Production Pathways of Carbon-Chain Molecules Inferred from their ^{13}C Isotopic Species

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

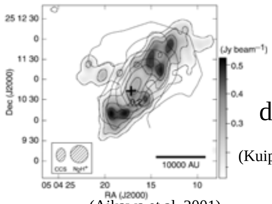
Abstract

We have observed the rotational spectral lines of ^{13}CCS and C^{13}CS with GBT in TMC-1 and L1521E, and have found that the abundances of these two isotopic species are significantly different from each other. This indicates that the two carbon atoms are nonequivalent in the main production pathway. This result gives a strong constraint on the production mechanism of CCS, and finally the CH + CS reaction is recognized as the most probable route. Furthermore ^{13}CCS is found to be diluted in comparison with the interstellar ^{13}C abundance. This is very novel, because the heavy isotope generally tends to fractionate into molecules due to the lower zero-point vibrational energies. If CCS is mainly produced by the CH + CS reaction, the dilution of ^{13}CCS originates from the dilution of ^{13}CH, which would be possible by the isotope selective photodissociation of CH. In our observation with GBT, we have also found that ^{13}CCCS is diluted, whereas C^{13}CCS and CC^{13}CS are not. Furthermore, we have found in the IRAM 30m observation that the abundances of ^{13}CCH and C^{13}CH are also different. The ^{13}C abundance variation thus seems common for carbon-chain molecules, which would tell us their formation pathways as in the case of CCS.

CCS

A good tracer for exploring the early evolutionary stage of starless cores

⇔ NH_3, N_2H^+; Tracers of the late stage



(Aikawa et al. 2001)

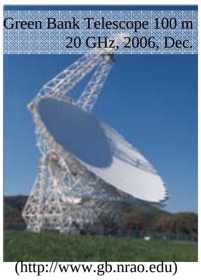
ex. **L1544**

Doughnut-like distribution of CCS

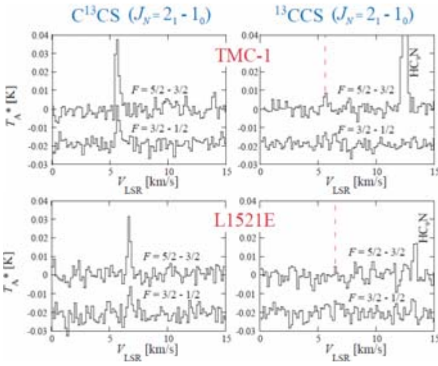
(Kuiper et al. 1996, Ohashi et al. 1999)

①Abundance Anomaly of the ^{13}C Isotopic Species of CCS

Observation



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



TMC-1

[CCS]/[C^{13}CS] = 54±5 (3σ)^{note}

[CCS]/[^{13}CCS] = 230±130 (3σ)^{note}

Interstellar [^{12}C]/[^{13}C] ratio ~ 60

(Lucas and Liszt 1998)

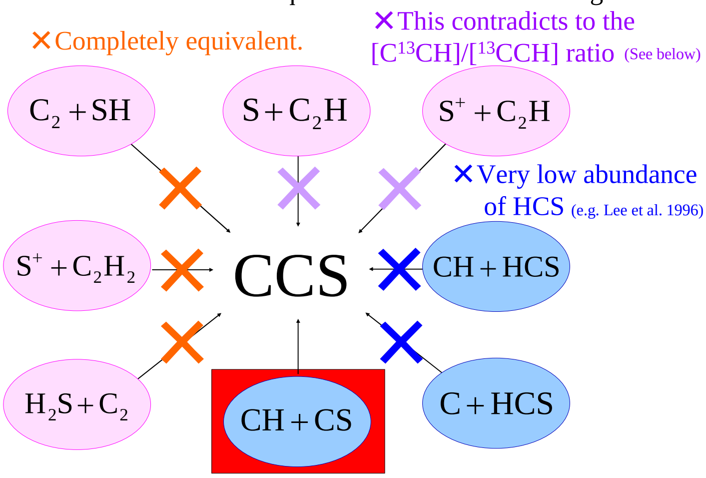
[C^{13}CS]/[^{13}CCS] = 4.2±2.3

◆The two carbon atoms in CCS are nonequivalent in the main production pathway.

◆**^{13}CCS is significantly *diluted* !!**

②Production Pathways of CCS (Millar and Herbst 1990, Petrie 1996, Yamada et al. 2002)

Contribution of nonequivalent routes has to be larger than 76% !



Most probable route; ΔE=59 kJ/mol

Dilution of ^{13}CCS ⇨ Dilution of ^{13}CH

[^{12}CH]/[^{13}CH] > 230±130

Heavy isotope generally tends to fractionate into molecules in cold dark clouds due to the lower zero-point vibrational energies.

e.g. $^{13}C^+ + CO \rightleftarrows C^+ + {}^{13}CO + \Delta E$

③CH as a Culprit of the ^{13}CCS Dilution

★ Abundant

N(CH) = 2 × 10^{14} cm^{-2} (@TMC-1, Irvine et al. 1987)

★ Low dissociation energy

D_e = 3.47 eV *cf* ; CS D_e = 7.36 eV (Huber and Herzberg 1979)

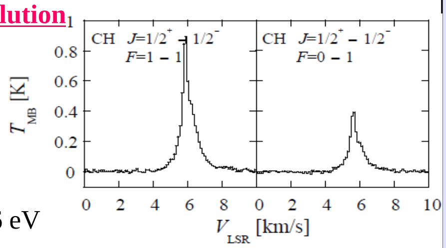
★ Predissociation is observed for CH

$C^2\Sigma^+$ (4 eV) and higher states (Herzberg and Johns 1969)

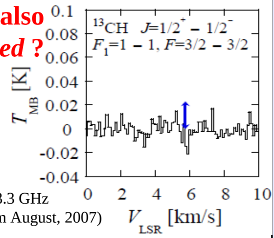
Isotope Selective Photodissociation of CH ?

cf ; CO (van Dishoeck and Blake 1998)

self-shielding, mutual-shielding



◆**^{13}CH is also *diluted* ?**



(Observation; 3.3 GHz @MPIfR 100 m August, 2007)

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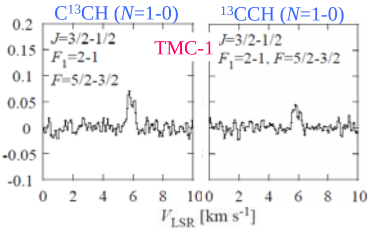
CCH

④Abundance Anomaly for CCH



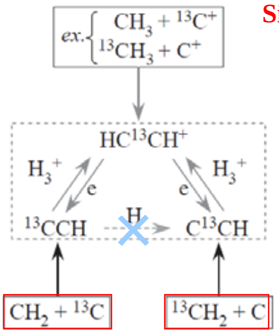
[C^{13}CH]/[^{13}CCH] = 1.6±0.4

Abundances of two species are different.

(@IRAM 30 m July, 2007)

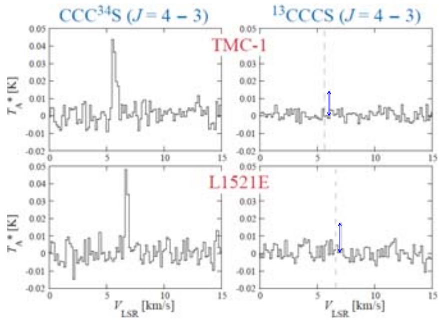
Significant contribution of

C + CH$_2$ → CCH + H



If ^{13}C were completely absent in the atomic form, only C^{13}CH is formed. Even in this ultimate case, the contribution of the above reaction is still 38 %.

CCCS



(The arrows represent the line intensity expected from the normal interstellar [^{12}C][^{34}S]/[^{13}C][^{32}S] ratio of 3.)

TMC-1

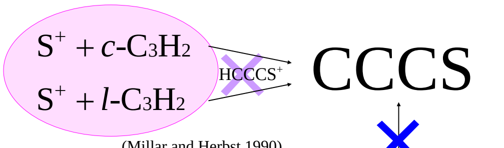
[CCC^{34}S]/[^{13}CCCS] > 8.4 (3σ)

[CCCS]/[^{13}CCCS] > 160^{note}

^{13}CCCS is also *diluted* !

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 and Liszt 1998)

⑤Abundance Anomaly for CCCS



(Millar and Herbst 1990)

× ^{13}C species of c-C_3H_2 is not diluted in TMC-1 (Kaifu et al. 2004)

(Yamada, Osamura & Kaiser 2002)

A possible route is, for example,

CH + CCS → CCCS + H + 369 kJ/mol.

But it is still puzzle......

Recently we detected C^{13}CCS and CC^{13}CS lines (@GBT, March, 2008)