CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

Measuring the cosmic rays and energetic particle sources/flux by observing galactic and extragalactic molecules

C. Ceccarelli

Université Grenoble Alpes / CNRS-INSU

Institut de Planétologie et d'Astrophisique de Grenoble (IPAG)

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CR: why they interest me

1- IN MOLECULAR CLOUDS, CR (=>IONS) ARE AT THE ORIGIN OF THE CHEMISTRY

2- CR (=>IONS AFFECT THE STAR AND PLANET FORMATION PROCESS (e.g. VIA AMBIPOLAR DIFFUSION AND MAGNETO-ROTATIONAL INSTABILITIES)

3- CR GOVERN THE STAR FORMATION IN REGIONS HIGHLY ILLUMINATED BY CR, LIKE AROUND AGNs

IPAG
Institut de Planétologie
et d'Astrophysique
de Grenoble

CR=
Cosmic Rays

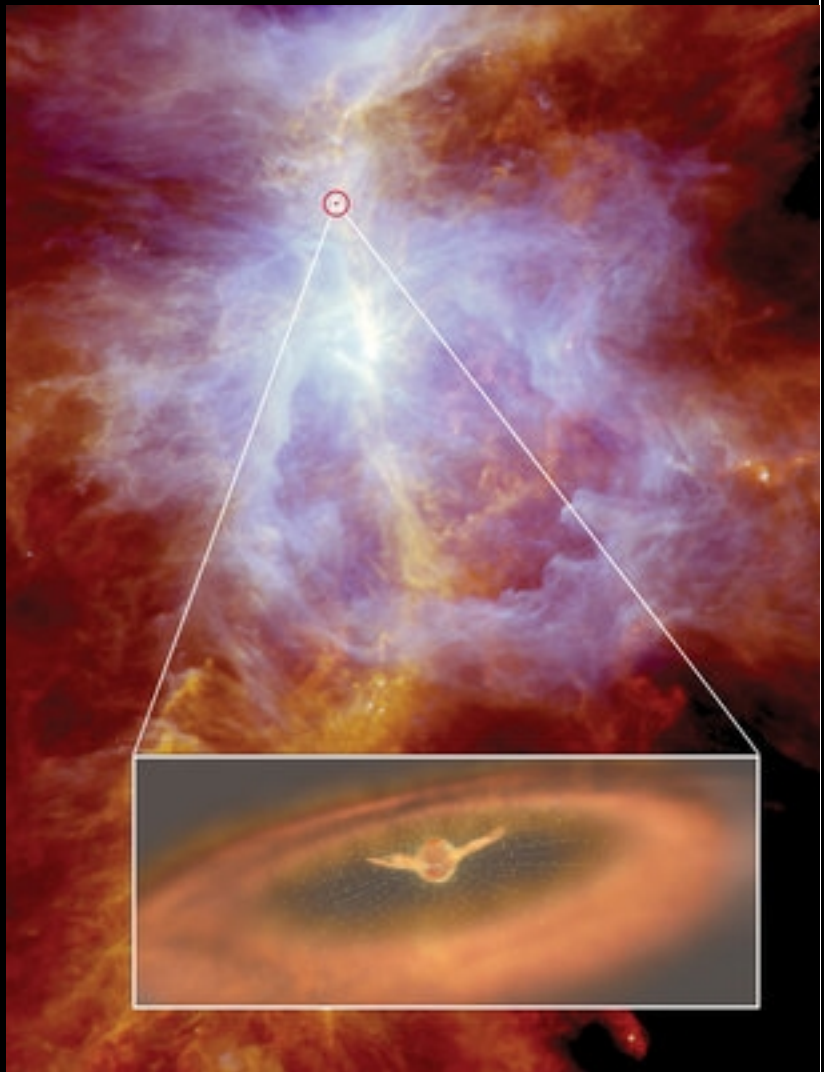
PEW=
Protostellar
Energetic
Winds

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

PROTOSTELLAR ENERGETIC WINDS

The birth of a star is all but a peaceful process



1) NEWBORN STARS ARE INTENSE X-RAY SOURCES (e.g., Feigelson & Montmerle 1999);

2) UV PHOTONS **ARE** EMITTED BY VIOLENT SHOCKS CAUSED BY THE GAS FALLING ONTO THE FUTURE STAR;

3) MATTER IS EJECTED AT SUPERSONIC SPEEDS IN PROTOSTELLAR OUTFLOWS;

4) INDIRECT EVIDENCE OF ENERGETIC (>MeV) PARTICLES WINDS: e.g. RADIO BURST BEFORE X-RAY FLARES

=> INFLUENCE ON THE STAR AND PLANET FORMATION

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

Introduction

C.Ceccarelli
Santa
Barbara
2016

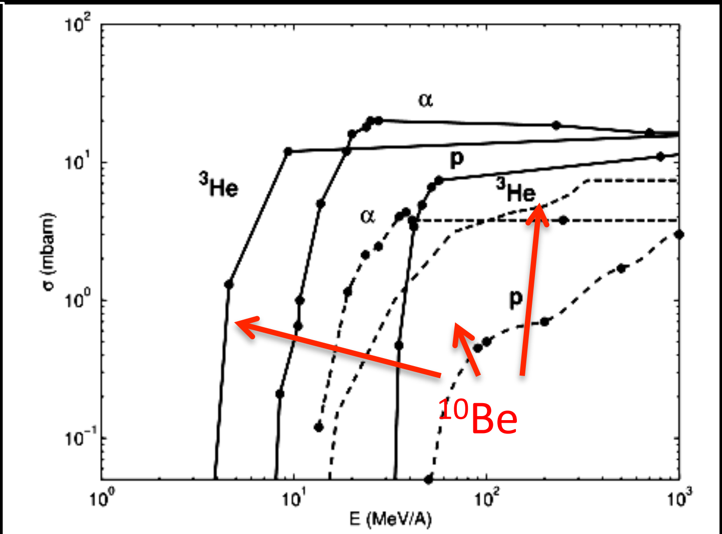
The birth of the Sun was not easy:

A VIOLENT START IN A CROWDED ENVIRONMENT

Adams 2010 ARAA, Dauphas & Chaussidon 2011 AREPS, Caselli & Ceccarelli 2012 RAA

AN IMPORTANT CLUE:
TRACES OF ENHANCED ABUNDANCES OF SHORT LIVED RADIONUCLEIDES (SLR) IN METEORITIC MATERIAL (CAI): ^{10}Be
(Meyer & Clayton 2000; Chaussidon et al. 2006)

^{10}Be = PRODUCTED BY SPALLATION REACTIONS OF ENERGETIC (>10 MeV) PARTICLES WITH O AND C ATOMS OF THE SURROUNDING MATERIAL:
➔INFERRED 10^{19}-10^{20} p/cm^2
(Gounelle et al. 2001, 2013)



CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

Introduction

WHAT COSMIC RAYS and PROTOSTELLAR ENERGETIC WINDS HAVE IN COMMON?

THE DIRECT DETECTION OF THEIR ACCELERATION SOURCES IS IMPOSSIBLE BECAUSE CHARGED PARTICLES ARE SCATTERED IN THE GALAXY BY THE MAGNETIC FIELDS

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

MeV-TeV particles - gas interaction

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

HOW TO CATCH THE CR AND PEW SOURCES?

LOOK AT THE INTERACTION OF
MeV-TeV PARTICLES
WITH THE GAS
(IN THE IMMEDIATE VICINITY)

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

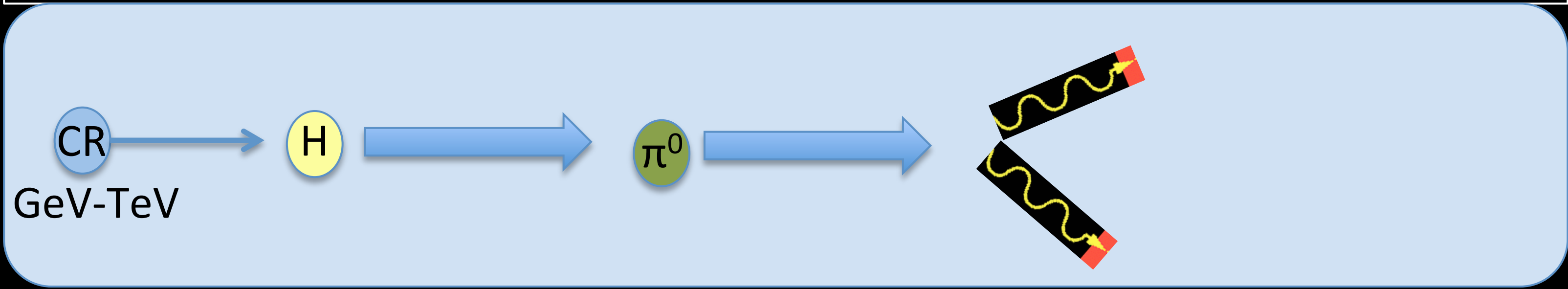
MeV-TeV particles - gas interaction

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

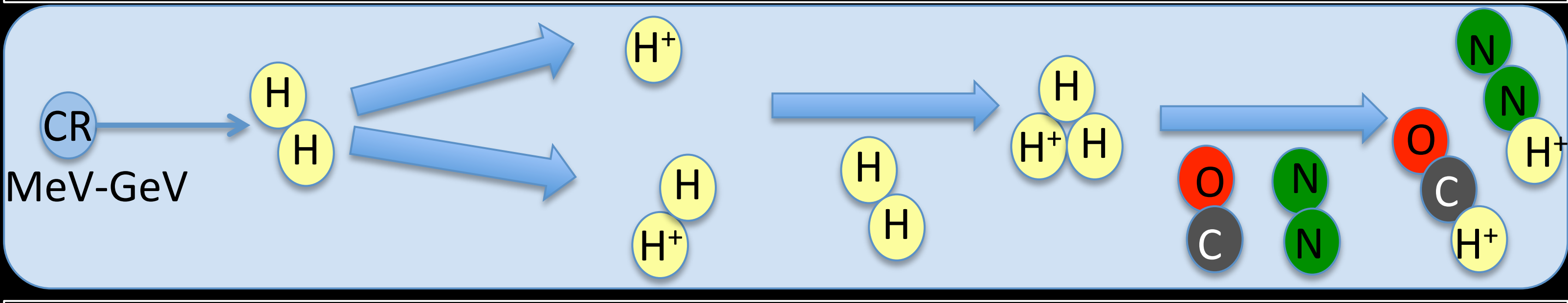
C.Ceccarelli
Santa Barbara
2016

THE MeV-TeV PARTICLES – GAS INTERACTION

1- WHEN GeV-TeV PARTICLES HIT ATOMS THEY CREATE γ-ray PHOTONS BY DECAY OF π^0-MESONS



2- MeV-GeV PARTICLES IONIZE THE GAS (H_2^+ , H^+), EVENTUALLY CREATING H_3^+ MOLECULES THAT TRANSMIT THE CHARGE TO OTHER SPECIES



3- MeV-GeV CR HEAT THE GAS

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

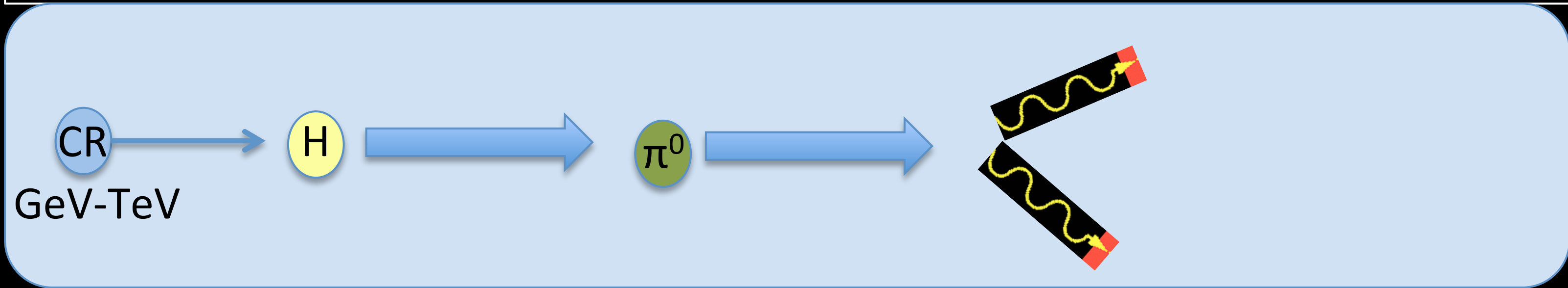
MeV-TeV particles - gas interaction

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

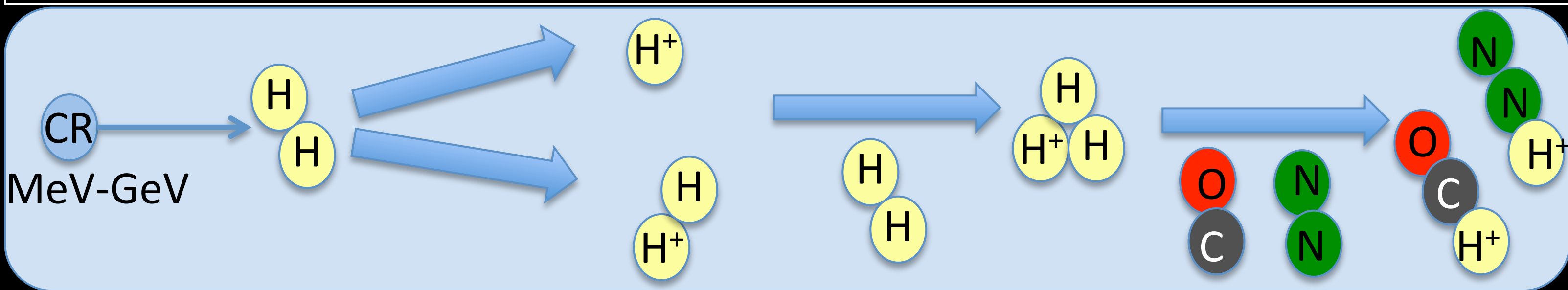
C.Ceccarelli
Santa Barbara
2016

THE MeV-TeV PARTICLES — OBSERVATIONS

1- WHEN GeV-TeV PARTICLES HIT ATOMS THEY CREATE γ-ray PHOTONS BY DECAY OF π^0-MESONS



2- MeV-GeV PARTICLES IONIZE THE GAS (H_2^+ , H^+), EVENTUALLY CREATING H_3^+ MOLECULES THAT TRANSMIT THE CHARGE TO OTHER SPECIES



~~3- MeV-GeV CR HEAT THE GAS: TOO "GENERIC"~~

CR=
Cosmic Rays

PEW=
Protostellar Energetic Winds

MeV-TeV particles - gas interaction

THE MeV-TeV PARTICLES

OBSERVATIONS

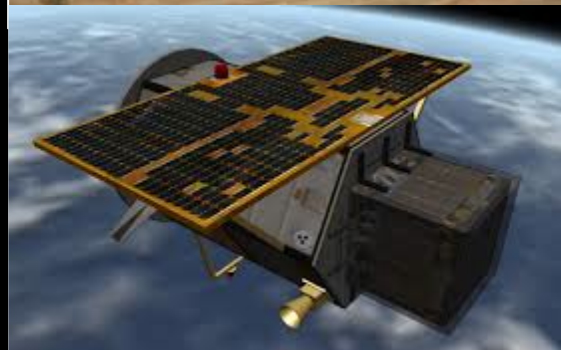
1) γ-ray EMISSION

>280MeV PARTICLE + p_{gas} → π^0 → 2γ

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

The γ-ray flux F_γ is

- proportional to the flux of >280MeV particles q_γ ;
- proportional to the cloud mass M_{cloud} ;
- inversely proportional to the distance *d* from the >280MeV particles accelerating shock.



BUT NOT UNIQUE

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

MeV-TeV particles - gas interaction

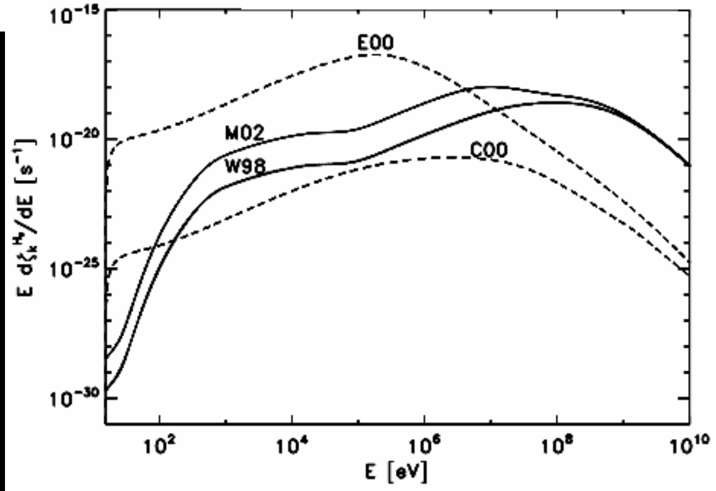
THE MeV-GeV PARTICLES – GAS INTERACTION

2) GAS IONIZATION

THE QUANTITY TO MEASURE IS THE *IONIZATION RATE*, CALLED ζ

$$\zeta^{\mathrm{H_2}}(\boldsymbol{r},t) = (1+\phi)\int_{E_{\min}}^{E_{\max}} \frac{\mathrm{d}^3 N_{\mathrm{p}}(\boldsymbol{r},E_{\mathrm{p}},t)}{\mathrm{d}E_{\mathrm{p}}\,\mathrm{d}A\,\mathrm{d}t}\,\sigma_{\mathrm{ion}}^{\mathrm{H_2}}(E_{\mathrm{p}})\,\mathrm{d}E_{\mathrm{p}}$$

CR case: Padovani et al. 2009



Differential contribution to the ionization rate ζ as a function of E

C.Ceccarelli
Santa Barbara
2016

CR= Cosmic Rays

PEW= Protostellar Energetic Winds

MeV-TeV particles - gas interaction

THE MeV-GeV PARTICLES

OBSERVATIONS

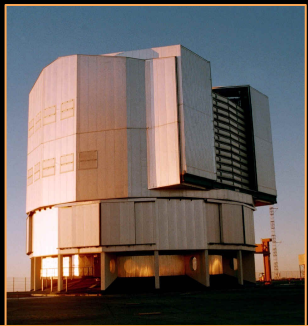
2) GAS IONIZATION

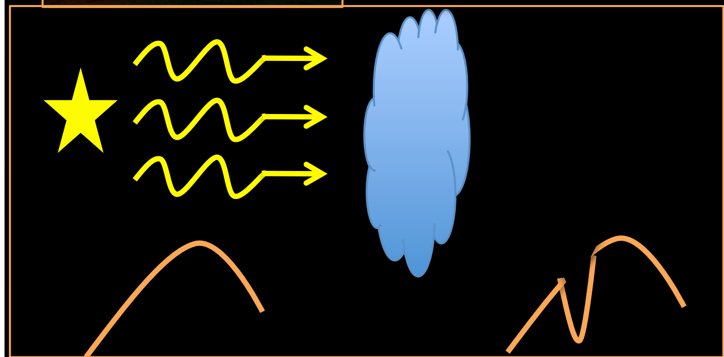
THE QUANTITY TO MEASURE IS THE *IONIZATION RATE*, CALLED ζ

USE "SIMPLE" IONS FORMED BY MeV-GeV PARTICLES:

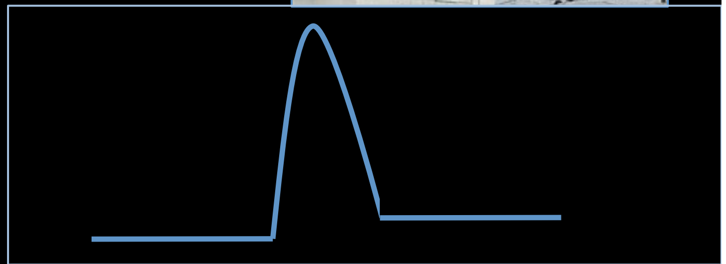
H_3^+, OH^+, **HCO^+, DCO^+, N_2H^+**

DIFFUSE vs **DENSE** CLOUDS





Absorption observations =>
limited by the presence of strong FIR sources behind
(e.g. Indriolo et al. & Neufeld et al.)



Emission observations =>
Non limited by the presence of strong IR/FIR sources behind

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

MeV-TeV
particles - gas
interaction

IPAG
Institut de Planétologie
et d'Astrophysique
de Grenoble

C.Ceccarelli
Santa Barbara
2016

THE MeV-TeV PARTICLES

OBSERVATIONS

2) GAS IONIZATION: a) 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. 1977):

$HCO^+ \leftarrow CO + H_3^+$ ← MeV-GeV PARTICLES

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

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

CR= Cosmic Rays

PEW= Protostellar Energetic Winds

MeV-TeV particles - gas interaction

THE MeV-TeV PARTICLES

OBSERVATIONS

2) GAS IONIZATION: a) 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. 1977):

$HCO^+ \leftarrow CO + H_3^+$ ← MeV-GeV PARTICLES

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

✓ H_2D^+/H_3^+ DEPENDS ON *n(e)*

$H_2D^+ \leftarrow HD + H_3^+$

$H_2D^+ + e \rightarrow H + H + D$

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

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

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

MeV-TeV particles - gas interaction

THE MeV-TeV PARTICLES OBSERVATIONS

2) GAS IONIZATION: a) 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. 1977):

  $HCO^+ \leftarrow CO + H_3^+$ ← MeV-GeV PARTICLES

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

- ✓ H_2D^+/H_3^+ DE…

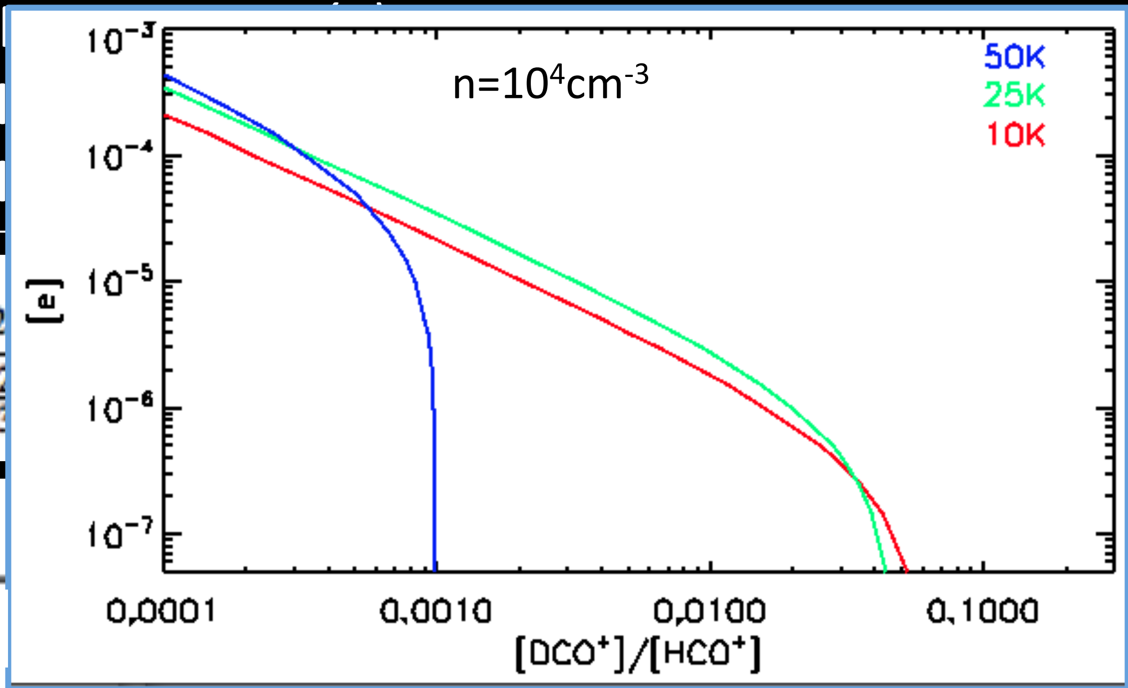
  H…

  H…

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

$$\frac{H_2D^+}{H_3^+} = [D] \dots$$

$k_e x_e$



C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

MeV-TeV particles - gas interaction

THE MeV-TeV PARTICLES

OBSERVATIONS

2) GAS IONIZATION: b) the HCO^+/N_2H^+ ratio*

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

✓ *n(e)* IS DERIVED BY OBSERVATIONS OF THE HCO^+/N_2H^+ RATIO (e.g. Ceccarelli et al. 2014):

$$HCO^+ \leftarrow CO + H_3^+$$
$$N_2H^+ \leftarrow N_2 + H_3^+$$

*ESPECIALLY USEFUL IN WARM GAS (WHERE DCO^+ HAS A LOW ABUNDANCE)

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CR source hunt

C.Ceccarelli
Santa Barbara
2016

OBSERVATIONS

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CR source hunt

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

THE CR-ISM INTERACTION

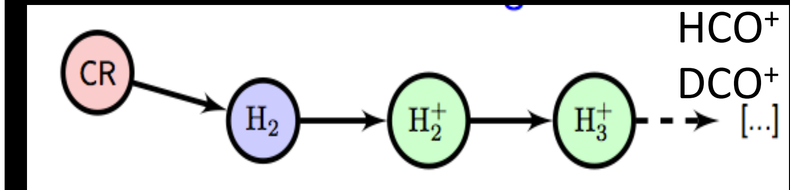
CR SPECTRUM

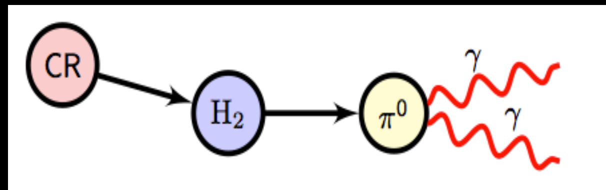
MeV GeV TeV

ENERGY

Gas ionization

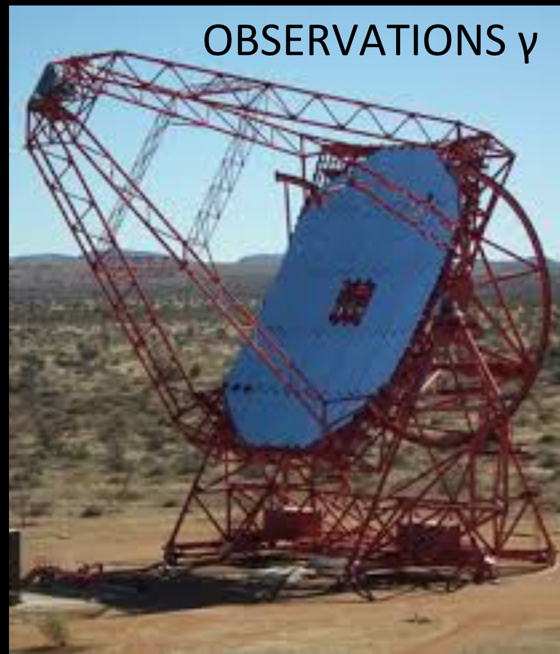
Emission of Y-ray photons





OBSERVATIONS of MOLECULAR IONS

IRAM



HESS

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CR source hunt

THE CR-ISM INTERACTION

CR SPECTRUM

MeV GeV TeV

ENERGY

Gas ionization

Emission of Y-ray photons

USE THE TWO TYPES OF OBSERVATIONS TO:
1- DETECT/CONFIRM THE CR ACCELERATION SITES
2- (ROUGHLY) CONSTRAIN THE CR EMERGING SPECTRUM AND, CONSEQUENTLY, THE CR DIFFUSION COEFFICIENT

OBSERVATIONS of MOLECULAR IONS

HESS

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

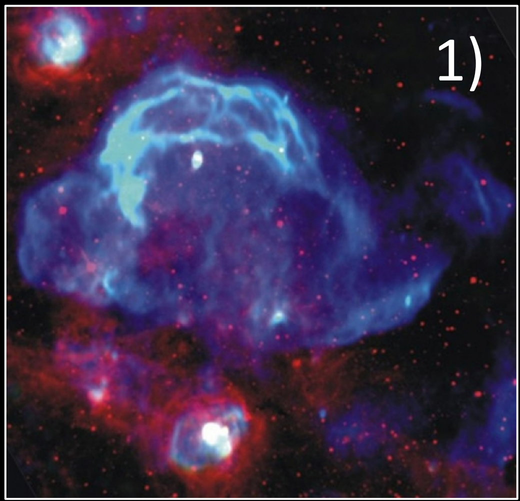
PEW=
Protostellar
Energetic
Winds

CR source hunt

WHERE TO SEARCH FOR THE CR PRODUCTION SITES

CRITERIA

1) MOLECULAR CLOUD CLOSE TO A SNR
2) MOLECULAR CLOUD OVERLAPPING WITH TeV EMISSION
3) GAS IONIZATION MUST BE ENHANCED



+

+

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

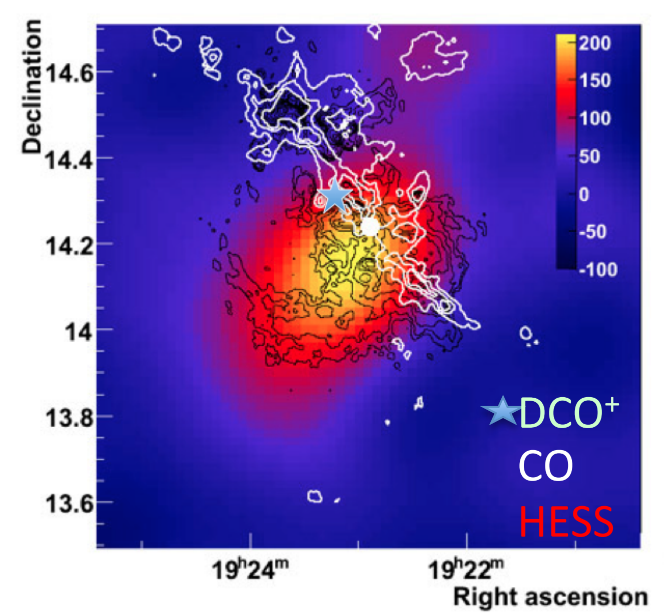
CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CR source hunt

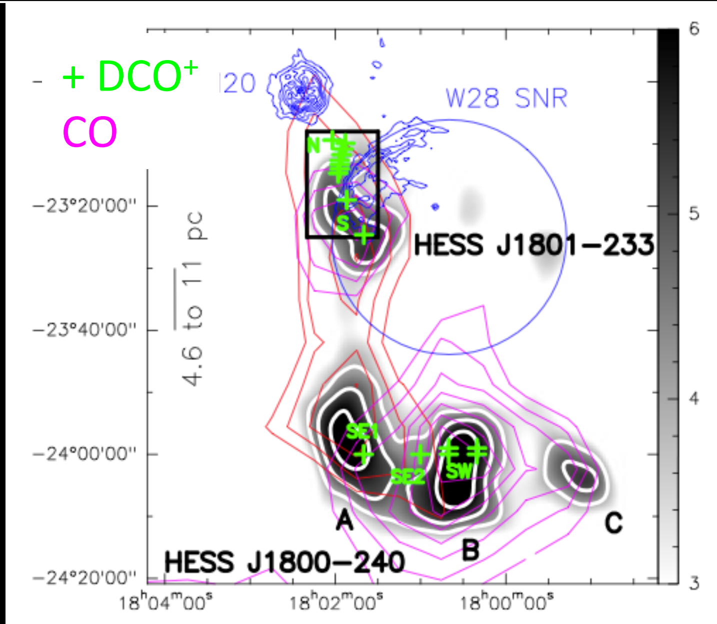
OBSERVATIONS TOWARDS TWO SNRs

W51: ~6Kpc distance, $3x10^4$yr old, associated with a bright TeV source, HESS J1923+141



Ceccarelli, Hily-Blant, Montmerle, Dubus, Gallant & Fiasson, 2011 ApJL

W28: SNR at 2-4Kpc distance, $\geq 10^4$yr old, associated with two bright TeV sources, HESS J1801-233 and J1800-240.



Vaupré, Hily-Blant, Ceccarelli, Dubus, Gabici & Montmerle, 2014 A&A

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CR source hunt

THE OBSERVATIONS towards W28

OBSERVATIONS OF :

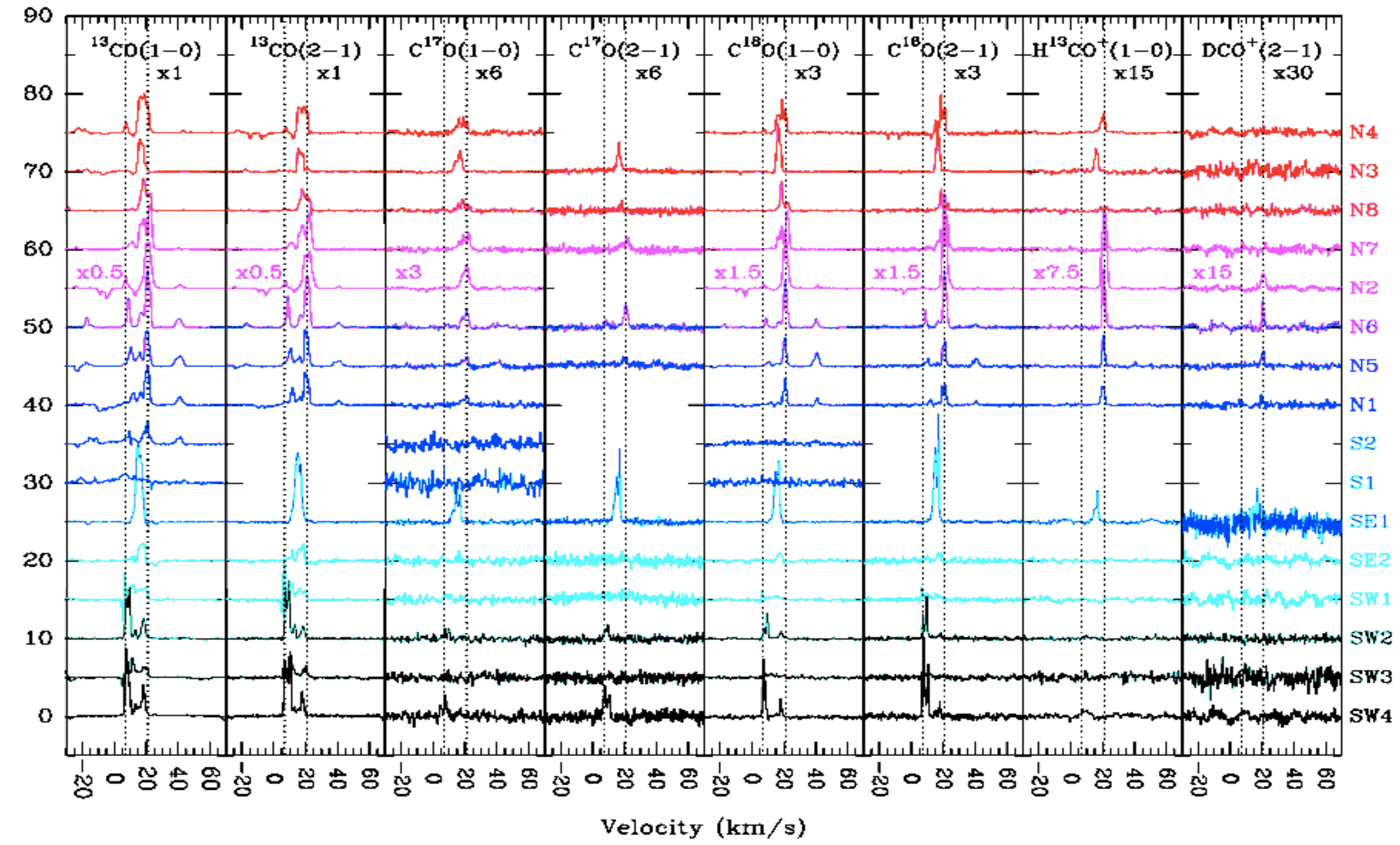
1) ^{13}CO and $C^{18}O$: 1-0 and 2-1 lines

➔TO DERIVE THE PHYSICAL PROPERTIES (dens, Temp, coldens)

2) $H^{13}CO^+$ 1-0 and DCO^+ 2-1 lines

➔TO DERIVE THE IONIZATION

W28



IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR= Cosmic Rays

PEW= Protostellar Energetic Winds

CR source hunt

THE OBSERVATIONS towards W28

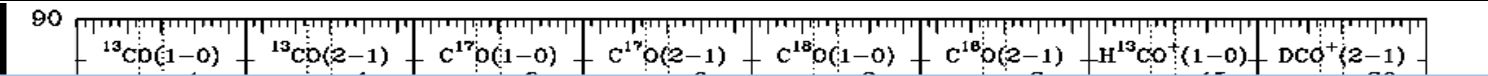
OBSERVATIONS OF :

1) ^{13}CO and $C^{18}O$: 1-0 and 2-1 lines

➔TO DERIVE THE PHYSICAL PROPERTIES (dens, Temp, coldens)

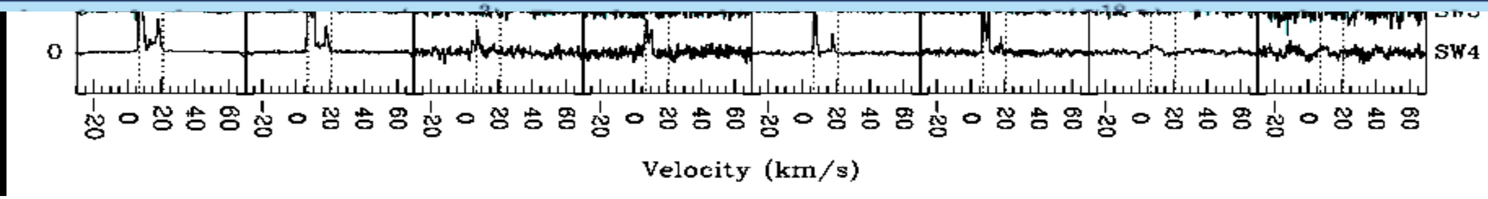
2) $H^{13}CO^+$ 1-0 and DCO^+ 2-1 lines

➔TO DERIVE THE IONIZATION



NON-LTE LVG (lvg_gre) ANALYSIS + NUMERICAL CHEMICAL MODEL

Pos.	Δv [km s^{-1}]	n_{H_2} [10^3 cm^{-3}]	T_{kin} [K]	$N(C^{18}O)$ [10^{15} cm^{-2}]	A_V [mag]	$N(H^{13}CO^+)$ [10^{12} cm^{-2}]	$N(DCO^+)$ [10^{12} cm^{-2}]	$R_D = \frac{[DCO^+]}{[HCO^+]}$	ζ [10^{-17} s^{-1}]
N1	3.5	0.6 {0.2 − 1}	15 ± 5	4 {2 − 6}	21 {11 − 32}	0.8 − 1.3	< 0.22	< 0.005	> 13
N5	3.0	4 {2 − 5}	10 ± 2	3 {2 − 8}	16 {11 − 32}	1.1 − 1.4	0.89 − 1.30	0.014 − 0.020	130 - 330
N6	3.0	4 {2 − 6}	13 ± 3	6 {4 − 20}	32 {21 − 105}	1.8 − 2.5	0.79 − 1.30	0.008 − 0.012	130 - 400
N2†	5.0	> 2	16 ± 2	20 {15 − 30}	105 {79 − 158}	5.6 − 8.9	1.10 − 2.00	0.003 − 0.006	-
N7	2.5	2 {2 − 5}	10 ± 2	4 {3 − 10}	21 {16 − 53}	0.6 − 0.9	< 0.25	< 0.007	> 130
N8	3.5	1 {0.6 − 2}	8 ± 1	3 {2 − 4}	16 {11 − 21}	< 0.2	< 0.35	-	-
N3	3.5	6 {4 − 10}	8 ± 1	6 {5 − 7}	32 {26 − 37}	1.0 − 1.4	< 0.35	< 0.006	> 260
N4	3.0	2 {0.6 − 4}	12 ± 3	2 {2 − 3}	11 {5 − 16}	1.0 − 1.4	< 0.35	< 0.006	> 40
SE1	4.0	2 {1 − 5}	19 ± 5	6 {5 − 20}	32 {26 − 105}	0.4 − 0.56	0.79 - 1.0	0.032 - 0.05	0.2 - 20
SE2	3.0	4 {2 − 10}	8 ± 2	0.9 {0.4 − 20}	5 {2 − 105}	< 0.2	< 0.28	-	-
SW2	1.5	2 {1 − 4}	20 ± 4	4 {3 − 10}	21 {16 − 53}	< 0.1	< 0.22	-	-
SW4†	1.5	6 {4 − 10}	16 ± 2	1.5 {1 − 3}	5 {5 − 16}	0.5 − 0.8	< 0.25	< 0.009	-

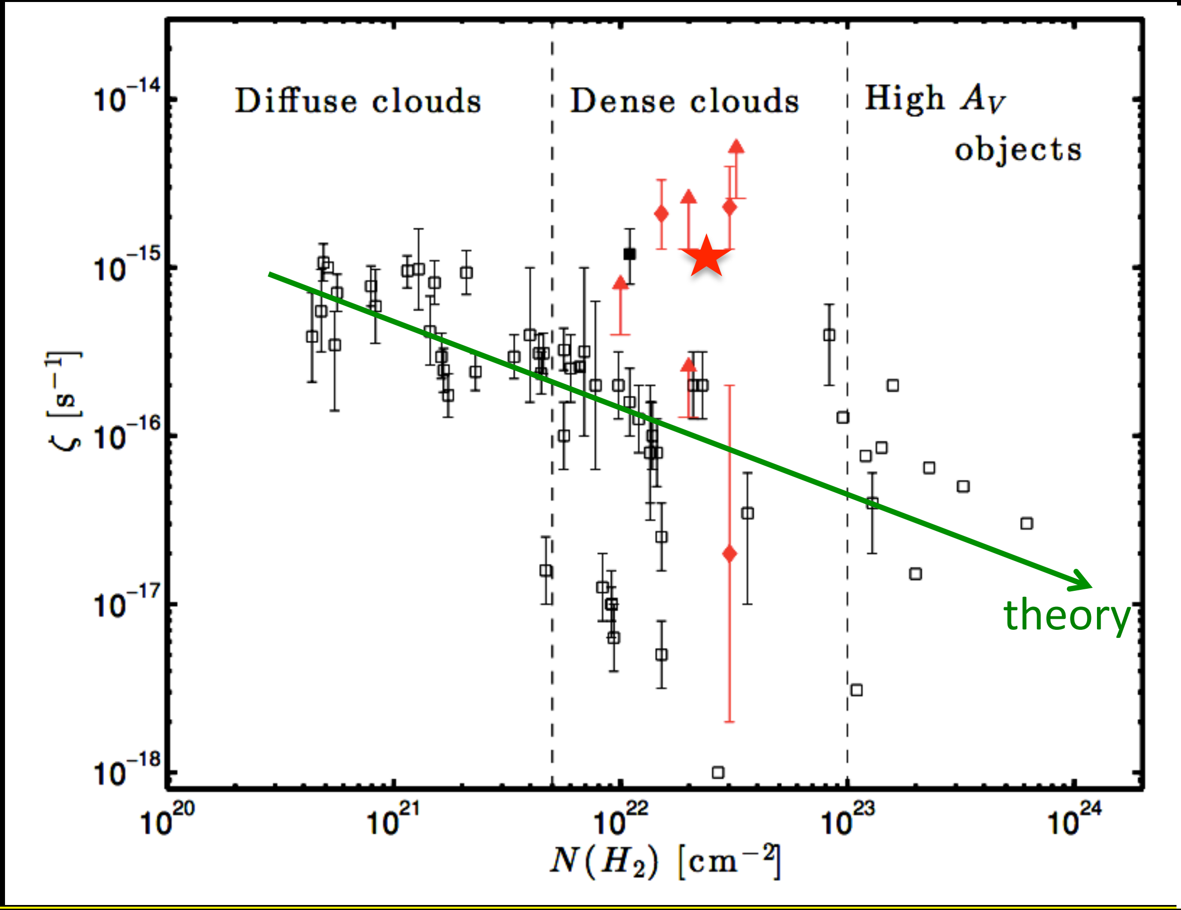


CR= Cosmic Rays

PEW= Protostellar Energetic Winds

CR source hunt

W51C-E and W28-N5/6: CLOSE TO SITES OF CR ACCELERATION?



Adapted by Vaupré et al. 2014 from Padovani et al. 2012

RESULT: THE MEASURED CR IONIZATION RATE IN W51C-E AND W28-N5/6 IS DEFINITIVELY LARGER (~100 times) THAN IN OTHER GALACTIC CLOUDS

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli Santa Barbara 2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

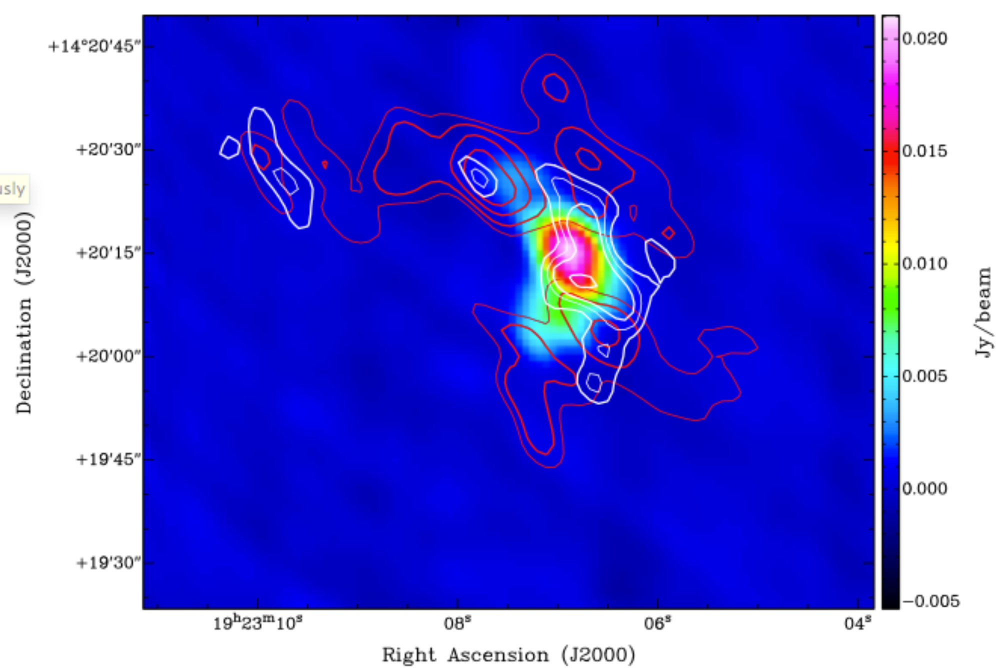
CR source hunt

W51C-E:
CLOSE TO A SITE OF CR ACCELERATION?

HIGH SPATIAL RESOLUTION (≈3”) OBSERVATIONS WITH IRAM PdB

Dumas, Ceccarelli, Hily-Blant, Dubus, Montmerle, Gabici, 2014 ApJL

COLOR= continuum; WHITE=$H^{13}CO^{+}$; RED=SiO



1) NO DCO^{+} DETECTED → THE WHOLE REGION ENCOMPASSED BY THE IRAM-30m BEAM IS IONISED
2) DETECTION OF SiO → PRESENCE OF TWO SHOCKS (ROUGHLY PERPENDICULAR TO THE DIRECTION OF THE SNR RADIUS): SITES OF MeV-GeV CR ACCELERATION???

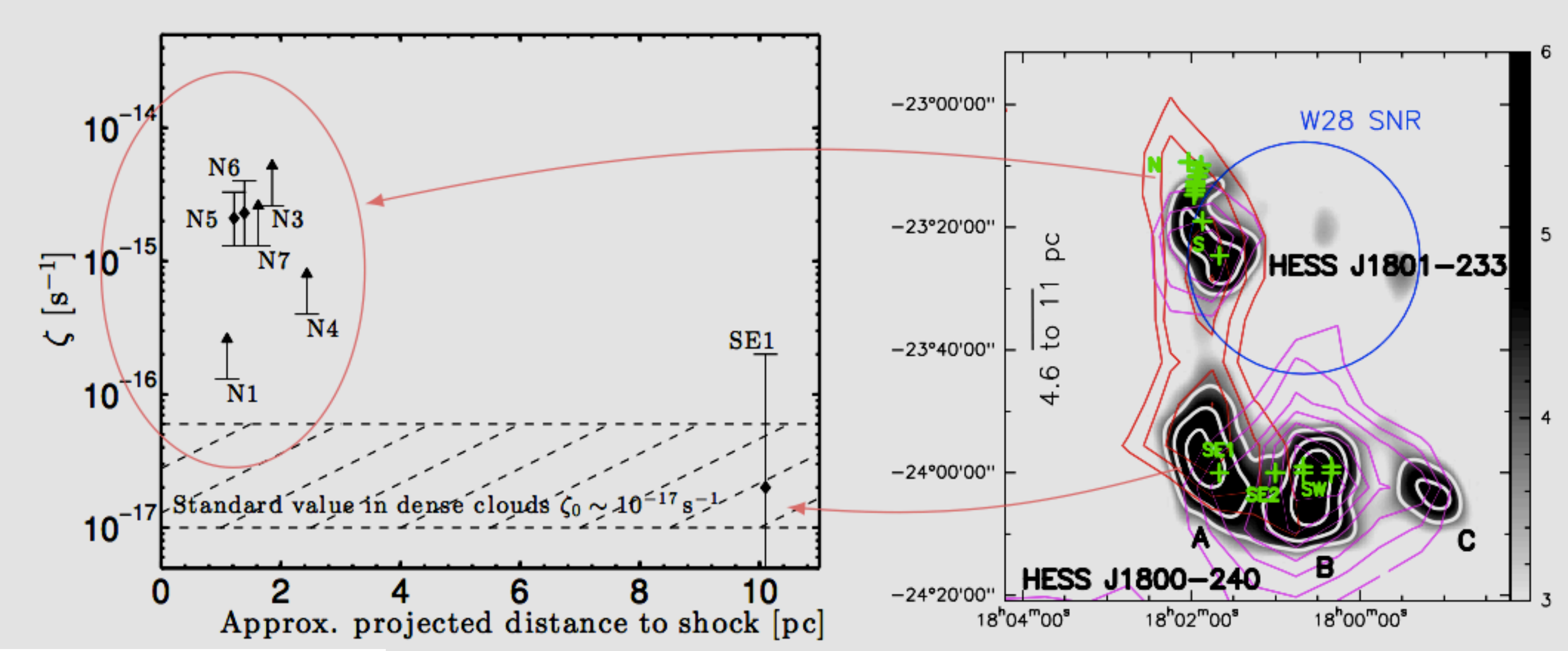
IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

CR= Cosmic Rays

PEW= Protostellar Energetic Winds

CR source hunt

W28 SE1 vs N5/N6: CLOSE TO A SITE OF CR ACCELERATION?



Vaupré et al. 2014

GAS IONIZATION ONLY ENHANCED IN THE NORTH CLOUD, WHICH IS ALSO CLOSER TO THE SNR BORDER (in 2D)

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

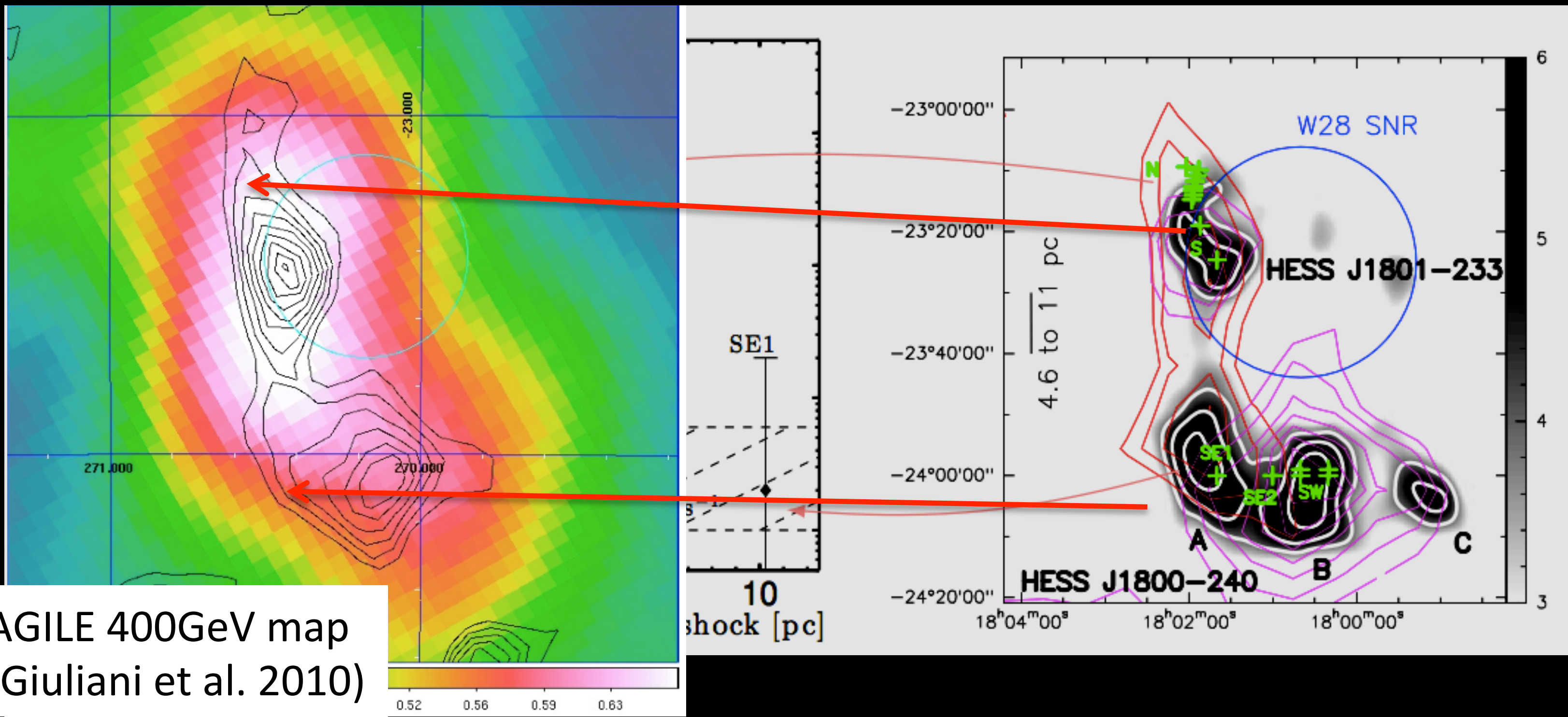
C.Ceccarelli Santa Barbara 2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CR source hunt

W28 SE1 vs N5/N6: CLOSE TO A SITE OF CR ACCELERATION?



AGILE 400GeV map (Giuliani et al. 2010)

GAS IONIZATION ONLY ENHANCED IN THE NORTH CLOUD, WHICH IS ALSO CLOSER TO THE SNR BORDER (in 2D)

AGILE AND FERMI-LAT GeV MAPS ALSO SHOW LITTLE EMISSION IN THE SOUTH CLOUD!

IPAG Institut de Planétologie et d'Astrophysique de Grenoble

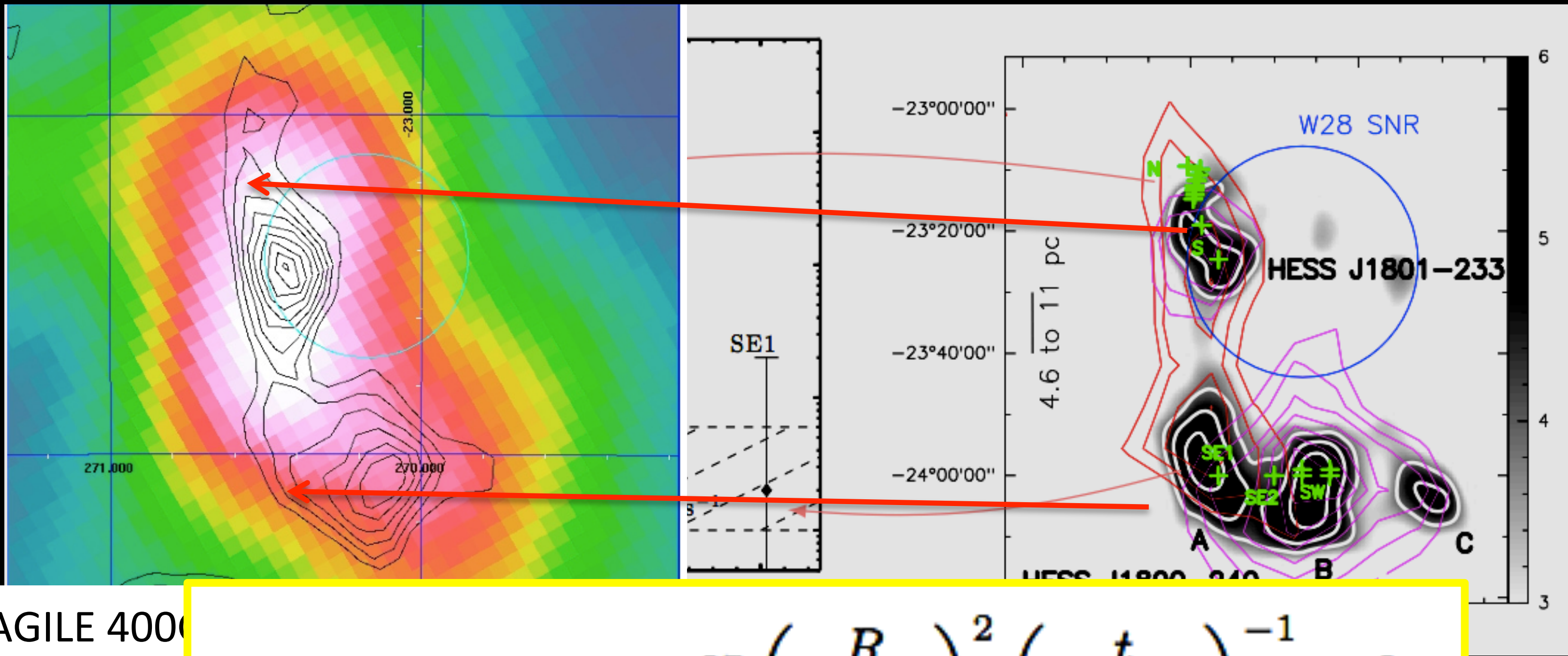
C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CR source hunt

W28 SE1 vs N5/N6: CLOSE TO A SITE OF CR ACCELERATION?



AGILE 400(
(Giuliani et

$$D_{(\approx 10\ \mathrm{GeV})} \gtrsim 3 \times 10^{27} \left(\frac{R}{10\ \mathrm{pc}}\right)^2 \left(\frac{t}{10^4\ \mathrm{yr}}\right)^{-1} \mathrm{cm}^2/\mathrm{s}$$

RESULT: THE LARGER THE CR ENERGY THE LARGER THE CR TRAVEL DISTANCE… IN AGREEMENT WITH THEORETICAL EXPECTATIONS!

=> Constraints on the CR DIFFUSION COEFFICIENT *D*

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

The EPW hunt

ENERGETIC WIND PARTICLES IN AN EMBEDDED PROTOSTAR AND THE LINK WITH THE SOLAR SYSTEM

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

The EPW hunt

C.Ceccarelli
Santa Barbara
2016

PROTOSTELLAR ENERGETIC WINDS

ENERGETIC PARTICLES ARE ACCELERATED BY THE NEW BORN STAR: THE EFFECT SHOULD BE MORE EVIDENT IN THE INNER REGIONS OF THE ENVELOPE
=> DENSE AND WARM GAS

THE DCO^+/HCO^+ RATIO NOT USABLE
=> HIGH LEVEL LINES FROM N_2H^+/HCO^+

CR=
Cosmic Rays

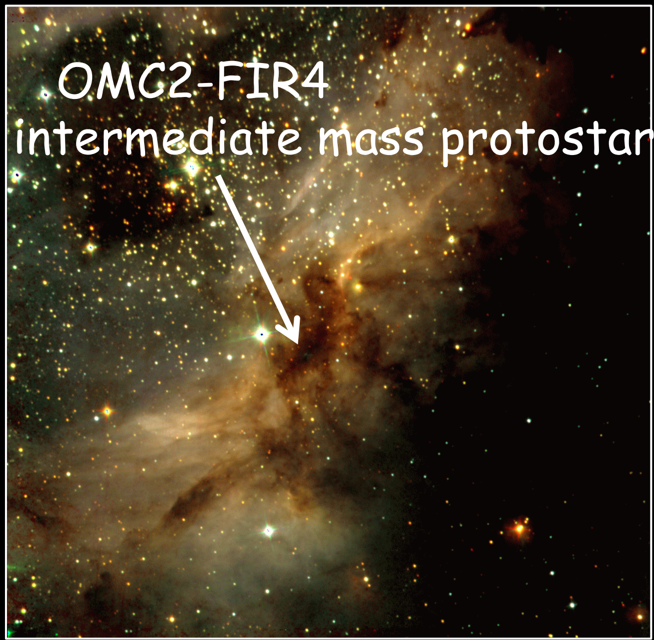
PEW=
Protostellar
Energetic
Winds

The EPW hunt

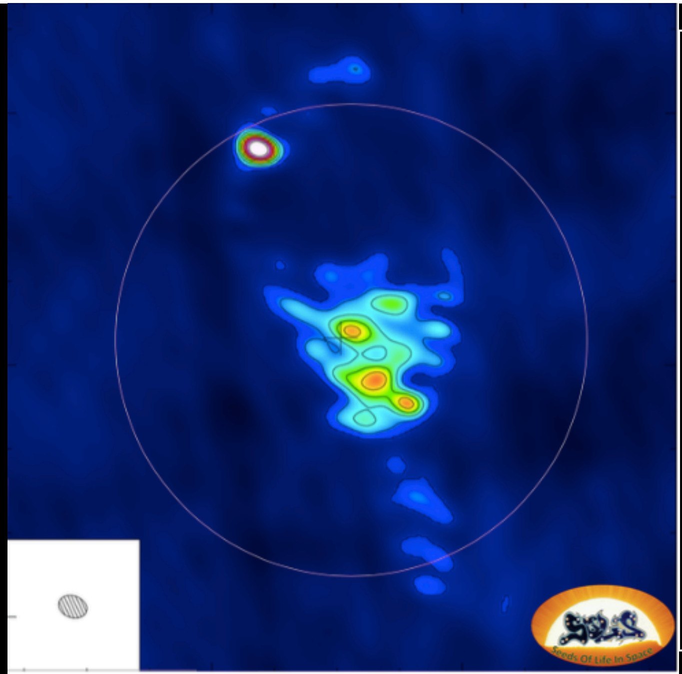
C.Ceccarelli
Santa Barbara
2016

PROTOSTELLAR ENERGETIC WINDS

OMC2-FIR4: a protocluster likely similar to the cluster where the Solar System was born



NOEMA observations (from SOLIS project)



Ceccarelli et al. in prep.

OMC2-FIR4: YOUNG CLUSTER OF LOW- AND INTERMEDIATE- MASS PROTOSTARS WITH A TOTAL BOLOMETRIC 100-1000Lo
(Crimier et al. 2010; Lopez-Sepulcre et al. 2013; Furlan et al. 2014)

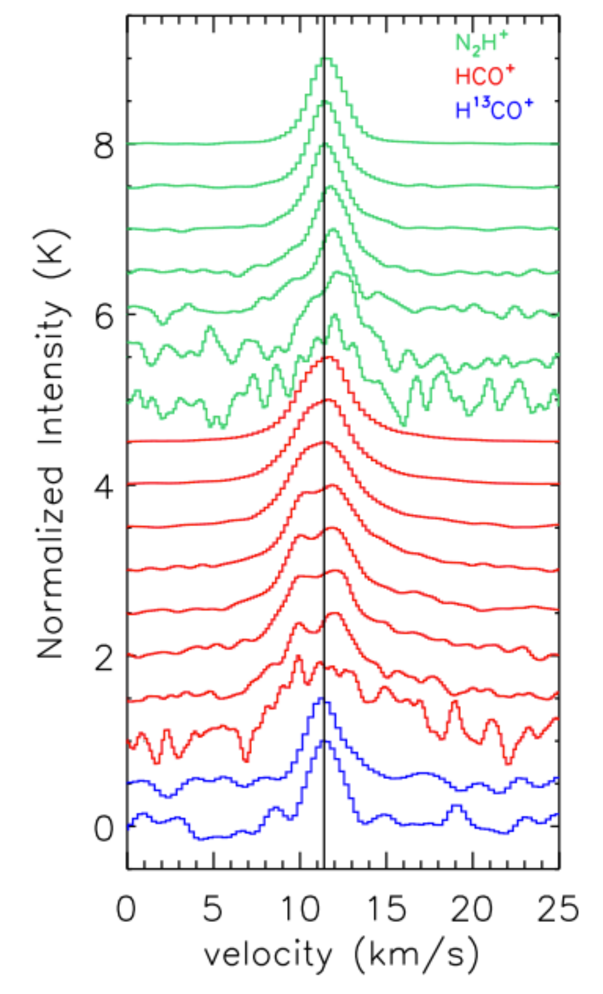
CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

The EPW hunt

HERSCHEL CHESS* OBSERVATIONS OF OMC2-FIR4

*CHESS = CHEMICAL HERSCHEL SURVEYS OF STAR FORMING REGIONS



DETECTION OF SEVERAL HIGH J LINES FROM HCO^+, $H^{13}CO^+$ AND N_2H^+

N_2H^+ LINES ARE ALMOST AS BRIGHT AS THE HCO^+ LINES

Kama, Lopez-Sepulcre, Ceccarelli, Dominik et al. 2013, A&A

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

The EPW hunt

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

OMC2-FIR4 SLED* ANALYSIS

* SLED =SPECTRAL LINE ENERGY DISTRIBUTION

	Warm Component		Envelope	
	Adopted Solution[a]	Range	Adopted Solution[a]	Range
Results from the non-LTE LVG analysis				
H_2 density (cm^{-3})	4.0×10^7	$1–80 \times 10^7$	1.2×10^6	$0.8–2 \times 10^6$
Temperature (K)	120	75–150	40	30–45
Source size (arcsec)	8	6–15	18	17–26
Source radius (AU)	1600	1250–3000	3700	3500–5000
$N(HCO^+)$ (cm^{-2})	7×10^{13}	$6–15 \times 10^{13}$	3×10^{14}	$2–6 \times 10^{14}$
$N(N_2H^+)$ (cm^{-2})	3×10^{13}	$2–5 \times 10^{13}$	1×10^{14}	$0.5–2 \times 10^{14}$
HCO^+/N_2H^+	3.5	3–4	3.5	3–4

A REMARKABLE VERY LOW, 3-4, HCO^+/N_2H^+ RATIO

Ceccarelli, Dominik, Lopez-Sepulcre, Kama, Padovani, Caux, Caselli 2014, ApJL

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

The EPW hunt

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

THE CHEMISTRY OF HCO^+ AND N_2H^+

IN "NORMAL" CONDITIONS

FORMATION:

$CO + H_3^+ \rightarrow HCO^+$

$N_2 + H_3^+ \rightarrow N_2H^+$

DESTRUCTION:

$HCO^+ + CO \rightarrow CO$

$N_2H^+ + CO \rightarrow HCO^+$

$HCO^+ / N_2H^+ >>$ elemental $C/N \approx 3$

$HCO^+ / N_2H^+ \approx$ elemental $C/N \approx 3$ IMPLIES A COMMON DESTROYER THAT DOES NOT FORM HCO^+ ➔ electrons

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

The EPW hunt

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

THE CHEMISTRY OF HCO^+ AND N_2H^+

IN "NORMAL" CONDITIONS

FORMATION:

$CO + H_3^+ \to HCO^+$

$N_2 + H_3^+ \to N_2H^+$

DESTRUCTION:

$HCO^+ + CO \to CO$

$N_2H^+ + CO \to HCO^+$

$HCO^+ / N_2H^+ >> \text{elemental } C/N \approx 3$

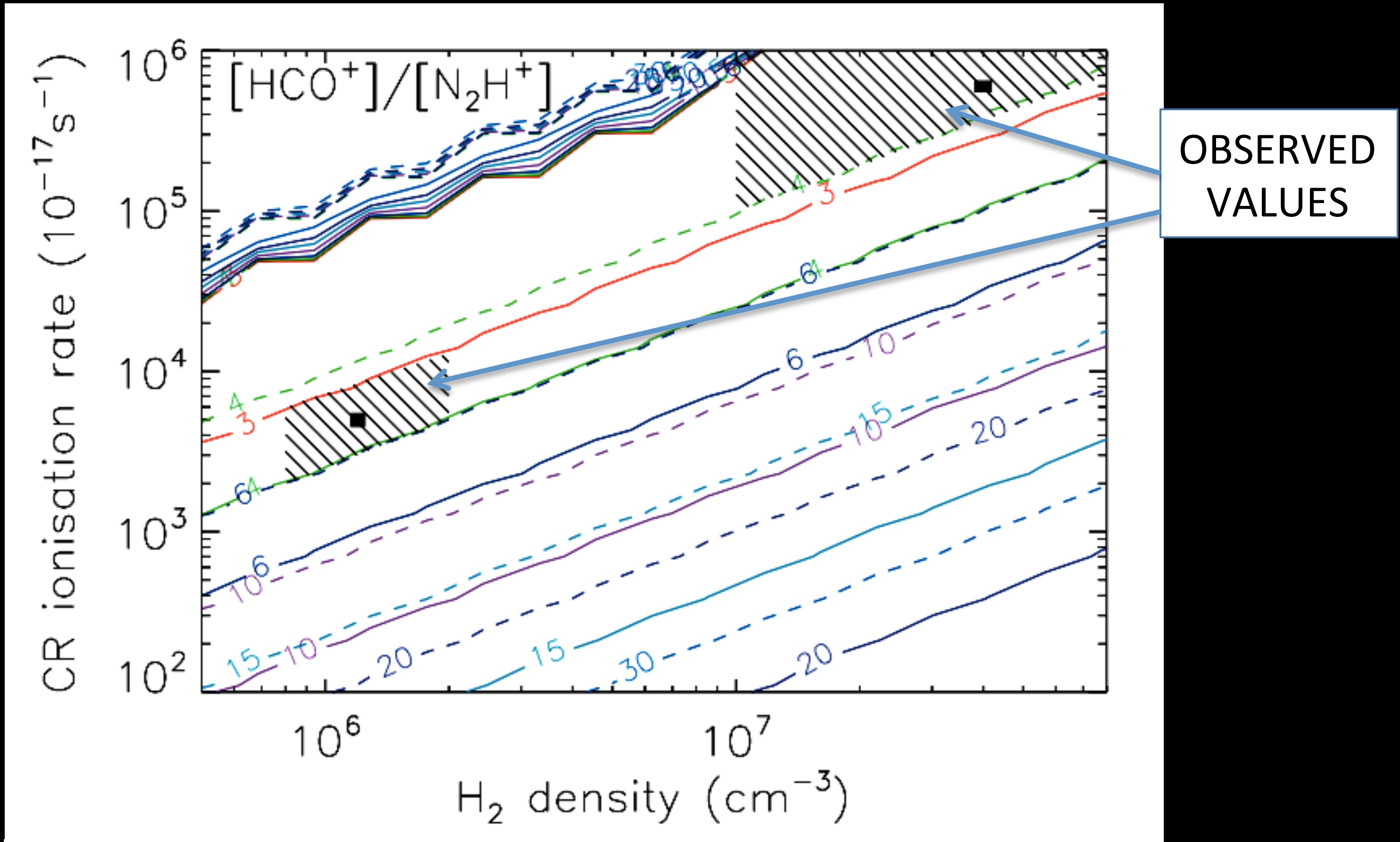
$HCO^+ / N_2H^+ \approx \text{elemental } C/N \approx 3$ IMPLIES A COMMON DESTROYER THAT DOES NOT FORM HCO^+ ➔ electrons

CR= Cosmic Rays

PEW= Protostellar Energetic Winds

The EPW hunt

THE CHEMISTRY OF HCO^+ AND N_2H^+



CHEMICAL MODEL: OBSERVATIONS vs PREDICTIONS

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

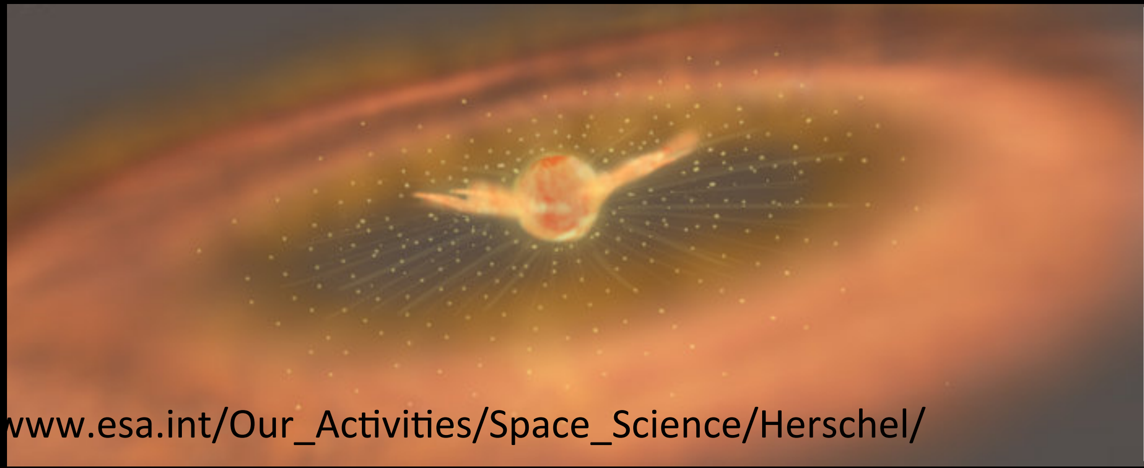
C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

The EPW hunt

THE EMERGING PICTURE



Ceccarelliet al. 2014

EVIDENCE OF THE PRESENCE OF >10MeV PARTICLES IN A YOUNG EMBEDDED PROTOSTAR

DERIVED >10MeV PARTICLES FLUX AT 1AU:
FLUENCE >10^{19}protons/cm^2/yr , i.e. CONSISTENT WITH THAT DERIVED FROM METEORITIC MATERIAL

OMC2-FIR4 = YOUNG SOLAR SYSTEM ANALOGUE ?

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CONCLUSIONS

MOLECULES CAN HELP DISCOVERING THE SOURCES OF ACCELERATION OF CR AND REVEAL THE PRESENCE OF ENERGETIC PROTOSTELLAR WINDS

MOLECULAR CLOUDS IN W51C AND W28 WITH TeV EMISSION AND ENHANCED IONIZATION, ABOUT A FACTOR 100 HIGHER THAN THE AVERAGE GALACTIC CLOUDS.
IN W51C-E TWO SHOCKS ARE PRESENTS, MAY BE GENERATING MeV-GeV CR
=> MORE TO COME! (e.g. W44)

HERSCHEL CHESS OBSERVATIONS REVEAL THE PRESENCE OF EPW IN AN EMBEDDED PROTOSTARS WHERE THE FLUX OF >10MeV PARTICLES IS ABOUT EQUAL TO THAT EXPERIENCED BY THE YOUNG SOLAR SYSTEM
=> MORE TO COME! (a sample of protostars)

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016

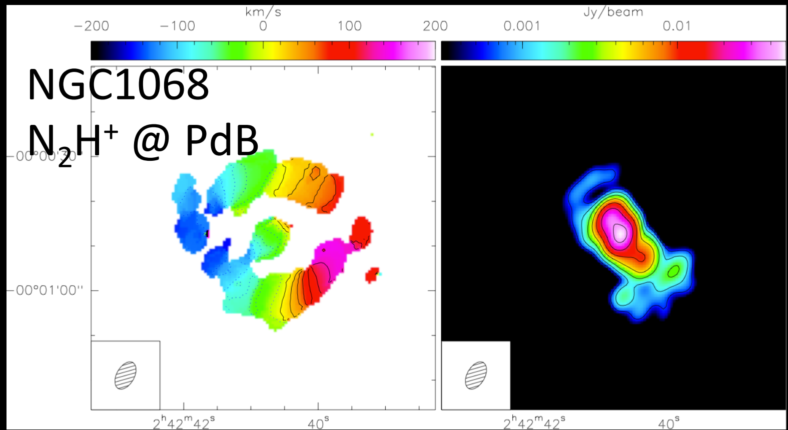
CR=
Cosmic Rays

PEW=
Protostellar
Energetic
Winds

CONCLUSIONS

MOLECULES CAN HELP DISCOVERING THE SOURCES OF ACCELERATION OF CR AND REVEAL THE PRESENCE OF ENERGETIC PROTOSTELLAR WINDS

=> APPLICATIONS TO EXTRAGALACTIC SOURCES



=> LA VIE EN ROSE: ALMA & NOEMA <=

IPAG
Institut de Planétologie et d'Astrophysique de Grenoble

C.Ceccarelli
Santa Barbara
2016