Chemistry induced by cosmic rays towards supernova remnants W28 and 3C391

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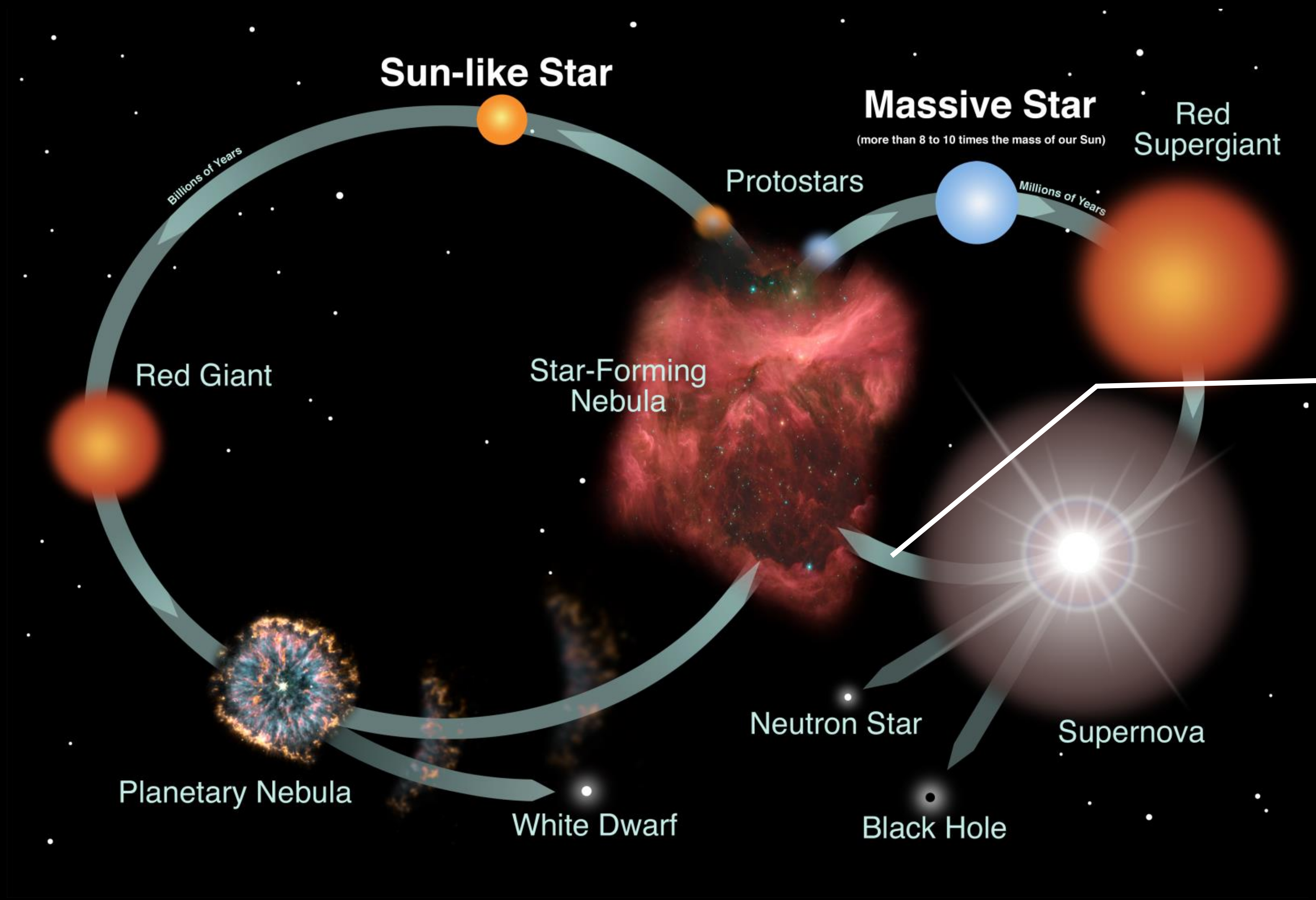
2024.10

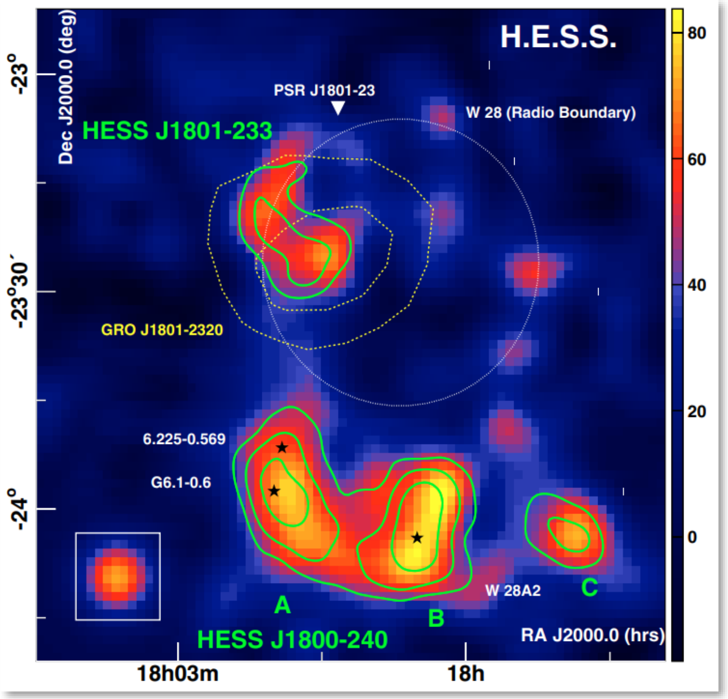
Supernova explosions and supernova remnants (SNRs)



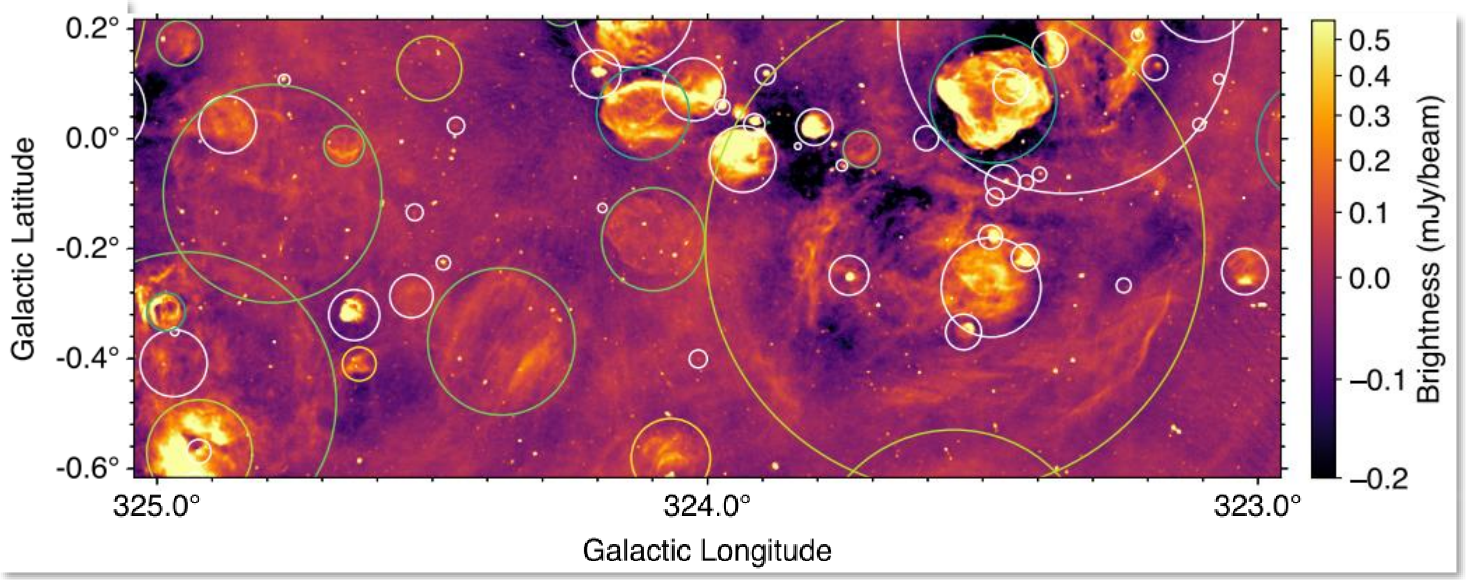
- ~ 10^{51} ergs back to the ISM
- Significant feedback on star formation and galaxy evolution

SNRs as accelerators of Galactic CRs

High-energy CRs
- Gamma-ray emission (by Fermi, HESS, etc. in many SNRs)
- Radio/X-ray synchrotron emission (many SNRs)



HESS TeV emission from W28. Aharonian+, 2008

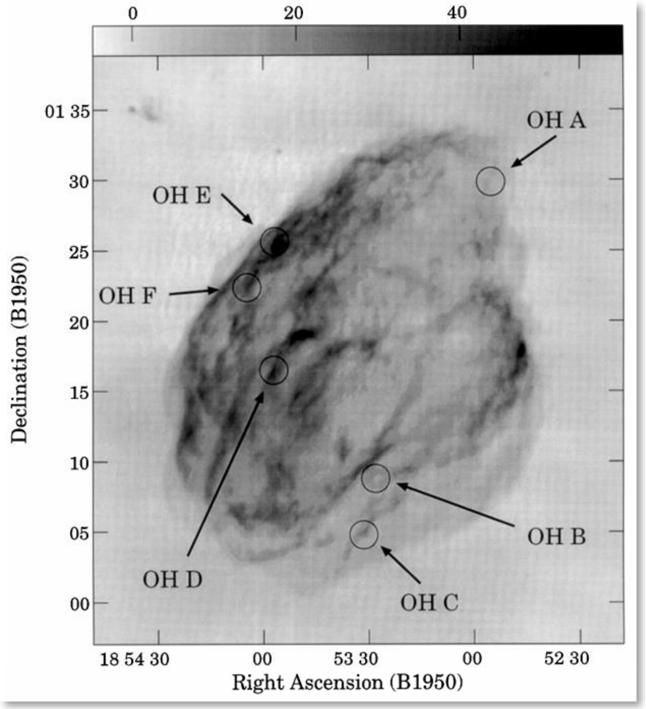


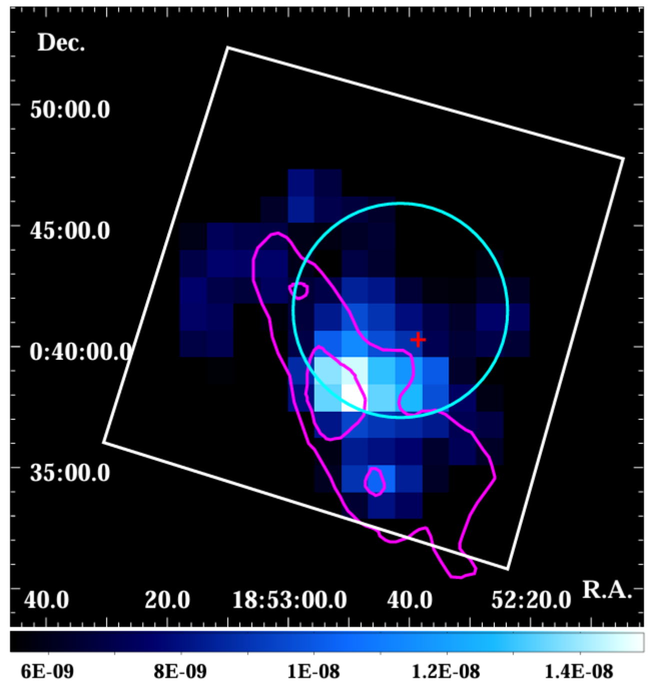
MeerKAT 1.3 GHz survey for new Galactic SNRs denoted as green/blue green/light green circles. Anderson+, 2024, arxiv: 2409.16607

SNRs as accelerators of Galactic CRs

Low-energy CRs

- 1720 MHz OH masers (many SNRs)
- Infrared H_3^+ absorption (e.g. IC443, Indriolo+ 2010)
- X-ray 6.4 keV Fe Kα line (e.g. W28, Kes 69, W44, Nobukawa+ 2018)
- **Molecular chemistry**
  - **DCO^+/HCO^+ (e.g. W51C, Ceccarelli+ 2011)**
  - **HCO^+/CO (W49B, Zhou+ 2022)**





Left: 1442 MHz radio continuum of SNR W44, with the positions of 1720 MHz OH masers
Claussen+ 1997

Right: 6.4 keV image of SNR Kes 79 with magenta contours of ^{13}CO.
Sato+ 2016

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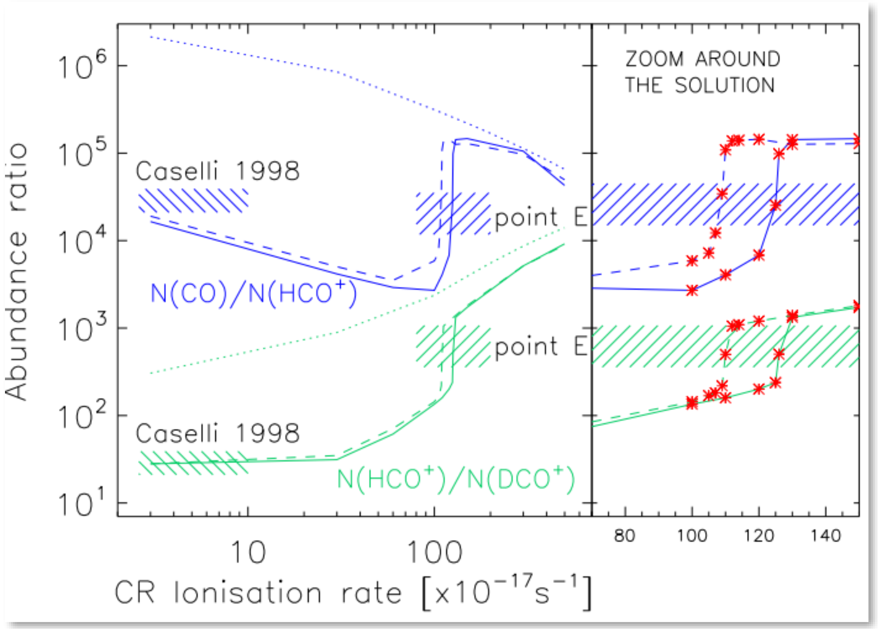

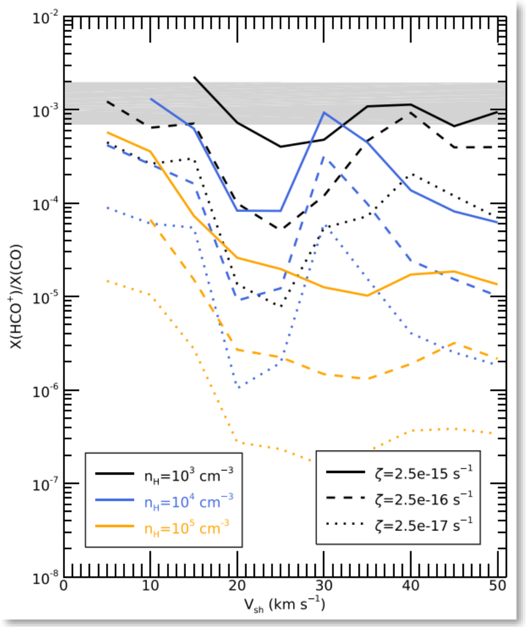

Left: Simulation of HCO^+/CO and DCO^+/HCO^+ towards W51C Ceccarelli+ 2011

Right: Simulation of HCO^+/CO in shocked MC towards W49B Zhou+ 2022

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■ How does SNRs affect the chemistry in molecular clouds?

1. Detailed study of SNR feedback on molecular clouds and star formation
2. Important test of molecular chemistry with enhanced CR ionization rates

01

Shock and Cosmic-Ray Chemistry Associated with the Supernova Remnant W28

Published in ApJ in 2024.

Collaborators: Ping Zhou (NJU),
Samar Safi-Harb (UManitoba)

SNR W28 and observation

■ Interaction between W28 and MCs

Numerous 1720 MHz OH masers

Broadened molecular lines spatially coincident with the radio boundary

Infrared H_2 emission filaments

■ CRs towards W28

GeV–TeV γ-rays

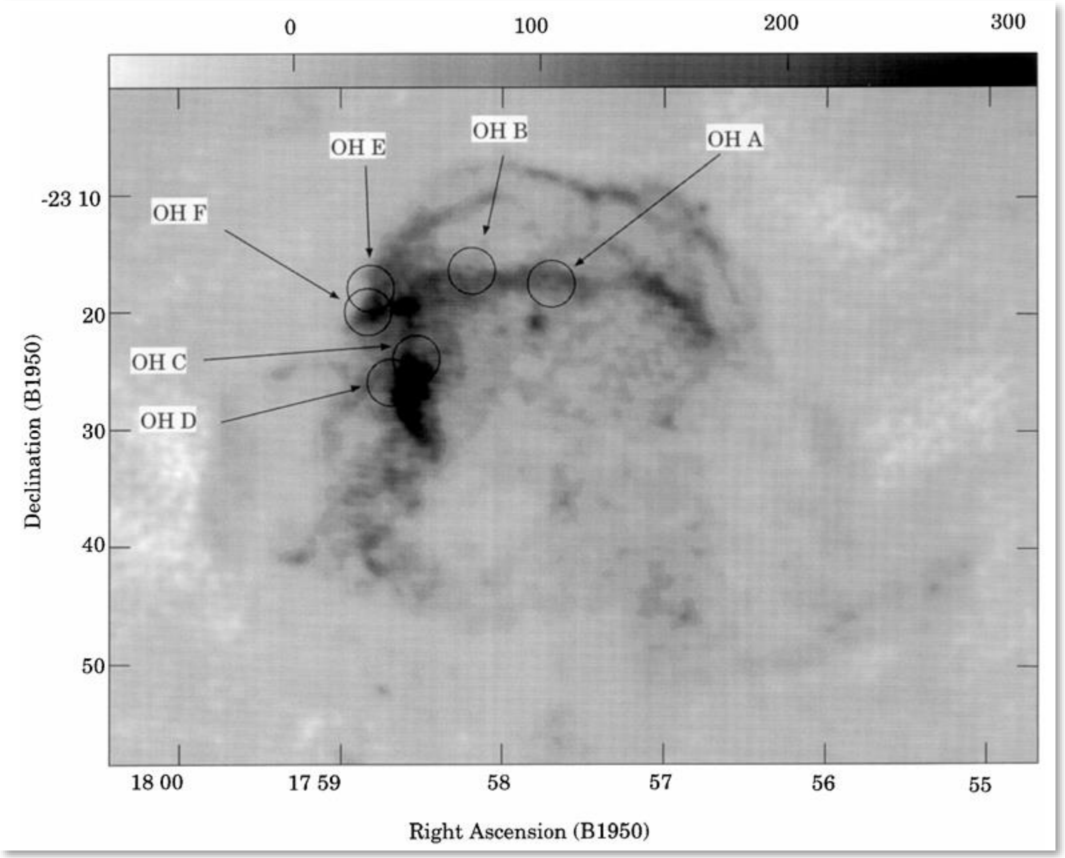
6.4 keV Fe Kα line

Enhanced CR ionization rate: ~ 10^{-15} s^{-1}

■ Our observation

PMOD 13.7m HCO^+ HCN HNC J=1–0

Supplementary CO and $H^{13}CO^+$ 1–0



327 MHz radio continuum of W28, with the positions of 1720MHz OH masers (Claussen+ 1997)

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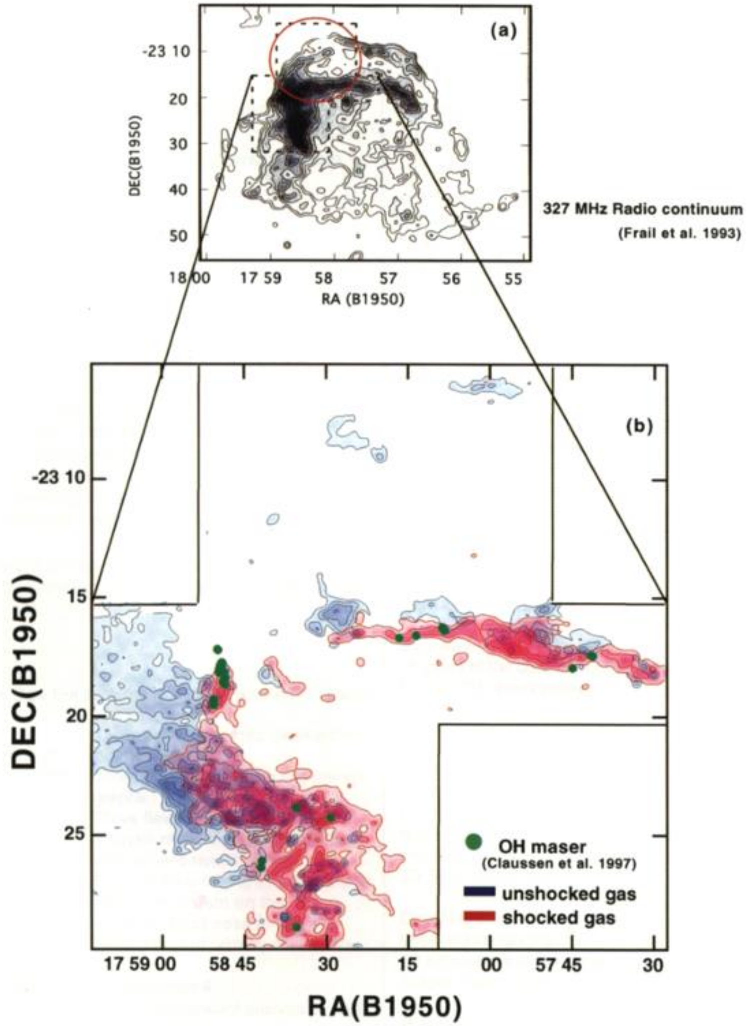

Shocked and unshocked CO 3–2 . Arikawa+ 1999

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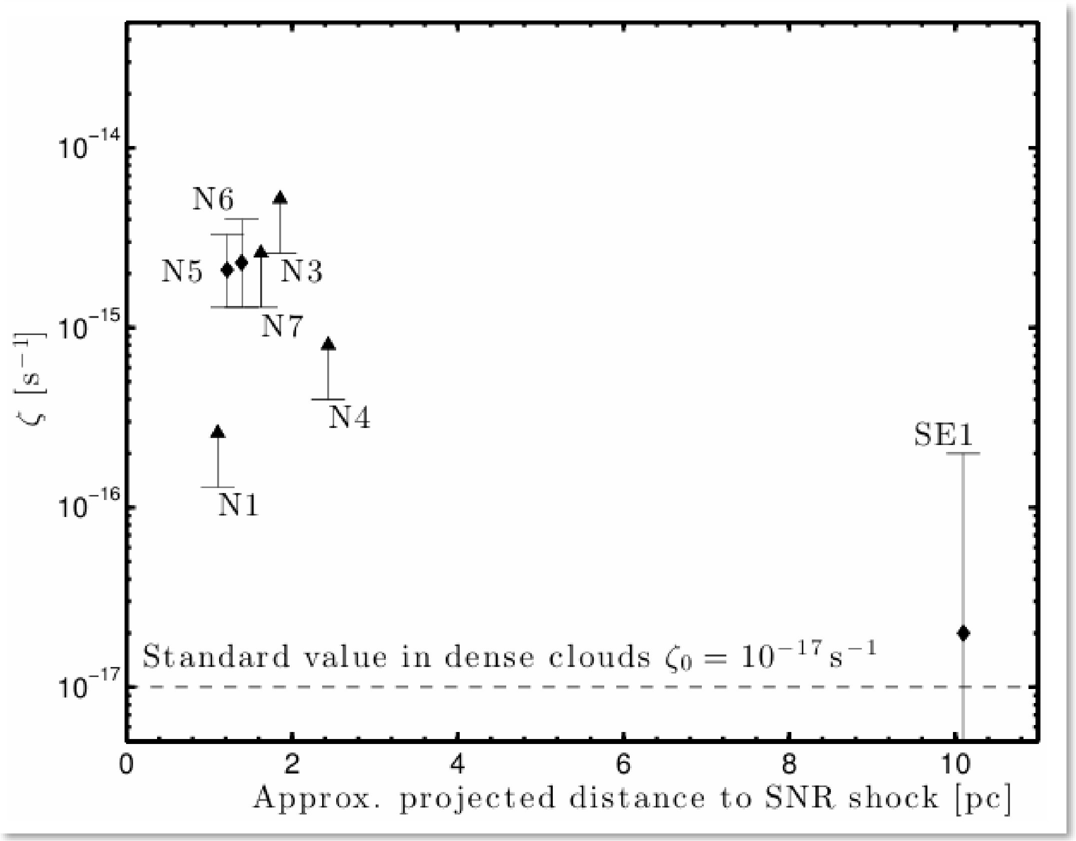

CR ionization rates estimated from HCO^+/CO and DCO^+/HCO^+ towards several points associated with W28

Vaupre+ 2014

SNR W28 and observation

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  - Broadened molecular lines spatially coincident with the radio boundary
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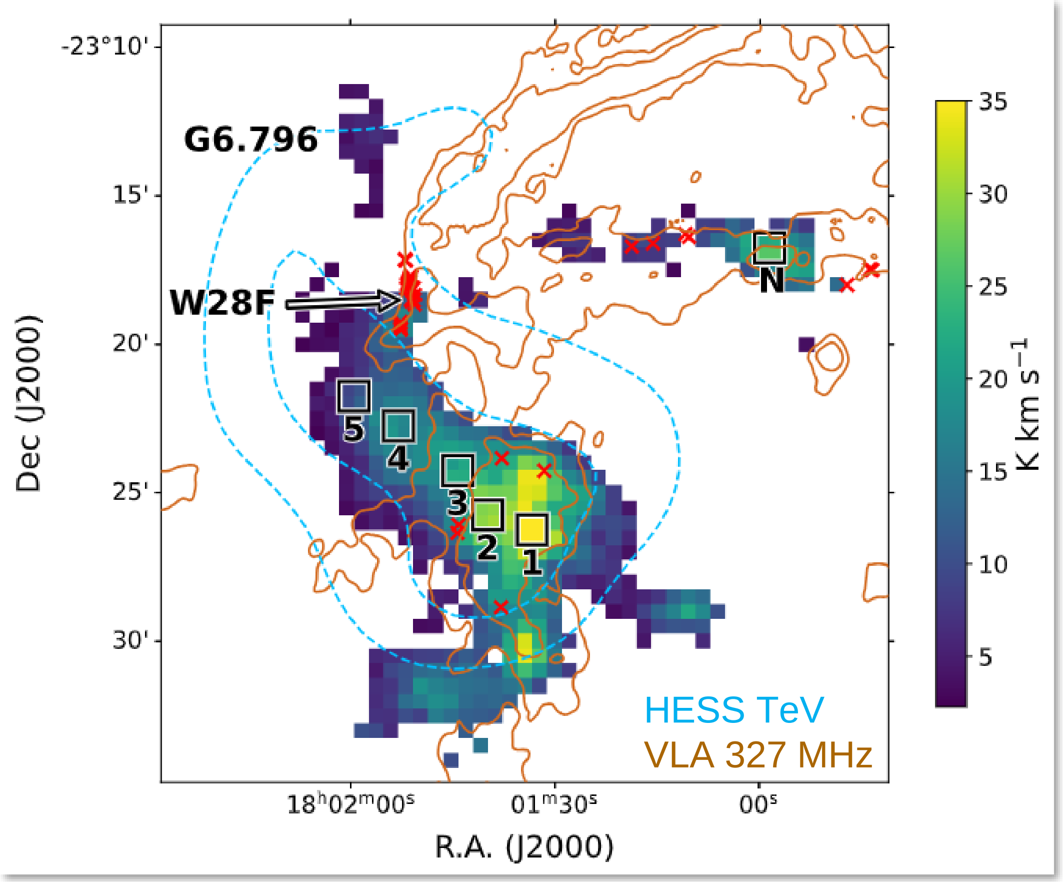


HCO^+ (1–0) integrated intensity map (-30 – +40 km/s)

Results and simulation of HCO^+/CO

- **The N(HCO^+)/N(CO) abundance ratio**

  $\sim 10^{-4}$ in shocked MCs, $\sim 10^{-5}$ in unshocked MCs

  Enhanced N(HCO^+)/N(CO) in shocked MCs

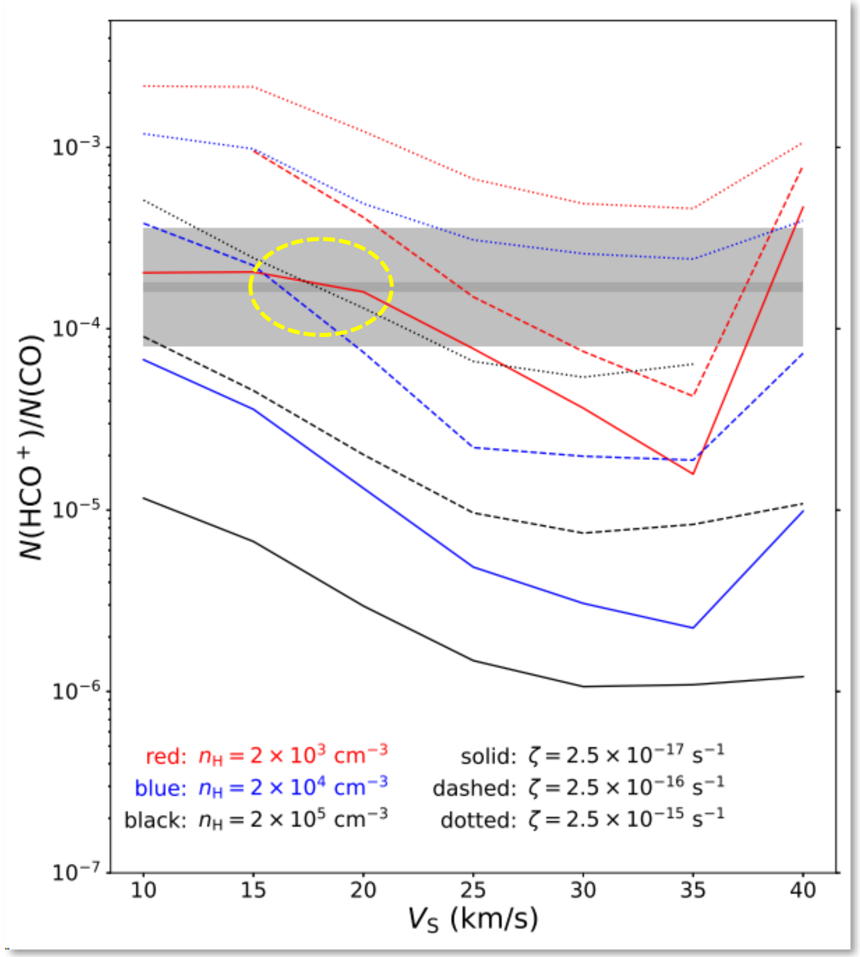
- **Simulation with Paris-Durham shock code:**

  $n_{\rm H} \sim 2 \times 10^5\ {\rm cm}^{-3}, \zeta \sim 2.5 \times 10^{-15}\ {\rm s}^{-1}, V_s \sim 20\ {\rm km/s}$ can explain the observed N(HCO^+)/N(CO) consistent with the parameters obtained by previous studies.

  $\rightarrow$ chemistry induced by shock and CRs

- **Note**

  The enhanced N(HCO^+)/N(CO) is a joint effect of shock and CRs



- **How about "pure" CR chemistry?**

02

A Yebes W-band Line Survey towards an Unshocked MC of SNR 3C391: Evidence of Cosmic-Ray-Induced Chemistry

Published in ApJ in 2024.

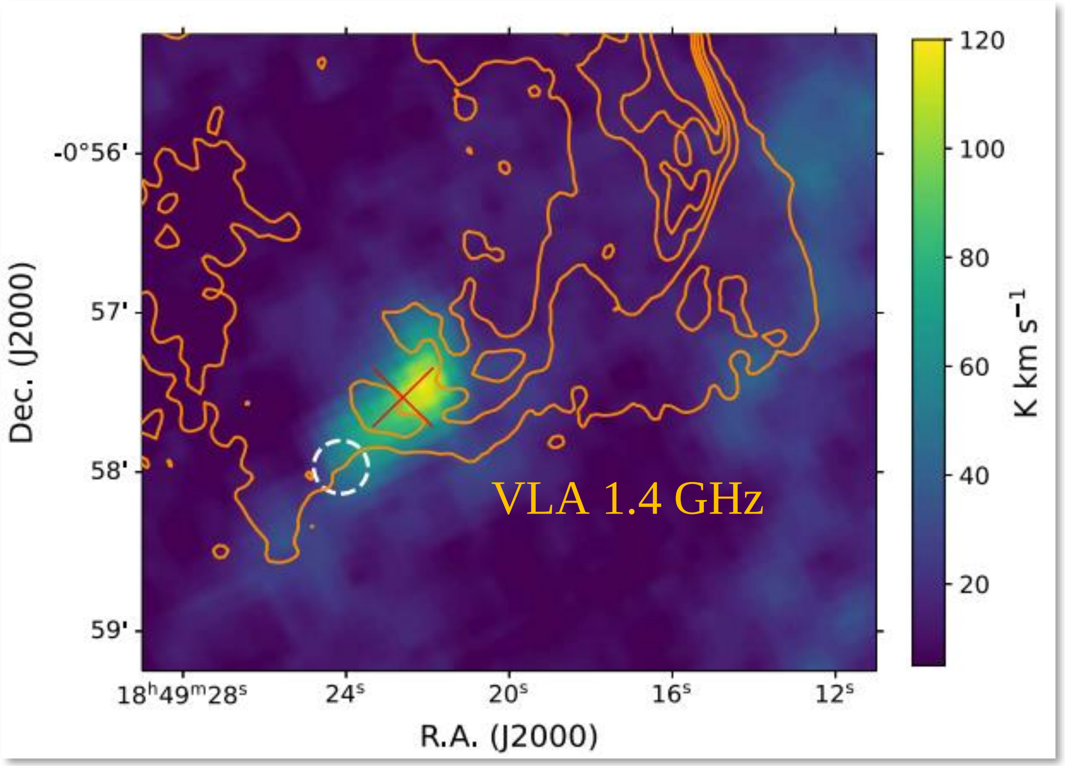
Collaborators: Prathap Rayalacheruvu (NICER),
Liton Majumdar (NICER),
Ping Zhou (NJU),
Miguel Santander García (Yebes)

Observation of 3C391

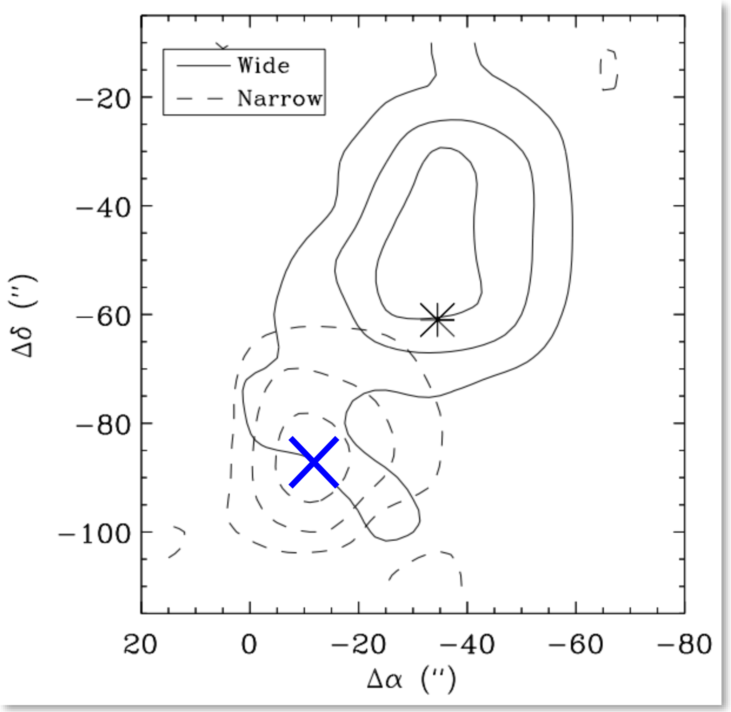
■ Unshocked molecular cloud towards SNR 3C391

Yebes 40m line survey in 71.5–90 GHz towards an unshocked MC associated with 3C391.

24 transitions from 18 molecules are detected.



Integrated intensity map of ^{12}CO 3–2



Contours of the integrated intensity of CS 2–1 broad and narrow components, Reach & Rho 1999

Unusual molecular abundance (ratios)

- **Estimation of the physical parameters**

  RADEX analysis gives n_{H2} ~ 10^5 cm^{-3} and T ≲ 40 K because of the non-detection of CS 5–4.

- **Unusual abundance (ratios)**

  $\zeta \gtrsim (2.9–4.1)\times10^{-14}$ s^{-1} estimated from $X(HCO^+)/X(CO)$ ~ 5×10^{-5} and $X(DCO^+)/X(HCO^+) \lesssim 3\times10^{-3}$.

  Caution on the result: not necessarily reached chemical equilibrium

  Other molecular species:

Abundance (ratio)	Observed	Typical	Possible explanation
$X(C_3H^+)$	$(2.2\text{-}6.2)\times10^{-11}$ ↑	~ 2.4×10^{-12} (TMC-1)	CO → C → C^+
$X(HCO^+)/X(HOC^+)$	130-140 ↓	~ 10^3	$C^+ + H_2O \rightarrow HOC^+/HCO^+$ (2:1) + H $CO^+ + H_2 \rightarrow HOC^+/HCO^+$ (1:1) + H
$X(HCS^+)/X(CS)$	0.14-0.18 ↑	~ 10^{-2}	CS + $H_3^+/HCO^+/H_3O^+ \rightarrow HCS^+$

- **All of the unusual abundance (ratios) can be due to CR chemistry.**

Simulation with DNautilus

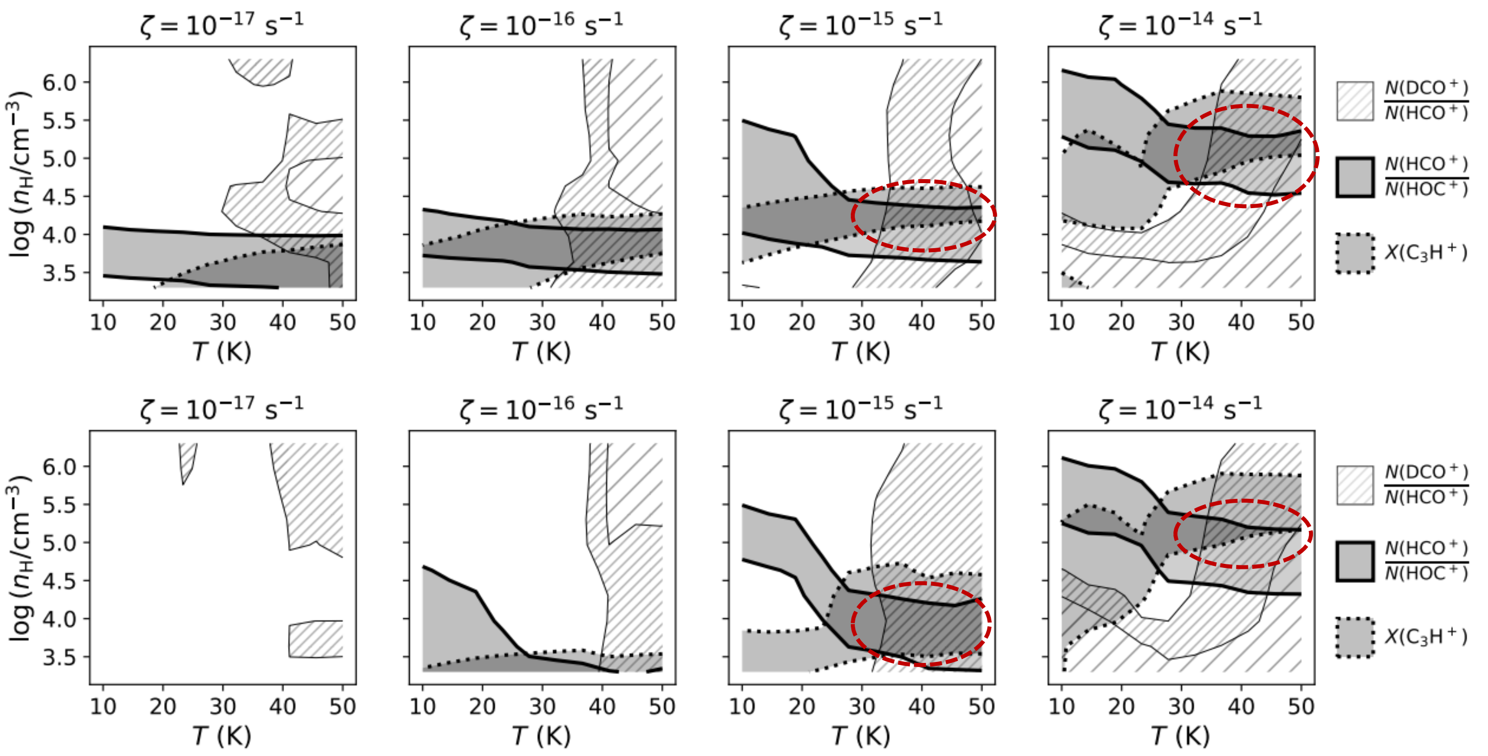
DNautilus chemical model: Nautilus + deuterium and spin chemistry

Step1: quiescent MC ~ $10^5/10^6$ yr (varying n_H, C/O); **Step2:** SN explosion ~ 8 kyr (varying ζ, T).

- The $X(HCS^+)/X(CS)$ cannot be fitted.
- Two combinations of parameters can reproduce the observed values:

  1. $T \sim 35$ K, $\zeta \sim 10^{-15}$ s^{-1}
  2. $T \sim 40$ K, $\zeta \sim 10^{-14}$ s^{-1}

  Both with CR heating.



■ **The unusual chemistry can be explained by enhanced CR ionization rates.**

Summary & Future work

■ Towards SNR W28:

1. HCO^+, HCN and HNC mapping observations;
2. **Enhanced N(HCO^+)/N(CO)** in shocked MCs by an order of magnitude;
3. The observed N(HCO^+)/N(CO) can be due to chemistry induced by shock and CRs.

■ Towards SNR 3C391:

1. Yebes W-band line survey (71.5–90 GHz)
2. **High X(C_3H^+), X(HCS^+)/X(CS) and low X(HCO^+)/X(HOC^+)** by an order of magnitude
3. **Enhanced CR ionization rate (~ 10^{-15} or 10^{-14})** with CR heating found by DNautilus model

□ Future work – please stay tuned

1. **Shock and CR chemistry:** high-resolution observation towards shocked MC of W28
2. **Pure CR chemistry:** molecular line surveys towards SNR W51C and Kes 79
3. **SNR feedback on dust and ice:** dust and ice absorption towards SNR W44 (shock+CR?)