Abundance Anomaly of the ^{13}C Isotopic Species of Carbon-Chain Radicals in Interstellar Clouds

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Abstract

In radio-astronomical studies, the ^{13}C species lines are usually used for evaluation of the optical depths of the normal species lines in order to derive the column density and the excitation temperature accurately. In this case, the molecular ^{12}C/^{13}C ratio is assumed to be the typical interstellar ratio in local interstellar medium of 60. However, we have recently shown that the molecular ^{12}C/^{13}C ratios are much different from this value, especially in carbon-chain molecules. In one of the famous dark cloud cores, TMC-1, we have found heavy dilution of the ^{13}C species in carbon-chain molecules such as CCH and CCS. From the further observation of various molecules including C_3S and C_4H, we have established that the molecular ^{12}C/^{13}C ratio is higher than the interstellar value of 60 for most species, if they are mainly formed in the gas phase from C^+. Furthermore, we have also found that the ^{12}C/^{13}C ratio is different from position to position of the carbon atom in the same molecule. By making use of such an isotope tracer, production pathways of carbon-chain molecules can be investigated, just as the laboratory experiments. We also examine the possibility of isotope exchange reactions at very low temperature in interstellar clouds.

Dark Cloud & Interstellar Molecule

- Dark clouds are formation sites of solar-type stars
- Low density (10^4-10^6 cm^{-3}) and low T (~10 K)
- More than 160 molecular species are detected
- Carbon-chain molecules are the most characteristic feature in interstellar chemistry. They can survive for a long time in the low-density condition.
  C_2H, C_3H, C_4H, C_5H, C_6H, C_4H^-, C_6H^-,......
  HC_3N, HC_5N, HC_7N, CCS, CCCS....etc.
- Taurus Molecular Cloud 1 (TMC-1) is the most famous cloud harboring carbon-chain molecules

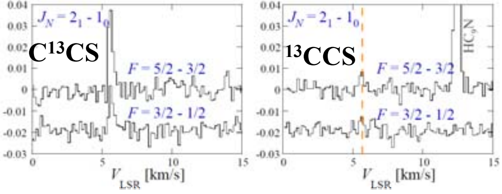
Interstellar [^{12}C]/[^{13}C] ratio ~ 60
(Lucas and Liszt 1998, A&A, 337, 246)

①Abundance Anomaly of the ^{13}C Isotopic Species of Carbon-Chain Radicals

CCS note

[C^{13}CS]/[^{13}CCS] = 4.2±2.3

Different abundances !



[CCS]/[C^{13}CS] = 54±5 (3σ)
[CCS]/[^{13}CCS] = 230±130 (3σ)

Diluted !

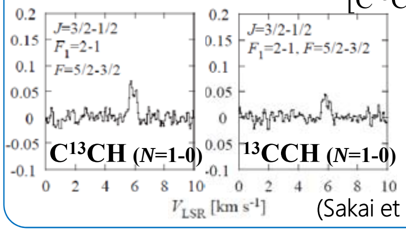
(Sakai et al. 2007, ApJ, 663 1174)

(http://www.gb.nrao.edu)

Note: Since the CCS (J=2-1) and CCCS (J=4-3) lines are optically thick, we observed CC^{34}S and CCC^{34}S, and adopted the interstellar [^{32}S]/[^{34}S] ratio of 19 (Lucas & Liszt 1998, A&A, 337, 246). For C_4H and CCH, we used hyperfine components to derive the abundances

D/H → Fractionated
^{12}C/^{13}C → Diluted ?!

CCH (Observation; 84 GHz, IRAM 30 m)



[C^{13}CH]/[^{13}CCH] = 1.6±0.4

Different abundances!

[CCH]/[C^{13}CH] > 170
[CCH]/[^{13}CCH] > 250

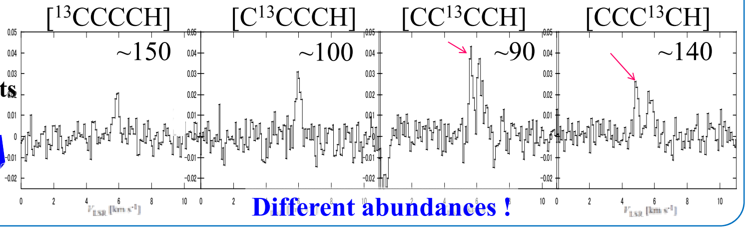
Diluted !

(Sakai et al. 2010, A&A, 512, A31)

CCCCH (Observation; 47GHz, GBT 100 m, 2011)

***N* = 5 -4**
Strongest hyperfine components

[CCCCH]/[^{13}CCCCH]	[CCCCH]/[C^{13}CCCH]	[CCCCH]/[CC^{13}CCH]	[CCCCH]/[CCC^{13}CH]
~150	~100	~90	~140

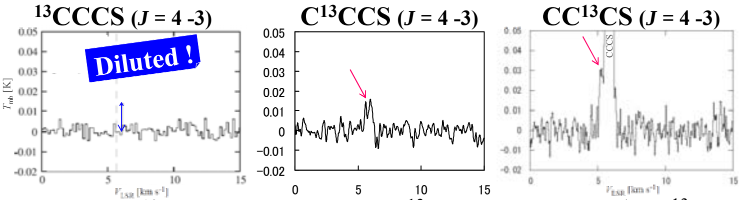


Diluted !

Different abundances !

CCCS note

Different abundances ! (Observation; 23GHz, GBT 100 m, 2010)



[CCCS]/[^{13}CCCS]	[CCCS]/[C^{13}CCS]	[CCCS]/[CC^{13}CS]
> 160	~ 60	~ 70

(Laboratory frequencies of CC^{13}CS are measured with FTMW spectroscopy in collaboration with Endo and Sumiyoshi.)

Molecular ^{12}C/^{13}C ratios in TMC-1

H^{13}CCCN	79±11	...(1)	^{13}CCCS	>160	...(4)
HC^{13}CCN	75±10	...(1)	C^{13}CCS	~ 60	...(6)
HCC^{13}CN	55± 7	...(1)	CC^{13}CS	~ 70	...(6)
HC_5N	79−103	...(2)	^{13}CCCCH	~ 150	...(6)
HC_7N	$87(^{+35}_{-19})$	...(3)	C^{13}CCCH	~ 100	...(6)
^{13}CCS	230±130	...(4)	CC^{13}CCH	~ 90	...(6)
C^{13}CS	54±5	...(4)	CCC^{13}CH	~ 140	...(6)
^{13}CCH	> 250	...(5)	CH_3OH	~ 60	...(6)
C^{13}CH	> 170	...(5)	^{13}CH	> 70	...(6) (non-detection:3σ)

Most of them are higher than 60 ! Diluted !!

- **^{13}C isotopic species are significantly diluted**
- **^{12}C/^{13}C ratios are different from position to position in the same molecule**

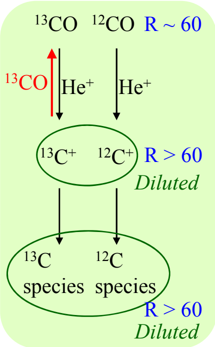
② Origin of the ^{13}C Dilution

- Main reservoir of ^{13}C in dark clouds → ^{13}CO
  Source of ^{13}C$^+$ for production of molecules
  $$^{13}CO + He^+ \rightarrow {}^{13}C^+ + O + He$$
- Main loss process of ^{13}C$^+$
  $$^{13}C^+ + {}^{12}CO \rightarrow {}^{12}C^+ + {}^{13}CO \quad (\Delta E=35\ K)$$

⇨ High ^{12}C/^{13}C ratio in various molecules

c.f. Langer et al. 1984, ApJ, 277, 581

Exceptions: Molecules produced from CO on dust grains (*ex;* CH_3OH)



③ Origin of the Different ^{12}C/^{13}C Ratios in the Same Molecule

CCS

[C^{13}CS]/[^{13}CCS] = 4.2±2.3

Equivalent $S^+ + C_2H_2$ ✕

Non-equivalent *CH + CS → *CCS + H ○ **76%↑**

CCH

[C^{13}CH]/[^{13}CCH] = 1.6±0.4

Equivalent $\left[\begin{array}{l} C_2H_2^+ + e \rightarrow CCH + H \\ C_2H_3^+ + e \rightarrow CCH + H_2 \end{array}\right]$ ○

Non-equivalent CH_2 + *C → *CCH + H ◎

Significant contribution

Powerful tool to trace the production pathways !!

Under two assumptions

Assumption 1: No migration of C atoms

CCS
$$\left[\begin{array}{l} {}^*CH + CS \rightarrow {}^*CCS + H \\ CH + {}^*CS \rightarrow C{}^*CS + H \end{array}\right.$$

CCH
$$\left[\begin{array}{l} CH_2 + {}^*C \rightarrow {}^*CCH + H \\ {}^*CH_2 + C \rightarrow C{}^*CH + H \end{array}\right.$$

?

Assumption 2: No isotope exchange reactions

i) H + *CCH → H*CC + H (ΔE=8 K) ?
1 : 1.6

ii) S + *CCS → S*CC + S (ΔE=17 K) ??
1 : 4.2

iii) H + *CCS → C*CS + H ???

H atom as the simplest catalyst !?

The effect of isotope exchange reactions are examined by Furuya et al. (2011, ApJ, 731, 38) using a gas-grain chemical network model.

References
(1) Takano et al. 1998, A&A, 329, 1156
(2) Takano et al. 1990, ApJ, 361, L15
(3) Langston & Turner 2007, ApJ, 658, 455
(4) Sakai et al. 2007, ApJ, 663, 1174
(5) Sakai et al. 2010, A&A, 512, A31
(6) Sakai et al. in prep.