Cosmic-ray ionization and chemistry: observations

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OUTLINE

0) Introductive remarks

1) Observations of the ISM in the Galaxy

2) Observations of the ISM close to a source of Cosmic-ray “production”

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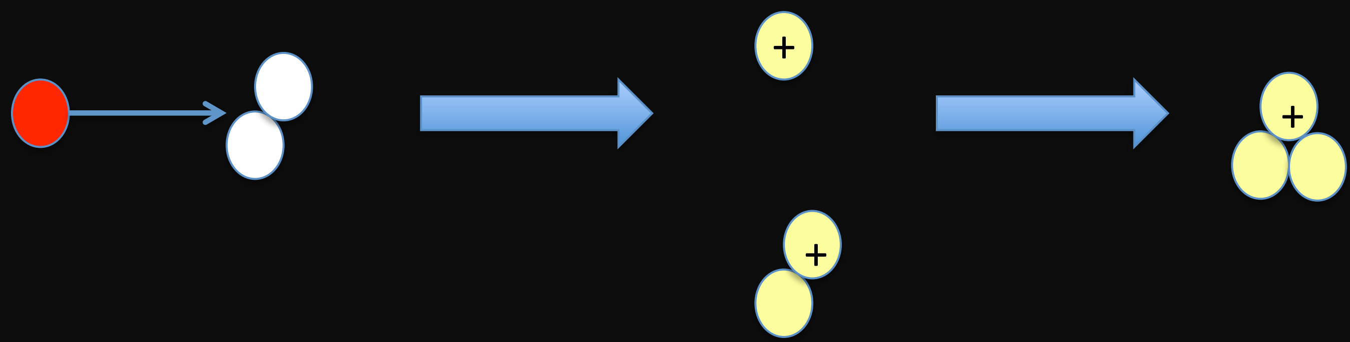
Cosmic-ray Ionization and chemistry: observations

0. Intruductive remarks

REMARK 1: REMINDER

THE INTERACTION CRs – MCs: CREATION OF H_3^+

THE STARTING POINT OF THE INTERSTELLAR CHEMISTRY IS THE CRs INTERACTION WITH H AND H_2 WHICH CREATES THE ION H_3^+



IN ASTROCHEMISTRY, ALL THE CR-ISM PROCESS IS REDUCED TO THE CRs IONIZATION RATE, ζ

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REMARK 2: DEFINITION

TWO TYPES OF CLOUDS, DEPENDING ON THEIR COLUMN DENSITY (~DENSITY)

DIFFUSE CLOUDS	DENSE CLOUDS
Av<5mag	Av>5mag

→A DIFFERENT INFLUENCE OF THE IS UV PHOTONS ON THE CLOUD CHEMISTRY

→ A DIFFERENT METHOD TO MEASURE THE CRs IONIZATION RATE, ζ

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1) Observations of the ISM in the Galaxy

1.1 DIFFUSE CLOUDS

1.2 DENSE CLOUDS

HOW TO MEASURE ζ IN DIFFUSE CLOUDS: 1) observations of H_3^+

ζ IS DERIVED BY MEASURING THE H_3^+ DENSITY.
At equilibrium it holds (e.g. Geballe et al. 1999):

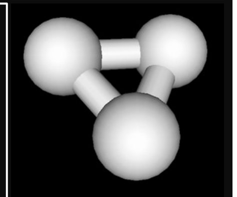
$$n(\mathrm{H}_2)\zeta_2 = k_e n(\mathrm{H}_3^+)\, n(e)$$

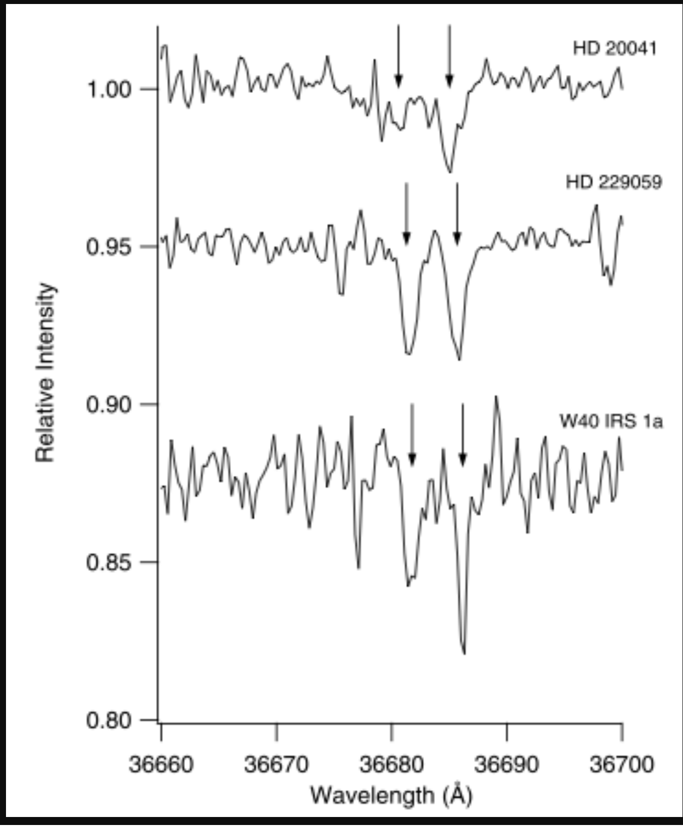
$$\zeta_2 = N(\mathrm{H}_3^+)\frac{k_e}{L}\frac{n(e)}{n(\mathrm{H}_2)}$$

$n(e)=\mathcal{A}_C$ (for diffuse clouds),
$n(H_2)$ and L are measured by other astro-observations,
k_e is measured in laboratory

HOW TO MEASURE ζ IN DENSE MCs: 1) observations of H_3^+

THE DIFFICULTY OF THE METHOD: OBSERVING H_3^+ !
BEING A SYMMETRIC MOLECULE IT DOESN'T HAVE A PERMANENT DIPOLE → OBSERVABLE ONLY VIA THE ROTO-VIBRATIONAL TRANSITIONS IN THE IR





OBSERVATIONS ARE MADE IN ABSORPTION AGAINST IR BRIGTH SOURCES
(in specific directions only)

Indriolo, Geballe, Oka, McCall 2007

HOW TO MEASURE ζ IN DENSE MCs: 1) observations of H_3^+

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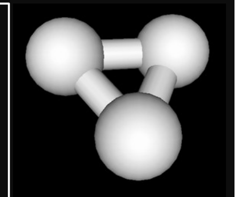

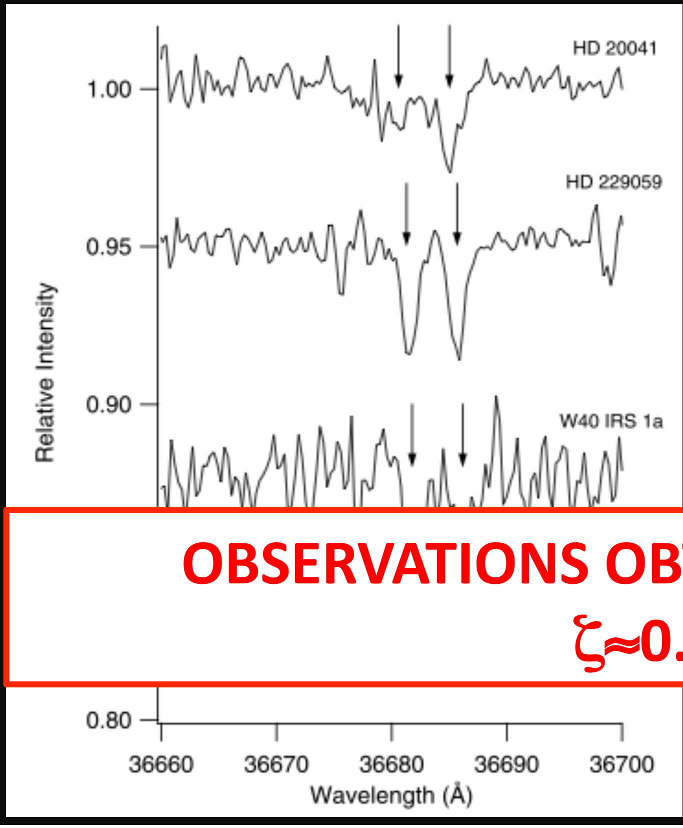

OBSERVATIONS ARE MADE IN ABSORPTION AGAINST IR BRIGTH SOURCES
(in specific directions only)

OBSERVATIONS OBTAINED TOWARDS ~20 LOS
$\zeta \approx 0.5\text{-}3 \times 10^{-16} s^{-1}$

Indriolo, Geballe, Oka, McCall 2007

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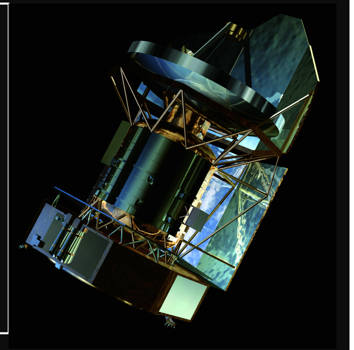
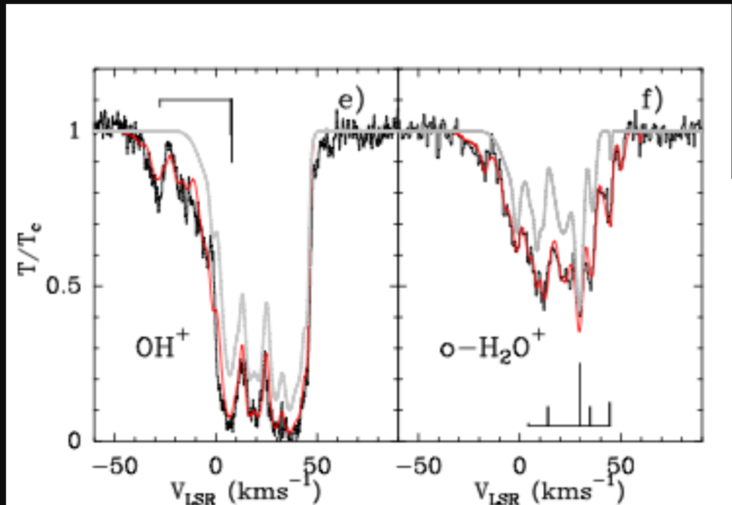
HOW TO MEASURE ζ IN DENSE MCs: 2) observations of OH^+ and OH_2^+

1.1 Diffuse clouds

THE DIFFICULTY OF THE METHOD: ROTATIONAL TRANSITIONS WHERE THE EARTH ATMOSPHERE IS OPAQUE!

FIRST OBSERVATIONS WITH HERSCHEL IN 2010





OBSERVATIONS ARE MADE IN ABSORPTION AGAINST FIR BRIGTH SOURCES
(in specific directions only)

OBSERVATIONS OBTAINED TOWARDS FEW LOS
$\zeta \approx 0.6\text{-}3 \times 10^{-16} s^{-1}$

Gerin et al. 2010, Neufeld et al. 2010, 2011

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HOW TO MEASURE ζ IN DENSE CLOUDS: the DCO^+/HCO^+ ratio

ζ IS DERIVED BY MEASURING THE ELECTRON DENSITY *n(e)*

n(e) IS DERIVED BY OBSERVATIONS OF THE DCO^+/HCO^+ RATIO (e.g. Guelin et al. 1997):

$$HCO^+ \leftarrow CO + H_3^+$$
$$DCO^+ \leftarrow CO + H_2D^+$$

$$\frac{DCO^+}{HCO^+} = \frac{H_2D^+/H_3^+}{3 \cdot (1 + \frac{2}{3} \cdot H_2D^+/H_3^+)}$$

$$\frac{H_2D^+}{H_3^+} = [D]\frac{2k_{form}}{k_e x_e + k_{CO} x_{CO} + k_{form} e^{220/kT}}$$

HOW TO MEASURE ζ IN DENSE CLOUDS: the DCO^+/HCO^+ ratio

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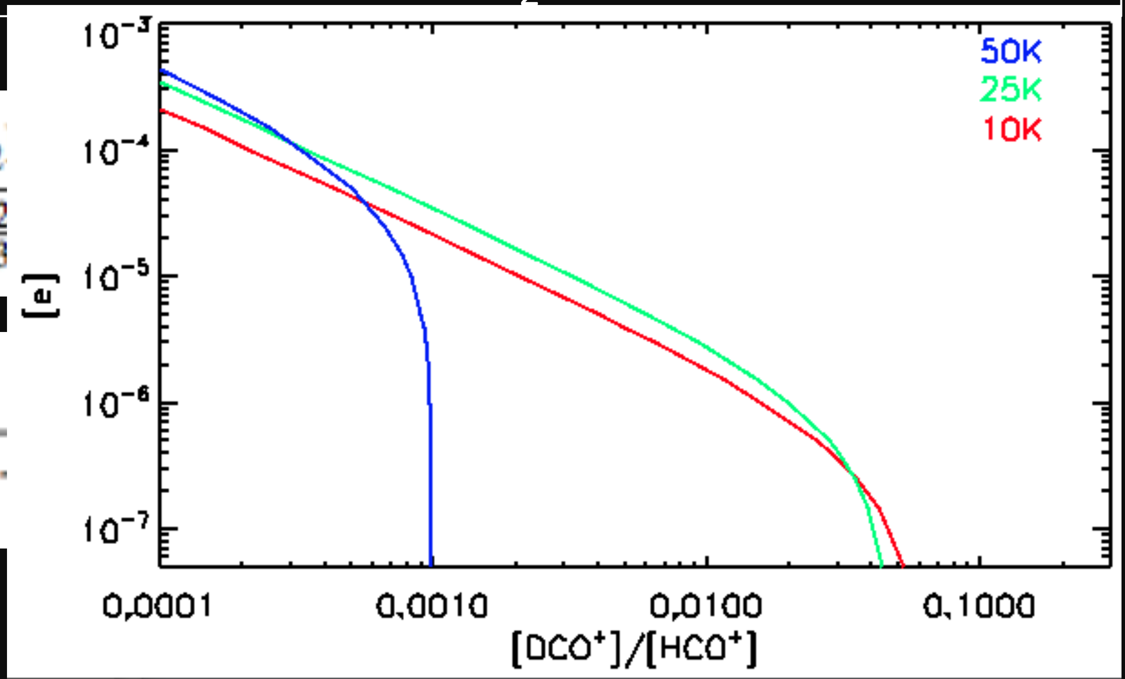
$$DCO^+ \leftarrow CO + H_2D^+$$

$$\frac{DCO^+}{HCO^+} = \frac{H_2 \ldots}{3 \cdot (1 + \frac{2}{3} \ldots}$$

$$\frac{H_2D^+}{H_3^+} = [D] \frac{\ldots}{k_e x_e \ldots}$$



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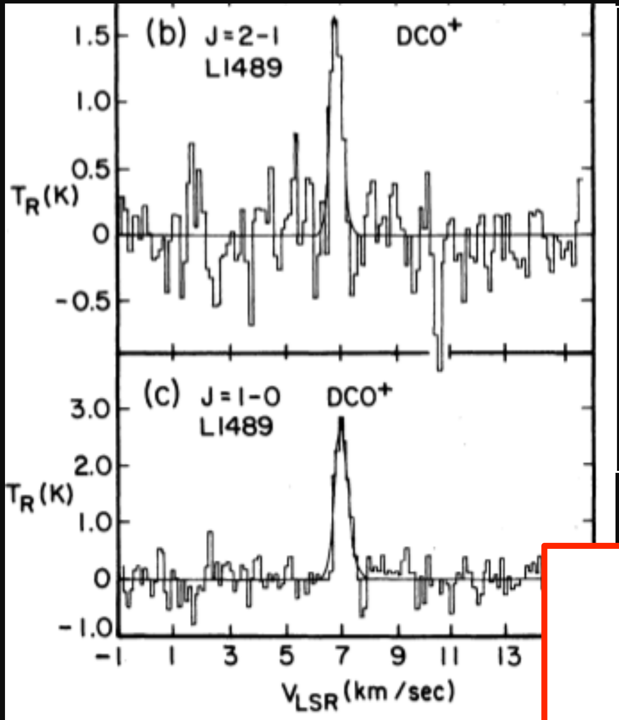
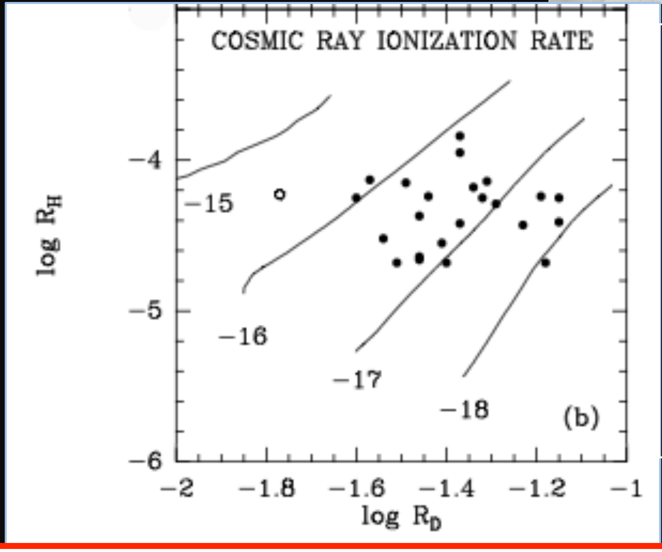
HOW TO MEASURE ζ IN DENSE CLOUDS: the DCO^+/HCO^+ ratio

BOTH HCO^+ AND DCO^+ HAVE NICE ROTATIONAL TRANSITIONS IN THE MILLIMETER WHICH CAN BE OBSERVED WITH GROUND TELESCOPES



Butner et al. 1995



Caselli et al. 1998

OBSERVATIONS OBTAINED TOWARDS SEVERAL SOURCES
$\zeta \approx 0.1\text{-}5 \times 10^{-17} s^{-1}$

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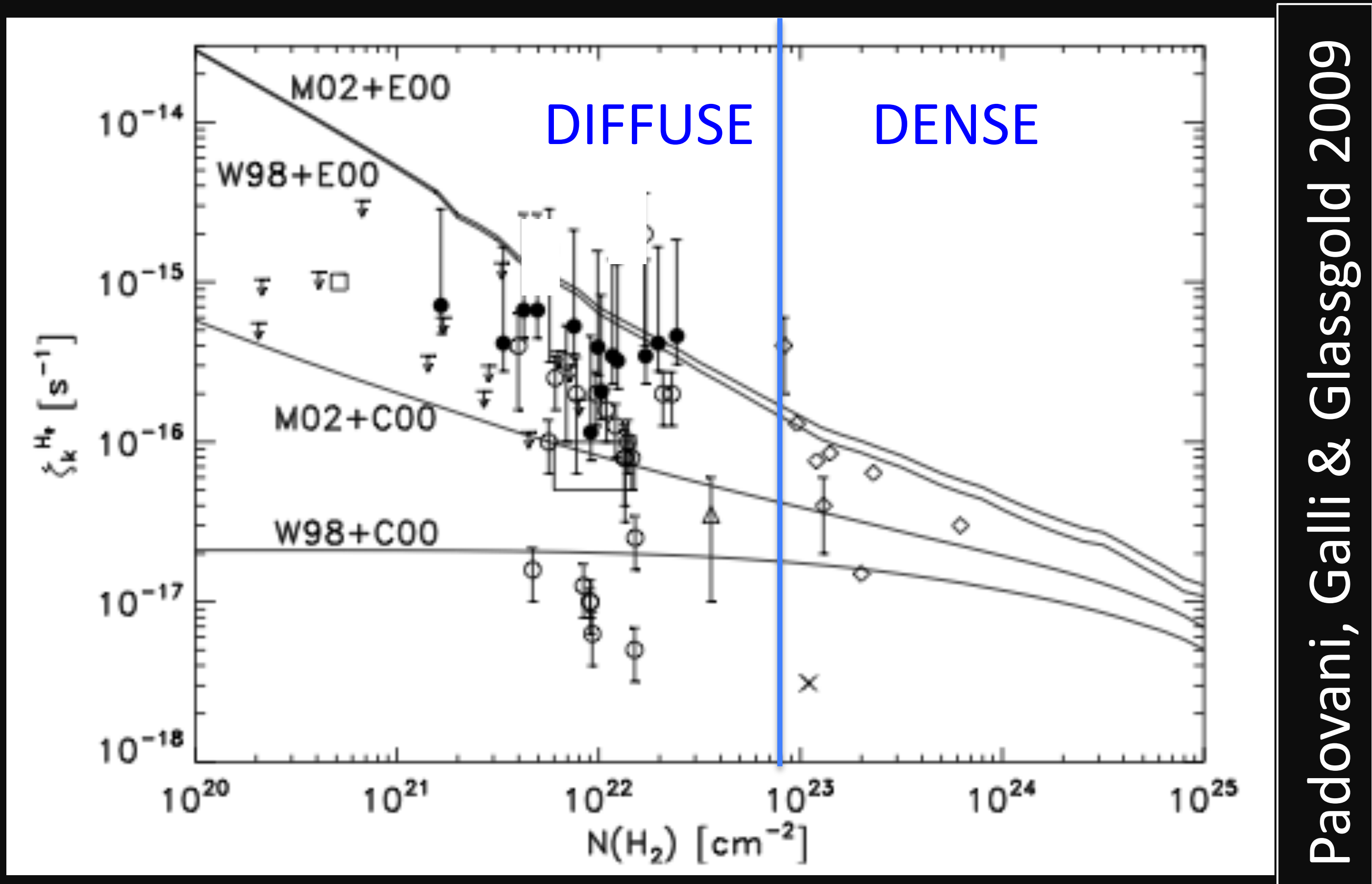
RECENT COMPILATION OF THE DERIVED CRs IONIZATION RATE ζ IN THE ISM



Diffuse clouds: $\zeta \approx 0.5\text{-}3 \times 10^{-16} s^{-1}$
Dense clouds: $\zeta \approx 0.1\text{-}5 \times 10^{-17} s^{-1}$

2) Observations of the ISM close to a source of Cosmic-ray "production"

2.1 WHERE TO LOOK FOR?

2.2 DIFFUSE CLOUDS

2.3 DENSE CLOUDS

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2) Observations of the ISM close to a source of Cosmic-ray "production": where to look for?

Theories predict that the collisions between cosmic rays with energies ≥GeV and the hydrogen atoms of the interstellar medium would produce γ-rays by π^0-meson decay (Hayakawa 1952…).

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

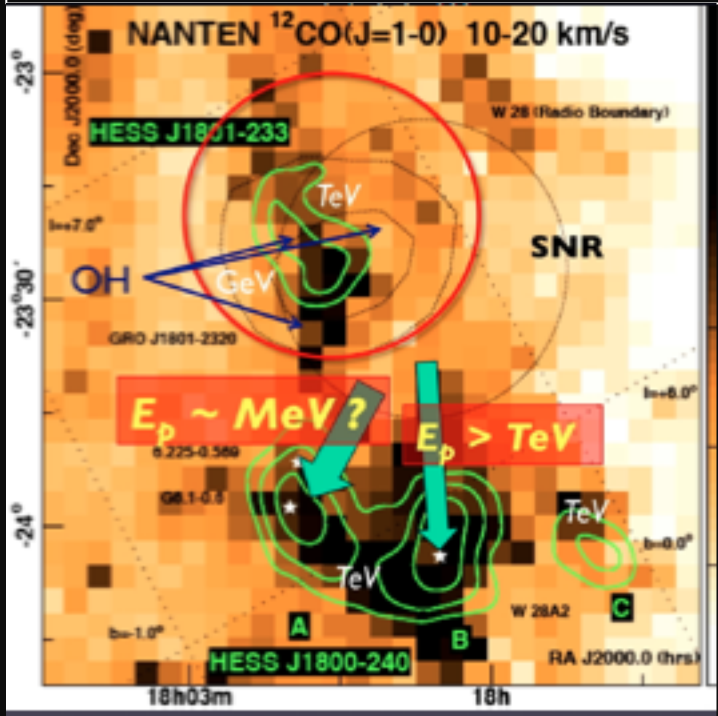
$$F_\gamma = q_\gamma \frac{M_{\rm cloud}}{m_p 4\pi d^2}$$

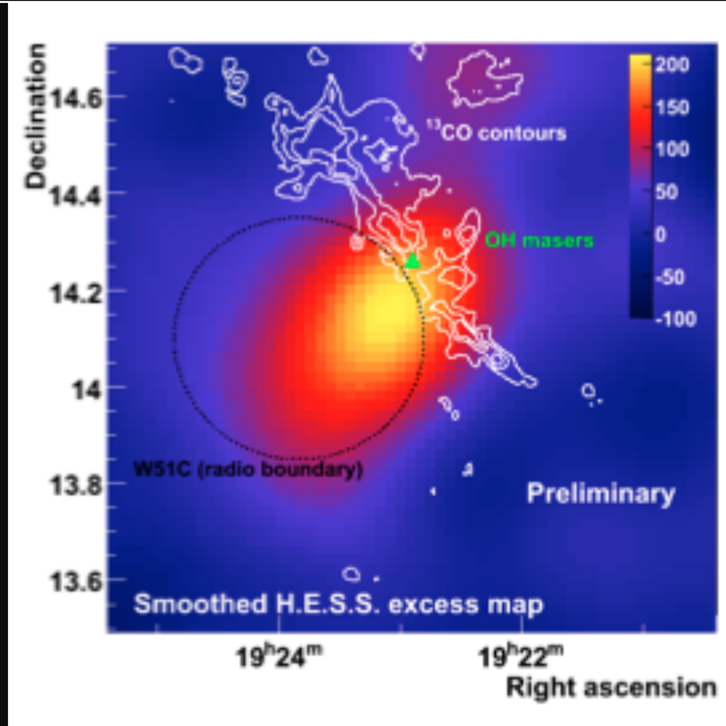
The larger the cloud mass the larger the γ-rays flux.
The smaller the distance from the CRs accelerating shock larger the γ-rays flux.

MOLECULAR CLOUDS ASSOCIATED WITH BRIGHT γ-RAY SOURCES LIKELY PROBE ENHANCED COSMIC RAYS DENSITY

Tev sources and MCs

New observations of HESS, MAGIC and FERMI-LAT have revealed several TeV sources in proximity of MCs.





IS THE TeV EMISSION ASSOCIATED DUE TO π^0-MESON DECAY ? => ENHANCED CRs FLUX ? => ENHANCED GAS IONIZATION ?

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2.1 Observations of the ISM close to a source of Cosmic-ray “production site”

SEVERAL SURVEYS TO IDENTIFY MCs CLOSE TO γ-RAYS SOURCES

STRATEGY:
LOOK FOR CO EMISSION SPATIALLY CONCIDENT WITH THE γ-RAYS EMISSION

RESULTS:
SEVERAL POTENTIAL MCs HAVE BEEN IDENTIFIED

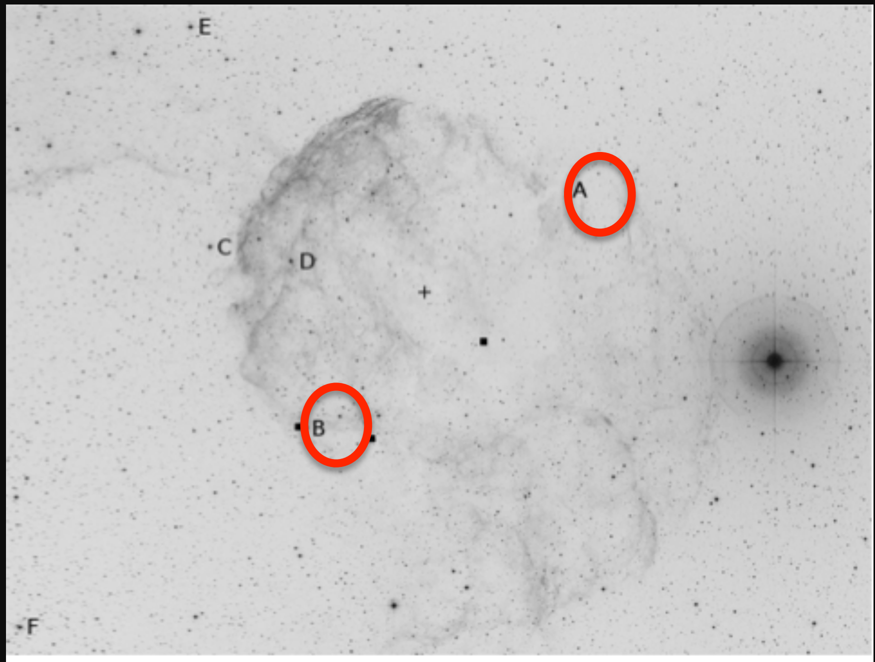
NEXT STEP:
DEMONSTRATE THE INTERACTION, NAMELY THE INCREASED IONIZATION DEGREE

Cosmic-ray Ionization and chemistry: observations

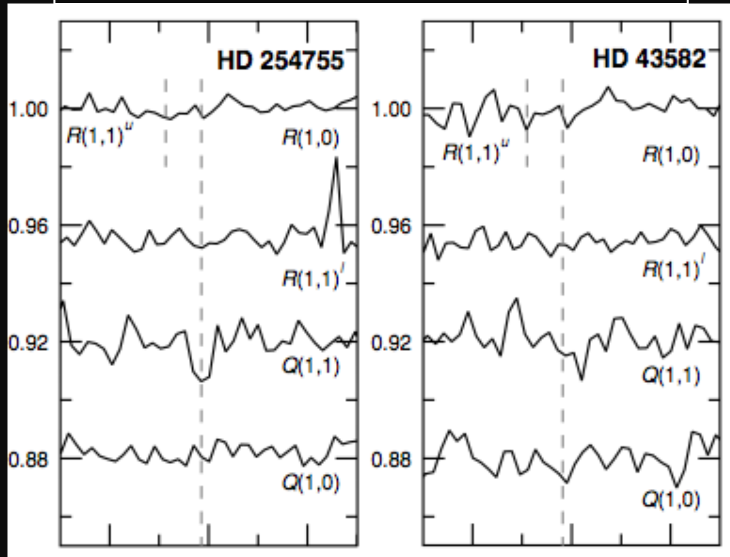
MEASURING THE IONIZATION IN DIFFUSE MCs CLOSE TO IC443

Indriolo, Blake, Goto, Usuda, Oka, Geballe, Fields, McCall ApJ 2010

2.2 Diffuse clouds



OBSERVATIONS OF H_3^+ TOWARDS 6 LOS



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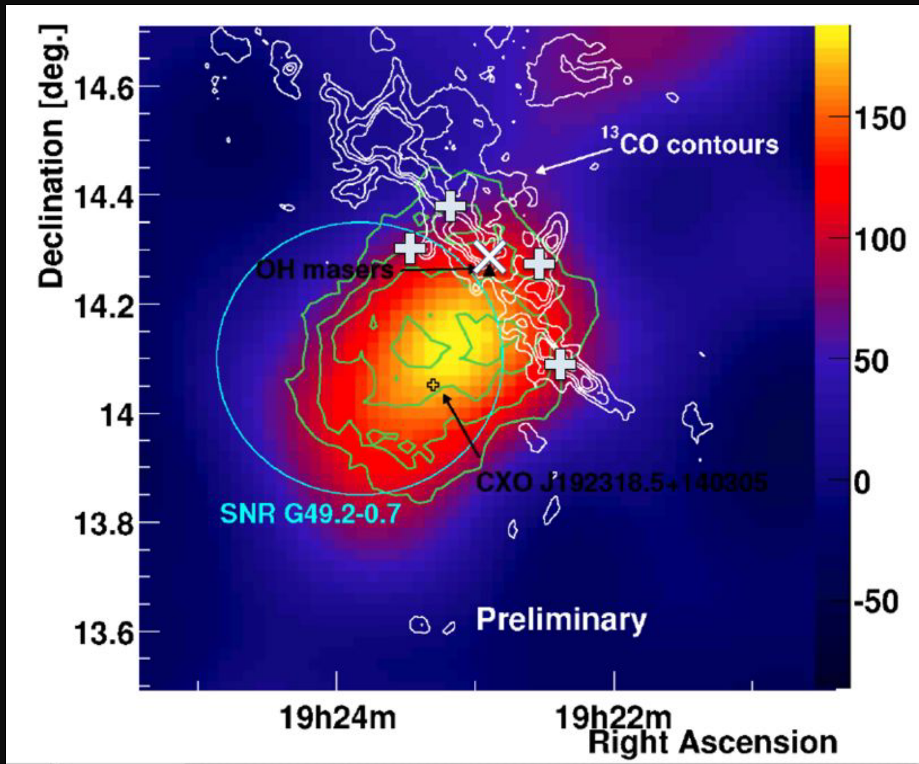
IN TWO OF THEM, MEASURED $\zeta \approx 2 \times 10^{-15} s^{-1}$, namely ≈5 TIMES LARGER THAN THE AVERAGE VALUE

MEASURING THE IONIZATION IN DENSE MCs CLOSE TO W51C

Ceccarelli, Hily-Blant, Montmerle, Dubus, Gallant & Fiasson (ApJL submitted)

W51C is a SNR associated with bright TeV emission.
A molecular cloud overlaps partially with the observed TeV emission.



OBSERVATIONS OF 6 LINES:
$C^{18}O$, ^{13}CO 1-0, 2-1
$H^{13}CO^+$ AND DCO^+ 1-0

TOWARDS FIVE POSITIONS

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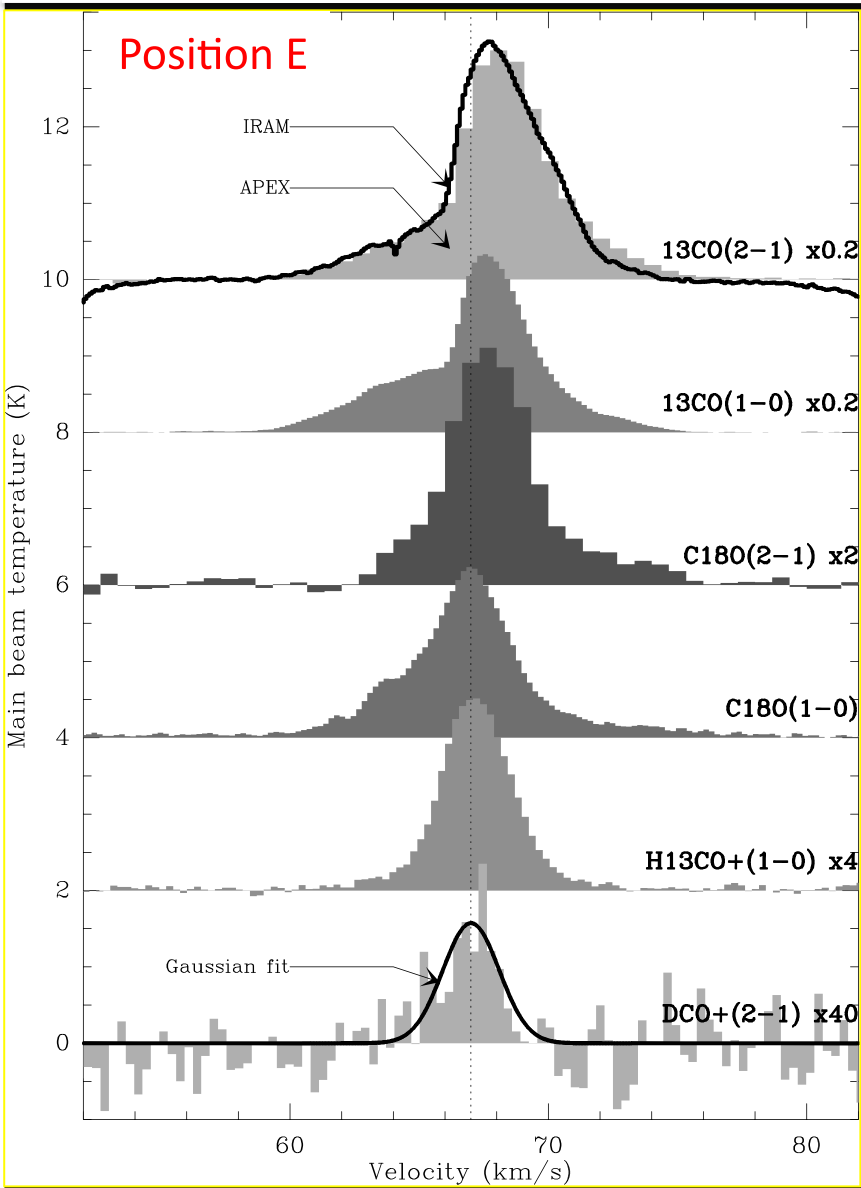
MEASURING THE IONIZATION IN DENSE MCs CLOSE TO W51C

2.3 Dense clouds



DETECTION OF DCO^+ TOWARDS POINT E

↓

POSSIBILITY TO MEASURE THE CRs IONIZATION RATE

STRINGENT UPPER LIMITS ON THE OTHER FOUR POINTS

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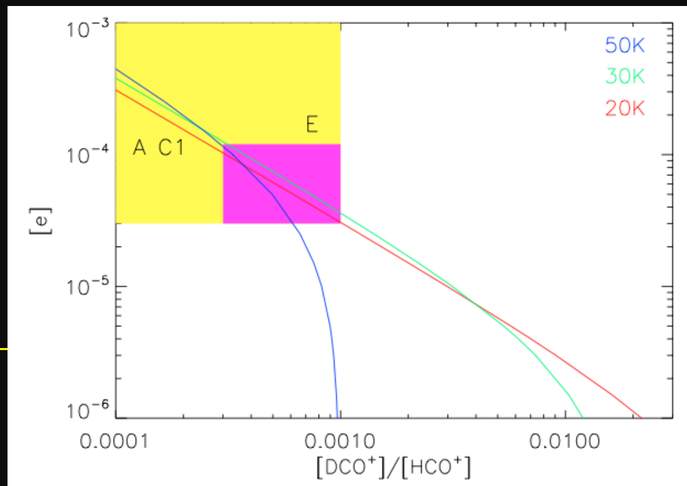
MEASURING THE IONIZATION IN DENSE MCs CLOSE TO W51C : the point E

1- PHYSICAL PARAMETERS (^{13}CO and $C^{18}O$ lines):

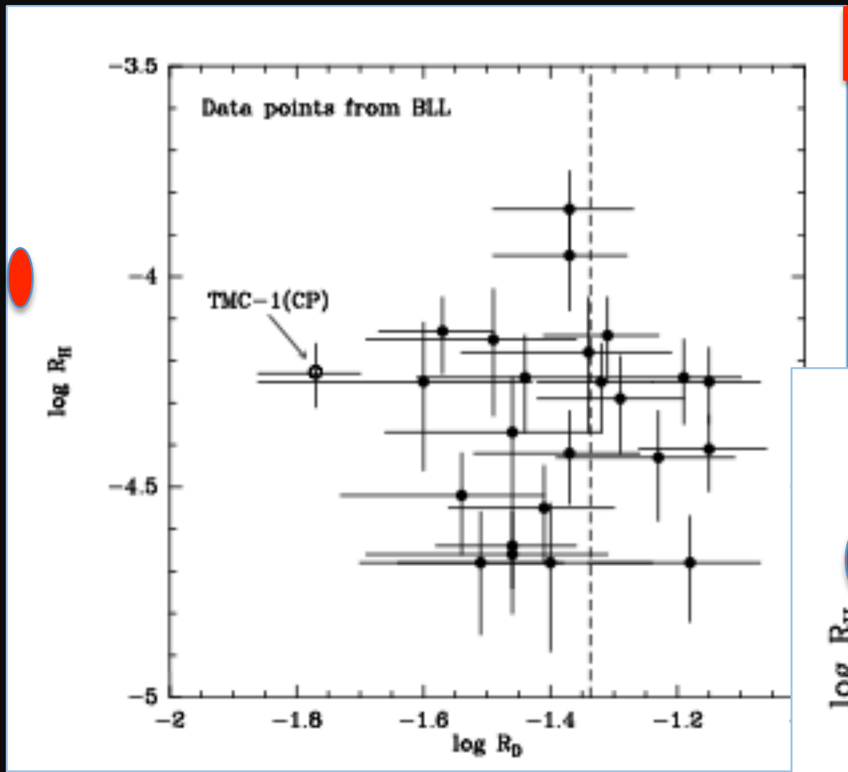
- T_{gas}=21-24 K
- dens=0.8-2 x10^4cm^{-3}
- N($C^{18}O$)=3.9-4.1 x10^{15}cm^{-2}
- Av=19-21mag

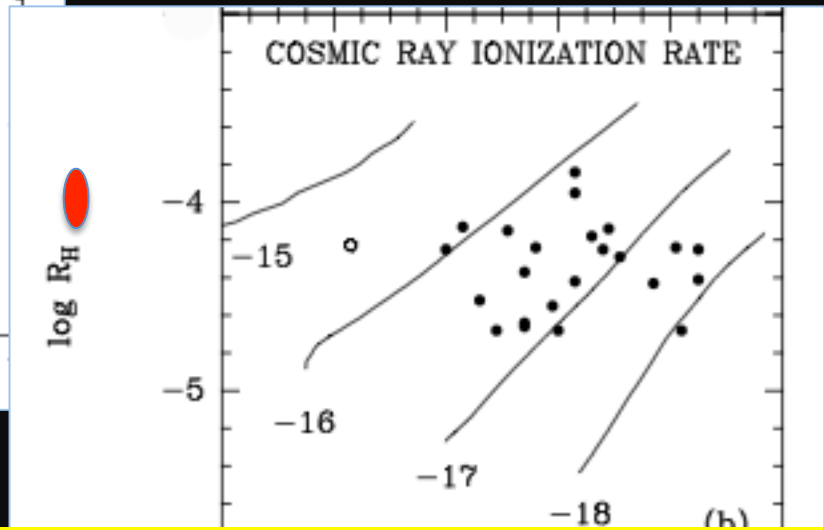
2- IONIZATION DEGREE ($H^{13}CO^+$ and DCO^+ lines):

- DCO^+/HCO^+=1.2-1.6 x10^{-3}
- -> x(e)>10^{-5}
- (based on the simple analytical formula)



POINT E: comparison with the Caselli's sample





R_H=[HCO^+]/[CO]
R_D=[DCO^+]/[HCO^+]

POINT E: $R_H=10^{-4}$, $R_D=10^{-3}$

POINT E IS DEFINITIVELY A PECULIAR, IONIZED REGION

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2.3 Dense clouds

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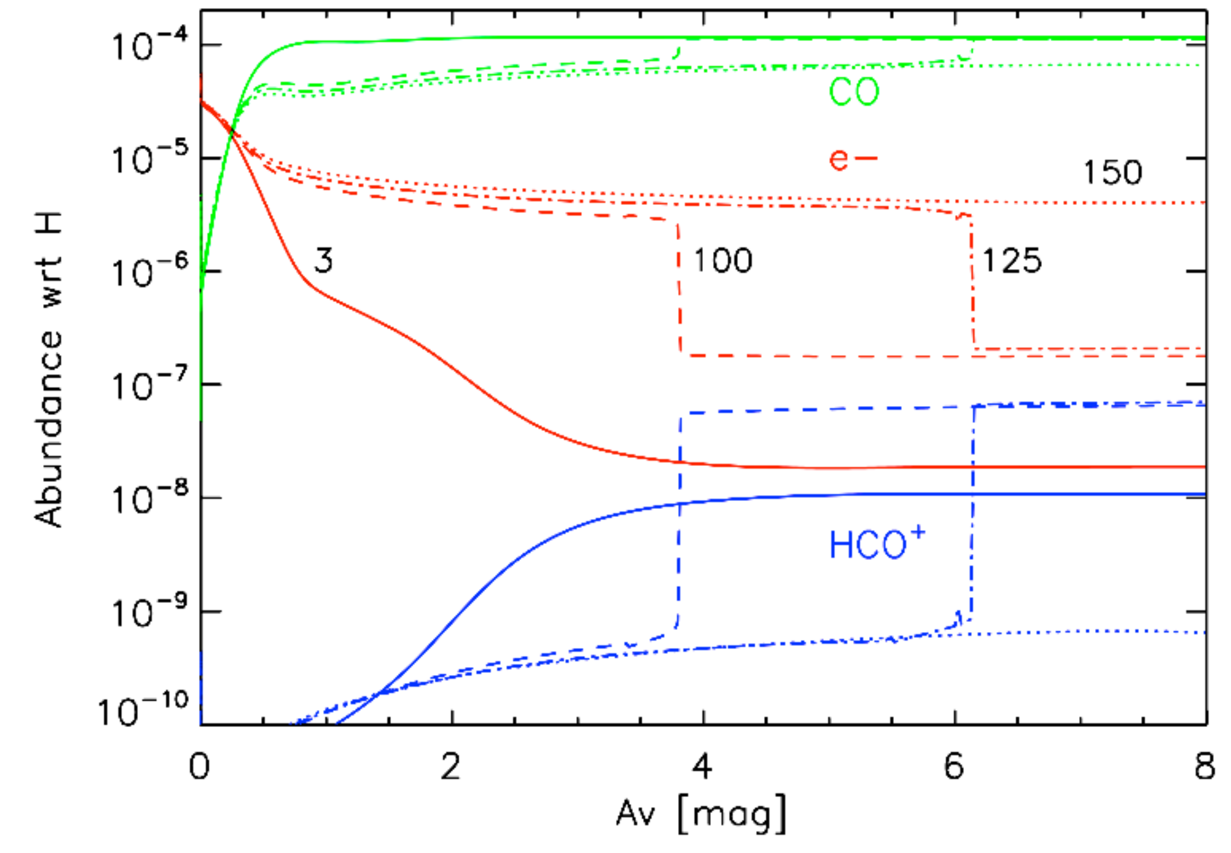
POINT E: WHAT'S GOING ON? some LIGHT from PDR* MODELS

*PDR = Photo-Dissociation Region

PREDICTED STRUCTURE OF THE OBSERVED CLOUD



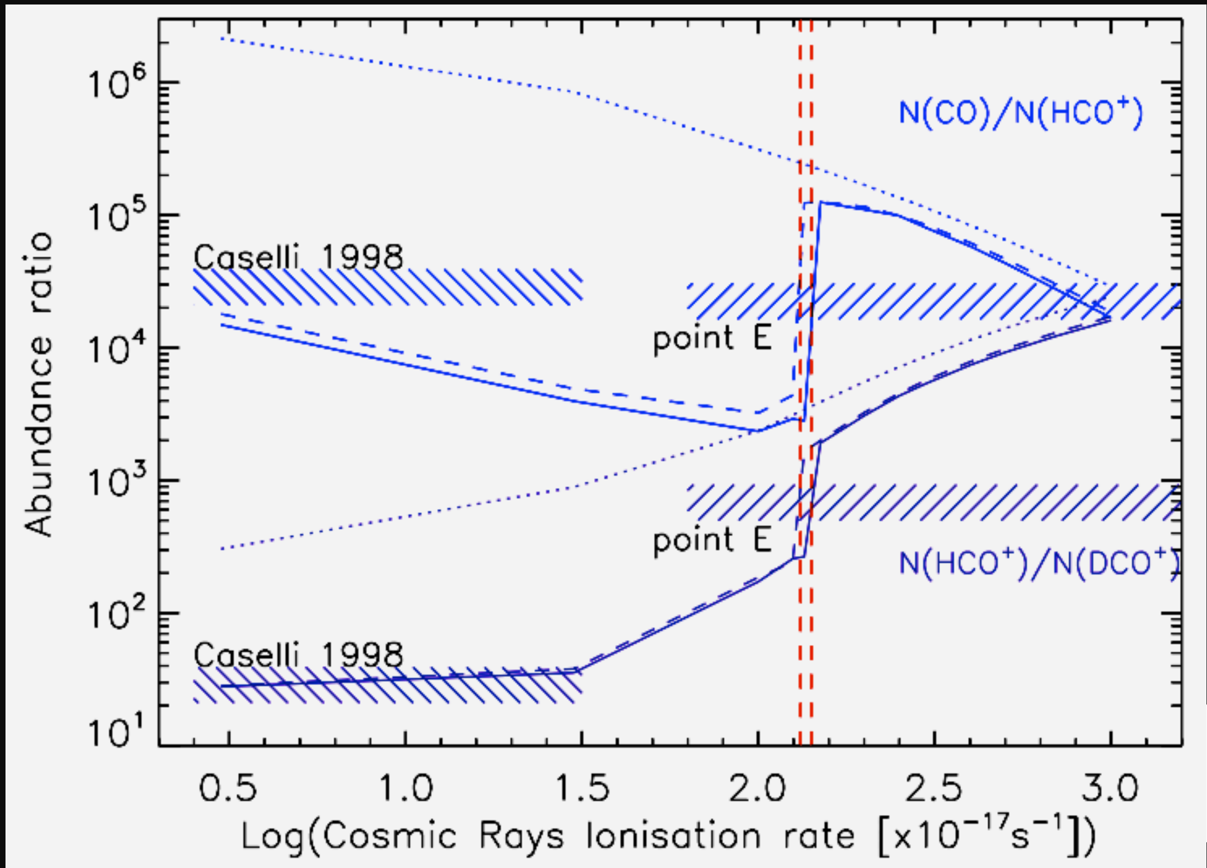
FOR DIFFERENT VALUES OF ζ ($x10^{-17}s^{-1}$)

(assumed low metallicity)

Meudon PDR model

POINT E: WHAT'S GOING ON? some LIGHT from PDR MODELS

COMPARISON MODEL PREDICTIONS vs OBSERVATIONS



AS A FUNCTION OF ζ and for different metal (S, Mg, Fe, Si…) abundances

Meudon PDR model

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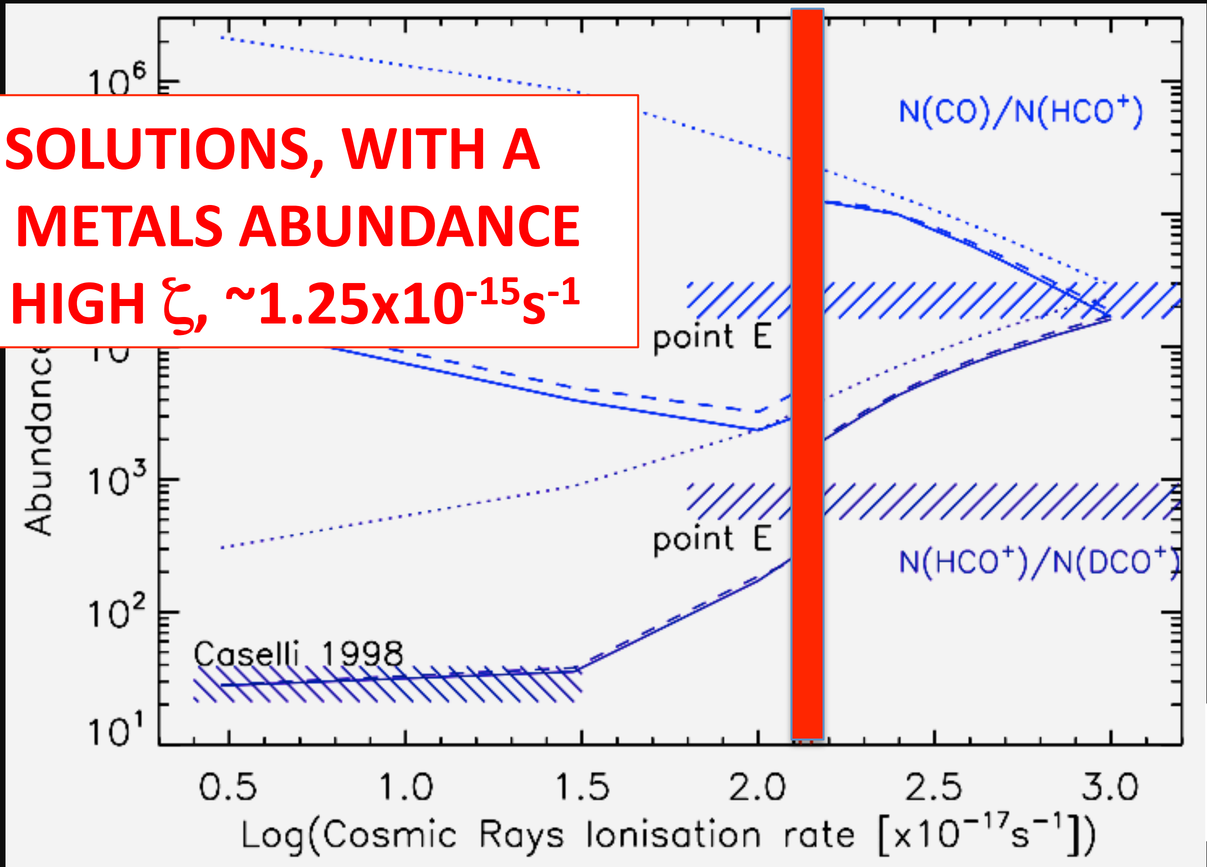
POINT E: WHAT'S GOING ON? some LIGHT from PDR MODELS

COMPARISON MODEL PREDICTIONS vs OBSERVATIONS

ONE SOLUTIONS, WITH A LOW METALS ABUNDANCE AND HIGH ζ, ~$1.25\times10^{-15}s^{-1}$



AS FUNCTION OF ζ and for different metal abundances

Meudon PDR model

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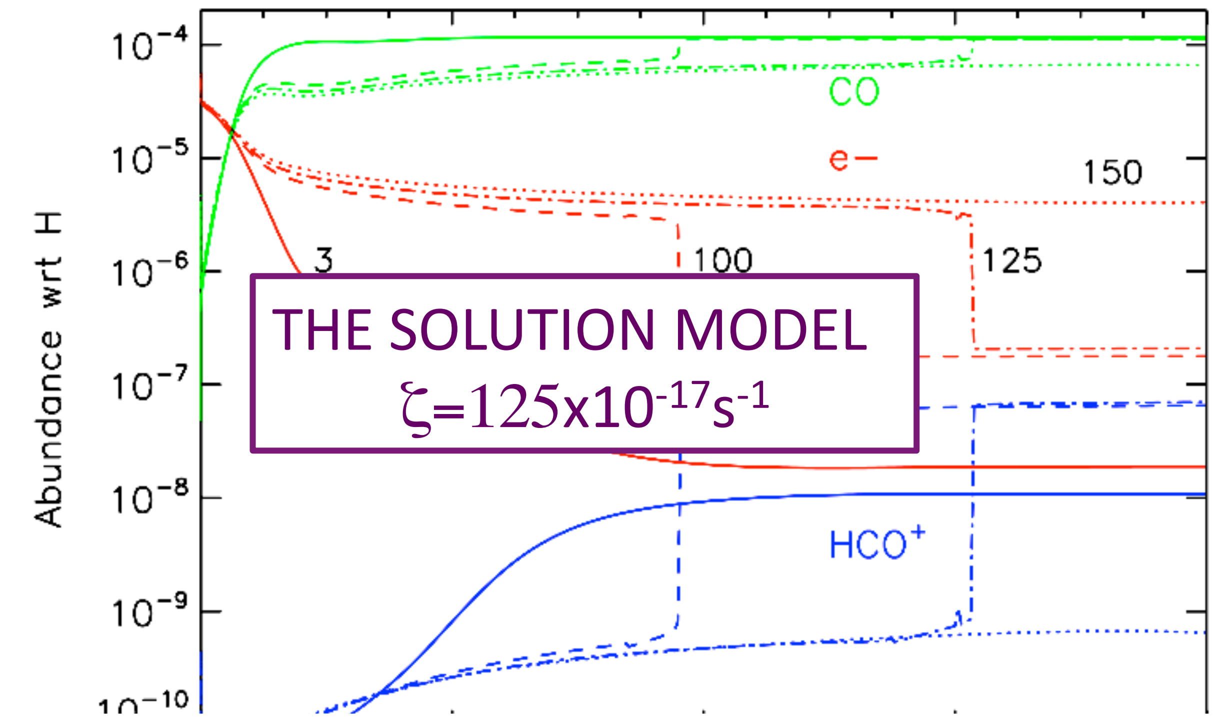
POINT E: WHAT'S GOING ON? some LIGHT from PDR MODELS

2.3 Dense clouds

PREDICTED STRUCTURE OF THE OBSERVED CLOUD



THE SOLUTION MODEL
$\zeta = 125 \times 10^{-17} s^{-1}$

FOR DIFFERENT VALUES OF ζ ($\times 10^{-17} s^{-1}$)

(assumed low metallicity)

TOWARDS POINT E, MEASURED $\zeta \approx 1.2 \times 10^{-15} s^{-1}$, namely ≈100 TIMES LARGER THAN THE AVERAGE VALUE

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SUMMARY

THE COSMIC RAYS IONIZATION RATE ζ IS:

A) IN MOLECULAR CLOUDS OF THE GALAXY
   1. DIFFUSE => average $\zeta \approx 4 \times 10^{-16} s^{-1}$
   2. DENSE => average $\zeta \approx 1 \times 10^{-17} s^{-1}$

B) IN MOLECULAR CLOUDS CLOSE TO COSMIC RAYS PRODUCTION SITES
   1. DIFFUSE => $\zeta \approx 1.6 \times 10^{-15} s^{-1}$, i.e. ≈5 times A
   2. DENSE => $\zeta \approx 1.2 \times 10^{-15} s^{-1}$, i.e. ≈100 times A

DISCOVERED SITES WHERE THE INTERACTION BETWEEN CR and ISM TAKES PLACES
=> INCREASE OF THE LOW ENERGY CR FLUX

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