Molecular isotopic ratios in the low-mass protostar L1527

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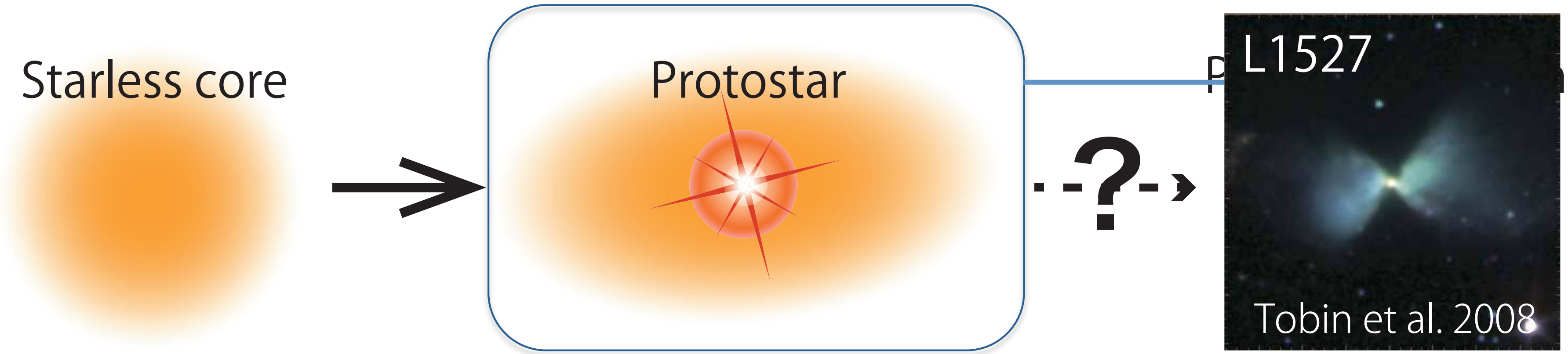
Introduction



Question

How do the isotope ratios evolve along star formation?

→ spatial distribution of molecular isotopic ratios

(1000 au → 100 au scale)

Topics

- ^{13}C species with single-dish telescopes
- Deuterated species with ALMA

Abundance anomaly of ^{13}C species

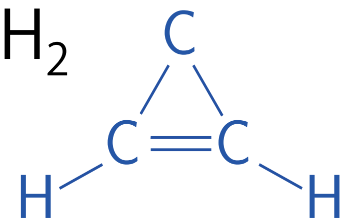
1. **Dilution of ^{13}C species**
   - $[CCS]/[^{13}CCS] = 230 \pm 130\ (3\sigma$; TMC-1) [1]
   - $[CCH]/[^{13}CCH] > 250$ (TMC-1) [2]
   - **$[CCH]/[^{13}CCH] > 135$ (L1527)** [2]

   c.f. $^{12}C/^{13}C$ elemental ratio ~ 60-70 [3,4]

2. **Nonequivalence of ^{13}C species**
   - $[^{13}CCS] : [C^{13}CS] = 1.0 : 4.2$ (TMC-1) [1]
   - $[^{13}CCH] : [C^{13}CH] = 1.0 : 1.6$ (TMC-1) [2]
   - **$[^{13}CCH] : [C^{13}CH] = 1.0 : 1.6$ (L1527)** [2]

[1] Sakai et al. 2007
[2] Sakai et al. 2010
[3] Lucas et al. 1998
[4] Milam et al. 2005

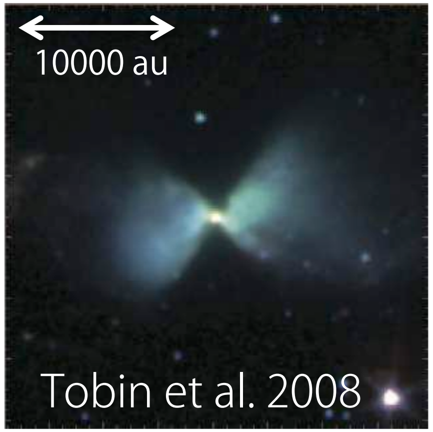
$c\text{-}C_3H_2$



- Closed shell molecule
- Ubiquitously distributed in ISM

→ studied in low-mass protostar L1527

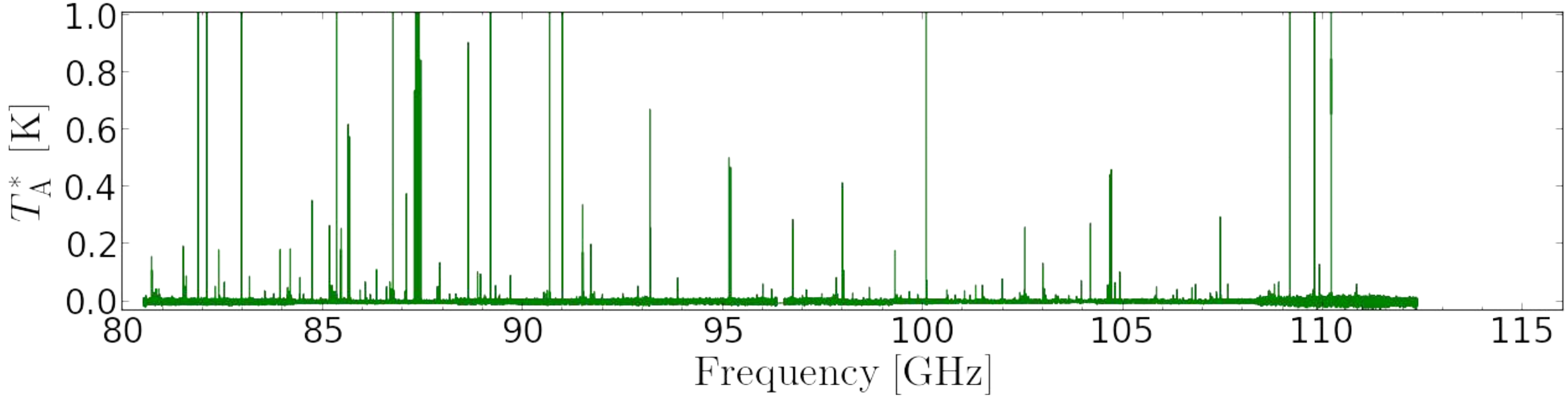
Line surveys toward L1527



- L1527: Class 0 low-mass protostar
  - Rich Carbon-chain molecules

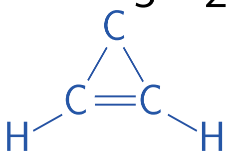
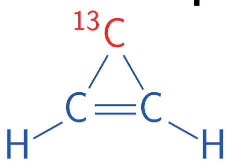
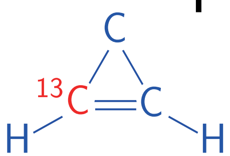
- Line surveys with NRO 45 m & IRAM 30 m (ASAI)
  - NRO 45 m: 3 mm band, IRAM 30 m: 1.3-3 mm bands
    (PI: S. Takano) (PI: B. Lefloch & R. Bachiller)

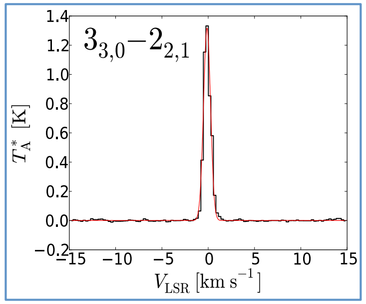
3 mm band in IRAM 30 m

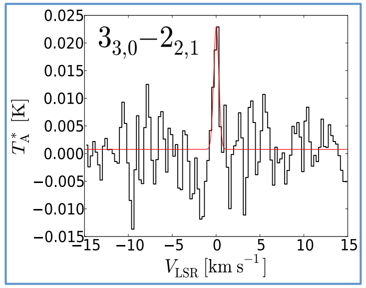


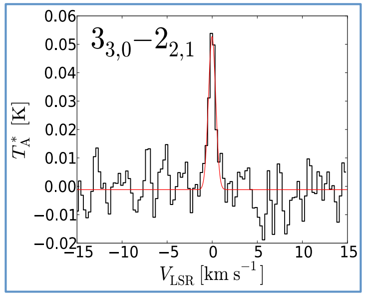
Detection of c-C_3H_2 and its ^{13}C species

Numbers of detected lines

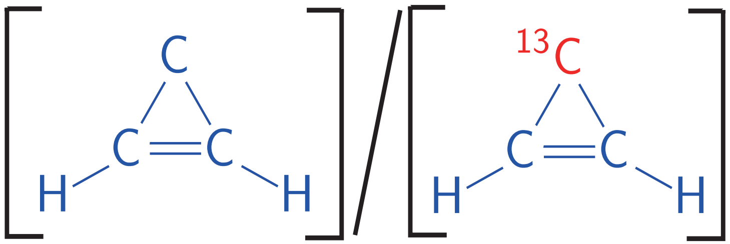
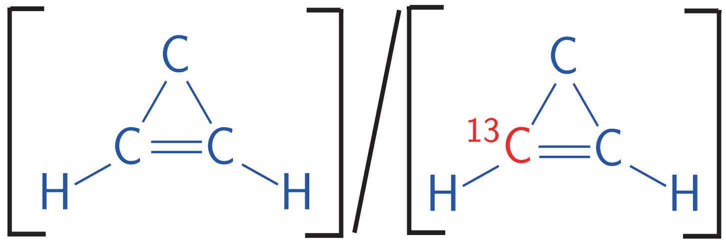
	IRAM 30 m (80-276 GHz)	NRO 45 m (80-116 GHz)
c-C_3H_2 	34 lines	7 lines
on-axis species 	6 lines	3 lines
off-axis species 	13 lines	6 lines



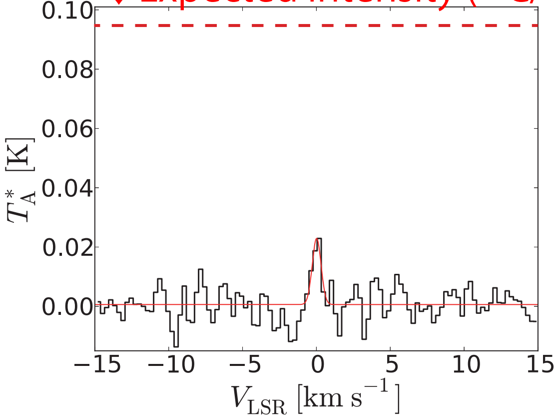




$^{12}C/^{13}C$ ratios of c-C_3H_2 species

	 (on-axis species)	 (off-axis species)
Observed	**310 ± 80**	**61 ± 11**
Expected	**60-70**	**30-35**

↓ Expected intensity ($^{12}C/^{13}C$=60)



on-axis; 3_{30}-2_{21}

T_{rot}: 8.3 K(normal), 8.6 K (off-axis), 7.3 K (on-axis)

→ Dilution of two ^{13}C species

$^{12}C/^{13}C$ ratios of c-C_3H_2 species

- c-C_3H_2 is produced from C^+
  - ^{13}C species are produced from $^{13}C^+$

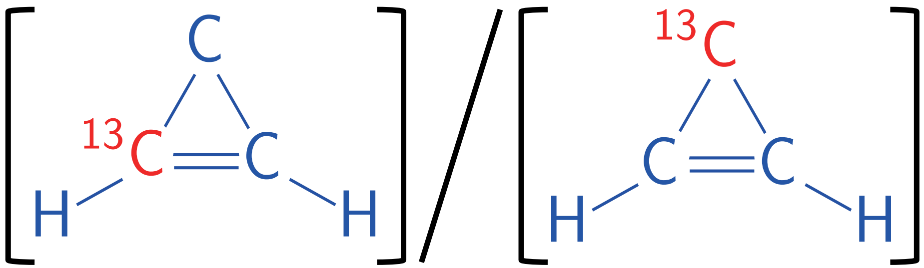
$$^{13}C^+ + {}^{12}CO \underset{\not\longleftarrow}{\longrightarrow} {}^{12}C^+ + {}^{13}CO + 35\ K$$

(Langer et al. 1984)

$$\downarrow$$

$^{13}C^+$ is deficient in molecular clouds

Nonequivalence of ^{13}C species



$= 5.0 \pm 1.3$

(off-axis species) (on-axis species)

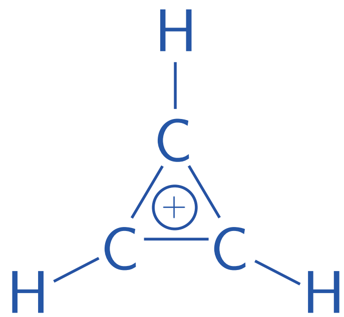
(Expected: 2.0)

→ Two species are nonequivalent.

Implication on the formation pathway

The possible precursor c-$C_3H_3^+$
has three equivalent carbon atoms.

⟶ Other reactions have to be considered:
e.g., $C_2H_2 + CH \rightarrow$ c-$C_3H_2 + H$.



(Yoshida et al. 2015, ApJ, 807, 66)

Summary (1)

- ^{13}C species of c-C_3H_2 (Single dish telescopes)
  - Two anomalies of ^{13}C species are confirmed at ~2000 au scale
    - Dilution of ^{13}C
    - Nonequivalence of ^{13}C species
  - High resolution observation with ALMA is needed.

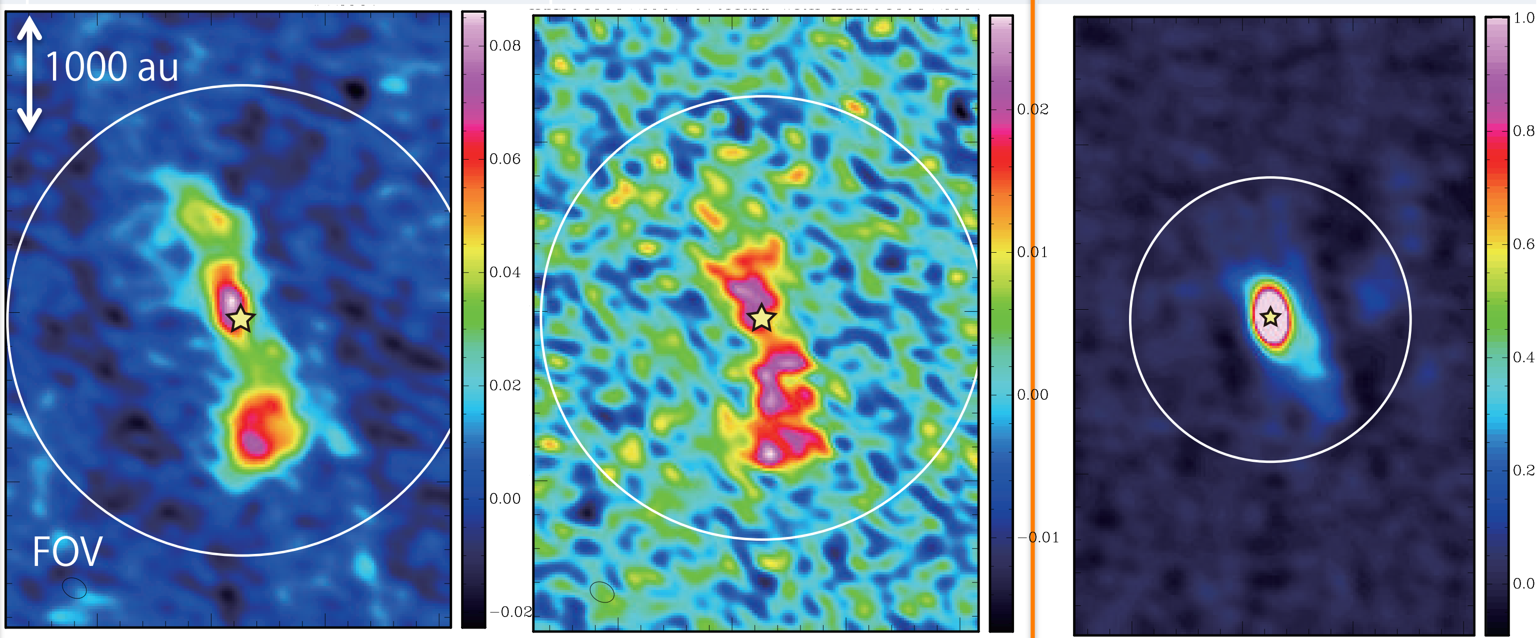
Next Topic: Deuterated species observed with ALMA

- D_2CO/H_2CO and CCD/CCH
- Spatial resolution ~ 200 au

→ How the D/H ratios change from the envelope to the protostar

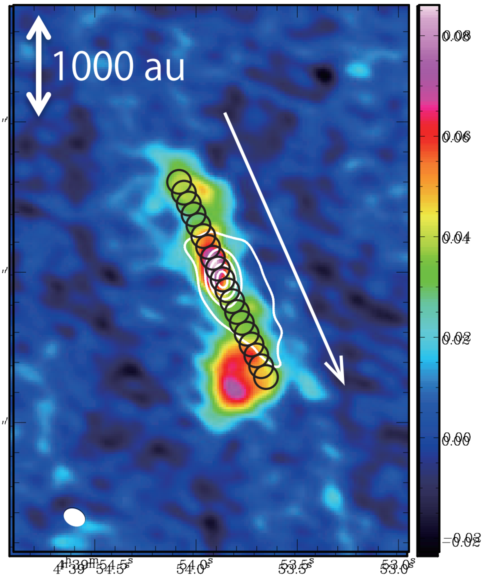
Observation of H_2CO & D_2CO with ALMA

	$D_2CO\ 4_{04}$-3_{03}	$D_2CO\ 4_{23}$-3_{22}	$H_2CO\ 5_{15}$-4_{14}
Eu (cm^{-1})	19.4	34.5	30.4
	Cycle 1 (Archival)	Cycle 2 (PI: N. Sakai)	Cycle 0 (PI: N. Sakai)
Baseline	18-780 m	15-350 m	21-400 m
Ang. res., P.A.	0.58″ × 0.47″, -64°	1.5″×1.1″, 61°	0.69″ × 0.56″, 28°
Largest ang. size	~9″ (1200 au)	~11″ (1500 au)	~5″ (700 au)

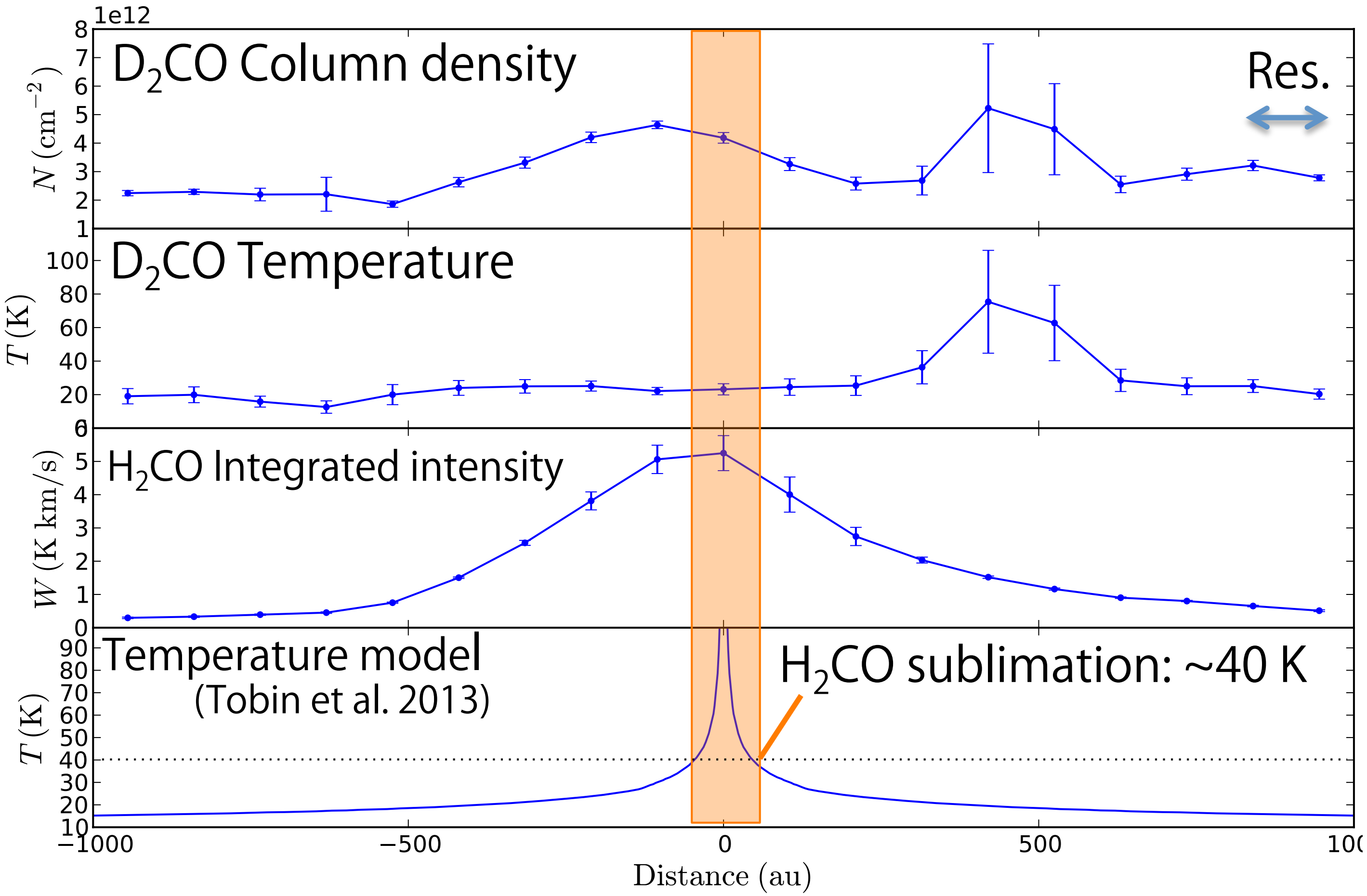


Derive temperature and column density

Column density & temperature of D_2CO



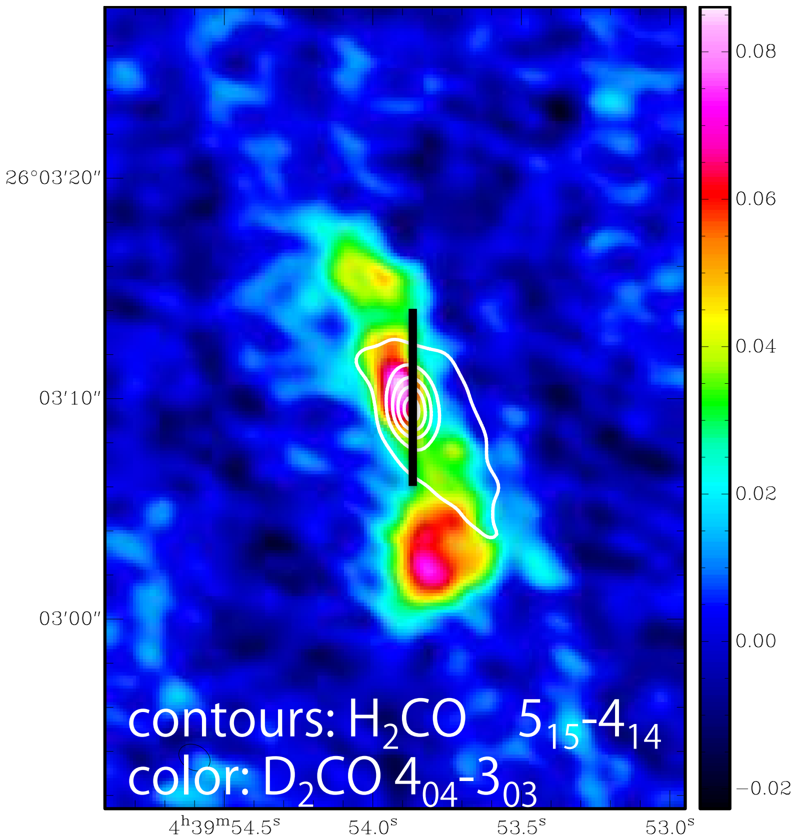
Color: D_2CO 4_{04}-3_{03}
Contours: H_2CO 5_{15}-4_{14}

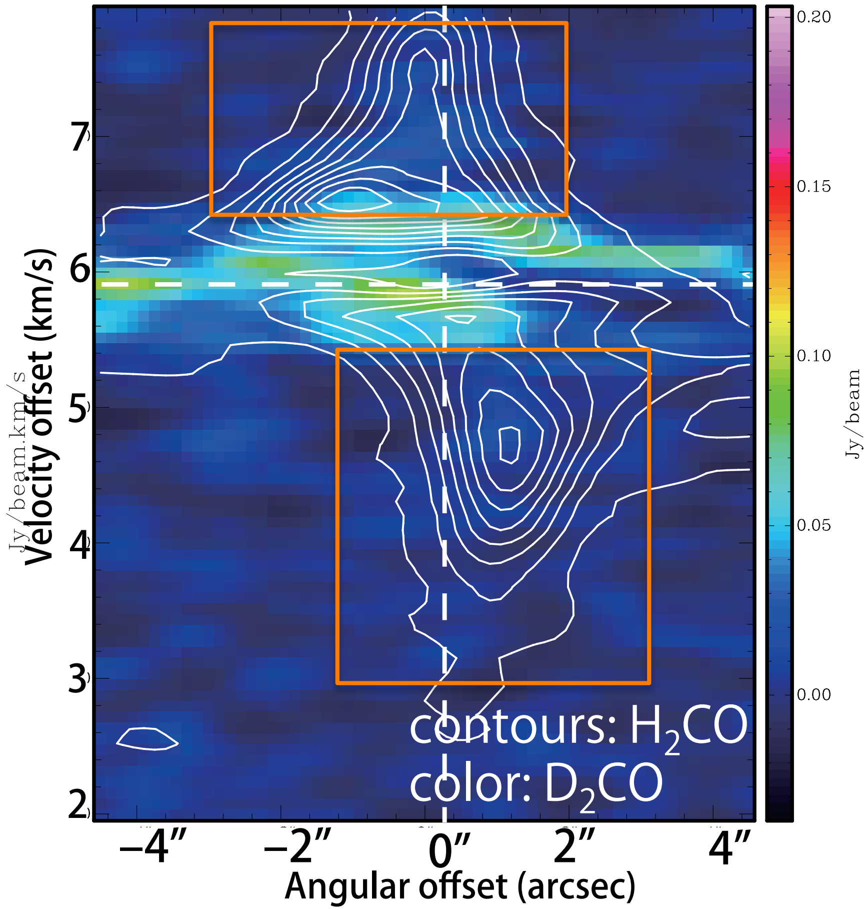


- Protostar position: No enhancement in *N* & *T* of D_2CO

Velocity structure of D_2CO

PV diagrams along the envelope direction

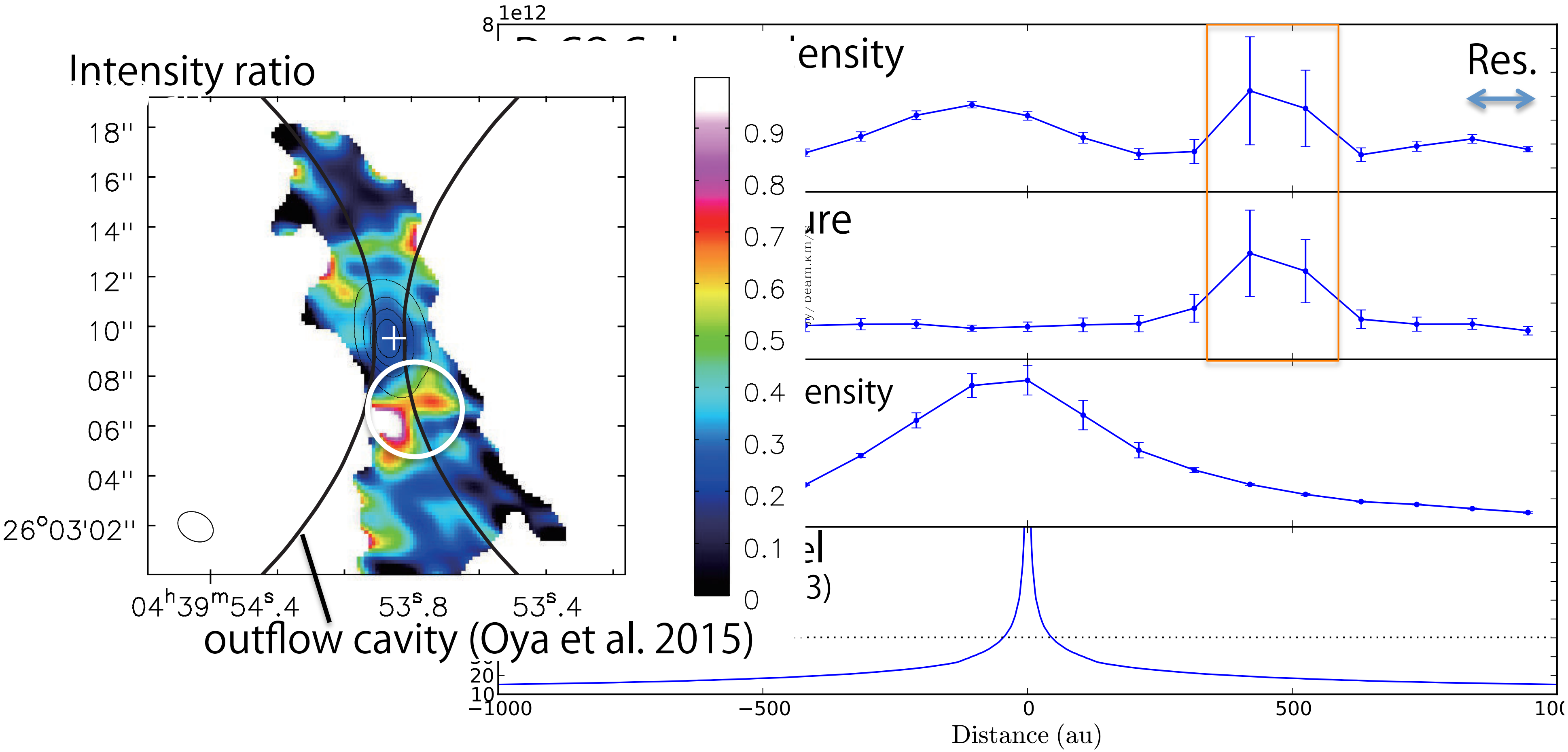




D_2CO: No high velocity component

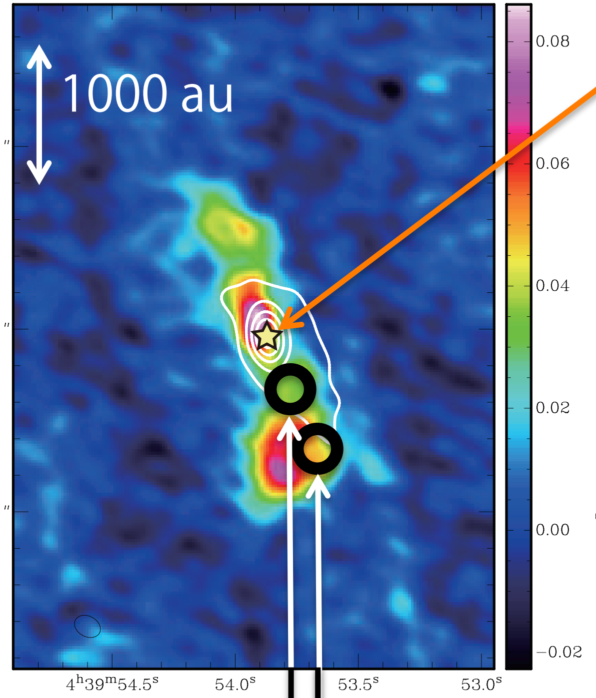
D_2CO is deficient within ~250 au

Column density & temperature of D_2CO



- High temperature at r~500 au from the protostar
  - shock by the outflow?

D_2CO/H_2CO ratio

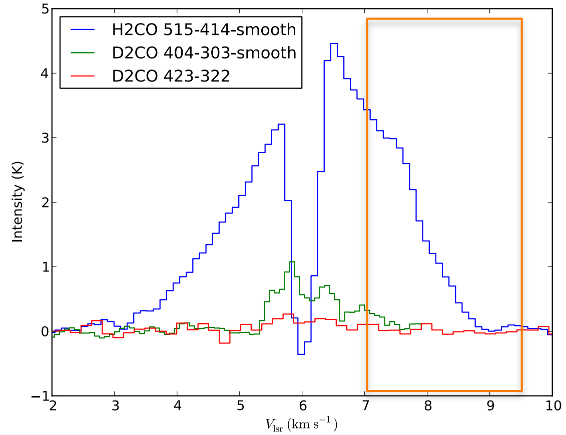


Protostar position

High v component (>7km/s)

D_2CO: rms→upper limit

$D_2CO/H_2CO < 0.05$



Envelope positions

A	$D_2CO/H_2CO = 0.66(4)$
B	$D_2CO/H_2CO = 1.2(5)$

c.f. Model (Aikawa et al. 2012)

$D_2CO/H_2CO \sim 10^{-4}$

→ resolved-out, optically-thick?

c.f. Single dish observations of D_2CO/H_2CO

ASAI observation	0.25(11)	(H_2CO: derived from $H_2C^{18}O$)
Parise et al. (2006)	$0.44^{+0.60}_{-0.29}$	
Roberts & Millar (2007)	0.016(5)	(H_2CO: derived from $H_2{}^{13}CO$)

Summary (2)

- Spatial distributions of H_2CO and D_2CO with ALMA
  - H_2CO: Central Concentration
  - D_2CO: No enhancement toward the protostar position

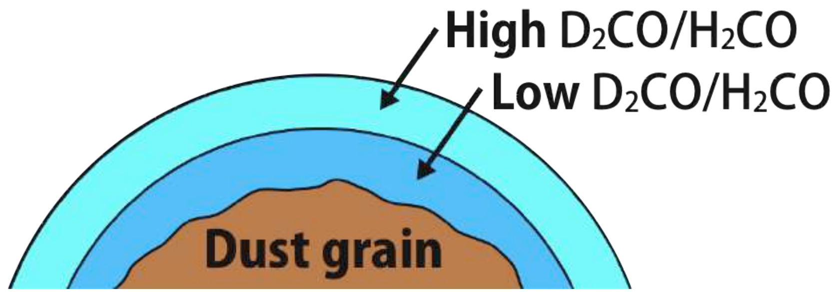
  → D_2CO/H_2CO decreases from the envelope to the center

↓

New supply of H_2CO

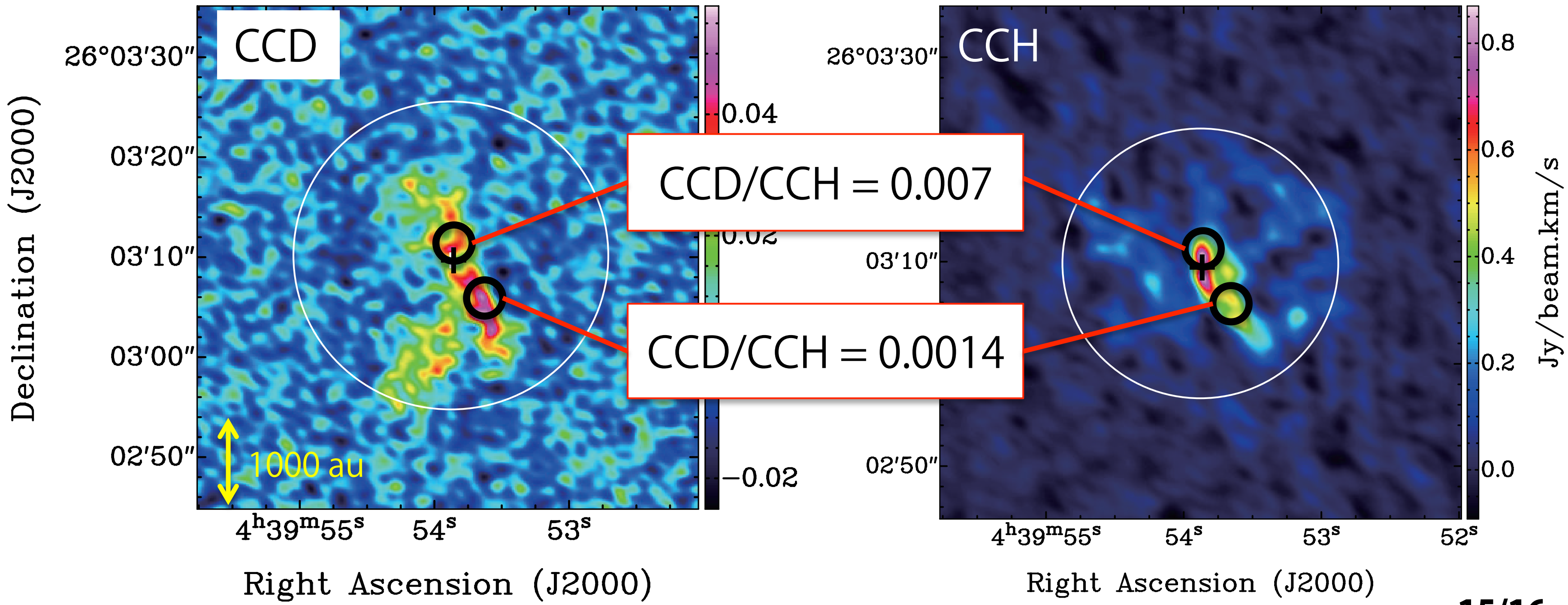
» Gas-phase formation of H_2CO

» Evaporation from layered ices?



Observation of CCH & CCD with ALMA

	CCD *N*=3-2, *J*=5/2-3/2	CCH *N*=3-2, *J*=5/2-3/2
	ALMA Cycle 2 (Band 6)	ALMA Cycle 0 (Band 6)
Baseline	15-350 m	21-400 m
Ang. res.	1.7″ × 1.2″, P.A. = 63°	0.94″×0.60″, P.A. = -41°
Largest ang. size	~11″	~7″



Summary

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  - Two anomalies of ^{13}C species are confirmed at ~2000 au scale
    - Dilution of ^{13}C
    - Nonequivalence of ^{13}C species
  - High resolution observation with ALMA is needed.

- Spatial distributions of deuterated species with ALMA
  - Deuterated species become deficient toward the inner envelope (D_2CO & CCD)
  - D/H ratios become lower at the protostar position
  - Regenaration of the normal species