and $v_{21}=1$



- Lines stronger than expected based on the ground state fit
- Some pumping mechanism?

Summary C_2H_5CN

- The ground state is tracing emission with ~125 K, consistent with a grain evaporation origin of the gas
- The column densities are within error the same for ground and vibrational states, but the excitation temperatures are not!

↓

Does the vib/torsionally excited state arise from the same region as the ground state?

Future work: compare with related species such as C_2H_3CN!

General conclusion

- Detailed study of the excitation of complex organics in a line-survey gives a plethora of information of the whereabouts and possible formation mechanism of species

- Interpretation of line-surveys is tricky and not straightforward!

Future line-surveys with Herschel and ALMA will serve as excellent to test our understanding of astrochemical processes!