Cosmic Rays and Gamma Rays in the InterStellar Medium

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The discovery of Cosmic Rays

• at the beginning of the 20th century, the discharge rate of an electroscope was used as a measure of the level of radioactivity
• electroscopes discharge slowly even in the absence of a radioactive source -> background radiation
• radiation from radioactive materials in the Earth?
The discovery of Cosmic Rays

If due to radioactive materials in the Earth, the effect should diminish with height

In 1912, during a balloon flight Victor Hess discovered that the effect was indeed increasing with height, and concluded that:

“a radiation of very high penetrating power enters our atmosphere from above”

V. Hess in 1912
What are Cosmic Rays?

Cosmic rays particles hit the Earth’s atmosphere at the rate of about 1000 per square meter per second. They are ionized nuclei - about 90% protons, 9% alpha particles and the rest heavy nuclei - and they are distinguished by their high energies. Most cosmic rays are relativistic, having energies comparable or somewhat greater than their masses. A very few of them have ultrarelativistic energies extending up to $10^{20}$ eV (about 20 Joules), eleven order of magnitudes greater than the equivalent rest mass energy of a proton. The fundamental question of cosmic ray physics is, “Where do they come from?” and in particular, “How are they accelerated to such high energies?”

T. Gaisser “Cosmic Rays and Particle Physics”

Also electrons are present in the cosmic radiation -> ~ 1%
The (local) Cosmic Ray spectrum
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power law $E^{-2.7}$

solar modulation
The (local) Cosmic Ray spectrum

- Power law $E^{-2.7}$
- Solar modulation
- "CR knee"
- $\sim 5$ PeV
The (local) Cosmic Ray spectrum

- **Solar modulation**
- **Power law $E^{-2.7}$**
- **"CR knee"**
- **Power law $E^{-3}$**
- **$\sim 5$ PeV**
The (local) Cosmic Ray spectrum

- Power law $E^{-2.7}$
- "CR knee"
- Power law $E^{-3}$
- "CR ankle"
- Solar modulation
- ~5 PeV
Cosmic Ray composition

Nuclear abundance: cosmic rays compared to solar system

Abundance relative to Carbon = 100

Gaisser & Stanev, 2005
Cosmic Ray composition

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Cosmic Ray composition

Nuclear abundance: cosmic rays compared to solar system

5 - 6 order of magnitude more Li, Be, B!
(Solar System -> primordial nucleosynthesis)

Gaisser & Stanev, 2005
Cosmic Ray composition

Nuclear abundance: cosmic rays compared to solar system

Abundance relative to Carbon = 100

Nuclear charge

Gaisser & Stanev, 2005
Cosmic Ray electrons

The CR electron spectrum is more structured (and more difficult to be measured) than the proton one

figure from Grasso et al, 2009
Cosmic Ray electrons

The CR electron spectrum is more structured (and more difficult to be measured) than the proton one.

\[ \approx E^{-3} \]

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Cosmic Ray electrons

The CR electron spectrum is more structured (and more difficult to be measured) than the proton one

\[ \approx E^{-3} \]

@ ~1 GeV \[ \rightarrow \frac{N_p}{N_e} \sim 100 \]
Cosmic Ray isotropy

\[ \delta = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]  

Cosmic Ray anisotropy: \( \delta \) (I -> CR intensity)

figure from Iyono et al, 2005
Cosmic Ray isotropy

Cosmic Ray anisotropy:

\[ \delta = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]  

(I \rightarrow CR intensity)

measures available only above ~500 GeV \rightarrow magnetic field of the solar system has no effect

figure from Iyono et al, 2005
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Cosmic Ray anisotropy measures available only above ~500 GeV, the magnetic field of the solar system has no effect.

\[ \delta \sim 10^{-3} \]

Figure from Iyono et al, 2005
Cosmic Ray isotropy:

\[ \delta = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

Cosmic Ray anisotropy: measures available only above \(~500\) GeV \(\rightarrow\) magnetic field of the solar system has no effect

\[ \delta \sim 10^{-3} \]

the anisotropy increases with particle energy

figure from Iyono et al, 2005
Cosmic Ray isotropy

Cosmic Ray anisotropy: \[ \delta = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

(I -> CR intensity)

CRs are very isotropic in the sky

the anisotropy increases with particle energy

\[ \delta \sim 10^{-3} \]

measures available only above \( \sim 500 \) GeV -> magnetic field of the solar system has no effect

figure from Iyono et al, 2005
Energy density

Cosmic Ray energy density: \( w_{CR} \sim 1 \text{ eV cm}^{-3} \)
Energy density

**Cosmic Ray energy density:**

\[ w_{CR} \sim 1 \text{ eV cm}^{-3} \]

**Magnetic field energy density:**

\[ w_B = \frac{B^2}{8\pi} \sim 1 \text{ eV cm}^{-3} \]

**Thermal gas energy density:**

\[ w_{\text{turb}}^{\text{gas}} = \rho_{\text{gas}} v_{\text{turb}}^2 \sim 1 \text{ eV cm}^{-3} \]

CRs are dynamically important in the Galaxy
Variations in time and space

- CR flux at Earth constant during the last $10^9$ yr
  (from radiation damages in geological and biological samples, meteorites, and lunar rocks)
- thus the CR flux must be constant along the orbit of the Sun around the galactic centre (many revolutions in a Gyr)

Stability in time and (hints for) spatial homogeneity
What we have to explain about CRs:

- Energy density
- Energy spectrum
- Chemical composition
- Isotropy
- Stability in time
- Spatial homogeneity (??)
Cosmic Rays undergo hadronic interactions in the Inter Stellar Medium:

\[ p + p \rightarrow p + p + \pi^0 \]

\[ \pi^0 \rightarrow \gamma + \gamma \]

The gamma ray emission traces the gas distribution (times the CR distribution)
Cosmic Rays and Gamma-Ray Astronomy

NASA’s Fermi telescope reveals best-ever view of the gamma-ray sky

Credit: NASA/DOE/Fermi LAT Collaboration
Gamma-Ray Astronomy: $p$-$p$ interactions

Energy threshold for neutral pion production:

$$p + p \rightarrow p + p + \pi^0$$

Before

\[ E_p, p_p \quad m_p \]

After

\[ m_p \quad m_p \quad m_{\pi^0} \]

\[ E^2 - p^2 c^2 \]
Energy threshold for neutral pion production:

\[ p + p \rightarrow p + p + \pi^0 \]

\[ E^2 - p^2 c^2 = (2m_p c^2 + m_{\pi^0} c^2)^2 \]
Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

\[ p + p \rightarrow p + p + \pi^0 \]

Before: \( E_p, p_p \) \hspace{2cm} m_p

After: \( m_p, m_p, m_{\pi^0} \)

\[
( E_p + m_p c^2 )^2 - p_p^2 c^2 = E^2 - p^2 c^2 = (2m_p c^2 + m_{\pi^0} c^2)^2
\]
Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

\[ p + p \rightarrow p + p + \pi^0 \]

Before

\[ E_p, p_p \quad m_p \]

After

\[ m_p \quad m_p \quad m_{\pi^0} \]

\[
\left( E_p \quad m_p c^2 \right)^2 - p_p c^2 = E^2 - p^2 c^2 = \left( 2m_p c^2 + m_{\pi^0} c^2 \right)^2
\]

\[
E_p - m_p c^2 > 2m_{\pi^0} c^2 + \left( \frac{m_{\pi^0}}{2m_p} \right) m_{\pi^0} c^2 \approx 280 \text{ MeV}
\]

CRs produce gammas
Gamma-Ray Astronomy: p-p interactions

Let’s calculate the spectrum of neutral pions:

We assume a power law spectrum for CRs:

\[ N_p(E_p) \propto E_p^{-\delta} \]

Fraction of proton kinetic energy transferred to pion (from data):

\[ f_{\pi^0} \approx 0.17 \]

\[
q_{\pi^0} = \int dE_p \ N_p(E_p) \ \delta(E_{\pi^0} - f_{\pi^0} E_{p,\text{kin}}) \ \sigma_{pp}(E_p) \ n_{\text{gas}} \ c
\]
Gamma-Ray Astronomy: p-p interactions

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q_{\pi^0} = \int dE_p \ N_p(E_p) \ \delta(E_{\pi^0} - f_{\pi^0} E_p,kin) \ \sigma_{pp}(E_p) \ n_{gas} \ c
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\( \sigma_{pp} \) ~ constant
Gamma-Ray Astronomy: p-p interactions

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Fraction of proton kinetic energy transferred to pion (from data):

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\[ \sigma_{pp} \sim \text{constant} \]

\[ q_{\pi^0} \approx E^{-\delta} \]
Let's now calculate the spectrum of photons from pion decay - I

The photon spectrum is the result of a "one-body-decay" (neutral pion)

The photon spectrum MUST exhibit a feature at an energy relate to the pion mass
Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - I

The photon spectrum is the result of a "one-body-decay" (neutral pion) and the photon spectrum MUST exhibit a feature at an energy relate to the pion mass.

Pion rest frame:

\[ E_{\gamma}^* = \frac{m_{\pi^0}}{2} \]
Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - I

The photon spectrum is the result of a “one-body-decay” (neutral pion)

The photon spectrum MUST exhibit a feature at an energy relate to the pion mass

Pion rest frame:

\[ E_{\gamma}^* = \frac{m_{\pi^0}}{2} \]

Lab frame:

\[ E_{\gamma} = \gamma \left( E_{\gamma}^* + \nu p_{\gamma}^* \cos \theta^* \right) \]

max and min energies \( \rightarrow \) \( \cos \theta^* = \pm 1 \)

\[ \frac{m_{\pi^0}}{2} \sqrt{\frac{1 - \beta}{1 + \beta}} \leq E_{\gamma} \leq \frac{m_{\pi^0}}{2} \sqrt{\frac{1 + \beta}{1 - \beta}} \]
Let's now calculate the spectrum of photons from pion decay - II

\[ E_{\gamma}^{\text{min}} = \frac{m_{\pi^0}}{2} \sqrt{\frac{1 - \beta}{1 + \beta}} \leq E_{\gamma} \leq \frac{m_{\pi^0}}{2} \sqrt{\frac{1 + \beta}{1 - \beta}} = E_{\gamma}^{\text{max}} \]

(1) \[ \frac{\log E_{\gamma}^{\text{max}} + \log E_{\gamma}^{\text{min}}}{2} = \log \left( \frac{m_{\pi^0}}{2} \right) \]

in log-scale, the centre of the interval is half the pion mass
Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - II

\[ E_{\gamma}^{min} = \frac{m_{\pi^0}}{2} \sqrt{\frac{1 - \beta}{1 + \beta}} \leq E_{\gamma} \leq \frac{m_{\pi^0}}{2} \sqrt{\frac{1 + \beta}{1 - \beta}} = E_{\gamma}^{max} \]

\[ \log E_{\gamma}^{max} + \log E_{\gamma}^{min} \]

\[ = \log \left( \frac{m_{\pi^0}}{2} \right) \]

(1) in log-scale, the centre of the interval is half the pion mass

(2) in the pion rest frame the photon distribution is isotropic

\[ \frac{dn_{\gamma}}{d\Omega^*} = const \]

\[ d\Omega^* = d\phi^* d(\cos \theta^*) \]

\[ E_{\gamma} = \gamma \left( E_{\gamma}^* + v p_{\gamma}^* \cos \theta^* \right) \rightarrow dE_{\gamma} \propto d(\cos \theta^*) \]

\[ \frac{dn_{\gamma}}{dE_{\gamma}} = const \]

The spectrum is flat!
Let's now calculate the spectrum of photons from pion decay - III

\[ q_{\pi^0} \approx E^{-\delta} \]

\[ n_\gamma = \frac{m_{\pi^0}}{2} \]
Gamma-Ray Astronomy: p-p interactions

Let’s now calculate the spectrum of photons from pion decay - III

\[ q_{\pi^0} \approx E^{-\delta} \]

\[ n_\gamma \approx \frac{m_{\pi^0}}{2} \]
Gamma-Ray Astronomy: p-p interactions

Let’s now calculate the spectrum of photons from pion decay - III

\[ q_{\pi^0} \approx E^{-\delta} \]

\[ \frac{m_{\pi^0}}{2} \]
Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - III

\[ q_{\pi^0} \approx E^{-\delta} \]

\[ n_\gamma \sim \frac{m_{\pi^0}}{2} \]
Let’s now calculate the spectrum of photons from pion decay - III
Gamma-Ray Astronomy: $p-p$ interactions

Let's now calculate the spectrum of photons from pion decay - III

$$\frac{m_{\pi^0}}{2}$$

$$q_{\pi^0} \approx E^{-\delta}$$
Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - III

\[ q_{\pi^0} \approx E^{-\delta} \]

\[ \frac{m_{\pi^0}}{2} \approx E^{-\delta} \]
Let's now calculate the spectrum of photons from pion decay - III

\[ q_{\pi^0} \approx E^{-\delta} \]

\[ E_{\gamma} \approx E_{\text{CR}} \frac{m_{\pi^0}}{10} \]

\[ \text{the gamma ray spectrum is symmetric (in log-log) with respect to: } \frac{m_{\pi^0}}{2} \sim 70 \text{ MeV} \]

\[ \text{at high energy the spectrum mimic the CR spectrum, with (roughly): } E_{\gamma} \approx \frac{E_{\text{CR}}}{10} \]
Let's now calculate the spectrum of photons from pion decay - III

\[ E_{\text{kin}} \approx E - \delta \]

the gamma ray spectrum is symmetric (in log-log) with respect to:

\[ \frac{m_{\pi^0}}{2} \sim 70 \text{ MeV} \]

at high energy the spectrum mimic the CR spectrum, with (roughly):

\[ E_\gamma \approx \frac{E_{CR}}{10} \]
Gamma-Ray Astronomy: $p$-$p$ interactions

Detectability condition for a Cherenkov Telescope

**HESS sensitivity:** $F_{HESS}^{\text{min}}(> 1 \text{ TeV}) \approx 10^{-12} \text{ph cm}^{-2} \text{s}^{-1} \rightarrow 2 \times 10^{-12} \text{erg/cm}^2/\text{s}$

Depends a bit on the spectrum
Gamma-Ray Astronomy: p-p interactions

Detectability condition for a Cherenkov Telescope

**HESS sensitivity:** \( F_{\text{HESS}}^{\text{min}}(> 1 \text{ TeV}) \approx 10^{-12} \text{ ph cm}^{-2} \text{s}^{-1} \rightarrow 2 \times 10^{-12} \text{ erg/cm}^2 \text{/s} \)

depends a bit on the spectrum

which corresponds to a luminosity:

\[
L_{\text{HESS}}^{\text{min}}(> 1 \text{ TeV}) = F_{\text{HESS}}^{\text{min}}(> 1 \text{ TeV}) 4\pi d^2 = 2 \times 10^{32} d_{\text{kpc}}^2 \text{ erg/s}
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Detectability condition for a Cherenkov Telescope

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which corresponds to a luminosity:
\[ L_{HESS}^{min}(> 1 \text{ TeV}) = F_{HESS}^{min}(> 1 \text{ TeV}) \times 4\pi d^2 = 2 \times 10^{32} d_{kpc}^2 \text{erg/s} \]

which corresponds to a CR total energy:
\[ W_{CR} = t_{pp} c_{p\rightarrow\gamma}^{-1} L_{HESS}^{min} = \]

p-p energy loss time
fraction of CR energy transferred to photon
**Gamma-Ray Astronomy: p-p interactions**

Detectability condition for a Cherenkov Telescope

**HESS sensitivity:**

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F_{HESS}^{\text{min}}(> 1 \text{ TeV}) \approx 10^{-12} \text{ph cm}^{-2} \text{s}^{-1} \rightarrow 2 \times 10^{-12} \text{erg/cm}^2/\text{s}
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which corresponds to a CR total energy:

\[
W_{CR} = t_{pp} \frac{1}{c_{p\rightarrow \gamma}} L_{HESS}^{\text{min}} =
\]

\[
t_{pp} = (n_{\text{gas}} \sigma_{pp} c k)^{-1}
\]

Depends a bit on the spectrum

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Gamma-Ray Astronomy: p-p interactions

Detectability condition for a Cherenkov Telescope

**HESS sensitivity:**  
\[ F_{H E S S}^{\text{min}}(> 1 \text{ TeV}) \approx 10^{-12} \text{ph cm}^{-2} \text{s}^{-1} \rightarrow 2 \times 10^{-12} \text{erg/cm}^2/\text{s} \]

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\[ t_{pp} = (n_{\text{gas}} \sigma_{pp} c k)^{-1} \]

which corresponds to a CR total energy:  
\[ W_{CR} = t_{pp} c_{p\rightarrow\gamma}^{-1} L_{H E S S}^{\text{min}} = \]

\[ = \left( \frac{10^{15}}{n_{\text{gas}}} \text{ s} \right) (10) (2 \times 10^{32} d_{\text{kpc}}^2 \text{erg/s}) = 2 \times 10^{48} n_{\text{gas}}^{-1} d_{\text{kpc}}^2 \text{ erg} \]
Gamma-Ray Astronomy: p-p interactions

SUMMARY:

- the gamma ray spectrum is symmetric (in log-log) with respect to: \( \frac{m_{\pi^0}}{2} \sim 70 \text{ MeV} \)

- at high energy the spectrum mimics the CR spectrum, with (roughly): \( E_\gamma \approx \frac{E_{CR}}{10} \)

- detectability condition: \( W_{CR} > 2 \times 10^{48} n_{gas}^{-1} d_{kpc}^2 \text{ erg} \)

\[ \uparrow \]

above \( \sim 10 \text{ TeV} \)
Gamma-Ray Astronomy: p-p interactions

Secondary electrons and positrons:

\[ p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^- \]
Gamma-Ray Astronomy: p–p interactions

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\[ \pi^0 \rightarrow \gamma + \gamma \]
Gamma-Ray Astronomy: p-p interactions

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\[ \pi^0 \rightarrow \gamma + \gamma \]

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \]

\[ \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu (\nu_\mu) + \nu_e (\bar{\nu}_e) \]
Gamma-Ray Astronomy: p-p interactions

Secondary electrons and positrons:

\[ p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^- \]

\[ \pi^0 \rightarrow \gamma + \gamma \]

\[ \pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu) \]

\[ \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu (\nu_\mu) + \nu_e (\bar{\nu}_e) \]

Final products of proton-proton interactions are not only gamma ray photons but also neutrinos, anti-neutrinos, electrons and positrons

\[ E_e \approx E_\nu \approx \frac{E_p}{20} \]
Production of gamma rays in the Galaxy

(1) proton-proton interactions: \( \alpha = \delta \)

CR proton spectrum: \( N_{CR} \propto E^{-2.7} \)  \hspace{1cm} gamma ray spectrum: \( q_\gamma \propto E^{-2.7} \)

(plus the pion bump at \( \sim 70 \) MeV)
Production of gamma rays in the Galaxy

(1) proton-proton interactions: \( (\alpha = \delta) \)

\[
N_{CR} \propto E^{-2.7} \quad \text{gamma ray spectrum:} \quad q_\gamma \propto E^{-2.7}
\]
(plus the pion bump at \( \sim 70 \text{ MeV} \))

(2) inverse Compton scattering:

\[
(\alpha = \frac{\delta + 1}{2})
\]

\[
N_e \propto E^{-3} \quad \text{gamma ray spectrum:} \quad q_\gamma \propto E^{-2}
\]
(plus the Klein-Nishina cutoff at \( \sim 50 \text{ TeV} \))
Production of gamma rays in the Galaxy

(1) proton-proton interactions: \((\alpha = \delta)\)

CR proton spectrum: \(N_{CR} \propto E^{-2.7}\)  
gamma ray spectrum: \(q_\gamma \propto E^{-2.7}\)

(plus the pion bump at \(\sim 70\) MeV)

(2) inverse Compton scattering: \(\left(\alpha = \frac{\delta + 1}{2}\right)\)

CR electron spectrum: \(N_e \propto E^{-3}\)  
gamma ray spectrum: \(q_\gamma \propto E^{-2}\)

(plus the Klein-Nishina cutoff at \(\sim 50\) TeV)

(3) relativistic Bremsstrahlung: \((\alpha = \delta)\)

CR electron spectrum: \(N_e \propto E^{-3}\)  
gamma ray spectrum: \(q_\gamma \propto E^{-3}\)
The gamma ray emission from the Galaxy

FERMI observation of the galactic diffuse emission

pion bump (shifted because $\propto E^2$)
more or less flat

FERMI DATA

$\sim E^{-2.7}$

$\sim E^{-3}$

p-p interactions dominate the diffuse emission
The gamma ray emission from the Galaxy

FERMI observation of the galactic diffuse emission

- pion bump (shifted because $\propto E^2$)
- more or less flat

CRs quite homogeneous in the Galaxy!
Take-home message

- We have plenty of data on CRs but we still don’t know where they are from;
- A connection exists between CR physics and Gamma Ray Astronomy because CRs produce gamma rays in interactions with matter and radiation fields;
- What we know about CRs seems to explain fairly well the gamma ray diffuse emission we observe from the Milky Way.