# The ionization degree of molecular clouds

P. Hily-Blant, C. Ceccarelli, G. Dubus, T. Montmerle, Y. Galland, A. Fiasson

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# Introduction

- HESS sources with no plausible counterpart at X-ray
- $\gamma$-ray sources associated with molecular clouds close to SNRs
- Interaction between high-energy protons accelerated by SNRs (presumably) with protons from the cloud

# Tracing low-energy cosmic rays

- Only way to trace accelerated protons is indirect
- $\pi^0$-meson decay produces $\gamma$-ray:

$$p_{>300\mathrm{MeV}} + p_{\mathrm{gas}} \rightarrow \pi^0 \rightarrow 2\gamma$$

THE COSMIC $\gamma$-RAY SPECTRUM FROM SECONDARY PARTICLE PRODUCTION 381

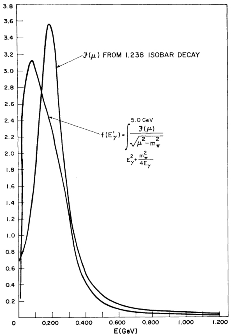



Fig. 3. The energy distribution function of pions in the BARS resulting from the decay of the $\Delta(1.238)$ isobar and the energy distribution function of $\gamma$-rays in the BARS resulting from the decay of these pions.

Stecker 1971

- continuous spectrum peaking at 70 MeV
- $\gamma$-ray flux:

$$F_\gamma \approx \frac{q\langle n\rangle V}{4\pi d^2}$$

- $\langle n\rangle$: average density (atoms $\mathrm{cm}^{-3}$)
- $q$: total rate of $\gamma$-ray production by $\pi^0$-meson decay ($\mathrm{s}^{-1}$) per atom of gas, $\approx 10^{-31}$ ph s$^{-1}$ atom$^{-1}$ (Aharonian & Atoyan 1996)

$$F_\gamma(>\ \mathrm{TeV}) \approx 10^{-12}\left(\frac{M}{10^6\,\mathrm{M}_\odot}\right)\left(\frac{1}{R_\mathrm{kpc}}\right)^2 \quad \mathrm{photons\,cm^{-2}\,s^{-1}}$$

- If distance accelerator–target-cloud $<$ m.f.p.: interaction possible with subsequent trapping by magnetic fields of the cloud
- Typical non-associated HESS source has $F_\gamma \approx 10^{-11}\,\mathrm{photons\,cm^{-2}\,s^{-1}}$ above 1 TeV.

# Motivation

- Look for interaction of accelerated protons (1–10 MeV) with the molecular cloud matter
- Test the possibility that
  1. molecular clouds are VHE sources and dark accelerators
  2. source of enhanced ionization degree of the cloud
- Enhancement of the ionization degree (not collisionally *e.g.* in a shock): association molecular cloud/$\gamma$-ray–source
- For such an association, should be possible to estimate the local density of cosmic rays

# The fractional ionization in the ISM

- gas dynamics: coupling to magnetic fields
  - transfer of angular momentum
  - dissipation by turbulence
  - formation of stars
- planetary atmospheres: ionosphere, chemistry

# Measuring the ionization degree in clouds

- Diffuse clouds exposed to enough UV field such that H/$\mathrm{H_2}$ transition not complete: Optical observation of $\mathrm{H_3^+}$

$$\zeta \approx 10^{-15} - 10^{-16}\,\mathrm{s^{-1}}$$

- Denser clouds, attenuation of UV by dust and self-shielding by $\mathrm{H_2}$: $\mathrm{H_3^+}$ much less abundant, different tracer of the ionization.
- Usual method (Guélin *et al* 1977): $\mathrm{DCO^+/HCO^+}$ abundance ratio

# $\mathrm{DCO^+/HCO^+}$ abundance ratio

Consider the minimal network of chemical reactions governing the formation and destruction of $\mathrm{HCO^+}$ and $\mathrm{DCO^+}$:

## Formation

$$\mathrm{H_3^+ + CO \xrightarrow[k_H]{} HCO^+ + H_2}$$
$$\mathrm{H_2D^+ + CO \xrightarrow[2k_D]{} HCO^+ + H_2}$$
$$\mathrm{H_2D^+ + CO \xrightarrow[k_D]{} DCO^+ + HD}$$

## Destruction

$$\mathrm{HCO^+ + e^- \xrightarrow[\beta_H]{} CO + H}$$
$$\mathrm{DCO^+} + e^- \xrightarrow[\beta_D]{} \mathrm{CO} + D$$

Steady-state: $\mathrm{d}n(X)/\,\mathrm{d}t = 0$, $\beta_H \approx \beta_D$, $k_H \approx 2k_D$

$$\frac{n(\mathrm{DCO^+})}{n(\mathrm{HCO^+})} = \frac{R'}{1+2R'}, \quad R' = \frac{1}{3}\frac{\mathrm{H_2D^+}}{\mathrm{H_3^+}}$$

ZZZ: Assumes low kinetic temperature (block endothermic reactions)

# The $H_2D^+/H_3^+$ ratio

**Formation**

$$AH^+ + HD \underset{k_1}{\longrightarrow} AD^+ + H_2 + \Delta E$$

$$k_1 \approx 10^{-9}, \Delta E/k_b = 220\ \mathrm{K}$$
$$k_{\rm rec} \approx 10^{-7} - 10^{-6}, k \approx 10^{-9}$$
$$k_1' = k_1\, e^{-\Delta E/k_B T}$$

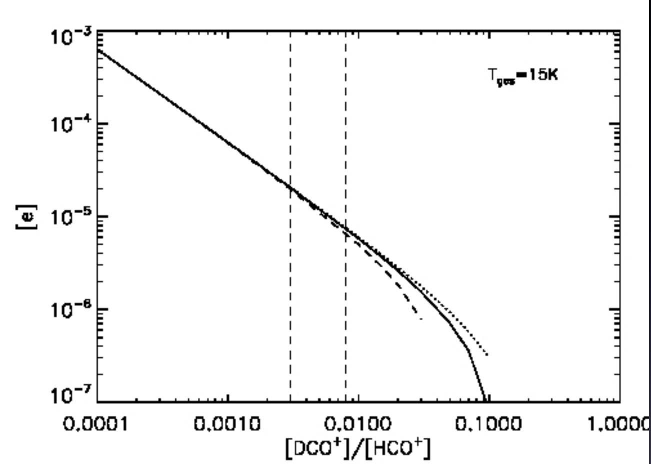
**Destruction**

$$AD^+ + e^- \underset{k_{\rm rec}}{\longrightarrow} A + D$$
$$AD^+ + H_2 \underset{k_1'}{\longrightarrow} AH^+ + HD$$
$$AD^+ + X \underset{k}{\rightarrow} \dots$$

Steady-state: (with A=$H_2$, X=$H_2$, CO), $x(X) = n(X)/n(H_2) \approx 2n(X)/n(H)$

$$R = \frac{H_2D^+}{H_3^+} = \frac{k_1 n(HD)/n(H_2)}{k_{\rm rec} x_e + k_1\, e^{-\Delta E/k_B T} + \sum_i k_i x_i}$$

Depends only on $x_e$ ([CO], D/H known) and $T < 20$ K



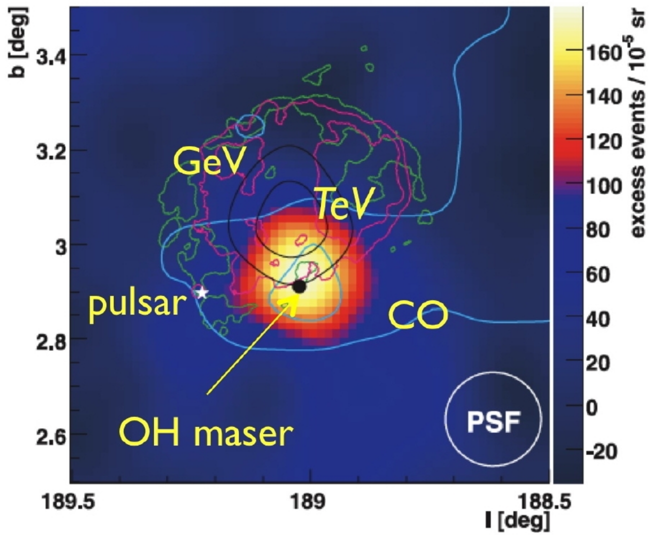
$T_{gas}$=15K
[e]
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.0001
0.0010
0.0100
0.1000
1.0000
$[DCO^+]/[HCO^+]$

# Radio observations

| Telescope | Location | Diameter | HPBW |
|---|---|---|---|
| CfA | USA/Chile | 1.2m | 550 |
| KOSMA | Switzerland | 3m | 220 |
| NANTEN | Chile | 4m | 165 |
| APEX | Chili | 12m | 26 |
| JCMT | Hawaii | 15m | 20 |
| IRAM | Spain | 30m | 10-20 |

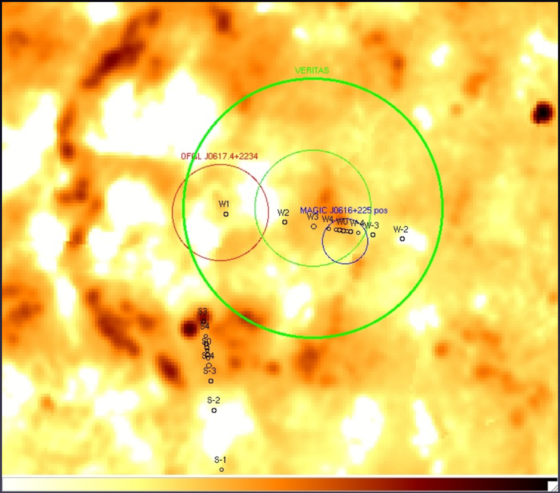
- NANTEN well suited for comparison with HESS
- Molecular clouds clumpy (*e.g.* W28): Probing interactions needs higher angular resolution.
- Provides extremely good constraints on kinematics

Albert *et al* 2007, Montmerle 2009



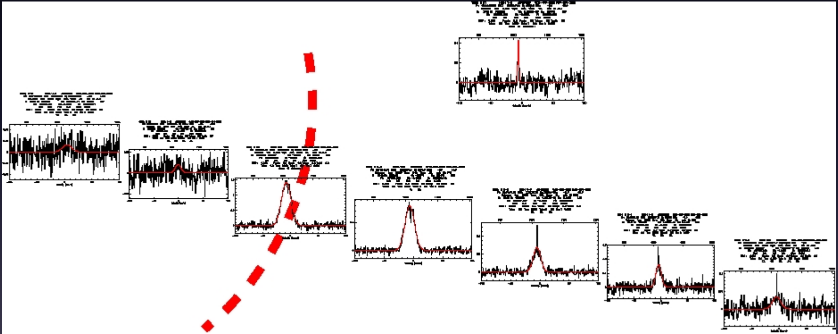

VLA 20cm (green), ROSAT X-ray (purple), $\gamma$-ray EGRET + source (black), MAGIC TeV source (color), 3mm CO(1-0) Dame (cyan)

# MAGIC-J0616+225/IC443



# MAGIC-J0616+225/IC443

HCO$^+$(3-2) with JCMT

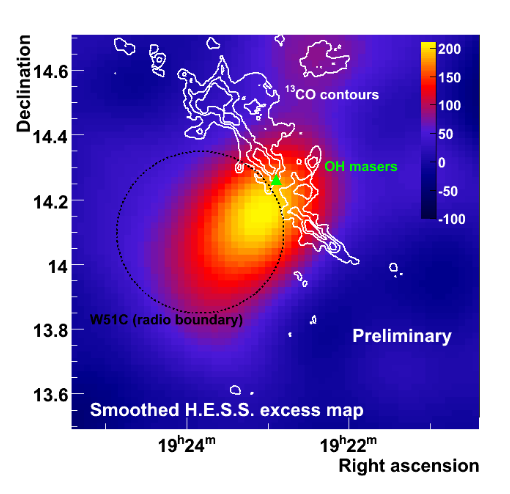


# MAGIC-J0616+225/IC443

- $DCO^+$ not detected
- upper limits on $[DCO^+]_{/}[HCO^+$ ratio
- lower limits on the ionization degree $x_e$
- analysis still under way...
- but at one position (shifted from the shock), $x_e \geq 1.5{\times}10^{-5}$. Good candidate for further integration.

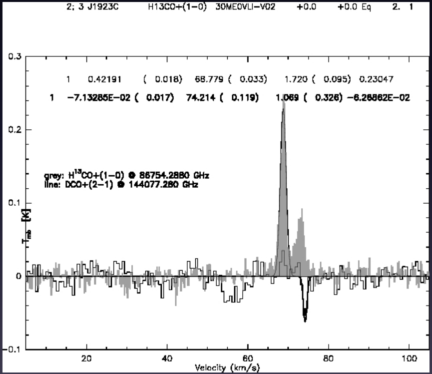
# J1923+141/W51C/G49.2-0.7

A. Fiasson, in prep.

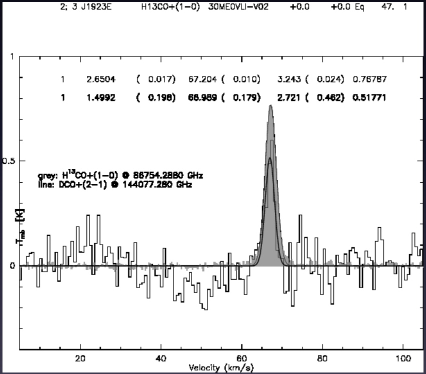


# J1923+141/W51C/G49.2-0.7

Upper limit




Detection



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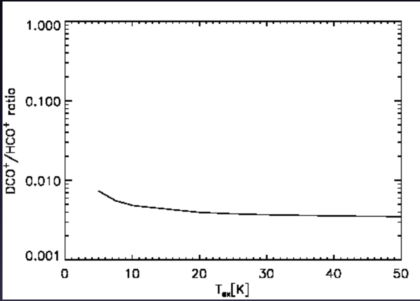
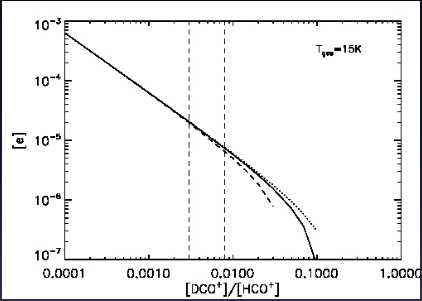


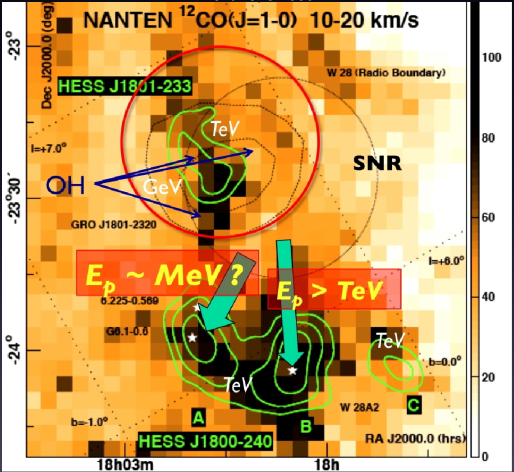



# J1923+141/W51C/G49.2-0.7

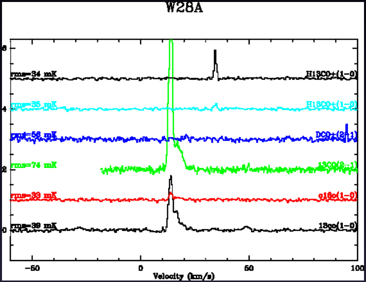
- Detected position: $x_e \approx 1.5\times10^{-5} \gg x_{\rm dark}$
- Undetected position: $x_e \geq 7\times10^{-5}$
- But collisional excitation probable so perhaps not conclusive

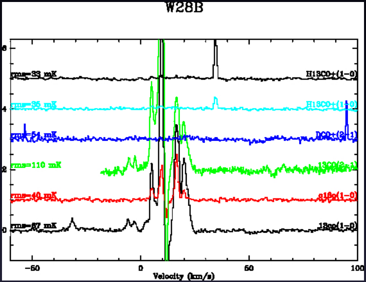
# W28

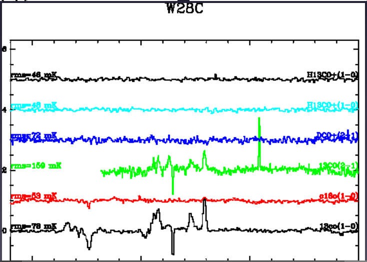
Montmerle 2009



# W28


W28A
H13CO+(1-0)
DCO+(2-1)
13CO(2-1)
c18o(1-0)
13co(1-0)
-50
0
50
100
Velocity (km/s)


W28B
H13CO+(1-0)
DCO+(2-1)
13CO(2-1)
c18o(1-0)
13co(1-0)
-50
0
50
100
Velocity (km/s)


W28C
H13CO+(1-0)
DCO+(2-1)
13CO(2-1)
c18o(1-0)
13co(1-0)

# Perspectives

- Difficulty to find a good “laboratory”
- W28 might be such a “laboratory” to test $\gamma$-ray–molecular clouds interactions
- Need for molecular maps at various spatial resolutions. High-resolution maps needed to pinpoint interaction regios which may be tiny.
- Large maps at high angular resolution at mm-wavelenght are very demanding (typically $0.5° \times 0.5° \rightarrow 40-80$ hrs)

- J1506-622 –> Mopra radio telescope, Dec 15th