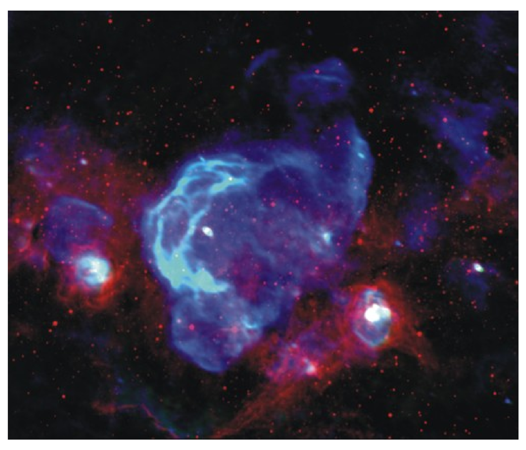


Cosmic-Ray Ionization of a Molecular Cloud interacting with the Supernova Remnant W28

S. Vaupré[1], C. Ceccarelli[1], P. Hily-Blant[1], G. Dubus[1] and T. Montmerle[2]

[1]Institut de Planétologie et d'Astrophysique de Grenoble; [2]Institut d'Astrophysique de Paris
solenn.vaupre@obs.ujf-grenoble.fr

Context: open questions

- **Cosmic-rays (CR)** induce **major modifications** in the physical conditions, dynamical evolution and chemical composition of **molecular clouds**
- Supernova remnants (SNR) to be confirmed as low-energy-CR accelerators
- **Unknown** initial **CR energy spectrum** at the acceleration site
- **Observational evidence** of **CR interaction** with molecular clouds:
  1. $\gtrsim$ GeV CR: γ-ray emission through π°-decay
  2. $\lesssim$ GeV CR: ionization of the dense gas

Goals

General goals:

- **Constrain the initial low-energy (ionizing) CR flux**, from millimeter observations
- **Constrain propagation properties of CR** with respect to energy
- **Identify new tracers of the ionization** in molecular clouds

This poster:

- **Determine the ionization fraction** of the molecular gas
- **Determine CR ionization rate ζ of the cloud** due to the nearby SNR, with DCO^+ and HCO^+ as molecular tracers

Observations

- Observations with IRAM 30m **radiotelescope**
- Data reduction with CLASS package of GILDAS software
- Linear spatial resolution < 0.13 pc (beam size < 29")
- Determine **abundances and abundance ratios** of the following species:

Species	Freq. (GHz)	
$^{13}CO(1-0)$	110.201	Phys. cond.
$^{13}CO(2-1)$	220.399	Phys. cond.
$C^{18}O(1-0)$	109.782	Phys. cond.
$C^{18}O(2-1)$	219.560	Phys. cond.
$DCO^+(2-1)$	144.077	Ionization
$H^{13}CO^+(1-0)$	86.754	Ionization

1. **CO isotopologues** to determine the physical conditions
2. **HCO^+, DCO^+** as tracers of the ionization

Source

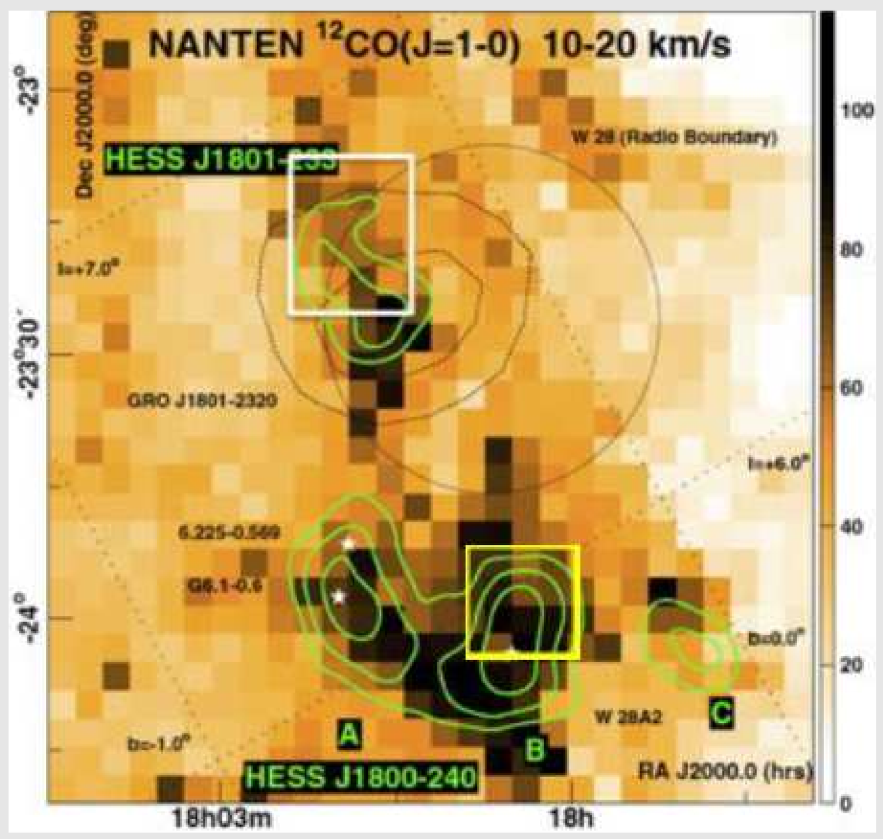
Molecular clouds nearby W28:

- Complex massive-star forming region at the edge of the SNR
- Density $\sim 10^3 - 10^4$ cm^{-3}
- $T \sim 10 - 25$ K
- **Overlapping** bright **TeV emission** observed with HESS telescope
- Targets within northern (white box) and southern (yellow box) clouds

About SNR W28:

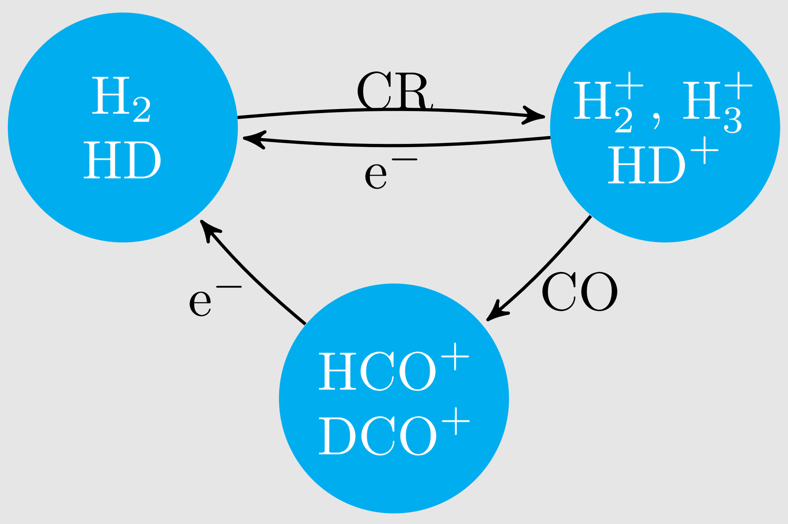
(Kaspi et al. 1993 [ApJ 409, L57])

- Distance 2-3 kpc
- Age 35-150 10^3 yr



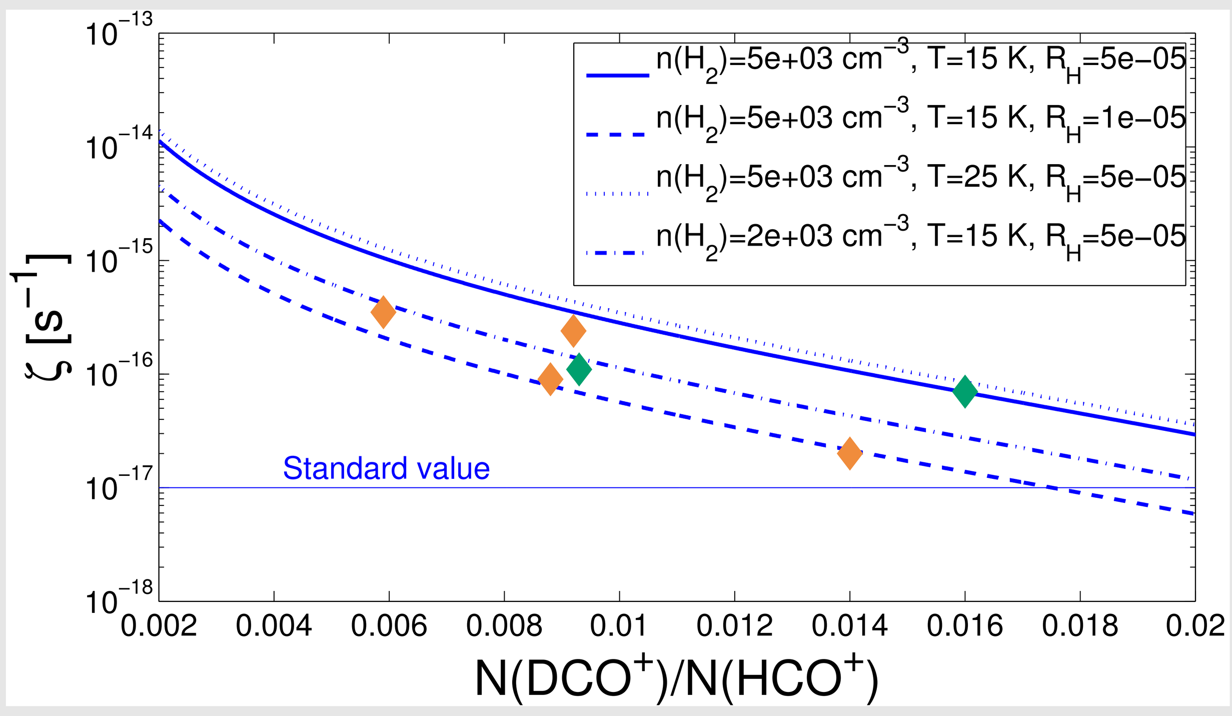
Map of the region: γ-ray emission seen with HESS telescope (green contours), overlapping ^{12}CO NANTEN observations (background). From Aharonian et al. (2008) [A&A 481, 401].

Method



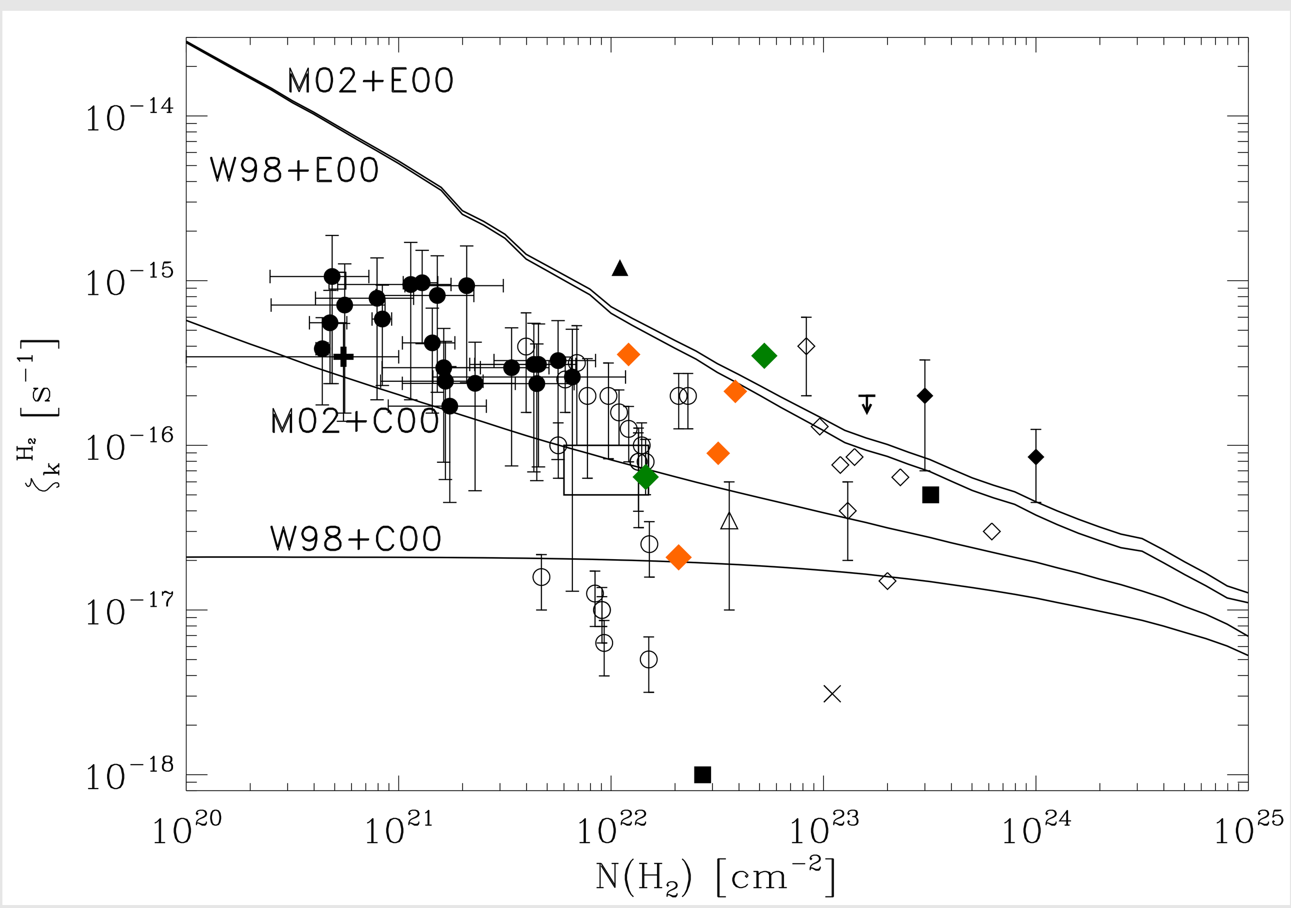
Chemical network

- **Derive physical conditions from observations** of CO isotopologues, by means of a large velocity gradient (LVG): density $n(H_2)$, temperature T, column density of ^{13}CO and emitting region size.
- Use **simple deuterated chemical network**, following Guélin et al. (1977) [ApJ 217, L165] and Caselli et al. (1998) [ApJ 499, 234].
- **Derive the ionization fraction $x(e) = n(e^-)/n(H_2)$ and CR ionization rate ζ** from physical conditions and abundance ratios $R_D = [DCO^+]/[HCO^+]$ and $R_H = [HCO^+]/[CO]$.



CR ionization rate ζ as a function of R_D, with different physical conditions.
Green diamonds represent the ζ values in points where DCO^+ is detected and orange diamonds lower limits from the non-detections.

Results and conclusions



Models and data points for ζ as a function of H_2 column density, from Padovani et al. (2013, in press). **Overplotted are the new data for W28**: green diamonds represent the ζ values in points where DCO^+ is detected and orange diamonds lower limits from the non-detections.

- **Physical conditions characteristic of dense clouds** ($A_V > 10$ mag) and consistent with published values of adjacent clouds (Lefloch et al. 2008 [A&A 489, 157]).
- **DCO^+ emission detected** in only two positions; upper limits derived for other positions give **lower limits on ζ** (table).
- **Partially enhanced CR ionization rates** compared to standard average $\zeta = 10^{-17}$ s^{-1}.

Pos	$n(H_2)$ (cm^{-3})	T (K)	R_H (10^{-4})	R_D	x_e	ζ (10^{-17} s^{-1})
N1	4e+03	15	0.43	< 0.0092	1.9e-06	> 24
N3	3e+03	10	0.23	< 0.0088	1.6e-06	> 9
N5	5e+03	15	0.47	0.016	7.9e-07	7
N6	2e+03	20	0.37	0.0093	2.3e-06	11
N7	2e+03	15	0.24	< 0.014	1.0e-06	> 2
SE1	4e+03	25	0.17	< 0.0059	4.9e-06	> 35

We acknowledge funding from Labex OSUG@2020 and national program PNHE.

Image courtesy of NRAO/AUI and Brogan et al.