Enhanced cosmic-ray ionization rate is needed to account for the molecular chemistry towards supernova remnant 3C391

A Yebes W band Line Survey towards an Unshocked Molecular Cloud of Supernova Remnant 3C391: Evidence of Cosmic-Ray-Induced Chemistry

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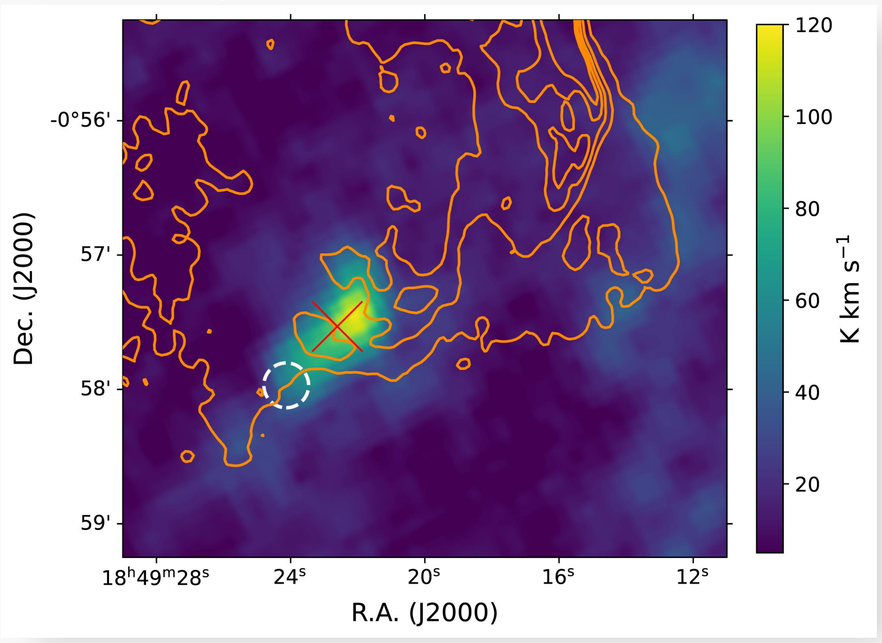
Cosmic-ray chemistry in molecular clouds

Cosmic rays (CRs) accelerated by supernova remnants (SNRs) have a strong influence on the chemistry in molecular clouds (MCs). The ionization process of H_2 by low-energy CR protons:

$H_2 \rightarrow H_2^+ + e^-$ followed by $H_2^+ + H_2 \rightarrow H_3^+ + H$,

produces the H_3^+ ion which starts the formation of poly-atomic molecular species in MCs. Other chemical effects of CRs include the transition of CO → C → C^+, non-thermal desorption, CR-induced UV photons, etc.

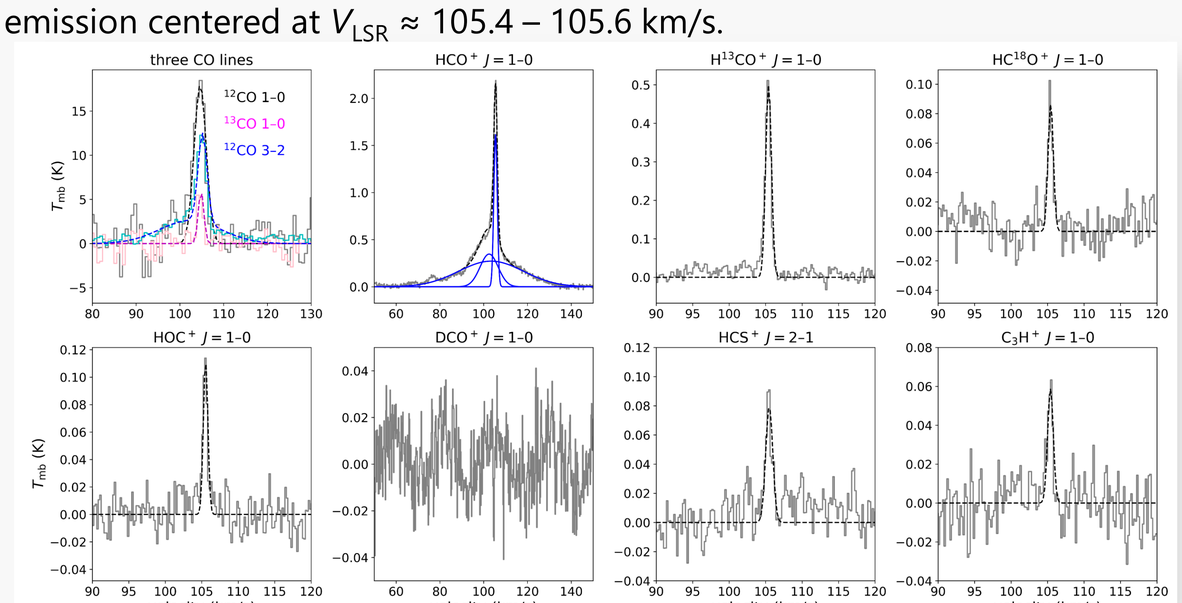
To study the detailed chemical effects of enhanced CR ionization rate in MCs, we conducted a W band (71.5 – 90 GHz) molecular line survey with Yebes 40m radio telescope towards 3C391:NML, an unshocked MC.



Integrated intensity map of the ^{12}CO *J* = 3 – 2 line between +100 and +110 km/s towards the south-western part of SNR 3C391, overlaid with contours of radio continuum. The red cross shows the 1720 MHz OH maser, while the dashed white circle delineates the 3C391:NML region we observed.

Results of the observation

In total, we detected transitions from 18 molecular species (including isotopes). A selection of the target transitions (among which DCO^+ is not detected) are shown below. All of the detected species show narrow line emission centered at V_{LSR} ≈ 105.4 – 105.6 km/s.



A selection of the target transitions. The CO lines are obtained from archival data. Spectra with lighter color shows the observed spectra, while the dashed lines show the results of (multi-)Gaussian fitting. For the spectrum of HCO+, the blue lines show the three velocity components.

Estimation of molecular column density

We used the RADEX code to estimate the column densities of CO, CS and *o*-*c*-C_3H_2, of which multiple transitions are available (the data of CS are taken from reference). For other species, the column densities are estimated based on the assumption of LTE and T_{ex} = 5 K or 10 K.

Species	Column density (cm^{-2})	Density (cm^{-3})
CO (20 K)	~ 3.7×10^{17}	~ 1.4×10^{3}
o-*c*-C_3H_2 (20 K)	~ 2.0×10^{12}	~ 2.4×10^{5}
CS (20 K)	~ 3.9×10^{12}	~ 1.9×10^{5}
CS (40 K)	~ 3.9×10^{12}	~ 1.0×10^{5}

Results of the RADEX analysis.
The adopted temperatures in the analysis are shown in the parentheses in the first column.

CR ionization rate with analytic method

The abundance ratios R_D = $N(DCO^+)/N(HCO^+)$ and R_H = $N(HCO^+)/N(CO)$ can be used to estimate the CR ionization rate, ζ:

$$\frac{\zeta}{n_{\rm H}} = \frac{\beta'}{k_{\rm H}} \left(2\beta x_{\rm e} + \delta\right) R_{\rm H} x_{\rm e}, \quad \text{and} \quad x_{\rm e} = \left(\frac{k_{\rm f} x({\rm HD})}{3R_{\rm D}} - \delta\right) \frac{1}{k_{\rm e}}$$

We obtained a lower limit: $\zeta \gtrsim 2.7 \times 10^{-14}$ s^{-1}, higher than typical values in MCs by 3 orders of magnitude.

However, we estimated that the timescale of CR-induced non-thermal desorption for CO ice is ~ 3 kyr, which is comparable to the age of 3C391 (4 – 19 kyr). Therefore, the chemistry may be highly dynamic around 3C391, and **the analytic method may not give a robust estimation of the CR ionization rate because of the deviation from chemical equilibrium.**

Chemical simulation of unusual abundance (ratios)

We discovered two abundance ratios and one abundance different from typical values found in dense MCs:

Abundance (ratios)	Observed	Typical
$N(HCO^+)/N(HOC^+)$	~ 160 – 180	~ 10^3
$N(HCS^+)/N(CS)$	~ 0.14 – 0.18	~ 10^{-2}
$X(C_3H^+)$	~ $2.9 – 6.0 \times 10^{-11}$	~ 10^{-12}

All of these unusual values can be qualitatively attributed to the chemistry induced by enhanced CR ionization rate.

We present a chemical simulation using the *DNautilus 2.0* chemical code. The simulation consists of two steps:

Step 1: evolution of a MC before SN explosion for t_1 = 0.1 and 1 Myr.

Step 2: model of the impact of CRs after the SN explosion.

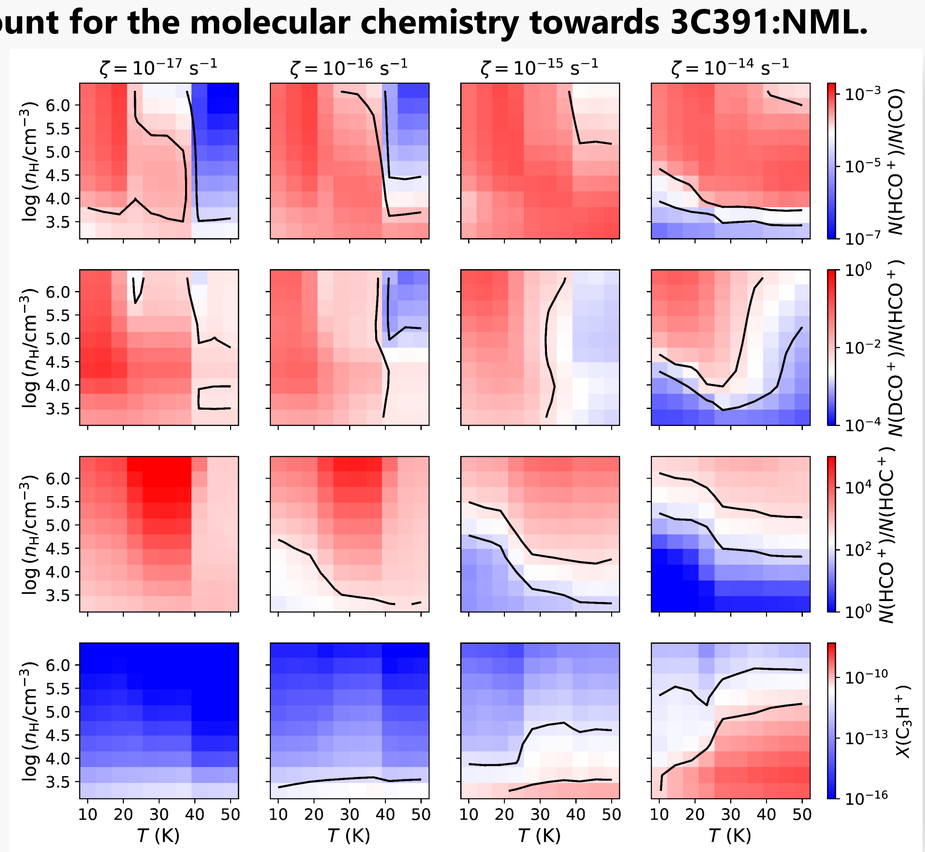
Two combinations of parameters can reproduce the other observed values ($N(HCS^+)/N(CS)$ cannot be explained by any models.):

(a) t_1 = 0.1 Myr, n_H ~ 10^4 cm^{-3}, T ~ 32 K, and ζ ~ 10^{-16} s^{-1},

(b) arbitrary t_1, n_H ~ 10^4 cm^{-3}, T ~ 19 K, and ζ ~ 10^{-14} s^{-1}.

Combination (a) is not valid for t_1 = 1 Myr, while (b) fails to reproduce the $N(HCO^+)/N(HOC^+)$ unless higher density (~ $10^{5.5}$ cm^{-3}) is adopted, and the temperature for (b) is too low to be compatible with the heating of CR.

However, in either case, **an enhanced cosmic-ray ionization rate is needed to account for the molecular chemistry towards 3C391:NML.**



Grid map of the chemical simulation results with t_1 = 1 Myr (please refer to the original paper for the results with t_1 = 0.1 Myr). The colorbars are adjusted to have whiter colors with the simulated values closer to the observed ones. The black contours show 2 × the maximum observed values and 0.5 × the minimum observed values as a rough estimate of the uncertainty.

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