A Yebes W band line survey towards Supernova remnant 3C391: Evidence of CR-induced chemistry

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Chemistry induced by cosmic rays

- **Chemical effects of cosmic rays (CRs)**

CR ionization

CR heating of gas

CR induced UV radiation

CR-induced grain global heating

CR sputtering

…

- **Observations and simulations**

High HCO^+/CO abundance ratio in SNR W49B (Zhou et al. 2022)

CO→C→C^+ transition with high CR ionization rate (Bisbas et al. 2017)

CR ionization rate is an important input parameter in chemical simulations.

SNRs as CR accelerators

Supernova remnants (SNRs) are believed to be the accelerators of Galactic CRs.

Hadronic γ-ray (high-energy CR protons):

$$p + p \rightarrow \pi^0 + X$$

$$\pi^0 \rightarrow 2\gamma$$

is detected in many SNRs.

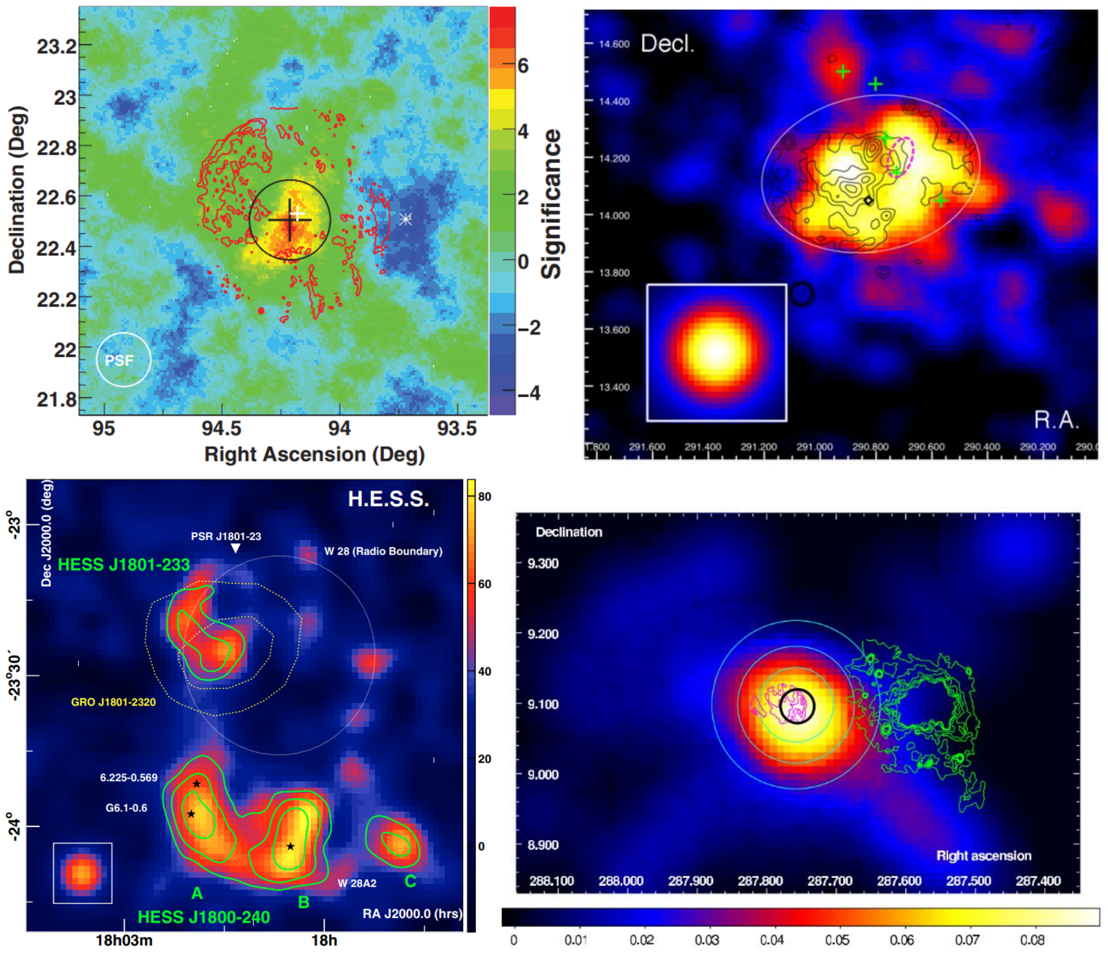
Enhanced CR ionization rate ($\zeta \sim 10^{-15}\ s^{-1}$):

IC443, W51C, W28, W49B, W44

- middle-aged/old SNRs with γ-ray detection and interacting with molecular clouds.

More samples?

Detailed CR chemistry?



γ-ray emission

IC443 (Acciari et al. 2009) W51C (Abdo et al. 2009)

W28 (Aharonian et al. 2008) W49B (Abdo et al. 2010)

SNR 3C391

- **Age**: ~4000-9000 yr

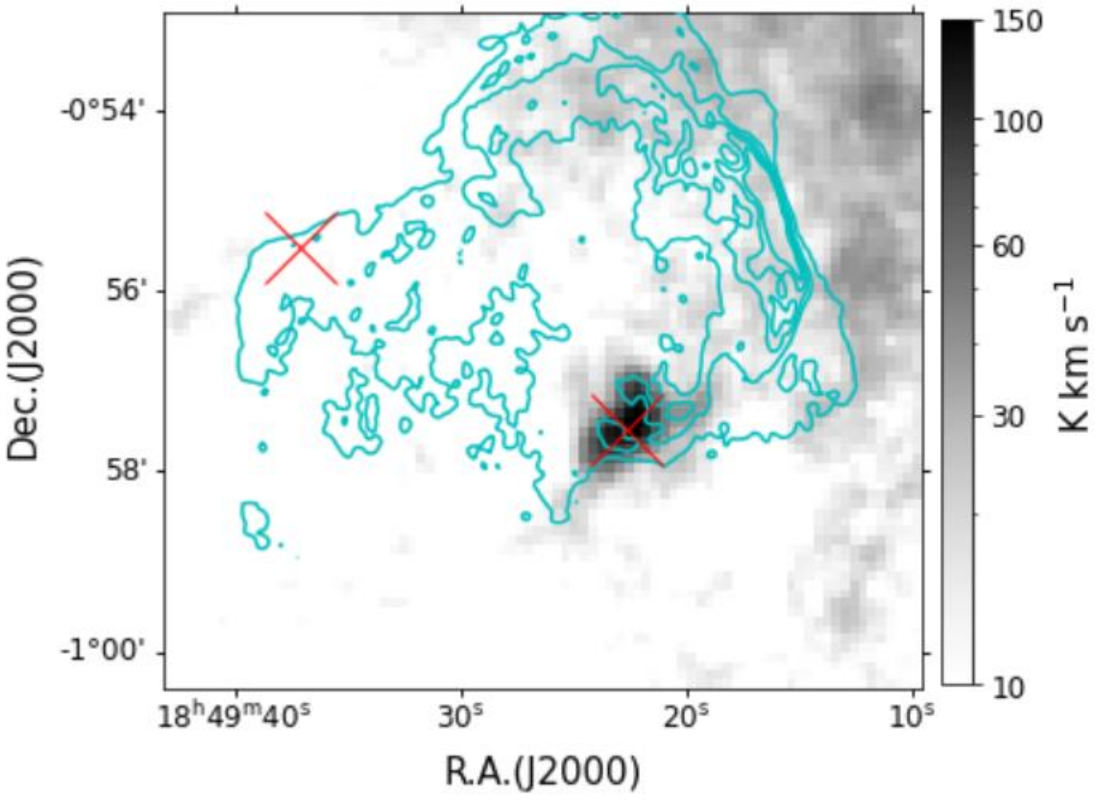
- **A typical SNR interacting with molecular cloud:**

OH 1720 MHz masers (Frail et al. 1996)
Broad molecular lines (Reach & Rho 1999)
etc.

- **Evidence of CRs:**

Fermi γ-ray detection (Ergin et al. 2014)

A possible good case to study CR chemistry:
well-defined unshocked gas – free from SNR shock disruption



Integrated intensity of ^{12}CO 3-2
Cyan contours: VLA 1.4GHz continuum
Red crosses: OH 1720MHz masers

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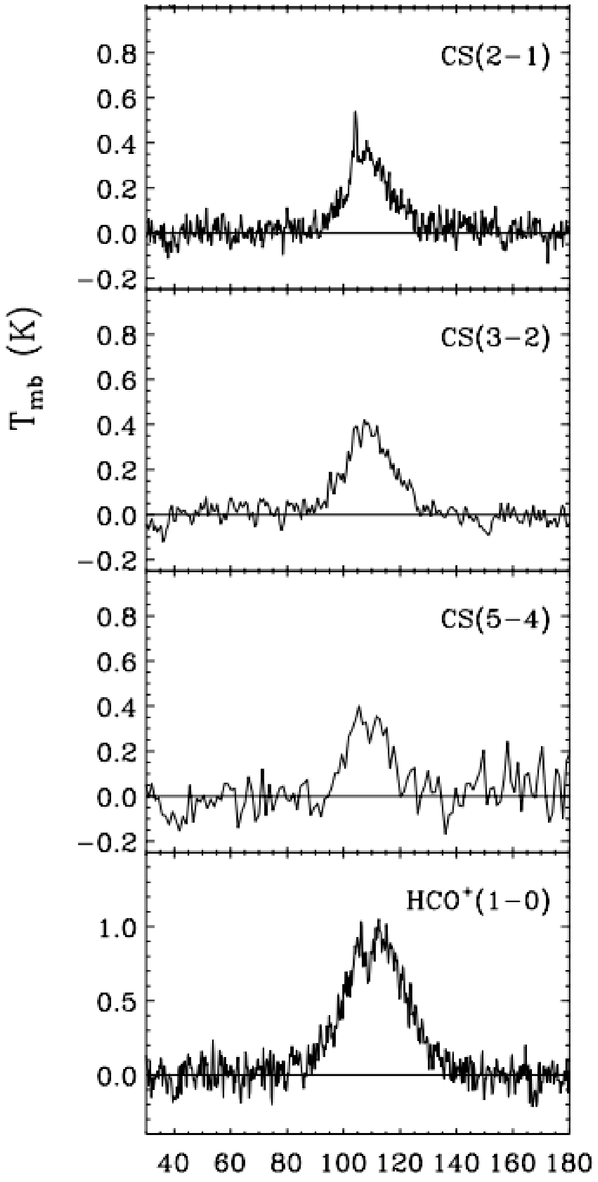

Reach & Rho 1999

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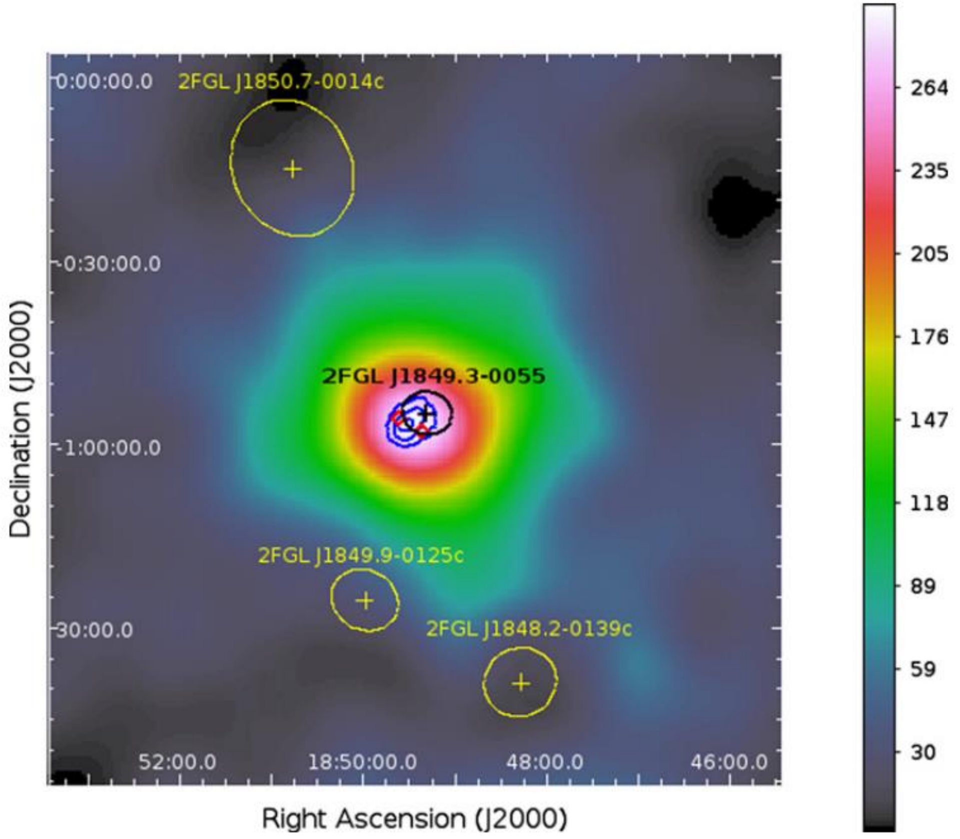

Ergin et al. 2014

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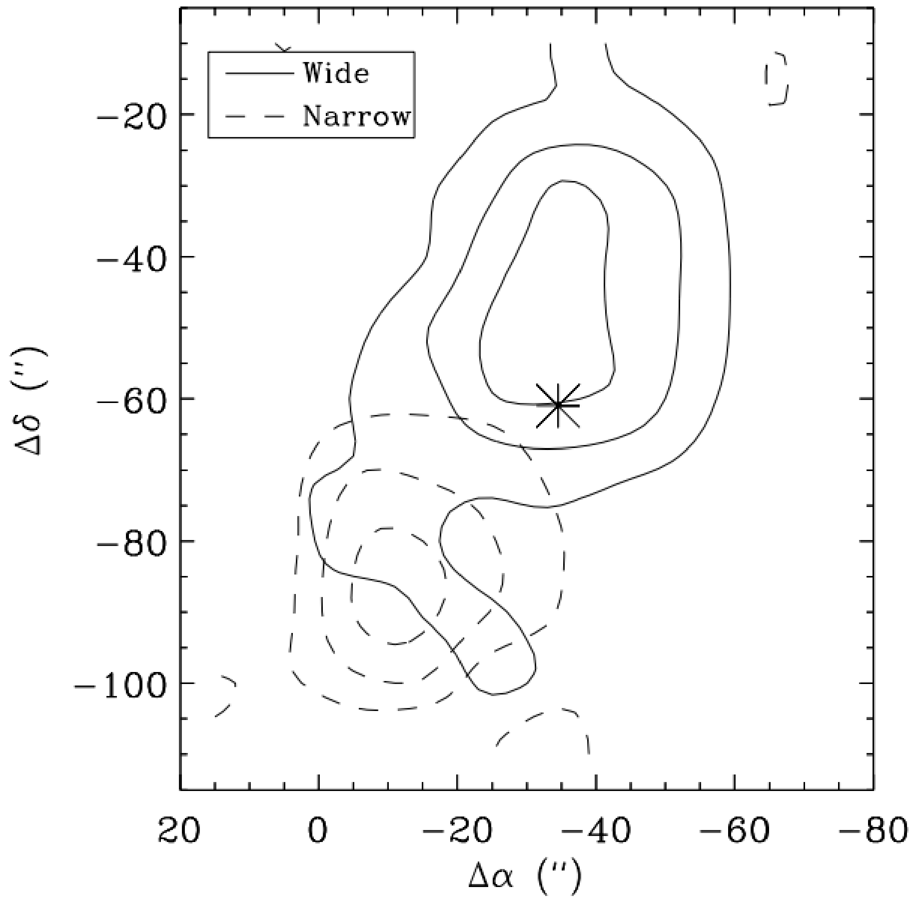


CS 2-1 (Reach & Rho 1999)

Observations

- **New observation:**

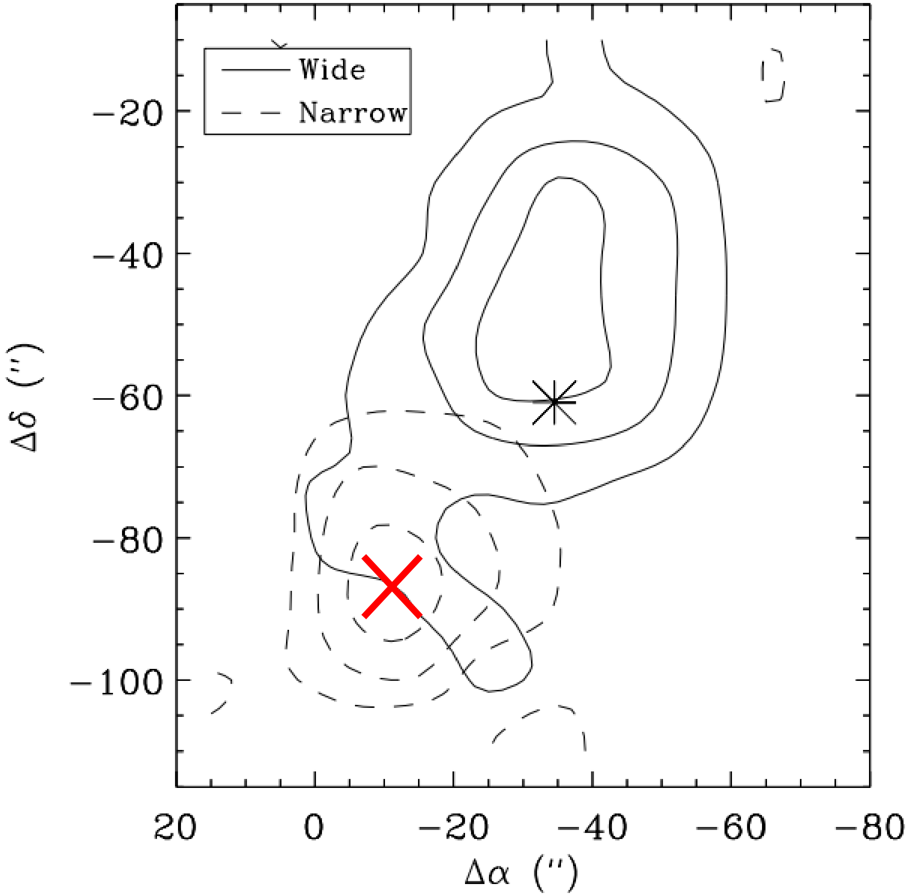
Yebes W band line survey at 71.5-90 GHz

RMS ~ 12-15 mK @ 0.2 km/s

- **Archival data:**

Nobeyama FOREST ^{12}CO ^{13}CO 1-0

JCMT COHRS ^{12}CO 3-2



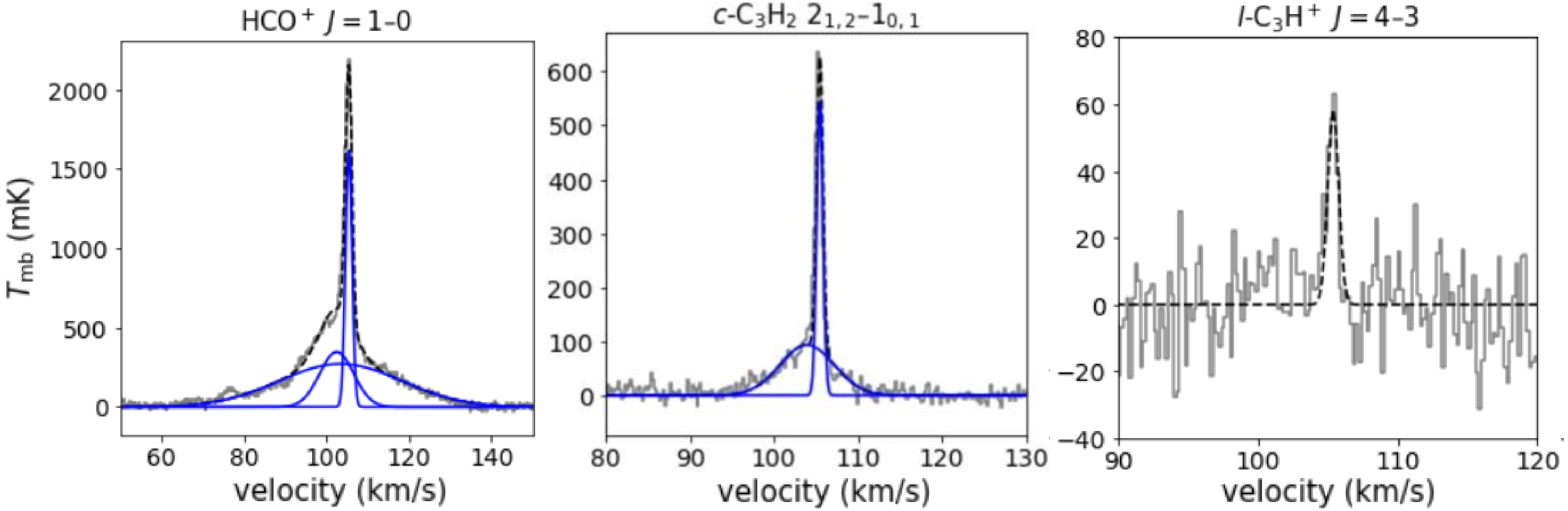
Contours of wide and narrow components of CS 2-1 line
Reach & Rho 1999

Results

18 molecules and 24 transitions (without HFS)

HCO^+-like	HCO^+, $H^{13}CO^+$, $HC^{18}O^+$, **HOC^+**, **HCS^+**
HCO-like	**HCO**, H_2CO
HCN-like	HCN, $H^{13}CN$, $HN^{13}C$
Carbon chain	C_2H, **C_4H**, **CCS**, HC_3N, **c-C_3H_2**, **l-C_3H^+**
Others	**CH_3CN**, **CH_2CO (H_2CCO)**

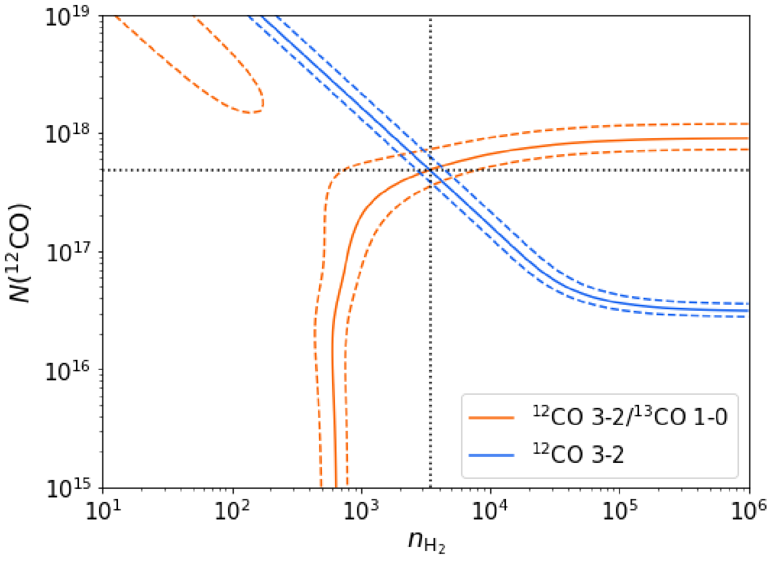
3 components:
~ 1 km/s
~ 6-10 km/s
~ 35 km/s

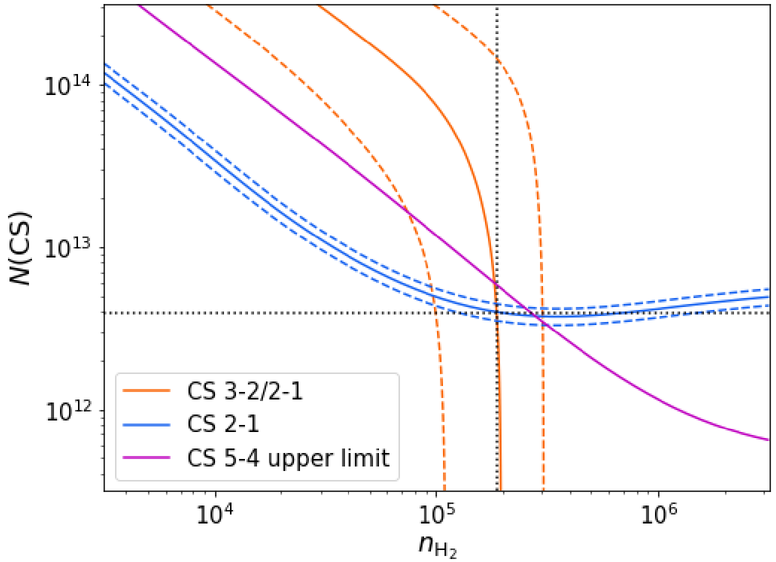


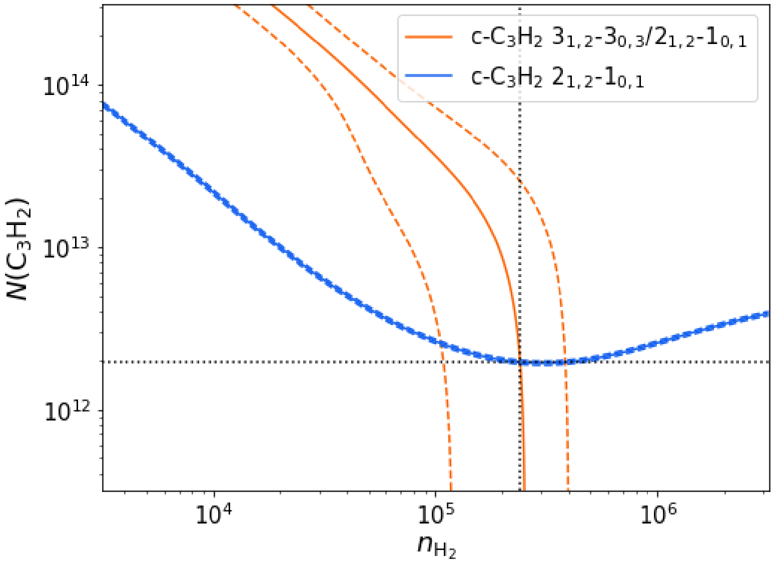
Molecular column densities – non-LTE

- **RADEX LVG estimation**

Assuming T_{kin} = 20K (Reach & Rho 1999, T_{ex} of ^{12}CO, and $I(H^{13}CN)/I(HN^{13}C)$ ratio)







Assuming $^{12}C/^{13}C$=45

$N(^{12}CO) \approx 4.9\times10^{17}$ cm^{-2}

$n_{H2} \approx 3.5\times10^{3}$ cm^{-3}

$N(CS) \approx 3.9\times10^{12}$ cm^{-2}

$n_{H2} \approx 1.9\times10^{5}$ cm^{-3}

$N(o\text{-}c\text{-}C_3H_2) \approx 2.0\times10^{12}$ cm^{-2}

$n_{H2} \approx 2.4\times10^{5}$ cm^{-3}

Molecular abundances (ratios)

Assuming ① T_{ex}= 5K or 10K, ② optically thin, ③ $^{12}C/^{13}C$=45, and ④ $N(H_2) = 7\times10^5 N(^{13}CO)$

Results:

$X(C_2H) \approx (2.4\text{-}3.0)\times10^{-8}$

$X(C_3H^+) \approx (2.2\text{-}6.2)\times10^{-11}$

$X(HCO+)/X(CO) \approx (5.2\text{-}5.7)\times10^{-5}$

$X(DCO^+)/X(HCO^+) \lesssim (2.8\text{-}2.9)\times10^{-3}$

$X(HCO^+)/X(HOC^+) \approx$ 130-140

$X(HCS^+)/X(CS) \approx$ 0.14-0.18

CR ionization rate

Vaupre et al. 2014:

$$x_{\mathrm{e}} = \left(\frac{k_{\mathrm{f}} x(\mathrm{HD})}{3R_{\mathrm{D}}} - \delta\right)\frac{1}{k_{\mathrm{e}}}$$

$$\frac{\zeta}{n_{\mathrm{H}}} = \frac{\beta'}{k_{\mathrm{H}}}(2\beta x_{\mathrm{e}} + \delta) R_{\mathrm{H}} x_{\mathrm{e}}$$

R_D = X(DCO^+)/X(HCO^+)

R_H = X(HCO^+)/X(CO)

Assuming x(HD) = 1.5×10^{-5}

Then $\zeta \gtrsim (2.9\text{-}4.1)\times10^{-14}$ s^{-1}

~ 10^3 higher than the typical value

~ 10 times higher than W51C and W28

$$\zeta_{\mathrm{gal}}^{\mathrm{H_2}} = 2 \times 10^{-16}\ \mathrm{s}^{-1}$$

Object	E_{lb}	$\zeta_{\mathrm{gal}}^{\mathrm{H_2}}(a = 2.0)$	$\zeta_{\mathrm{gal}}^{\mathrm{H_2}}(a = 1.0)$
W28	1 GeV	0.249	0.350
	100 MeV	7.56	9.87
	30 MeV	24.5	24.9
W51C	1 GeV	0.0259	0.0353
	100 MeV	0.615	0.800
	30 MeV	2.95	3.46
3C391	1 GeV	9.28	16.4
	100 MeV	91.4	121
	30 MeV	567	663

Schuppan et al. 2012

a and E_{lb} are parameters about the spectrum of CR protons

Compare with typical abundances (ratios)

- $X(C_2H) \approx (2.4\text{-}3.0)\times10^{-8}$

~ $\mathbf{10^{-10}}$ **–** $\mathbf{10^{-8}}$ in dark clouds (Wootten et al. 1980), ~ $\mathbf{10^{-8}}$ in diffuse clouds (Lucas & Liszt 2000)

$$CH_2 \xrightarrow{C^+} C_2H^+ \xrightarrow{H_2} C_2H_2^+ \xrightarrow{e^-} C_2H$$

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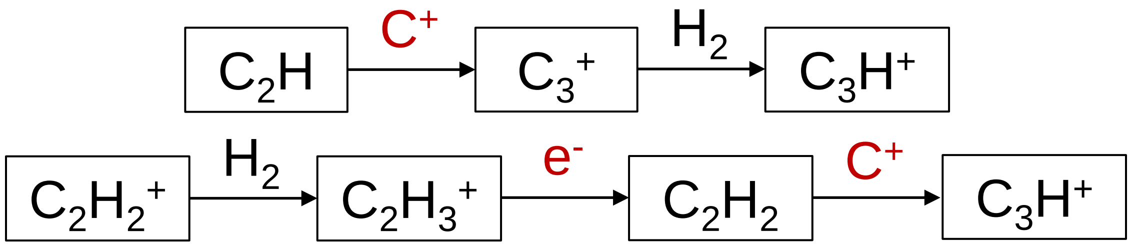
- **$X(C_3H^+) \approx (2.2\text{-}6.2)\times10^{-11}$**

~ $\mathbf{10^{-11}}$ in Horsehead PDR (Guzmán et al. 2015), ≈ $\mathbf{2.4\times10^{-12}}$ in TMC-1 (Cernicharo et al. 2022)



Compare with typical abundances (ratios)

- X(C_2H) ≈ (2.4-3.0)×10^{-8}

~ **10^{-10} – 10^{-8}** in dark clouds (Wootten et al. 1980), ~ **10^{-8}** in diffuse clouds (Lucas & Liszt 2000)

- **X(C_3H^+) ≈ (2.2-6.2)×10^{-11}**

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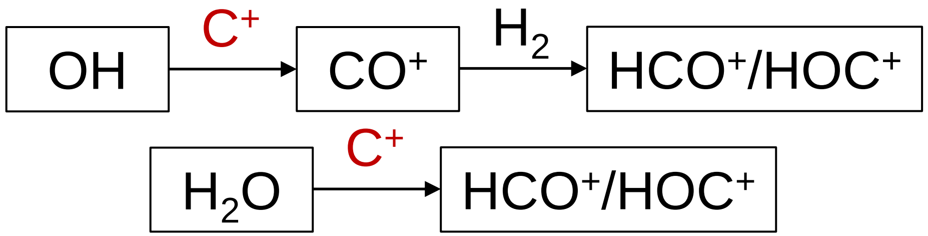
- **X(HCO^+)/X(HOC^+) ≈ 130-140**

~ **10^3** in dense clouds, ~**10^2** in PDRs (Harada et al. 2021)



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- **$X(HCS^+)/X(CS) \approx 0.14\text{-}0.18$**

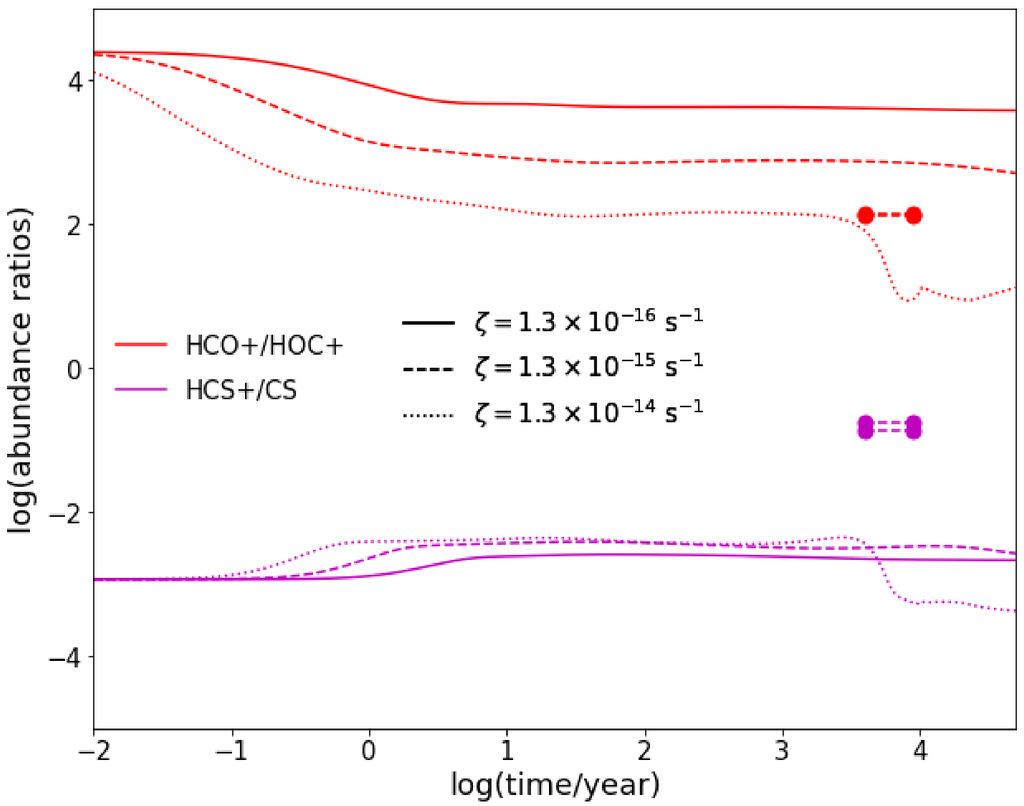
~ **10^{-2}** in Taurus, Perseus and Orion MCs (Rodríguez-Baras et al. 2021)

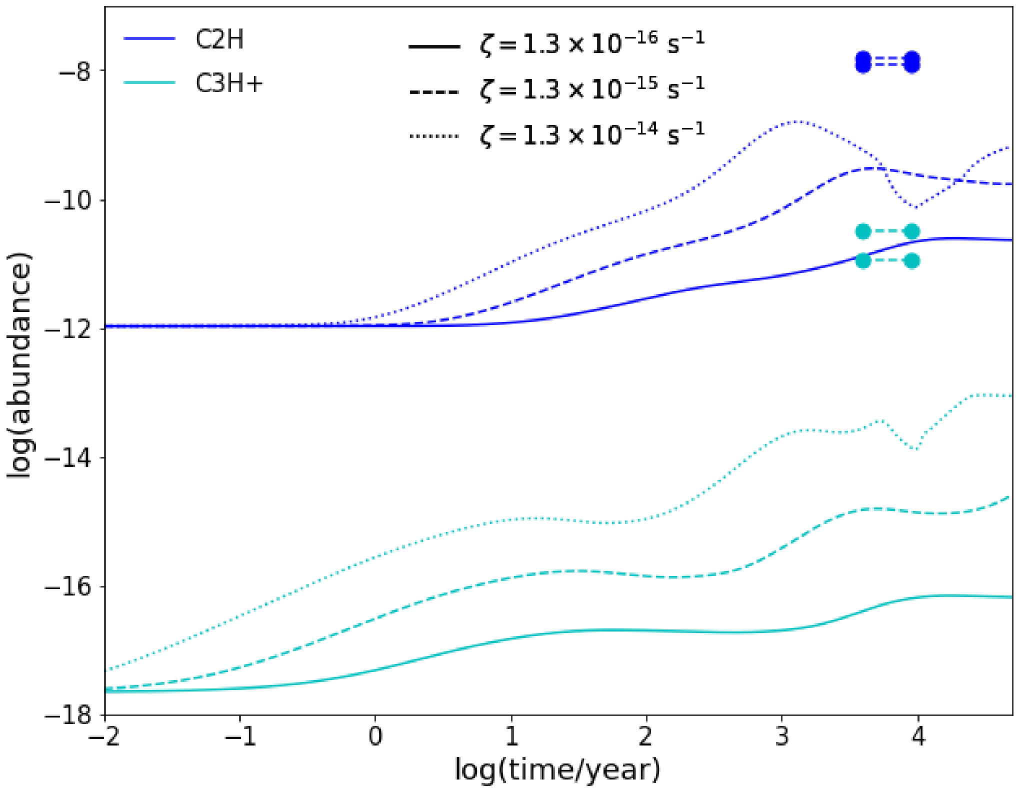
– The observed values can be attributed to CR chemistry.

Chemical simulation

Run phase 1 for 10^6 years with low ζ, then phase 2 for 5×10^4 years with enhanced ζ.

n_{H2} = 2×10^5 cm^{-3}, T = 20 K





The chemical model can explain the $X(HCO^+)/X(HOC^+)$ with high ζ.

$X(HCS^+)/X(CS)$, $X(C_2H)$ and $X(C_3H^+)$ are underestimated by the model.

Conclusion

- We present new Yebes 71.5-90 GHz line survey towards an unshocked cloud of SNR 3C391. We detected 24 transitions from 18 molecular species.
- The CR ionization rate is estimated to be $\zeta \gtrsim (2.9\text{-}4.1)\times10^{-14}\ s^{-1}$, which is 10^3 higher than the typical value found in molecular clouds and 10 times higher than W51C and W28.
- Compared with typical molecular clouds, $X(C_3H^+)$ ↗↗ , $X(HCS^+)/X(CS)$ ↗↗ , $X(C_2H)$ ↗ , while $X(HCO^+)/X(HOC^+)$ ↘↘ . These values can be attributed to CR chemistry.
- The chemical model can explain the $X(HCO^+)/X(HOC^+)$ with enhanced CR ionization, but cannot explain the $X(C_2H)$, $X(C_3H^+)$ and $X(HCS^+)/X(CS)$.

Thank you for your listening!