IAU Symposium 280: The Molecular Universe
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Observations of Complex Molecules in Low-Mass Protostars

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"Complex Organic" Molecules

What is the "organic" molecule?

・・・(Biological origin)
C-bearing molecules except for CO, CO_2, etc.

What is the "complex" molecule?

・・・Molecules with 6 atoms or more ?
(e.g. Herbst & van Dishoeck, 2009, ARA&A)

Complex Organic Molecules (COMs):

- Saturated COMs

  (CH_3OH, CH_3CN, CH_3CHO), $HCOOCH_3$, $(CH_3)_2O$, C_2H_5CN, etc.

  (Hot cores in massive SFRs & GC)

  (e.g. Turner et al. 1989; Blake et al. 1996; Kim et al. 2000)

- Unsaturated COMs(Carbon-chain molecules)

  CH_3CCH, C_4H_2, HC_5N, HC_7N, C_5H, C_6H, etc.

  (Young starless cores & Evolved stars)

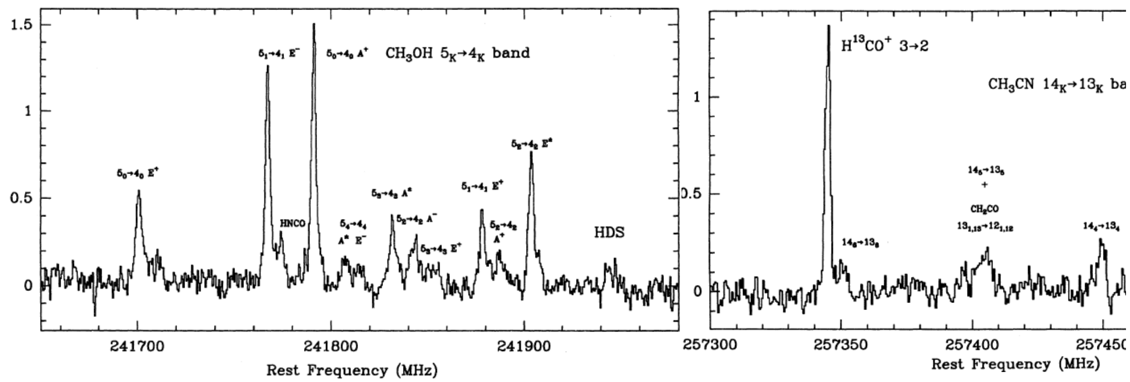
  (e.g. Kaifu et al. 2004; Kalenskii et al. 2004; Cernicharo et al. 2000)

Complex Organic Molecules in Low-Mass SFRs

Line Survey toward Low-Mass Protostars

ex.) IRAS16293-2422 : 239-250, 338-347 GHz

(Blake et al. 1994; van Dishoeck et al. 1995)



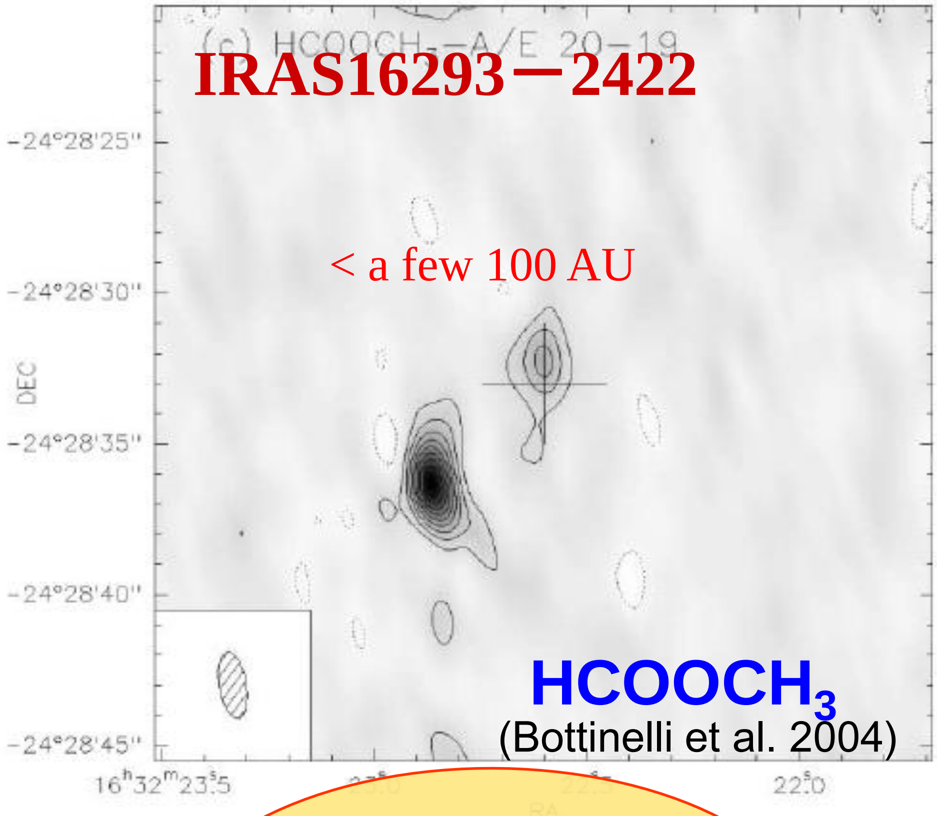
265 lines belonging to 44 species (+24 isotopomers)

No COMs !

Molecular Column Densities and Abundanc

Species	N (cm^{-2}) Rot. Diagram[a]	Exc. Calculation	IRAS 16293[b]
HCO^+	...	...	1.8 (−9)[c]
$H^{13}CO^+$	...	1.5 (12)	7.5 (−12)
$HC^{18}O^+$	...	7.0 (11)	3.5 (−12)
HCN	...	...	1.9 (−9)[c]
$H^{13}CN$	...	2.8 (12)	1.4 (−11)
$HC^{15}N$	...	1.4 (12)	7.0 (−12)
HNC	...	...	1.5 (−10)[c]
$HN^{13}C$	...	5.0 (11)	2.5 (−12)
CN	(3.7 ± 2.0) (13)	2.0 (13)	1.0 (−10)
C_2H	(9.2 ± 5.9) (13)	5.0 (13)	2.5 (−10)
C_3H_2	(8.6 ± 3.0) (11)	7.0 (12)	3.5 (−11)
H_2CO	(2.1 ± 0.3) (14)	1.4 (14)	7.0 (−10)
CH_3OH	(8.8 ± 1.0) (14)	...	4.4 (−9)
CH_3CN	(3.0 ± 2.0) (13)	...	1.5 (−10)
CH_3C_2H	(1.3 ± 1.0) (14)	...	6.5 (−10)
HC_3N	(3.5 ± 1.5) (12)	5.0 (12)	2.5 (−11)
HNCO	(3.4 ± 1.5) (13)	...	1.7 (−10)
CH_2CO	3.6 (13):	...	1.8 (−10):
DCO^+	(4.8 ± 2.0) (12)	3.0 (12)	1.5 (−11)
DCN	(4.6 ± 2.0) (12)	5.0 (12)	2.5 (−11)
DNC	(2.5 ± 2.0) (12)	1.0 (12)	5.0 (−12)
CCD	...	9.0 (12)	4.5 (−11)
HDO	...	2.0 (15)	1.0 (−8)
HDCO	(2.2 ± 2) (13)	...	1.1 (−10)
NH_2D	(1.9 ± 0.7) (14)	...	1.0 (−9)
HDS	(3.0 ± 1.5) (13)	...	1.5 (−10)
NO	<1 (19)	...	<5 (−5)
C_3O	<2 (14)	...	<1 (−9)
C_3S	<1 (15)	...	<5 (−9)
H_3O^+	...	<1 (13)	<5 (−11)
HCO	<4 (13)	...	<2 (−10)
HCOOH	<6 (13)	...	<3 (−10)
CH_3CHO	<2 (13)	...	<1 (−10)
C_2H_5OH	≲4 (13)	...	≲2 (−10)[f]
CH_3OCH_3	<3 (14)	...	<2 (−9)
C_2H_3CN	<1 (15)	...	<5 (−9)
C_2H_5CN	<2 (14)	...	<1 (−9)
CH_2NH	<1 (14)	...	<5 (−10)
NH_2CHO	<8 (12)	...	<4 (−11)
NH_2CN	<2 (12)	...	<1 (−11)

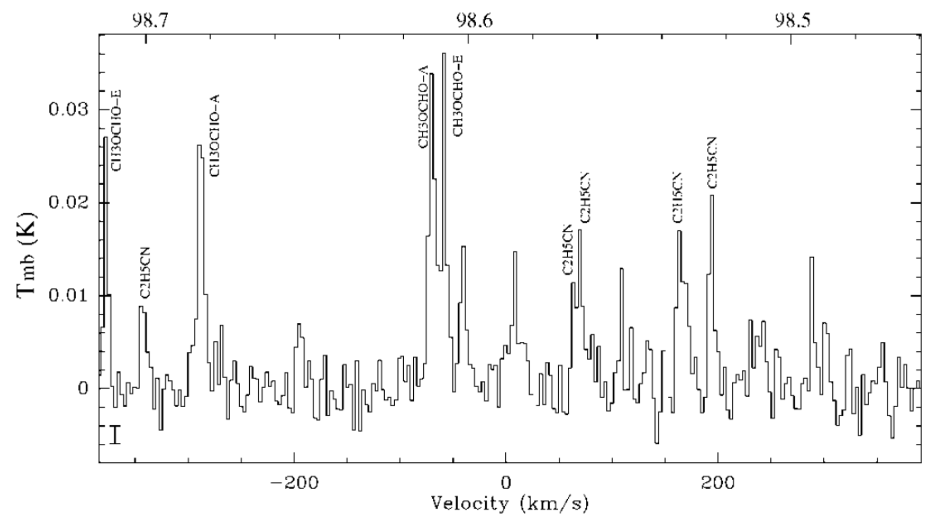
Detection of Saturated Complex Organic Molecules



IRAS16293−2422

< a few 100 AU

$HCOOCH_3$
(Bottinelli et al. 2004)



Sensitive Observations toward Low-Mass Class 0 Protostars !

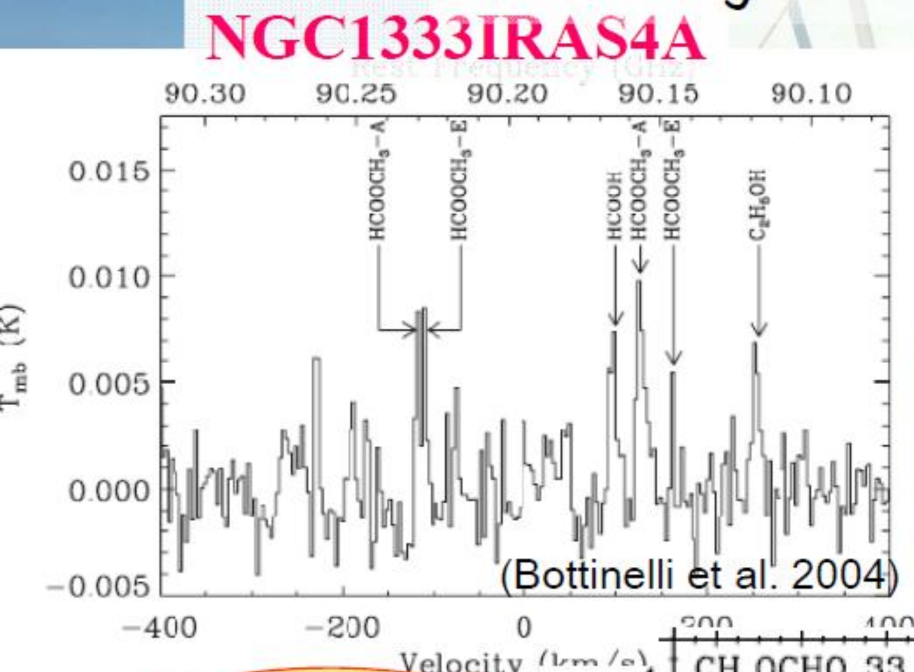
- **High fractional abundance of complex organic molecules**

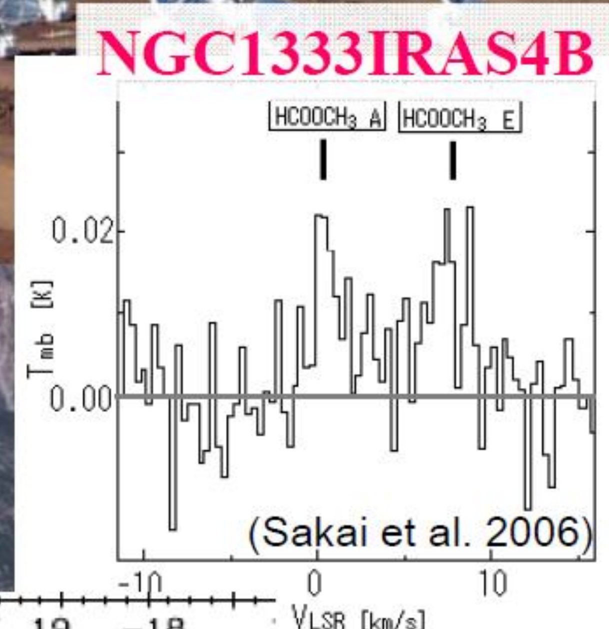
(e.g. Cazaux et al. 2003)

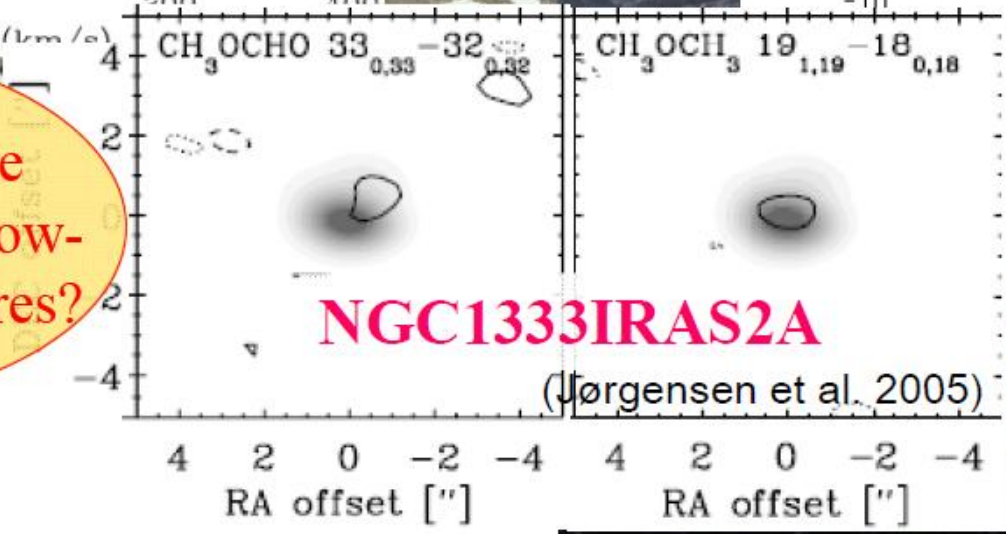
$HCOOCH_3$, $(CH_3)_2O$, C_2H_5CN, etc.

Low-Mass Protostars with Complex Organic Molecules

~Discovery of Hot Corino Chemistry~



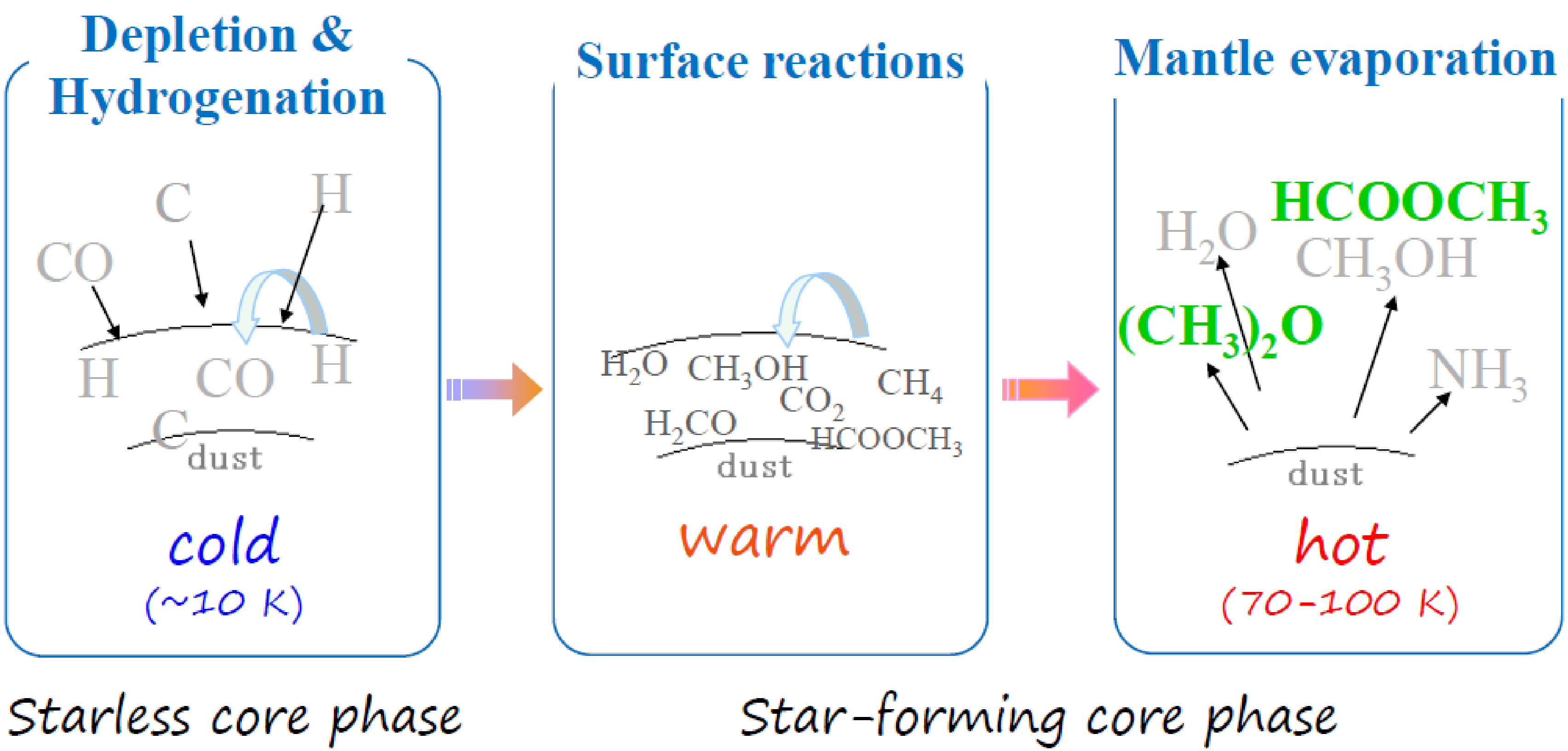




Saturated COMs are generally formed in low-mass star forming cores?

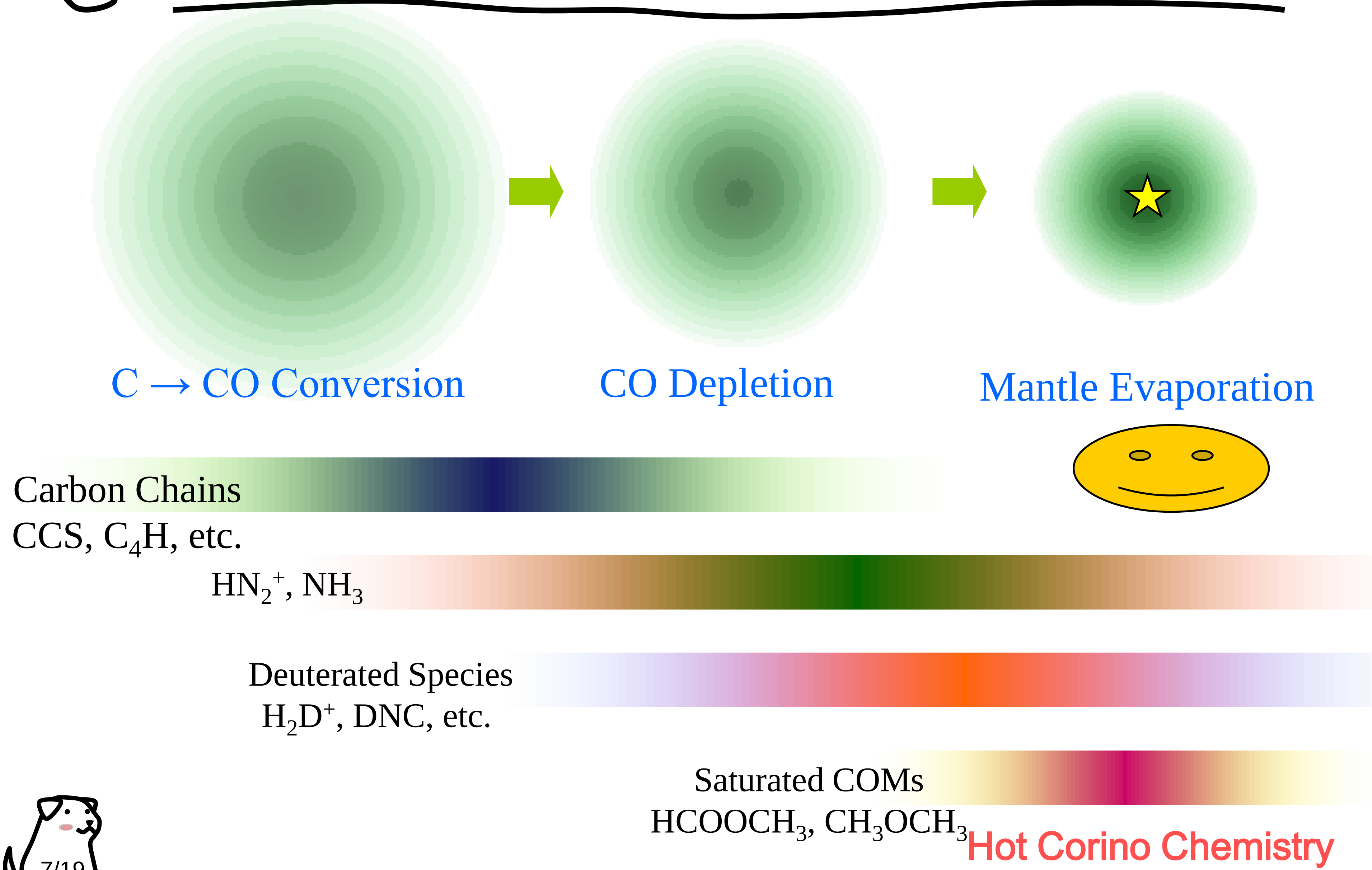
Hot Corino Chemistry

Evaporation of icy mantles from dust grains



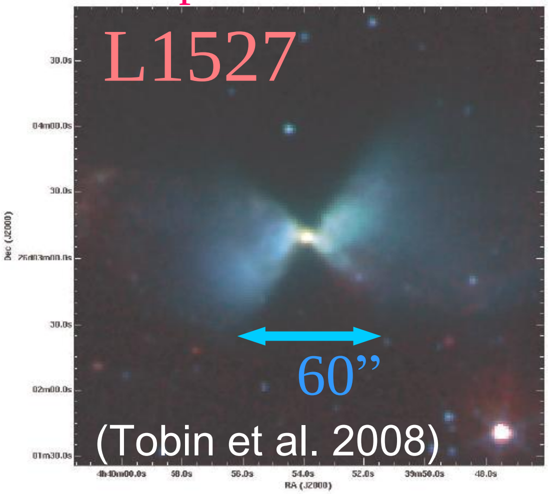
(e.g. Garrod et al. 2006)

Chemical Evolution of Molecular Clouds



Carbon-Chain Rich Star-Forming Region, L1527

Class 0 protostar in ***Taurus***

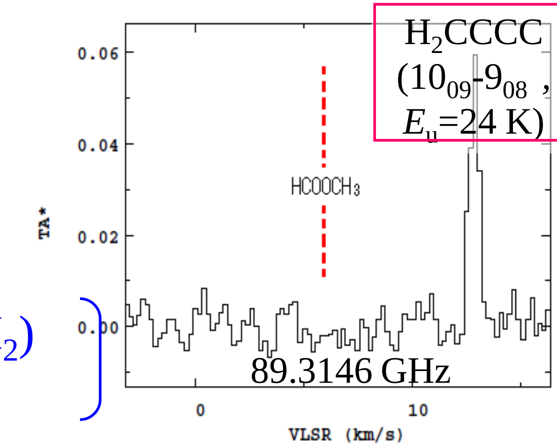


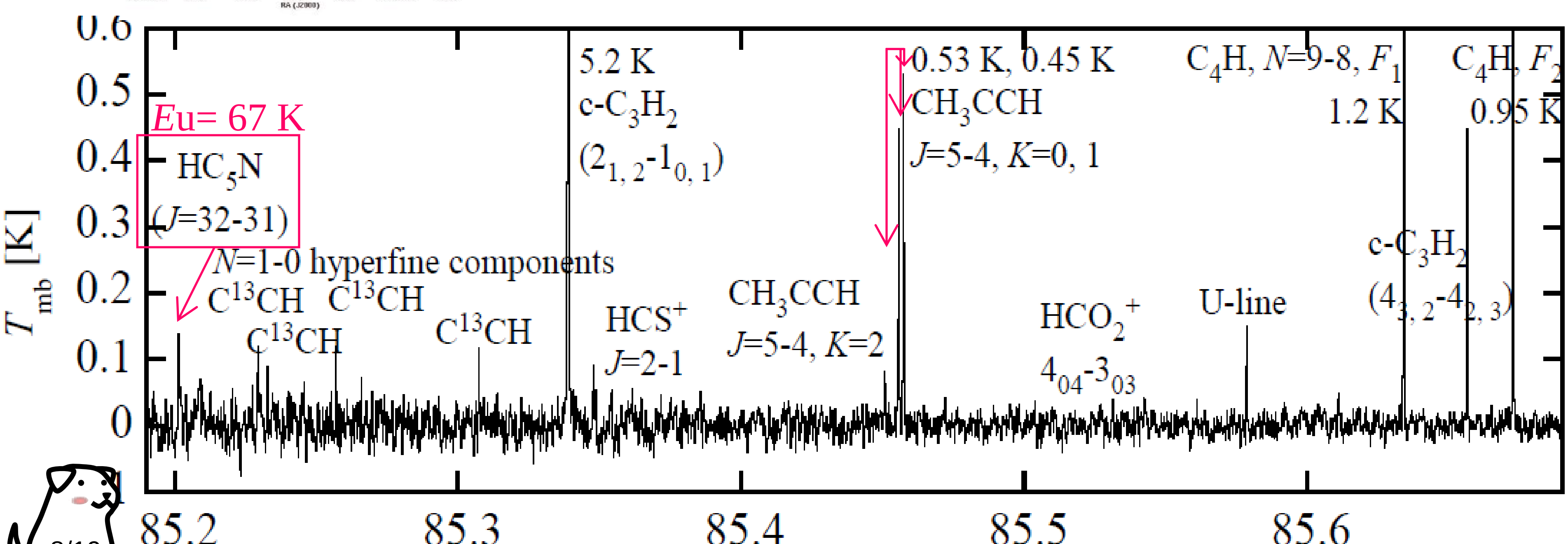
★ Strong high excitation lines

T_K = 13.9±1.3 K (CH_3CCH)

thermarize ⟷ T_{rot} = 12.3±2.3 K (C_4H_2)

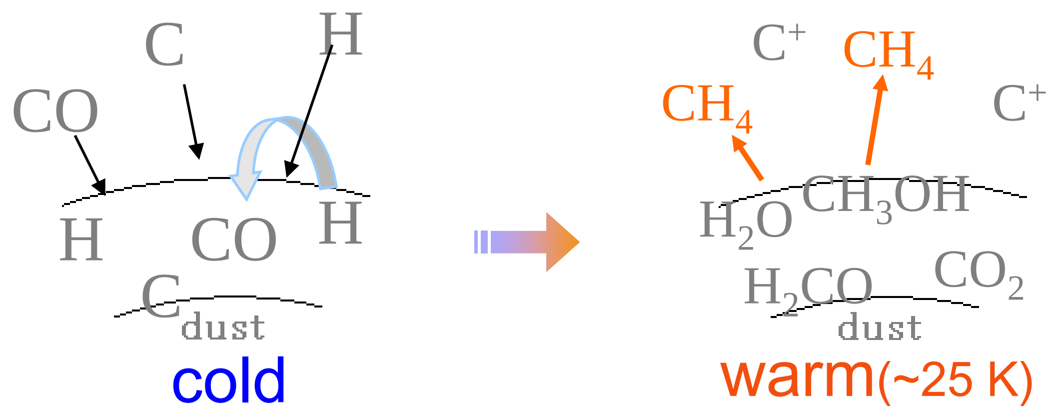
(*cf;* T_{rot} =3.8±1.5 K (C_4H_2) @TMC-1)





(e.g. Sakai et al. 2007; 2008) Frequency [GHz] @45 m, beam size 20’ (~2700AU)

Regeneration of Carbon-Chain Molecules



Warm Carbon Chain Chemistry (WCCC)

(Sakai et al. 2008; 2009)

C_nH_m series

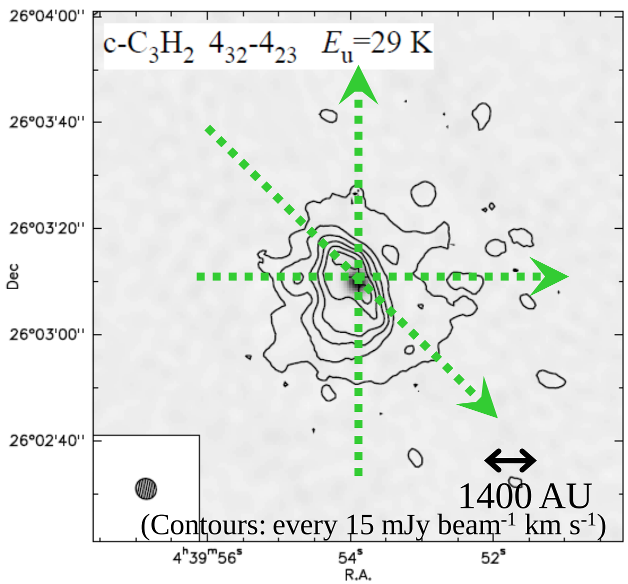
$$CH_4 + C^+ \rightarrow C_2H_3^+ + H$$
$$\rightarrow C_2H_3^+ + e \rightarrow \mathbf{C_2H} + H + H \rightarrow - - - -$$

Carbon-chain production by evaporation of CH_4 from grain mantles

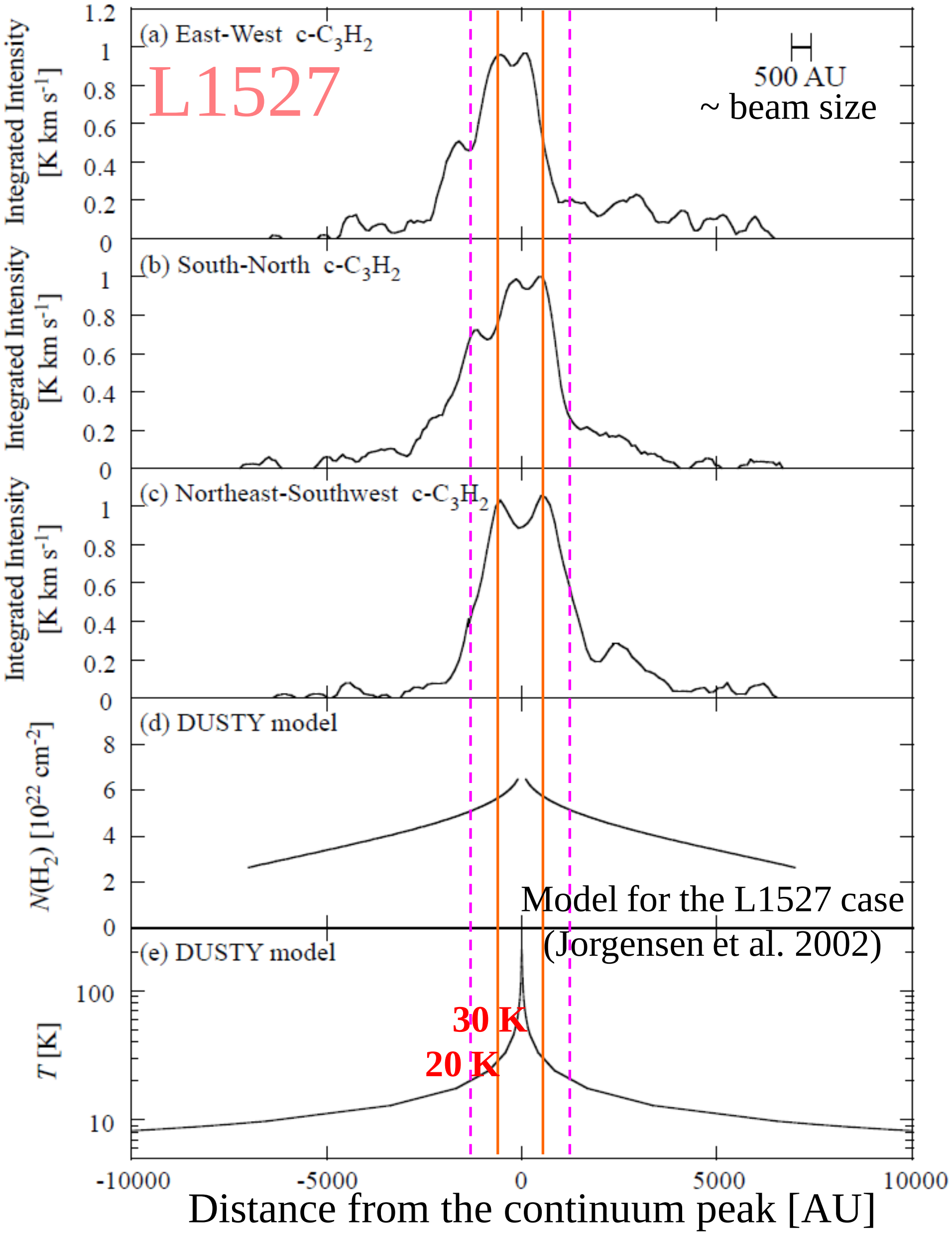
(Chemical model calculations: e.g. Aikawa et al. 2008; Hassel et al. 2008)

Enhancement of Carbon-Chains around the Protostar

Enhancement of $c\text{-}C_3H_2$
in the 20-30 K region



(PdBI: Sakai et al. 2010)



CCH and C_4H are also enhanced

Chemical Compositions of Low-Mass SFRs

Hot Corino Chemistry

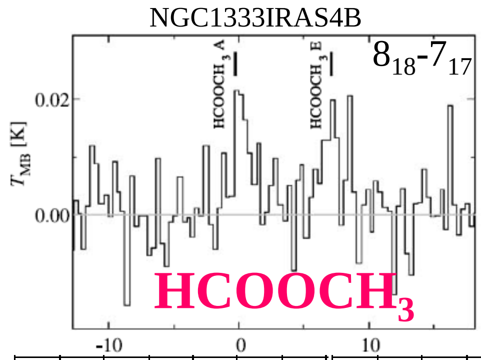
IRAS16293-2422,
NGC1333 IRAS4A/4B, etc.

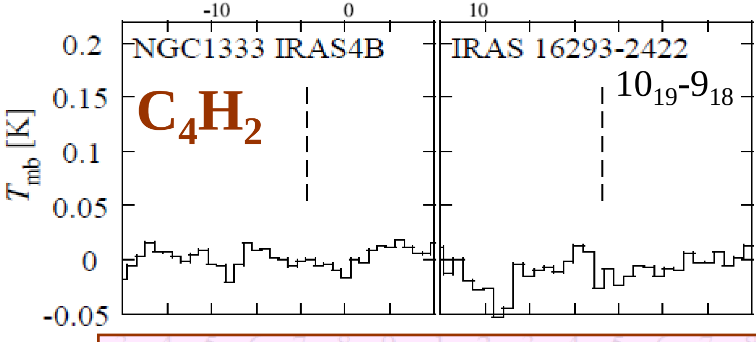
↔

Warm Carbon-Chain Chemistry

L1527, IRAS15398-3359

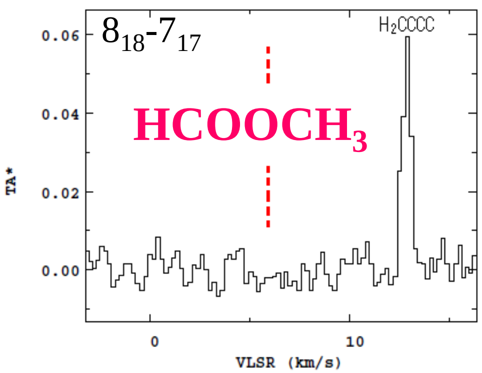
★Complex Organic Molecules

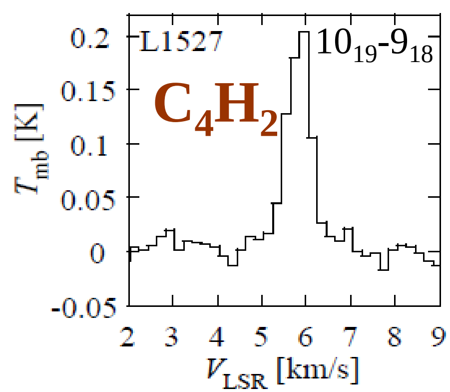




$N < 1.2 \times 10^{11}$ cm^{-2} (3 sigma)
$f < 3.9 \times 10^{-13}$

★Carbon-Chain Molecules





$N = 1.6 \times 10^{12}$ cm^{-2}
$f = 5.3 \times 10^{-11}$

Carbon Chemistry around Low-Mass Protostars

(1) CO evaporation at 20 K

Source of C^+ for production of various molecules

$CO + He^+ \rightarrow C^+ + O + He$

$C^+ + H_2 \rightarrow CH_2^+ + h\nu$ (very slow 10^{-16} cm^3s^{-1})

(2) CH_4 evaporation at 25 K

CH_4 can be a main destructor of C^+, if $f_{(CH4)} > 10^{-7}$

$CH_4 + C^+ \rightarrow C_2H_3^+ + H$ (fast 10^{-9} cm^3s^{-1})

$C_2H_3^+ + e \rightarrow C_2H + H + H \rightarrow$ - - - -

(Carbon-Chain Production)

(3) Ice evaporation at 70-100 K

H_2O becomes the main destructor of C^+.

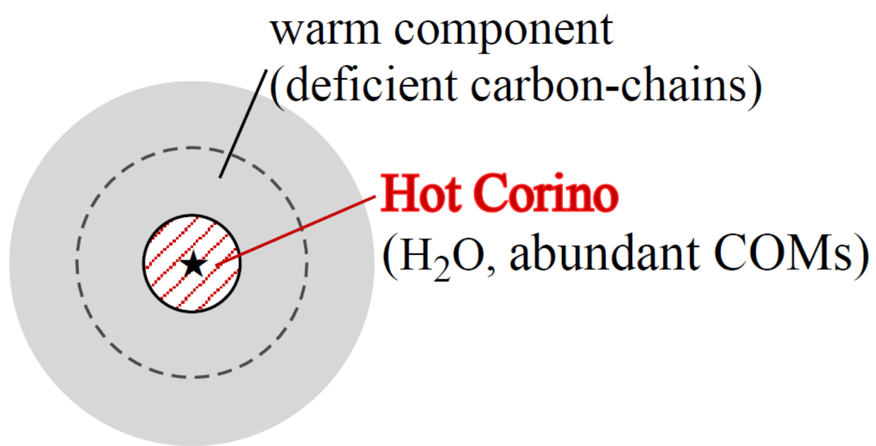
$H_2O + C^+ \rightarrow CO^+ + H + H$

$(HCO^+ + H$, $CH^+ + OH)$

(Evaporation of Saturated Organic Molecules)

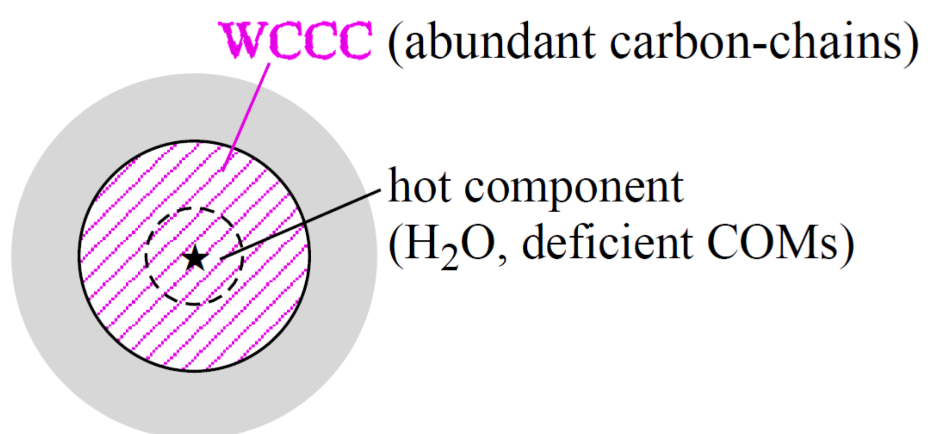
Chemical Structures of Low-Mass SFRs

Class 0 Protostars, IRAS16293, NGC1333IRAS4A/4B, etc.



This is NOT the evolutionary effect !

Class 0 to I Protostars, L1527 and IRAS15398



Different chemical composition!

Carbon Chemistry around Low-Mass Protostars

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(Carbon-Chain Production)

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$H_2O + C^+ \rightarrow CO^+ + H + H$

($HCO^+ + H$, $CH^+ + OH$)

(Evaporation of Saturated Organic Molecules)

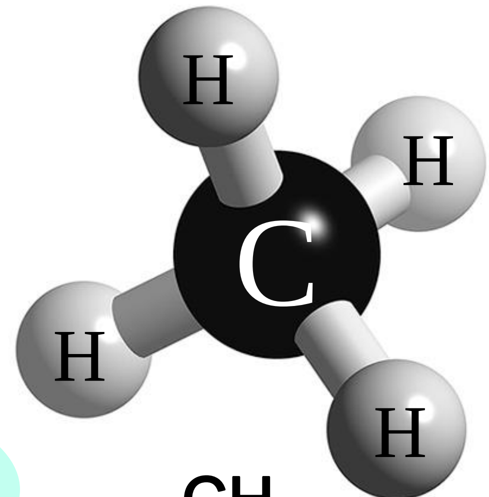
How to Know CH_4 Abundances in the Gas-Phase?

CH_4

cf; Icy grain mantles
→ Infrared absorption of ν_3 & ν_4 bands
(e.g. Oberg et al. 2008)

No permanent dipole moment
→ No ordinary rotational spectral lines

Infrared vibration-rotation spectra of
ν_3 (C-H asym-stretching: 3 μm)
ν_4 (CH_2 asym-bending: 7 μm)
→ Difficult in low-mass SFRs



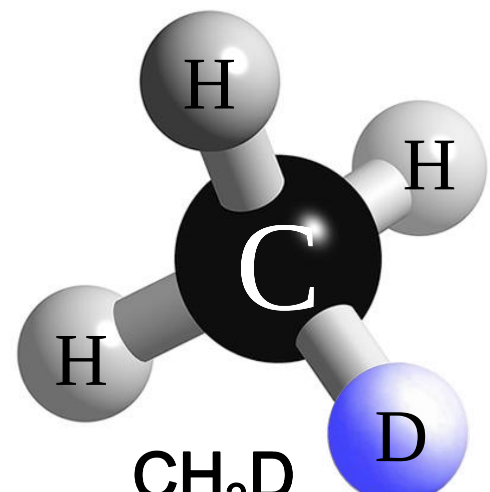
CH_4

CH_3D

μ = 0.005657 D
(Wofcy et al. 1970; Watson et al. 1979)

Millimeter-wave rotational transition line !

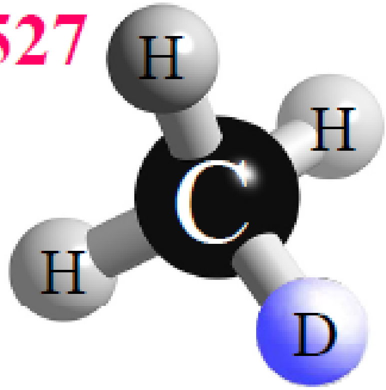
Search for CH_3D toward Orion KL･･･non-detection
(Pickett et al. 1980; Womack et al. 1996)



CH_3D

Tentative Detection of Deuterated Methane

L1527

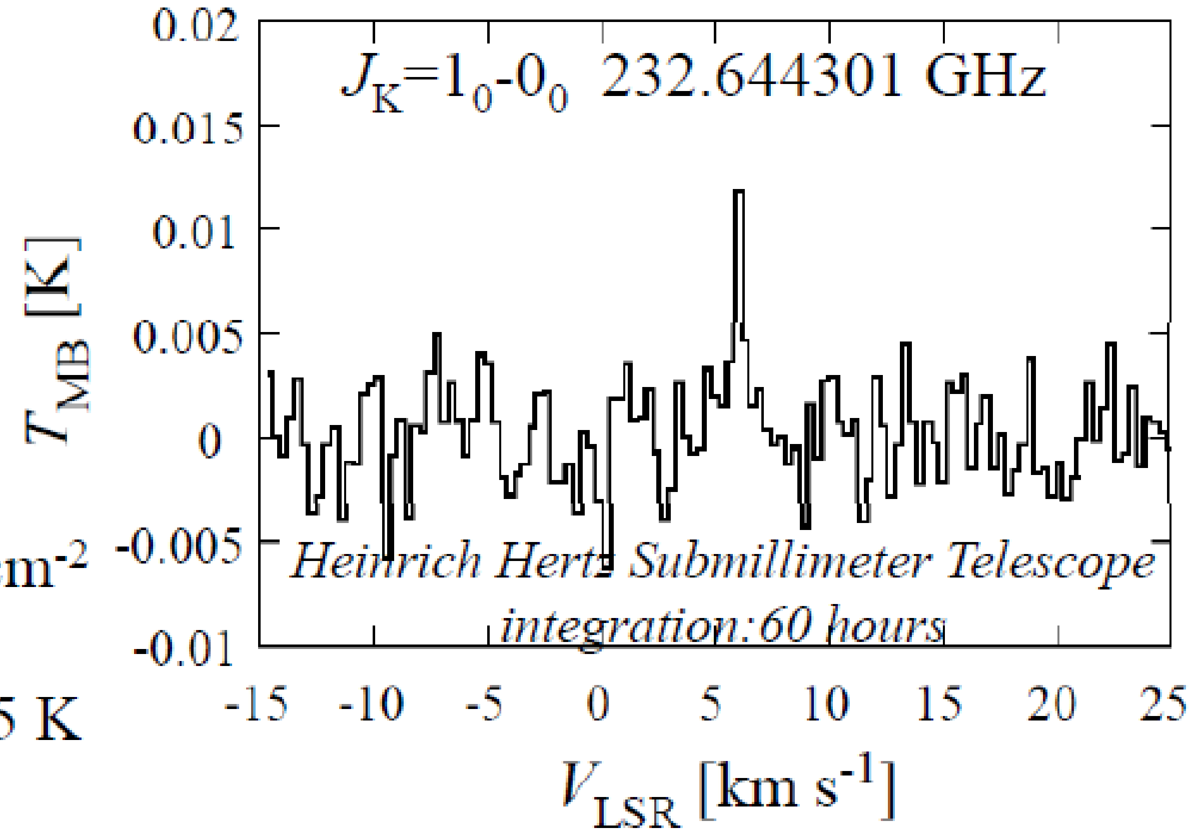


CH_3D abundance

N=(9.1±3.4) × 10^{15} cm^{-2}

f=(3.0±1.1) × 10^{-7}

@25 K



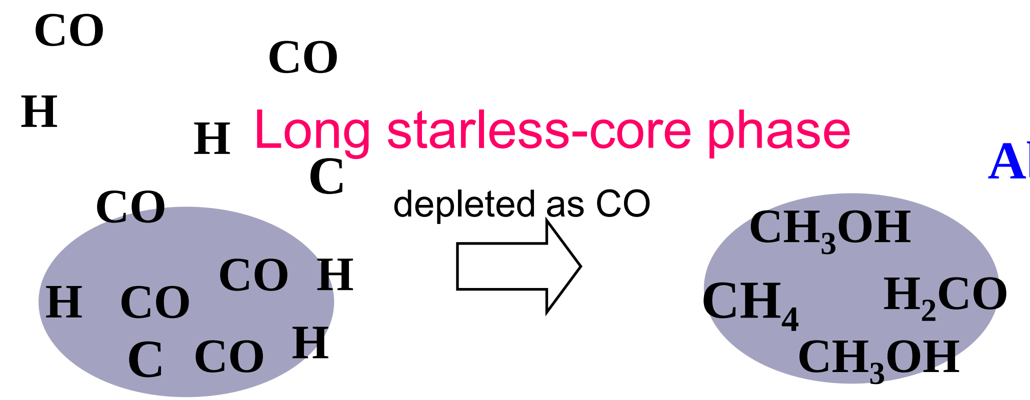
CH_4 abundance

If $[CH_3D]/[CH_4]$ ~ 2-7 % ➡ N = (1.3 - 4.6) x 10^{17} cm^{-2}

f = (4.3 - 15.2) x 10^{-6}

(Sakai et al. 2011, in prep.)

Origin of the Chemical Diversity



Abundant COMs (HCOOCH_3, etc.)

⇨ **Hot Corino**

(IRAS16293,NGC1333
IRAS4A/4B, etc.)

cold starless core phase

star-forming core phase

Abundant Carbon-Chains

⇨ **WCCC**

(L1527 and IRAS15398)

The variation originates from differences in chemical composition of grain mantles

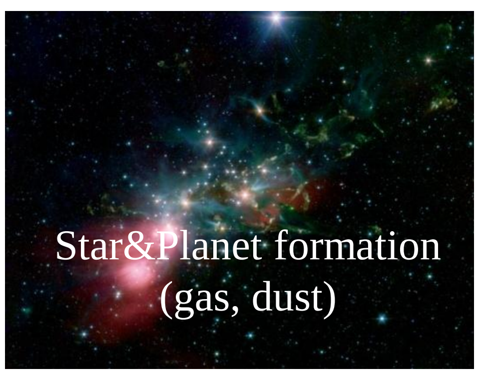
(e.g. Sakai et al. 2008; 2009)

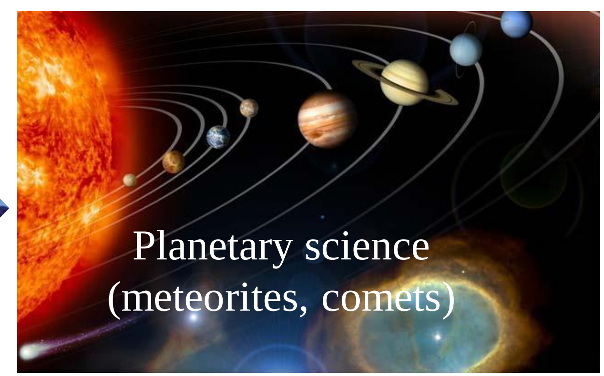
What should we know ?

- Are there Hot Corino activities inside the WCCC sources?
- Are there “intermediate” sources? (See Poster #99 by Watanabe, Y.)

  --How unique is WCCC and Hot Corino chemistry among the low-mass SFRs?

- What is the relation between Hot Corino and protostellar disk?
- How is the chemical variation brought into the protoplanetary disks?





Why do we observe COMs?

- Fundamental species exist everywhere

- COMs represent chemical characteristic clearly
  ← Sensitive observations are needed.

- “Complex molecules” give us fruitful information,
  NOT “complex” information!

Collaborators:
Takeshi Sakai, Tomoya Hirota, Yoshimasa Watanabe,
Yancy Shirley, and Satoshi Yamamoto