Cosmic rays
in the interstellar medium

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Low-energy cosmic rays: regulators of the dense interstellar medium

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Cosmic rays are energetic particles hitting the Earth’s atmosphere from outer space. Most of them (90%) are protons. Most people believe they are accelerated at supernova remnant shocks.
Cosmic ray sources: why is it so difficult?

We cannot do CR Astronomy.

Need for indirect identification of CR sources.
Solar modulation

Solar activity

Protons

Minimum

Intermediate

Maximum

$J(E) [m^{-2} s^{-1} sr^{-1} MeV^{-1}]$

E [MeV]

Gabici 2022 (adapted from Vos & Potgieter 2015)
Solar modulation

Gabici 2022 (adapted from Vos & Potgieter 2015)
the local interstellar spectrum of CRs is very well measured from Earth at high energies, but is modulated at low energies (< 20 GeV)
Voyager probes

September 5 1977
the launch of Voyager 1

August 20 1977 launch of the twin probe Voyager 2
Voyager probes crossed the heliopause

~160 AU

~130 AU

~45 years after the launch, the CR detectors onboard still collect data!
An epic journey

V1 HET 2 PENH (daily average rate)

Cummings+ 2016
An epic journey

V1 HET 2 PENH (daily average rate)

~11 yr Solar cycle

Cummings+ 2016
An epic journey

V1 HET 2 PENH (daily average rate)

~11 yr Solar cycle

wind termination shock

Cummings+ 2016
An epic journey

V1 HET 2 PENH (daily average rate)

wind termination shock

heliopause

~11 yr Solar cycle

Cummings+ 2016
An epic journey

~11 yr Solar cycle

wind termination shock

heliopause

unaffected by Solar wind!

V1 HET 2 PENH (daily average rate)

Rate (s⁻¹)

0.1 1


Year

Cummings+ 2016
The local interstellar spectrum of CRs

Gabici 2022 (adapted from Vos & Potgieter 2015)
Electron spectrum in the local ISM

Cummings+ 2016
flux of particles

spectral energy distribution
most nuclei have energies 100 MeV-1 GeV

how many CR electrons?
flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

\[ \approx 10^{-9} - 10^{-10} \text{ cm}^{-3} \]
flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution

energy is carried mainly by particles of energy 100 MeV-10 GeV

\[ \approx 10^{-9} - 10^{-10} \text{ cm}^{-3} \]
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spectral energy distribution

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\[ \approx 10^{-9} - 10^{-10} \text{ cm}^{-3} \]

\[ \approx 1 \text{ eV/cm}^3 \]
Flux of particles

Most nuclei have energies 100 MeV-1 GeV.

How many CR electrons?

Spectral energy distribution

Energy is carried mainly by particles of energy 100 MeV-10 GeV.

$p$ compare with ISM density...

$\approx 10^{-9} - 10^{-10} \text{ cm}^{-3}$

$\approx 0.1 - 1 \text{ cm}^{-3}$

$\approx 1 \text{ eV/cm}^3$
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energy is carried mainly by particles of energy 100 MeV-10 GeV

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compare with ISM density...

\[ \approx 0.1 - 1 \text{ cm}^{-3} \]

same order as magnetic, thermal, and turbulent energy in the ISM!

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compare with ISM density...

$\approx 0.1 - 1 \text{ cm}^{-3}$

the origin of cosmic rays: where is this energy from?

same order as magnetic, thermal, and turbulent energy in the ISM!

$\approx 1 \text{ eV/cm}^3$
flux of particles

most nuclei have energies 100 MeV-1 GeV

how many CR electrons?

spectral energy distribution

energy is carried mainly by particles of energy 100 MeV-10 GeV

ionisation, heating, chemistry?

the origin of cosmic rays: where is this energy from?

same order as magnetic, thermal, and turbulent energy in the ISM!

≈ 1 eV/cm³

≈ 10⁻⁹ – 10⁻¹⁰ cm⁻³

compare with ISM density...

≈ 0.1 – 1 cm⁻³
Far away cosmic rays

Predicted by Hayakawa in 1952 ....... the gamma-ray sky seen by Fermi/LAT now
Far away cosmic rays

Predicted by Hayakawa in 1952 ....... the gamma-ray sky seen by Fermi/LAT now
Far away cosmic rays

Predicted by Hayakawa in 1952 ....... the gamma-ray sky seen by Fermi/LAT now

$E_{th} > 280$ MeV
Far away cosmic rays

Predicted by Hayakawa in 1952 ....... the gamma-ray sky seen by Fermi/LAT now
Gamma-rays from distant cosmic rays

Fermi and Voyager observations are complementary
How well we know the spatial distribution of cosmic rays throughout the Galactic disk?
Molecular clouds as cosmic ray probes

see e.g.

Black & Fazio 1973
Molecular clouds as cosmic ray probes

A MC immersed in the CR sea emits γ-rays

See e.g. Black & Fazio 1973
Molecular clouds as cosmic ray probes

if a CR source is present, the MC emits more γ-rays

see e.g.
Black&Fazio1973
Aharonian&Atoyan1996
Molecular clouds as cosmic ray probes

If a CR source is present, the MC emits more $\gamma$-rays. See e.g. Black & Fazio 1973, Aharonian & Atoyan 1996, McKee 1989.

Ionizing UV photons do not penetrate molecular clouds.
Molecular clouds as cosmic ray probes

- A MC immersed in the CR sea emits $\gamma$-rays.
- If a CR source is present, the MC emits more $\gamma$-rays.
- Ionizing UV photons do not penetrate molecular clouds; only cosmic rays can penetrate and drive the chemistry in the cloud.

See e.g.:
- Black & Fazio 1973
- Aharonian & Atoyan 1996
- McKee 1989
- Herbst & Klemperer 1973

Only cosmic rays can penetrate and drive the chemistry in the cloud.
Molecular clouds as cosmic ray probes

- If a CR source is present, the MC emits more \( \gamma \)-rays.
- \( \gamma \)-rays amplify the \( \gamma \)-ray emission from CR interactions.
- Filter all ionizing agents but (MeV) CRs.
- Only cosmic rays can penetrate and drive the chemistry in the cloud.

\[ \text{Molecular clouds} \rightarrow \text{ampify the } \gamma\text{-ray emission from CR interactions} \]
\[ \rightarrow \text{filter all ionizing agents but (MeV) CRs} \]

See e.g.
- Black & Fazio 1973
- Aharonian & Atoyan 1996
- McKee 1989
- Herbst & Klemperer 1973
Molecular clouds as cosmic ray probes

- IR/mm observations -> chemistry -> MeV CR spectrum
- space/ground based γ-ray observations -> GeV/TeV CR spectrum

- only cosmic rays can penetrate and drive the chemistry in the cloud
- amplify the γ-ray emission from CR interactions
- filter all ionizing agents but (MeV) CRs

McKee 1989
Herbst&Klemperer1973
Gamma rays from molecular clouds
Gamma rays from molecular clouds
Gamma rays from molecular clouds

\[ L_\gamma \sim \sigma_{pp} n_{CR} n_{gas} V \propto n_{CR} M_{cl} \]
Gamma rays from molecular clouds

\[ L_\gamma \sim \sigma_{pp} n_{CR} n_{gas} V \propto n_{CR} M_{cl} \]

\[ F_\gamma = \frac{L_\gamma}{4\pi d^2} \propto n_{CR} \left( \frac{M_{cl}}{d^2} \right) \]
Gamma rays from molecular clouds

\[ L_{\gamma} \sim \sigma_{pp} n_{CR} n_{gas} V \propto n_{CR} M_{cl} \]

\[ F_{\gamma} = \frac{L_{\gamma}}{4\pi d^2} \propto n_{CR} \left( \frac{M_{cl}}{d^2} \right) \]
Gamma rays from molecular clouds

\[ L_\gamma \sim \sigma_{pp} n_{CR} n_{gas} V \propto n_{CR} M_{cl} \]

\[ F_\gamma = \frac{L_\gamma}{4\pi d^2} \propto n_{CR} \left( \frac{M_{cl}}{d^2} \right) \]

gamma-ray bright molecular clouds are cosmic ray barometers

measured
Spatial distribution of cosmic rays

data from Acero+ 16, Aharonian+ 20, Peron+ 21
Spatial distribution of cosmic rays

factor of few over the entire disk

data from Acero+ 16, Aharonian+ 20, Peron+ 21
CR ionization rate in isolated MCs

$\zeta_{\text{CR}}$ (E$_{\text{min}}$ = 3 keV) 

$\zeta_{\text{CR,p}}$ (E$_{\text{min}}$ = 3 MeV)

$\zeta_{\text{CR,e}}$ (E$_{\text{min}}$ = 3 keV)

$\zeta_{\text{CR,e}}$ (E$_{\text{min}}$ = 3 MeV)

H$_3^+$, HCO$^-$, DCO$^+$, OH$^+$, H$_2$O$^+$, H$_3$O$^+$ ...

Caselli+98, van der Tak&van Dischoeck00, Maret&Bergin07, Hezareh+08, Indriolo&McCall12, Morales Ortiz+14, Indriolo+15, Fuente+16, Neufeld&Wolfire17, Sabatini+20

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CR ionization rate in isolated MCs

$\zeta_{CR}^{H_3^+}, HCO^+, DCO^+, OH^+, H_2O^+, H_3O^+ ...$

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Caselli+98, van der Tak&van Dischoeck00, Maret&Bergin07, Hezareh+08, Indriolo&McCall12, Morales Ortiz+14, Indriolo+15, Fuente+16, Neufeld&Wolfire17, Sabatini+20

diffuse clouds

dense clouds

$\zeta_{CR,e}^{H_3^+}(E_{min}=3 \text{ keV})$

$\zeta_{CR,e}^{H_3^+}(E_{min}=3 \text{ MeV})$

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$N(H_2) [\text{cm}^{-2}]$
CR ionization rate in isolated MCs

$\xi_{\text{CR}}^H$, $H_3^+$, $HCO^+$, $DCO^+$, $OH^+$, $H_2O^+$, $H_3O^+$, ...

Voyager protons

$\xi_{\text{CR,e}}(E_{\text{min}}=3 \text{ keV})$

$\xi_{\text{CR,e}}(E_{\text{min}}=3 \text{ MeV})$

$N(H_2)$ [cm$^{-2}$]

Caselli+98, van der Tak&van Dischoeck00, Maret&Bergin07, Hezareh+08, Indriolo&McCall12, Morales Ortiz+14, Indriolo+15, Fuente+16, Neufeld&Wolfire17, Sabatini+20

Gabici 2022
CR ionization rate in isolated MCs

$H_3^+$, $HCO^-$, $DCO^+$, $OH^+$, $H_2O^+$ $H_3O^+$ ...

Voyager protons
Voyager electrons

Caselli+98, van der Tak&van Dischoeck00, Maret&Bergin07, Hezareh+08, Indriolo&McCall12, Morales Ortiz+14, Indriolo+15, Fuente+16, Neufeld&Wolfire17, Sabatini+20

Gabici 2022
CR ionization rate in isolated MCs

H₃⁺, HCO⁺, DCO⁺, OH⁺, H₂O⁺, H₃O⁺ ...

Voyager electrons extrapolated down to 3 keV

Caselli+98, van der Tak&van Dischoeck00, Maret&Bergin07, Hezareh+08, Indriolo&McCall12, Morales Ortiz+14, Indriolo+15, Fuente+16, Neufeld&Wolfire17, Sabatini+20

Gabici 2022
**CR ionization rate in isolated MCs**

- No trend for a broad interval of $N_{\text{H}}$...
- $H_3^+, HCO^-, DCO^+, OH^+, H_2O^+, H_3O^+$...

![Graph showing ionization rate vs. $N(H_2)$](image)

- Voyager protons
- Voyager electrons extrapolated down to 3 keV

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**References**

Caselli+98, van der Tak&van DISchoeck00, Maret&Bergin07, Hezareh+08, Indriolo&McCall12, Morales Ortiz+14, Indriolo+15, Fuente+16, Neufeld&Wolfire17, Sabatini+20
Energy losses (mainly ionisation)

Gabici 2022
(adapted from Padovani+ 18)
Energy losses (mainly ionisation)

CRs cool after crossing this gas column density

Gabici 2022
(adapted from Padovani+ 18)
Ballistic penetration into clouds

CRs penetrate clouds moving along straight lines

Graph showing the relationship between $\xi_{CR}$ and $N(H_2)$, with data points for protons, electrons, and total CRs.
Ballistic penetration into clouds

CRs penetrate clouds moving along straight lines

- Protons
- Electrons
- Total

$\xi_{CR}^2 [s^{-1}]$

$N(H_2) [\text{cm}^{-2}]$

OK

not OK
Ballistic penetration into clouds

- CRs penetrate clouds moving along straight lines
- is this a realistic scenario?

Graph showing the relationship between $N(H_2)$ [cm$^{-2}$] and $\xi_{\text{CR}}$ [s$^{-1}$] for protons, electrons, and total, with points marked as OK and not OK.
Ballistic penetration into clouds

CRs penetrate clouds moving along straight lines

is this a realistic scenario?

Most likely not...

Cosmic ray streaming into a cloud $\rightarrow$ plasma instability (streaming instability) $\rightarrow$ turbulence! $\rightarrow$ diffusive transport $\rightarrow$ CR intensity is more heavily suppressed!

$\rightarrow$ see Minh Phan’s talk tomorrow morning
Comparison with data

Figure 7. Ionization rate derived from Voyager spectra compared to observational data as a function of the column density. The two-dot-dashed line represents the model predictions of ionization losses into the cloud. Data points are from various sources: Maret & Bergin (2007) (purple asterisk), Indriolo & Caselli (2016) (blue filled circles), Williams et al. (1998) (blue triangles), and Cassen et al. (2007) (orange triangles).

Figure 6. Comparison with data from different phases of the ISM. The model predictions are shown as lines, while data points indicate observational results.

References


Cosmic ray ionization in different phases of the ISM. The return of the CR carrot?

The simple flux-balance argument mentioned in Sec. 2 and discussed in great detail in Morlino & Gabici (2018) could also enhance the ionization rate, as recently proposed by Padovani et al. (2015, 2016). Fluctuations of different amplitude should be invoked for MeV and GeV particles; indeed expected to exist, due for example to the discrete nature of CR sources (see for example Gabici & Montmerle 2015, and references therein).

However, we recall that the simple flux-balance argument mentioned in Sec. 2 and discussed in great detail in Morlino & Gabici (2018) could also enhance the ionization rate, as recently proposed by Padovani et al. (2015, 2016). Fluctuations of different amplitude should be invoked for MeV and GeV particles; indeed expected to exist, due for example to the discrete nature of CR sources (see for example Gabici & Montmerle 2015, and references therein).

Inhomogeneous distribution of ionizing CRs in the ISM could be incorrect. Fluctuations in the CR intensity are unlikely to result in a prediction different from the presented here (as required to fit data).
Comparison with data (???)

The existence of an unseen cosmic ray (CR) component, was proposed a long time ago (Cesarsky 1975; Cesarsky & Völk 1978), was recently observed by Voyager data (Li et al. 2015). Voyager data strongly constrain such a component, that should become dominant below particle energies of few MeV (the energy of the CR return of the CR carrot, was proposed a long time ago). However, such a component of low energy CRs, called "the CR carrot", could also enhance the ionization rate, as recently proposed by Padovani et al. (2015, 2016); candidate could be protostars, which might accelerate MeV CRs, accelerated locally by CR accelerators residing inside MCs. Obvious disagreement between the calculated ionization rates obtained neglecting propagation and ionization losses into the cloud.

Voyager protons

Voyager electrons

large discrepancy!
Spatial distribution of cosmic rays

**GC:** Oka+, LePetit+,
**Far:** Neufeld&Wolfire

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Spatial distribution of cosmic rays

factor of few over
the entire disk

GC: Oka+, LePetit+
Far: Neufeld&Wolfire

high energies

low energies

Gabici 2022
Spatial distribution of cosmic rays

factor of few over the entire disk

GC: Oka+, LePetit+, Far: Neufeld&Wolfire

~10-100

high energies

low energies
Spatial distribution of cosmic rays

factor of few over the entire disk

GC: Oka+, LePetit+, Far: Neufeld&Wolfire

high energies

low energies

~10-100

~100

Gabici 2022
Spatial distribution of cosmic rays

factor of few over the entire disk

4 orders of magnitude

GC: Oka+, LePetit+, Far: Neufeld&Wolfire

high energies

low energies

~10-100

~100

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Possible solutions

Protons in the LISM

Maxwellian: \( n = 0.1 \text{ cm}^{-3}; v = 26 \text{ km s}^{-1}; T = 8500 \text{K} \)

- V1 CRS 12/342−15/181
- Leaky-box model LIS

\[ J = 4.40 \times 10^{-3} E^{-1.5} e^{(-E/0.2)} \]

a CR carrot?
Possible solutions

Protons in the LISM

Maxwellian: \( n = 0.1 \text{ cm}^{-3}; \, v = 26 \text{ km s}^{-1}; \, T = 8500 \text{K} \)

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Possible solutions
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- V1 CRS 12/342-15/181
- Leaky-box model LIS

\[ J = 4.40 \times 10^{-3} \times E^{-1.5} \times e^{(-E/0.2)} \]

Voyager

extremely fast cooling

\[ \epsilon_{\text{H}} E / L_{\text{iso}} (E) \text{ [cm}^{-2} \text{]} \]

protons
electrons
Possible solutions

A CR carrot?

Maxwellian: \( n = 0.1 \text{ cm}^{-3}; v = 26 \text{ km s}^{-1}; T = 8500 \text{K} \)

- V1 CRS 12/342-15/181
- Leaky-box model LIS

\[ J = 4.40 \times 10^{-3} \ E^{-1.5} \ e^{(-t/0.2)} \]

Voyager

Protons in the LISM

extremely fast cooling

the carrot requires too much energy!

Recchia+ 2019
Possible solutions

CR sources within clouds?

→ what about starless cores? (see works by Padovani+)

a CR carrot?

Protons in the LISM

Maxwellian: \( n = 0.1 \text{ cm}^{-3}; v = 26 \text{ km s}^{-1}; T = 8500 \text{K} \)

- V1 CRS 12/342–15/181
  - Leaky-box model LIS

\( J = 4.40e^{-3} E^{-1.5} e^{-t/0.2} \)

thermal

Voyager

extremely fast cooling

the carrot requires too much energy!

Recchia+ 2019
Stochasticity of sources

← position of known SNR in the MW

Ranasinghe & Leahy 2022
Stochasticity of sources

<— position of known SNR in the MW

Ranasinghe & Leahy 2022

Phan+ 2021
Stochasticity of sources

Ranasinghe & Leahy 2022

Phan+ 2021
Stochasticity of sources

Ranasinghe & Leahy 2022

<— position of known SNR in the MW

dispersion

median

Phan+ 2021
Stochasticity of sources

Position of known SNR in the MW

Enhancement of ionisation rate? Stay tuned! (Phan+ submitted —> HIS TALK TOMORROW!)

Median
dispersion

Phan+ 2021
Open questions on low energy CRs

We do not understand the origin of the ionisation rates measured in clouds.

Several questions need then to be answered.

- What induces the large ionisation rates observed in clouds?
- Are the spectra of low energy CRs measured in the local ISM representative of the entire Galaxy? Or, what is the spatial distribution of low energy CRs throughout the Galactic disk?
- Why are diffuse atomic and molecular clouds, despite their different column density, characterised by the same ionisation rate?
- Why is the ionisation rate so large in the Galactic centre region?
- What are the sites of acceleration of the low energy CRs responsible for the ionisation of clouds? —> turbulent reaccelerating in clouds? (Gaches+)
- Does the observed intensity of LECRs in the local ISM reflects the fact that we live in a special place in the Galaxy? —> Local Bubble? (Silsbee & Ivlev 2019)
The future (I): JWST

\[ \text{CR} + \text{H}_2 \rightarrow \text{CR} + \text{H}_2^+ + e^- \]

\[ e^- + \text{H}_2 \rightarrow \text{rovibrational line emission (IR)} \]
The future (I): JWST

\[ \text{CR} + \text{H}_2 \rightarrow \text{CR} + \text{H}_2^+ + e^- \]

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The future (I): JWST

\[ \text{CR} + \text{H}_2 \rightarrow \text{CR} + \text{H}_2^+ + e^- \]

\[ e^- + \text{H}_2 \rightarrow \text{rovibrational line emission (IR)} \]

detectable by JWST

NO CHEMISTRY!!!

Padovani+ 2021
The future (II): Athena

cold gas irradiated by CRs
$\rightarrow$ Fe Kα line @6.4 keV

← tentative evidence from a number of SNRs
(Nobukawa+ 2018)

→ we need Athena
The future (III): MeV astronomy

De-excitation nuclear gamma-ray line emission (Ramaty+)

\[ E^2 \times dN/dE \, (\text{erg cm}^{-2} \, \text{s}^{-1}) \]

-80° < l < 80° ; -8° < b < 8°

Fermi-LAT

e-ASTROGAM

de Angelis+ 2018
The future (IV): SKA

Synchrotron radiation from low energy electrons

\[ \log_{10} \left( \frac{\dot{J}_e}{\text{eV}^{-1} \text{s}^{-1} \text{cm}^{-2} \text{sr}^{-1}} \right) = \log_{10} [E/\text{eV}] \]

- Red: 10 \( \mu \text{G} \)
- Blue: 100 \( \mu \text{G} \)
- Green: 1 mG

Padovani & Galli 2018
Merci!
Backup slides
Pioneering studies

energy losses

$\propto E$

$10 \text{ MeV}$

$100 \text{ MeV}$

Hayakawa et al. 1961 $\rightarrow \zeta_{CR}^{H} \gtrsim 4 \times 10^{-16} \text{ s}^{-1}$
Pioneering studies

Spitzer & Tomasko 1968 (Glassgold & Langer 1973) → \( \zeta_{CR}^{H_2} \sim 10^{-17} \text{s}^{-1} \)

Hayakawa+ 1961 → \( \zeta_{CR}^{H} \gtrsim 4 \times 10^{-16} \text{s}^{-1} \)

energy losses

\( \alpha E \)

Fluxes of Cosmic Rays

(1 particle per m²-second)

Knee

(1 particle per m²-year)
Pioneering studies

for some reason, the Spitzer value became the standard reference

Spitzer & Tomasko 1968 (Glassgold & Langer 1973) → \( \zeta_{CR}^{H_2} \sim 10^{-17} \text{ s}^{-1} \)

Hayakawa+ 1961 → \( \zeta_{CR}^{H} \gtrsim 4 \times 10^{-16} \text{ s}^{-1} \)

\( \alpha E \)

Energy losses

10 MeV

0.85 GeV

fluxes of cosmic rays

(1 particle per m²-second)

Knee

(1 particle per m²-year)
So?

More refined model? (better description of transition from hot to neutral medium, time dependence induced by turbulence?) $\rightarrow$ the flux balance argument seems quite solid...
**So?**

- More refined model? (better description of transition from hot to neutral medium, time dependence induced by turbulence?) → the flux balance argument seems quite solid...

- Non-homogeneous distribution of MeV CRs in the Galaxy? (see Cesarsky 1975 for a pioneering work)

---

![Graph showing ionization rates as a function of column density.](image-url)
More refined model? (better description of transition from hot to neutral medium, time dependence induced by turbulence?) \(\rightarrow\) the flux balance argument seems quite solid...

- Non-homogeneous distribution of MeV CRs in the Galaxy?
  (see Cesarsky 1975 for a pioneering work)

- CR acceleration inside molecular clouds?
  (turbulence \(\rightarrow\) Dogiel+,
  protostars \(\rightarrow\) Padovani+)
More refined model? (better description of transition from hot to neutral medium, time dependence induced by turbulence?) —> the flux balance argument seems quite solid...

Non-homogeneous distribution of MeV CRs in the Galaxy? (see Cesarsky 1975 for a pioneering work)

CR acceleration inside molecular clouds? (turbulence —> Dogiel+, protostars —> Padovani+)

Hidden (very low energy) component in the CR spectrum?
Figure 1. A cosmic ray carrot?

In Fig. 3 we compare this typical distance for CR electrons and protons in a cloud of size L with a typical cloud size \( r_{\text{cloud}} \) estimated in Cummings et al. (2016) as \( 10^{16} \) cm, able to predict an ionization rate of \( 10^{-41} \) erg/s roughly corresponds to 10% of the CR electron luminosity of MW, with a typical cloud size \( 10^{16} \) cm, able to predict an ionization rate of \( 10^{-41} \) erg/s roughly corresponds to 10% of the CR electron luminosity of MW, with a typical cloud size \( 10^{16} \) cm, able to predict an ionization rate of \( 10^{-41} \) erg/s roughly corresponds to 10% of the CR electron luminosity of MW, with a typical cloud size \( 10^{16} \) cm, able to predict an ionization rate of \( 10^{-41} \) erg/s roughly corresponds to 10% of the CR electron luminosity of MW, with a typical cloud size \( 10^{16} \) cm, able to predict an ionization rate of \( 10^{-41} \) erg/s roughly corresponds to 10% of the CR electron luminosity of MW, with a typical cloud size \( 10^{16} \) cm, able to predict an ionization rate of \( 10^{-41} \) erg/s roughly corresponds to 10% of the CR electron luminosity of MW, with a typical 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A cosmic ray carrot?

- ISM
- MC
- 

**Figure 2.**

- Dashed line
- C-2016

**Figure 1.** Any choice of a broader spectrum in the range 1 keV–1 MeV will lead to a lower predicted level of ionization. Notice that this result is not expected to change with respect to the ionization timescale in the range 0.1–1 MeV. This roughly corresponds to 10% of the CR p luminosity of MW and 0.1% of the CR e luminosity of MW. The ionization timescale in the range 0.1–1 MeV governs the life of sources. Cosmic ray carrot?

- Protons
- Electrons
- Cloud

**Figure 3.** In Fig. 3 we compare this typical distance for CR electrons and protons in a cloud of density given by $n_c = 100 \text{ cm}^{-3}$ ($\tau_{\text{life}} \approx 3 \text{ yr}$) with $E_{\text{grav}} = 1 \text{ MeV}$, able to predict the same ionization level in MCs, will be able to keep a cloud of electrons and protons of energy in the range $E_{\text{loss}} = 10^6 \text{ MeV}$ for a proton (electron) component. Moreover, this estimated power is a very conservative estimate of the total power in CR protons needed to keep a cloud before losing all their energy due to ionization losses, for different assumptions on the spectral shape of the low energy component. In fact here we assumed that the unknown CR power for them is $< 500 \text{ erg/s}$ roughly corresponds to 10% of the total power of galactic supernova explosions. Since supernova remnants are considered the major source of Galactic CRs, with the short lifetime of low energy CRs in the ISM (see Eq. 5), any choice of a broader spectrum in the range 0.1 keV–1 MeV (or the suprathermal tail of Cummings et al. 2016) as a cosmic ray carrot?
So?

- More refined model? (better description of transition from hot to neutral medium, time dependence induced by turbulence?) —→ the flux balance argument seems quite sound...
- Non-homogeneous distribution of MeV CRs in the Galaxy? (see Cesarsky 1975 for a pioneering work)
- CR acceleration inside molecular clouds? (turbulence —→ Dogiel+, protostars —→ Padovani+)
- Hidden (very low energy) component of the CR spectrum?
The importance of being a SNOB

Montmerle 1979

tentative spatial association between SNOBs and COS B hot spots

SuperNovae  OB associations
The importance of being a SNOB

Montmerle 1979

tentative spatial association between SNOBs and COS B hot spots

OB stars

supernovae

SuperNovae

OB associations
The importance of being a SNOB

Montmerle 1979

tentative spatial association between SNOBs and COS B hot spots

OB stars

supernovae

CR acceleration

SuperNovae

OB associations

SNRs
The importance of being a SNOB

Montmerle 1979

- Tentative spatial association between SNOBs and COS B hot spots

OB stars

Supernovae

OB associations

SNRs

CR acceleration

Black & Fazio 1973

Molecular cloud

\( \gamma \)-rays
The importance of being a SNOB

Montmerle 1979

tentative spatial association between SNOBs

OB stars

supernovae

γ-rays

 associations between SNRs & MCs are expected, and are ideal targets for gamma-ray observations due to the enhanced rate of CR interactions with the gas

→ STAR FORMING REGIONS/SUPERBUBBLES

CR acceleration

Black & Fazio 1973
SNR/MC associations in γ-rays

spatial correlation between γ-ray and CO emission
2 scenarios: interaction or runaway CRs?


shock/MC interaction
2 scenarios: interaction or runaway CRs?


shock/MC interaction

W51C
W44
IC443
2 scenarios: interaction or runaway CRs?


shock/MC interaction

runaway CRs

2 scenarios: interaction or runaway CRs?


shock/MC interaction

runaway CRs

Interaction versus escape: who's who?

both scenarios require an overdensity of GeV-TeV CRs at the MC.
The aim of this paper is to present measurements of the ionization fraction within the molecular clouds in the vicinity of the W51 SNR. This supports the idea of the pion-decay production by both HESS and MAGIC telescopes close to the vicinity of the W51 SNR. The detection of TeV emission involving electron CR. In this alternative scenario, the scattering of the cosmic microwave background (e.g. Morfill et al. 2013) specifically support a hadronic origin of W44 SNR with the Fermi -LAT telescope (Ackermann et al. 2011). Yet, this scenario cannot explain the spatial correlation of TeV emission with molecular clouds. Moreover, recent observations of the IC443 and W44 SNR with the W51C acting as a TeV + gas -> multi-TeV CR protons.
Indeed, in CC2011, an enhanced ionization fraction was reported towards one position, W51C-E, which required a CR reduction of molecular cloud is evidence of a physical interaction with the vicinity of the W51 SNR. The detection of TeV emission can be explained mainly by inverse Compton radiation by both HESS and MAGIC telescopes close to the SNR shock front, whilst the low-energy tail of the most energetic CR protons diage down.

From a theoretical point of view, it is expected that the interaction of the SNR shock with molecular clouds gives additional evidence supporting a physical interaction of the SNR shock with molecular clouds. It also gives additional evidence supporting a physical interaction of the SNR shock with molecular clouds. Moreover, recent observations of the IC443 and W44 SNR with the W51C acting as a sub-solar cloud in the W28 complex (zoom on the SE1 box).

This idea was put forward by Ceccarelli et al. (2011) for the presence of freshly accelerated CR, with energies located in the vicinity of SNR could be the smoking gun that an enhanced electron abundance in molecular clouds explain the spatial correlation of TeV emission with molecular clouds. Hence, it has been proposed that any ionization enhancement by low energy CR should be localized accordingly. In CC2011, however, only one location was identified.

However, the interpretation is not straightforward, as H01. Moreover, recent studies show an enhancement of a factor of 10-100 in the ionization fraction of the dense gas. It has thus been proposed that an enhanced CR protons can be traced indirectly by measuring the ionization fraction in several directions.

The combined observations of two extreme energy points show TeV emission as seen by HESS and MAGIC. SNR paradigm specifically support a hadronic origin of W51C-E with the LC (Lefloch et al. 2008). Diamonds show the locations of OH masers in the region (Claussen et al. 1997). The blue circle gives the approximate radio boundary of the SNR W28 (Brogan et al. 2006).

Approx. projected distance to shock [pc]

Standard value in dense clouds \( \zeta_0 \sim 10^{-17} \text{s}^{-1} \)}
The aim of this paper is to present measurements of the SNR paradigm for the origin of CR. Indeed, in CC2011, an enhanced ionization fraction was required a CR production cannot be traced by the emission integrated over 15-25 km s\(^{-1}\) with W51C acting as a \(\gamma\)-ray emitter. Nevertheless, recent calculations suggest that an enhanced CRI in low density molecular clouds. Altogether, from a theoretical point of view, it is expected that the interaction of the SNR shock with molecular clouds.

The W28 complex on large scales. Moreover, recent observations of the IC443 and the W44 SNR with the W51C molecular cloud, located in the vicinity of SNR could be the smoking gun for the presence of freshly accelerated CR, with energies located in the vicinity of SNR. The detection of TeV emission can be explained mainly by inverse Compton scattering of the cosmic microwave background (e.g. Morlino et al. 2009; Abdo et al. 2011). Yet, this scenario cannot explain the spatial correlation of TeV emission with molecular clouds. Moreover, recent observations of the IC443 and the W28 complex specifically support a hadronic origin of W51C-E, which required a CR production by both HESS and MAGIC telescopes close to the SNR. This supports the idea of the pion-decay process.

The combined observations of two extreme energy ranges, namely TeV and millimeter, seems a powerful method to characterize an enhanced concentration of protons (Padovani et al. 2009). Accordingly, low-energy CR protons can be traced indirectly by measuring the ionization fraction of the dense gas. It has thus been proposed that any ionization enhancement by low energy CR should be used to derive the ionization fraction, and that any ionization enhancement by low energy CR should be consistent with the so-called SNR paradigm for the origin of CR. With energies located in the vicinity of SNR, the ionization of UV-shielded gas is mostly due to keV-GeV proton CR. It also gives additional evidence supporting a physical interaction with the vicinity of the W51 SNR. The detection of TeV emission in the W51C-E molecular cloud, located in the vicinity of SNR could be the smoking gun for the presence of freshly accelerated CR, with energies located in the vicinity of SNR. The detection of TeV emission can be explained mainly by inverse Compton scattering of the cosmic microwave background (e.g. Morlino et al. 2009; Abdo et al. 2011). Yet, this scenario cannot explain the spatial correlation of TeV emission with molecular clouds. Moreover, recent observations of the IC443 and the W28 complex specifically support a hadronic origin of W51C-E, which required a CR production by both HESS and MAGIC telescopes close to the SNR. This supports the idea of the pion-decay process.

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Indeed, in CC2011, an enhanced ionization fraction was reported towards one position, W51C-E, which required a CR production rate two orders of magnitude larger than the typical value of the ionization rate. This supports the idea of the pion-decay production by both HESS and MAGIC telescopes close to the vicinity of the W51 SNR. The detection of TeV emission even in absence of an increased CR flux demonstrates the spatial correlation of TeV emission with molecular clouds. Moreover, recent observations of the IC443 and W28 complexes on large scales, particularly in the vicinity of SNR, show the CO(1-0) emission (Dame et al. 2001) integrated over 15-25 km s\(^{-1}\) with the IRAM-30m and discussed in this paper. The blue contours show the 20 cm free-free emission in the M20 region (Yusef-Zadeh et al. 2014), which could be the smoking gun for the origin of the CRI rate in molecular clouds. Altogether, these studies show an enhancement of a factor of 10-100 as Padovani et al. (2009) showed that the penetration of CR protons with kinetic energy below the Galactic CR Flux production cannot be traced by the emission. Nevertheless, recent calculations suggest that any ionization enhancement by low energy CR should be localized accordingly. In CC2011, however, only one location was used at larger distances ahead of the SNR shock front, whilst the low-energy tail of the most energetic CR protons diffuse as Padovani et al. (2009) showed that the penetration properties as McCall et al. 2012) with respect to the canonical value. McCall 2012) with respect to the canonical value.}

\[
\zeta \sim 10^{-17} \text{s}^{-1}
\]

The combined observations of two extreme energy ranges, namely TeV and millimeter, seems a powerful method to characterize an enhanced concentration of protons (hereafter CC2011), who measured the ionization fraction of the dense gas. It has thus been proposed that any ionization enhancement by low energy CR should be localized accordingly. In CC2011, however, only one location was used at larger distances ahead of the SNR shock front, whilst the low-energy tail of the most energetic CR protons diffuse as Padovani et al. (2009) showed that the penetration properties as McCall et al. 2012) with respect to the canonical value. McCall 2012) with respect to the canonical value.

\[
\zeta \sim 10^{-17} \text{s}^{-1}
\]
**W28**

Vaupré, Hily-Blant, Ceccarelli, Dubus, SG, Montmerle (2014)

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**Diagram:**

- **TeV gamma-rays**
  - HESS J1801-233
  - SNR shock

- **IRAM pointings**
  - A, B, C
  - 00-240

- **mol. cloud**
  - DCO+/HCO+

- **Excess of MeV-GeV CRs close to the SNR shock!**

*also CR electrons contribute to ionization*
Indeed, in CC2011, an enhanced ionization fraction was reduced from the SNR. This supports the idea of the pion-decay production by both HESS and MAGIC telescopes close to the vicinity of the W51 SNR. The detection of TeV emission (hereafter CC2011), who measured the ionization fraction for the presence of freshly accelerated CR, with energies located in the vicinity of SNR could be the smoking gun that an enhanced electron abundance in molecular clouds is evidence of a physical interaction with protons (Padovani et al. 2009). Accordingly, low-energy CR can be traced indirectly by measuring the ionization fraction of the dense gas. It has thus been proposed that CR protons with kinetic energy below the threshold of primary CR (see e.g. Hillas 2005, for a review).

From a theoretical point of view, it is expected that the production into the cloud of high energy CR results into an enhanced CRI in low density molecular clouds as Padovani et al. (2009) showed that the penetration power in clouds close to SNR has been carried out using different techniques, such as studies show an enhancement of a factor of 10-100 as H$^+_0$ absorption (McCall et al. 2003). Also, these measurements give additional evidence supporting a physical interaction with the ionization properties of the W51C molecular cloud, located in the vicinity of the W51 SNR shock front, whilst the low-energy tail of the most energetic CR protons di...
CR ionization rate in MCs next to SNRs

**7. Discussion**

Fig. 6. Diagram showing the range of column densities for different values of visual extinctions. The dashed lines represent the range of column densities observed in various objects. The blue circle in Fig. 7 indicates the projected distance from the SNR radio boundary.

- **Diffuse clouds**: The ionization rates are lower compared to dense clouds and high $A_V$ objects.
- **Dense clouds**: The ionization rates are significantly higher than in diffuse clouds.
- **High $A_V$ objects**: These show the highest ionization rates.

Note that for observations of N5 and N6, we assumed different values of visual extinctions of 5 and 100 mag, respectively. On the left, the ionization rates are measured in various objects, with high $A_V$ objects marked.

The visual extinction is a critical parameter in determining the ionization rates, especially in high density environments. The figure illustrates how the ionization rate changes with the gas temperature and the projected distance from the shock.

**Compilation of measured CR ionization rates**

- **Vaupré et al 2014**: The compilation includes measurements from different SNRs and dense molecular clouds, corresponding to typicall dense clouds. The ionization rates are derived following the method described in Table 5, which lists the observed positions and the corresponding CR ionization rates.

- **Hip 2013**: The measurements include various SNRs and their associated dense clouds, with the ionization rates measured in different energy ranges.

- **CC2011**: The ionization rates are also measured in various objects, with a focus on high $A_V$ objects. The measurements show a significant increase in ionization rates with projection effects at the southern part of the SNR.

Yet, this can still provide us with precious constraints on the ionization rates in dense molecular clouds.
CR ionization rate in MCs next to SNRs

Discussion

such as infrared dark clouds or protoplanetary disks. Visual extinctions of 5 and 100 mag, respectively. On the left lie dashed lines showing the range of column densities.

\[ \zeta \]  

Compilation of measured \( \zeta \) as a function of the gas temperature. Use clouds. Dense clouds in the HIP for temperatures \( T \). Use clouds close to SNR have visual extinctions of 5 and 100 mag, respectively. On the left lie dashed lines showing the range of column densities.

Red contours: from 2 to 5 \( \times 10^{18} \) as a function of the gas temperature. Use clouds. Dense clouds in the HIP for temperatures \( T \).

This idea was put forward by Ceccarelli et al. (2011) for the origin of 10\(^{17}\)-rays with W51C acting as a high-energy CR protons with kinetic energy below the GeV. This idea was put forward by Ceccarelli et al. (2011) for the origin of 10\(^{17}\)-rays with W51C acting as a high-energy CR protons with kinetic energy below the GeV. This idea was put forward by Ceccarelli et al. (2011) for the origin of 10\(^{17}\)-rays with W51C acting as a high-energy CR protons with kinetic energy below the GeV.

The W28 complex on large scales. The W28 complex on large scales. The W28 complex on large scales.

From a theoretical point of view, it is expected that the propagation properties of CR, as it will be discussed in this paper, are those with the highest values, together with the CC2011 (from Padovani & Galli 2013), plus our measurements. In general, the propagation properties of CR, as it will be discussed in this paper, are those with the highest values, together with the CC2011 (from Padovani & Galli 2013), plus our measurements.
CR ionization rate in MCs next to SNRs

Infrared dark clouds or protoplanetary disks

Visual extinctions of 5 and 100 mag, respectively.

Isolated clouds and highly obscured environments

Clouds next to SNR are indeed irradiated

Magnetic field

H.E.S.S.

HESS J1801–233

M20

W28 SNR

Fig. 7.
W51C

color $\rightarrow$ TeV gamma-rays (MAGIC)

green $\rightarrow$ CO
W51C

- **color** -> TeV gamma-rays (MAGIC)
- **green** -> CO
- **white contours** -> TeV gamma-rays
- **black contours** -> CO
- **dashed** -> Fermi

\[ \zeta_{\text{CR}} \sim \text{few } 10^{-15} \text{ s}^{-1} \]

Ceccarelli+ 2011
Figure 2.

Figure 3.

SiO emission → slow shock → shock-clump interaction? → downstream of SNR shock

W51C

color → TeV gamma-rays (MAGIC)
green → CO

white contours → TeV gamma-rays
black contours → CO
dashed → Fermi

ζCR ~ few 10^{-15} s^{-1}

Ceccarelli+ 2011

Dumas+ 2014

SiO emission → slow shock → shock-clump interaction? → downstream of SNR shock
CR ionization rate in MCs next to SNRs

Vaupré et al 2014 - Ceccarelli et al 2011

\[ \zeta \text{ [s}^{-1}] \]

\[ N(H_2) \text{ [cm}^{-2}] \]

Diffuse clouds | Dense clouds | High \( A_V \) objects

Note that for different values of \( \tau \), the cloud is always in the LIP, regardless of the temperature. For \( \tau > 1 \), such as infrared dark clouds or protoplanetary disks, the cloud is always in the LIP.
IC443

age $\sim 3 \times 10^4$ yr, evidence of shocked cloud material, clumps

runaway CRs

SNR/MC interaction

Torres+ 2010

Uchiyama+ 2010
IC443

age ~ 3 x 10^4 yr, evidence of shocked cloud material, clumps

runaway CRs

SNR/MC interaction

H_3^+ lines from A,B,...,F

Indriolo+ 2010 (Keck, Subaru)

Torres+ 2010

Uchiyama+ 2010
IC443

age ~ 3 x 10^4 yr, evidence of shocked cloud material, clumps

runaway CRs

SNR/MC interaction

ζ_{CR} ~ few 10^{-15} s^{-1}

non detections: propagation effects? gas up-downstream of the shock?

H_3^+ lines from A, B, ..., F

 Torres+ 2010

Indriolo+ 2010 (Keck, Subaru)
CR ionization rate in MCs next to SNRs

Fig. 6. Diagram showing the CR ionization rate (ζ) as a function of the gas temperature (T) in Galactic clouds. This is shown in Fig. 6, where the ionization rate is plotted against the gas temperature, with different symbols representing various cloud types:

- **Diffuse clouds** are represented by green symbols.
- **Dense clouds** are represented by red symbols.
- **High A_v objects** are represented by blue symbols.

The diagram includes data from various studies:
- **Vaupré et al 2014**
- **Ceccarelli et al 2011**
- **Indriolo et al 2010**

The x-axis represents the column density of H_2 (N(H_2) [cm^{-2}]), while the y-axis represents the ionization rate (ζ [s^{-1}]). The diagram illustrates the variation of ionization rate with different column densities and gas temperatures for various cloud types.
W28: cosmic rays or X-rays?

Contour map for the W28 region. The approximate radio contours of the SNR shell, as traced by its radio emission (Dubner et al. 2000; Brogan et al. 2006). Observations of W28 and its surroundings. The short-dashed red circle is the best-fit disk size for the Fermi-LAT source associated to the north-eastern MC. The filled black circle and square indicate the position of the SNR/MC interaction rate measured in the north-eastern MC.

The filled black circle and square indicate the position of the SNR/MC interaction rate measured in the north-eastern MC. Puzzlingly, Fe I Kα line emission is the origin for the line emission and the excess in the ionization rate is due to CR protons, electrons, or X-ray photons is one of the goals of this paper (see Sec. 3).

The presence of the gamma-ray emission from the MCs (Fujita et al. 2009; Gabici et al. 2010; Li & Chen 2010; Ohira et al. 2011; Nava & Gabici 2010). Remarkably, the H.E.S.S. collaboration reported on the detection of very-high-energy gamma-ray emission from the MCs in the region (Matsunaga et al. 2001; Aharonian et al. 2008). The enhanced region of Fe I Kα line in the X-ray spectrum. This line is produced by interactions between low energy (MeV domain) CRs and the cold gas, and it is therefore tempting to propose a common origin for the line emission and the excess in the ionization rate.

As we will see in the following, X-rays are in this case explained by assuming that CR protons were accelerated in the cloud (Claussen et al. 1997; Hewitt et al. 2018). These observations revealed the presence of the Fe I Kα line in the X-ray spectrum. This line is produced by interactions between low energy (MeV domain) CRs and the cold gas, and it is therefore tempting to propose a common origin for the line emission and the excess in the ionization rate.
Figure 1: Contour map for the W28 region. The approximate radio boundary of the SNR shell is shown as a purple dot-dot-dashed circle. The solid blue contours represent the $4\sigma$ significance levels used to constrain the CR proton and electron spectra (see text). The short-dashed red circle is the best-fit disk size for the LAT GeV source associated to the north-eastern MC (Cui et al. 2014). The large triangle represents the position of the H.E.S.S. LAT gamma-ray source, while the small square is the position of the XMM-Newton hard X-ray source (Phan et al. 2014). The region of enhanced ionization is marked by a yellow star. 

Figure 2: Differential ionization rate for different assumed proton and electron characteristics. The ionization rates are shown as a function of energy. The ionization rate for different assumed proton and electron characteristics is shown. The maximum possible value for the ionization rate is shown by the short-dashed red line, and the minimum possible value is shown by the short-dashed green line. The differential ionization rates for different assumed proton and electron characteristics are shown by the solid blue and green lines, respectively.
W28: cosmic rays or X-rays?

Fig. 2 in Phan et al. 2018). In fact, energy losses can be up to 10\(\times\)10\(^{-16}\) times the solar one, respectively. Observational data taken at radio wavelengths (mainly ionization losses) in the dense gas, over a characteristic time \(T\propto\xi/n\) which is obtained after assuming that CR protons have to cross a gas column of density \(n\) to reach the centre of the cloud moving a distance \(\xi\) characterized by a quite steep power law spectrum, below energies above 10\(\times\)10\(^{-15}\) MeV, which is a factor of few smaller than 10\(\times\)10\(^{-14}\) eV.

Another possible scenario is that the SNR shock has reached only the outer parts of the SNR radio boundary and therefore has not been reached by the shock yet. In the following, we will focus on the interaction region, and for this reason we need to combine high and low energy observations of the gamma-ray bright MCs (Fujita et al. 2009; Gabici et al. 2015). Such emission has been shown to be in good agreement with a thin disk model (Vaupré et al. 2014; Gabici & Montmerle 2015). Such emission is due to non-thermal Bremsstrahlung have been shown to fit to gamma-ray data only if unrealistic values of the low energy CRs at low energy. However, our understanding of the electron spectrum is far from being settled. Predictions for the photo-ionization rate are shown by the solid and dashed red lines (metallicity of 1 and 0.3 respectively).

It should be noticed that, in this scenario, the range of accuracy in spectral features varies from 10\(\times\)10\(^{-13}\) to 10\(\times\)10\(^{-14}\). It is due to non-thermal Bremsstrahlung have been shown to fit to gamma-ray data only if unrealistic values of the low energy CRs at low energy. However, our understanding of the electron spectrum is far from being settled. Predictions for the photo-ionization rate are shown by the solid and dashed red lines (metallicity of 1 and 0.3 respectively).

As stated above, the decay of neutral pions produced in the hadronic interaction of cosmic rays with ambient gas column densities along the line of sight \(N_1\) and solar abundance.

\[\frac{N_1}{N_{H}}\approx 10^{-10}\]

The short-dashed red circle is the best-fit disk size for the radio source (Rho & Borkowski 2002; Zhou et al. 2014), and another possible scenario is that the SNR shock has reached only the outer parts of the SNR radio boundary and therefore has not been reached by the shock yet. In the following, we will focus on the interaction region, and for this reason we need to combine high and low energy observations of the gamma-ray bright MCs (Fujita et al. 2009; Gabici et al. 2015). Such emission has been shown to be in good agreement with a thin disk model (Vaupré et al. 2014; Gabici & Montmerle 2015). Such emission is due to non-thermal Bremsstrahlung have been shown to fit to gamma-ray data only if unrealistic values of the low energy CRs at low energy. However, our understanding of the electron spectrum is far from being settled. Predictions for the photo-ionization rate are shown by the solid and dashed red lines (metallicity of 1 and 0.3 respectively).
W28: cosmic rays or X-rays?

The diagram shows a comparison between different observation methods and data points for the SNR W28. The X-ray emission is highlighted in green, while the radio and infrared emissions are shown in blue and purple, respectively. The data points from the Fermi and HESS telescopes are also plotted.

The X-ray data is shown in the inset graph, with the X-ray brightness plotted against the hydrogen column density. The green band represents the CR ionization rate, while the red and blue lines are the X-ray emission predictions.

The text explains that the excess in the gas ionization observed with the IRAM 30-m telescope can be explained by assuming that CR protons were accelerated in a hadronic origin of the gamma-ray emission. Observations of the SNR W28 and its surroundings support this scenario.
W28: bridging high and low energy CRs

fit with a proton spectrum

$$f_{CR} \propto p^{-2.8}$$

gammas produced by protons of energy

$$E \gtrsim 1 \text{ GeV}$$
W28: bridging high and low energy CRs

**γ-rays** fit with a proton spectrum

\[ f_{CR} \propto p^{-2.8} \]

gammas produced by protons of energy

\[ E \gtrsim 1 \text{ GeV} \]

\[ \zeta_{CR} \gtrsim 2 \times 10^{-15} \text{ s}^{-1} \]

\[ E_{min} \approx 30 - 300 \text{ MeV} \]
W28: bridging high and low energy CRs

\[ \tau_{age} \sim \tau_{ion} \rightarrow E \approx 400 \text{ MeV} \]

\[ \tau_{cross} \sim \tau_{ion} \rightarrow E \approx 10 \text{ MeV} \]

\[ \zeta_{CR} \gtrsim 2 \times 10^{-15} \text{ s}^{-1} \]

fit with a proton spectrum \( \propto p^{-2.8} \)

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Phan+ 2020
W28: bridging high and low energy CRs

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we report a compilation of the exception of the SE1 point, in all other points in the previous section. First thing to notice is that, with CR ionization rates, derived following the method described in di

[$\zeta$] [$s^{-1}$]

[$N(H_2)$] [$cm^{-2}$]

Diffuse clouds

Dense clouds

High $A_V$ objects

Yet, this can still provide us with precious constraints on the following.

- High energy ($\sim 10^{17}$ eV) extra-galactic gamma rays are detected towards W51 by HESS. This means that the clouds are illuminated by very high energy particles.
- The SE1 ionization rate corresponds to a solid angle, that could be reached by CR TeV particles (or more, if projection effects play a role) to the southern clouds coincident with sources of TeV emission, as noted by Padovani et al. (2013). Consequently, the ionization rate measured in the SE1 point tells us that the ionizing lower energy CR remain contained in the SNR shell but are not able to escape the shell and consequently cannot be detected by HESS. This means that the clouds are irradiated by CR particles, thus exhibiting a lack of GeV emission is probably located at a distance from the shock significantly larger than the projected distance from the SNR radio boundary (blue circle in Fig. 7). Remarkably, the point SE1 tells us that the ionizing lower energy CR remain confined closer to the SNR. In the same vein, GeV emission has been detected towards the northern region but only towards a part of the southern one. This discrepancy is, of course, an analysis does not take into account the 3D structure of the SNR complex.

Another result to notice regards the dependence of the visual extinctions of 5 and 100 mag, respectively. On the left lie filled square shows squares), as reported by Padovani & Galli (2013). The black filled square shows different values of $N_1$ in Galactic clouds. This is shown in Fig. 6, where [$N_0$] [$cm^{-2}$] in W51 (Ceccarelli et al. 2011). Red points correspond to typical densities (see text).
Conclusions (?)

![Graph showing the relationship between $\zeta$ and $N(H_2)$ across different types of clouds and objects.]

- **Diffuse clouds**
  - Lower values of $\zeta$ are observed in diffuse clouds.
- **Dense clouds**
  - Higher values of $\zeta$ are observed in dense clouds.
- **High $A_V$ objects**
  - The highest values of $\zeta$ are found in these objects.

*Note: We don't understand this.*
Conclusions (?)

maybe we are starting to understand this

we don’t understand this
we really don't understand this

Conclusions (?)

we report a compilation of the least 10 to 260 times larger than the standard value (the exception of the SE1 point, in all other points in the previous section. First thing to notice is that, with CR ionization rates, derived following the method described such as infrared dark clouds or protoplanetary disks.

The di visual extinctions of 5 and 100 mag, respectively. On the left lie 10 dashed lines show the range of column densities (squares), as reported by Padovani & Galli (2013). The black squares, a marked.

Note that for different values of HIP, as a function of the gas temperature in W51 (Ceccarelli et al. 2011). Red points maybe we are starting to understand this.

Fig. 6.

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R = \frac{DCO}{HCOD} \times 10^{10}
\`

Gal. centre

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Another thing we don't understand:
Spallogenic nucleosynthesis of Li–Be–B

Figure 2
Observations of Be abundances vs. [Fe/H] (panel a) and [O/H] (panel b). Data are from Refs. (45, black dots) and (46, red circles). The dashed lines of slope one represent a primary Be production and the dotted lines of slope two a secondary Be production (see text). In panel (b), the solid line shows a fit to the data with a secondary Be production component plus a primary component of constant Be/Fe = 7.2 × 10^-7.

The Be vs. Fe data (panel a) are consistent with a constant Be/Fe = 7.2 × 10^-7.

The Li–Be–B story experienced an unexpected development in the 1990s, when further observations of metal-poor halo stars (e.g. 43, 44) revealed that Be and B abundances increase linearly with [Fe/H]. This is illustrated for the Be evolution in Figure 2a with the data of Refs. (45, 46); measurements by other groups (e.g., 47, 48) show a similar trend (see Figure 1 in Ref. 35). The observed metallicity dependence of Be was unexpected, because this element was thought to be synthesized by spallation of increasingly abundant CNO nuclei in both the ISM and the GCRs, which is a secondary production process leading to a quadratic dependence of the nucleosynthesis product with metallicity (see 49, 50).

The observed linear evolution of Be with [Fe/H] is equivalent to a constant abundance ratio for the entire period of Galactic evolution: Be/Fe = 7.2 × 10^-7 (Figure 2a). For [Fe/H] up to about 1, the bulk of Fe is thought to be produced in core-collapse SNe, with a mean Fe yield per SN of ~0.07 M⊙, independent of the metallicity of the massive progenitor star (51). It implies that the Be production rate was essentially constant in the early ages of the Galaxy, with a mean Be production yield of 1.1 × 10^48 atoms per SN.

This result is consistent with the predicted Be production at the current epoch, assuming that about 10% of the total energy in SN ejecta is converted to GCR energy (53, 54, see also Sect. 3.2.1 below). But the Be production yield was expected to be much lower in the early Galaxy, at the time where both the ISM and the GCRs were presumably strongly depleted in CNO nuclei. As first suggested by Duncan et al. (55), the observed Be evolution can be explained if GCRs, or at least the Be-producing CRs, have always had the same...

Asplund et al. (38) reported observations of high 6Li abundances in metal-poor halo stars unexplainable by GCR nucleosynthesis, which would require an additional source also for this isotope. Several production scenarios were proposed in the literature: (i) non-standard BBN (e.g., 39, and references therein), (ii) pre-galactic nucleosynthesis during structure formation (e.g., 40) or (iii) in situ production by stellar flares (41). But these high 6Li abundances were not confirmed by subsequent observations (42).

e.g. Parizot 2000, for a review see Tatischeff&Gabici 2018
Another thing we don't understand: Spallogenic nucleosynthesis of Li-Be-B

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![Graph showing Be abundances vs. [Fe/H] and [O/H].](image)

**Figure 2**

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(Real) conclusions