Gamma ray signatures of Ultra High Energy Cosmic Ray accelerators

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The beginning of cosmic ray research: Victor Hess

The air in electroscope instruments became ionized, no matter how well the containers were insulated. Radioactivity from ground minerals? The effect should diminish with height.

In 1912, during a balloon flight at an altitude of ~5000 meters Victor Hess discovered that: “a radiation of very high penetrating power enters our atmosphere from above”. Word “cosmic” first used by Robert A. Millikan in 1925.

Nobel prize in 1936
94 years later...

The origin of CRs is considered an almost century old puzzle, even if SNRs are widely believed to be the responsible for the acceleration up to the knee (and maybe beyond).

\[ \delta = 2.75 \text{ (galactic)} \]

\[ \delta = 3 \text{ (extragalactic?)} \]

\[ \delta = 2.7 \text{ (?)} \]

Measured up to \( E \sim 3 \times 10^{20} \text{ eV} \)

Roughly one single power law over 10 orders of magnitude in energy!!!

UHECRs
\( E > 5 \times 10^{19} \text{ eV} \)
Who is accelerating UHECRs?

The Hillas plot

In order to be accelerated, particles have to be confined in the accelerator

\[ 2 R_L(E) < L_{acc} \]
\[ B(G) L_{acc}(pc) > \frac{0.2}{Z} \left( \frac{E}{10^{20} \text{eV}} \right) \]

This is a necessary, but not sufficient condition!
One should consider energy losses!

Both during the acceleration (Aharonian et al., 2002) and the escape from the source (Norman, Melrose & Achterberg, 1995)

adapted from Hillas (1984)
Acceleration is not enough: propagation

Two main processes: photo-pion production

\[ p + \gamma_{\text{CMB}} \rightarrow p + \pi^0 + \pi^\pm \]

photo-pair production

\[ p + \gamma_{\text{CMB}} \rightarrow p + e^+ + e^- \]

If sources are distributed homogeneously in the Universe we do expect a strong suppression in the CR spectrum at \( \sim 10^{20} \text{eV} \)

\[ \Rightarrow 10 \div 20 \text{ Mpc} \]
Can you see the cutoff?
Data: GZK or not?

Compilation of data from different experiments

Red = AGASA  Blue = HiRes

Is there a cutoff?  We need more data!!!  (De Marco, Blasi & Olinto, 2003)

Anchordoqui et al., 2003
The origin of UHECRs:
Bottom-Up versus Top-Down models

how can we explain this?

😊 local overdensity?
😊 δ = 20 too big!
😊 galactic sources?
😊 isotropy: iron nuclei
😊 galactic halo?
😊 which sources?

Bottom-Up scenario
Astrophysical sources
Yes, but which ones???

Top-Down
or hybrid scenarios
New Physics
The origin of UHECRs: Bottom-Up versus Top-Down models

how can we explain this?

local overdensity?

$\delta = 20$ too big!

galactic halo?

which sources?

Bottom-Up scenario
Astrophysical sources
Yes, but which ones???

Top-Down or hybrid scenarios
New Physics

Working hypothesis: astrophysical accelerators of UHECRs do exist.
Propagation: the beginning of CR astronomy?

Transition between diffusive and straight line propagation

\[ B = 10^{-9} \, \text{G} \]
\[ \text{B random} \]
\[ \text{cell size} = 1 \, \text{Mpc} \]
\[ \text{box size} = 40 \, \text{Mpc} \]

oversimplified (e.g. \( \nabla \cdot \mathbf{B} \neq 0 \)) but useful picture.

**Condition for straight line propagation:** can we do CR astronomy?

\[
B < 10^{-10} \left( \frac{E}{4 \times 10^{19} \, \text{eV}} \right) \left( \frac{\theta_{\exp}}{2^\circ} \right) \left( \frac{D}{1 \, \text{Gpc}} \right)^{-1/2} \left( \frac{L_c}{1 \, \text{Mpc}} \right) \, \text{G}
\]

poor angular resolution!
How strong is the intergalactic magnetic field?

Simple minded estimates

Equipartition magnetic field: (not the one of Radio Astronomers!)

\[ \frac{3}{2} n k_B T = \frac{B_{eq}^2}{8 \pi} \]

<table>
<thead>
<tr>
<th></th>
<th>$n$ (cm$^{-3}$)</th>
<th>$T$ (K)</th>
<th>$B_{eq}$ (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clusters</td>
<td>$10^{-4}$</td>
<td>$10^8$</td>
<td>$7 \times 10^{-6}$</td>
</tr>
<tr>
<td>Filaments</td>
<td>$10^{-5}$</td>
<td>$10^6$</td>
<td>$2 \times 10^{-7}$</td>
</tr>
<tr>
<td>Diffuse</td>
<td>$10^{-7}$</td>
<td>$10^4$</td>
<td>$2 \times 10^{-9}$</td>
</tr>
</tbody>
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Clusters of galaxies fill only $10^{-5}$ of the volume of the universe
Magnetic field outside clusters: observations


✔ 0.3÷0.6 $\mu$G  Coma-A1367 filament (Kim et al., 1989)

⇒ It's INSIDE the virial radius!!!!

✔ 0.3 $\mu$G  ZwCl2341.1+0000 filament (Bagchi et al., 2002)

✔ 0.3 $(L_c/500\text{kpc})^{-1/2} \mu$G  Hercules & Perseus-Pisces Superclusters

(Xu et al., 2005)

✔ (personal) conclusion: observations are challenging → magnetic field on scales larger than clusters is basically unknown
Magnetic field outside clusters: simulations

The origin and evolution of cosmic magnetic field, Bologna, September 2005
(AN, Vol. 327, issues 5-6)

✔ $10^{-10} \div 10^{-9} \text{G in filaments (Dolag)} \rightarrow \theta_{\text{CR}} < 1^\circ \ @ 10^{20} \text{eV}$

✔ $3 \times 10^{-9} \text{G in a filament @ } z = 0.5 \text{ (Brüggen)}$

✔ $\sim 10^{-7} \text{G in filaments (Sigl et al. 2004)} \rightarrow \theta_{\text{CR}} \sim 20^\circ \text{ up to } 10^{20} \text{ eV}$

✔ $\sim 10^{-7} \text{G in filaments (Ryu)}$

✔ (personal) conclusion: results from simulations are (at least) confusing
Small scale anisotropies

AGASA

57 events with \( E > 4 \times 10^{19} \text{eV} \)
4 pairs and 1 triplet

weak magnetic field?

7 pairs observed, 2.2 expected
(probability 0.0075)

Is this result robust? (see Cronin, 2005)

- why \( 4 \times 10^{19} \text{eV} \)? (small deflection+statistics)
- 89 events (AGASA + other experiments)
- 12 pairs, 6.0 expected (probability 0.02)
- 2 triplets, 0.7 expected (probability 0.10)
- \( E > 5 \times 10^{19} \text{eV} \), only 2 triplets left (probability 0.003)
- More data!!! → AUGER!!!
A new possibility: searching for UHECR accelerators in gamma rays

Ferrigno et al., 2005; *SG* and Aharonian, 2005, 2006; Armengaud et al., 2006

\[ p + \gamma_{\text{CMB}} \rightarrow p (n) + \text{pions} \]
\[ \pi^0 \rightarrow \gamma + \gamma \]
\[ \pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm + \text{neutrinos} \]
\[ E_\gamma = 10^{19} E_{p,20} \text{ eV} \]
\[ E_e = 5 \cdot 10^{18} E_{p,20} \text{ eV} \]

Interactions with background photon fields and magnetic field

\[ e^\pm \rightarrow \text{Inverse Compton and Synchrotron} \rightarrow \gamma \]
\[ \gamma \rightarrow \text{Pair Production} \rightarrow e^\pm \]

Can we detect these photons?
In which energy band?
Electromagnetic cascade initiated by a UHECR

SG and Aharonian, 2005, 2006

\[ \epsilon_b E_{e/\gamma} \gg m^2 c^4 : e \rightarrow \gamma \rightarrow e ... \]

\[ \epsilon_b E_{e/\gamma} \ll m^2 c^4 : \text{EM cascade} \]

NO MAGNETIC FIELD!!!

Gould & Rephaeli, 1978

One leading particle!!!

Lots of particles
The case of the unmagnetized Universe

Ferrigno, Blasi and De Marco, 2005

Ideal case: \( B = 0 \, \text{G} \rightarrow \text{one-dimensional cascade} \) (no losses, no deflection)

\[ L = 2 \times 10^{43} \, \text{erg/s}, \ B = 0 \, \text{G} \]

What does “unmagnetized” mean?

EM cascade might be observed @ TeV energies by Cherenkov telescopes

\[ L_{\text{UHECR}} = 2 \times 10^{43} \, \text{erg/s} \rightarrow d < 100 \, \text{Mpc} \]
What does “unmagnetized” mean?

Part I: energy losses

Gabici & Aharonian, 2005

![Graph showing energy loss as a function of magnetic field strength and energy.]

- **Synchrotron**
- **Compton-pair production**

The cascade is suppressed if:

\[
B \geq 10^{-9} G
\]

\[
E_\gamma = 10^{19} E_{p,20} \text{ eV}
\]

\[
E_e = 5 \cdot 10^{18} E_{p,20} \text{ eV}
\]
What does “unmagnetized” mean?

Part II: deflection

@ 1 TeV we observe the radiation from:

\[ E_e \approx 20 \left( \frac{E_{\gamma}^{\text{obs}}}{\text{TeV}} \right)^{1/2} \text{ TeV} \]

Electrons are *isotropized* if they cool in one Larmor time

\[ B \geq 10^{-12} \left( \frac{E_\gamma}{\text{TeV}} \right) \text{ G} \]
Three different regimes

(1) $B \ll B_{\text{ISO}} \sim 10^{-12} \text{G}$ \quad \rightarrow \text{one-dimensional cascade}

the cascade is unaffected by $B$: no deflection nor energy losses

(2) $B_{\text{ISO}} \leq B \ll B_{\text{syn}} \sim 10^{-9} \text{G}$ \quad \rightarrow \text{giant pair halo}

low energy electrons are isotropized, no energy losses

(3) $B \geq B_{\text{syn}}$ \quad \rightarrow \text{no cascade}

the development of the cascade is strongly suppressed
Regime 1: one-dimensional cascade

SG & Aharonian, 2006

$B \ll B_{\text{ISO}} \sim 10^{-12} \text{ G}$

proton interaction length

De Marco et al., 2004
Regime 1: one-dimensional cascade

*SG* & Aharonian, 2006

\[ B \ll B_{ISO} \sim 10^{-12} \text{ G} \]

the first generation electron (photon) determines the size of the “Klein-Nishina cascade”

\[ \lambda (\text{Mpc}) \]

\[ E (\text{eV}) \]

\[ 10^{-8} \text{ G}, \quad z = 0 \]

\[ 10^{-9} \text{ G}, \quad z = 1 \]

\[ 10^{-10} \text{ G} \]

\[ \sim 5 - 10 \text{ Mpc} \]
Regime 1: one-dimensional cascade

SG & Aharonian, 2006

the last generation photon determines the size of the “Thomson cascade”

\[ B \ll B_{\text{ISO}} \sim 10^{-12} \, \text{G} \]
Regime 1: one-dimensional cascade

\textit{SG} & Aharonian, 2006

\[ B \ll \text{B}_{\text{ISO}} \sim 10^{-12} \text{ G} \]

- \(~ 3-30 \text{ Mpc}
- \sim 5-10 \text{ Mpc}
- \leq 20 \text{ Mpc}

\[ B \ll 10^{-9} \text{ G} \]

- to avoid energy losses

\[ B \ll 10^{-12} \text{ G} \]

- to avoid isotropization
  - it is a very small magnetic field!
  - but not ruled out...

\[ B / B_{\text{ISO}} \sim 10^{-12} \text{ G} \]
Regime 1: one-dimensional cascade

(Ferrigno, Blasi and De Marco, 2005)

Ideal case: $B = 0 \, G \rightarrow$ one-dimensional cascade (no losses, no deflection)

$L = 2 \times 10^{43} \, \text{erg/s}, \ B = 0 \, G$

EM cascade might be observed @ TeV energies by Cherenkov telescopes

$L_{UHECR} = 2 \times 10^{43} \, \text{erg/s} \rightarrow d < 100 \, \text{Mpc}$
Regime 2: giant pair halo

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2006

\[ B_{\text{ISO}} \leq B \ll B_{\text{syn}} \sim 10^{-9} \, \text{G} \]
Regime 2: giant pair halo

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2006

\( B_{\text{ISO}} \leq B \ll B_{\text{syn}} \sim 10^{-9} \, \text{G} \)

\( \geq 20 \, \text{TeV} \)
Regime 2: giant pair halo

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$B_{\text{ISO}} \leq B \ll B_{\text{syn}} \sim 10^{-9} \text{ G}$

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$20 \text{ TeV}$
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\[ B_{\text{ISO}} \leq B \ll B_{\text{syn}} \sim 10^{-9} \text{ G} \]
Regime 2: giant pair halo

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2006

\[ B_{\text{ISO}} \leq B \ll B_{\text{syn}} \sim 10^{-9} \text{ G} \]

you (observer)

conservative (!!!) estimate of the halo size

\[ \theta_h \geq 10^\circ \left( \frac{l_{\text{halo}}}{20 \text{ Mpc}} \right) \left( \frac{D}{100 \text{ Mpc}} \right)^{-1} \]

LARGER THAN THE HESS FIELD OF VIEW!!!!
If a ~nG magnetic field is present, the cascade is suppressed at its first (one particle) step!

\[ E_{\text{syn}} \sim 2 \left( \frac{B}{nG} \right) \left( \frac{E}{10^{19} \text{ eV}} \right)^2 \text{ GeV} \]

GLAST energy range!!!

Gabici & Aharonian, 2005
New way to identify UHECR sources!

steady UHECR source

B \sim 1 \text{nG}

magnetized region

10 \div 20 \text{ Mpc}

super clusters?
bigger than the interaction loss length!
New way to identify UHECR sources!

steady UHECR source

$B \sim 1 \, \text{nG}$
magnetized region

$10^{20} \text{eV proton} \Rightarrow \text{NO DEFLECTION!!!}$

$10 \div 20 \, \text{Mpc}$

super clusters?
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steady UHECR source

$B \sim 1 \text{ nG}$

magnetized region

$10^{20} \text{eV proton} \Rightarrow \text{NO DEFLECTION!!!}$

$p + \gamma_{\text{CMB}} \rightarrow p(n) + \pi'$s

$\pi \rightarrow \mu \rightarrow e$

$E_e \sim 10^{19} \text{eV}$

$10 \div 20 \text{ Mpc}$

super clusters?
bigger than the interaction loss length!
New way to identify UHECR sources!

steady UHECR source

B \sim 1 \text{nG}

magnetized region

10^{20}\text{eV} \text{ proton} \Rightarrow \text{NO DEFLECTION!!!}

Electrons immediately cool via synchrotron emission!

E_{\text{syn}} \sim 10 \text{GeV}

10 \div 20 \text{ Mpc}

super clusters?
bigger than the interaction loss length!
New way to identify UHECR sources!

steady UHECR source

B ~ 1 nG

magnetized region

10⁰ eV proton ⇔ NO DEFLECTION!!!

the Universe is transparent to GeV photons

super clusters?
bigger than the interaction loss length!
New way to identify UHECR sources!

- Steady UHECR source
- $B \sim 1 \text{ nG}$
- Magnetized region
- $10^{20} \text{eV}$ proton $\Rightarrow$ NO DEFLECTION!!!

You don't see this

The Universe is transparent to GeV photons

Super clusters? Bigger than the interaction loss length!
New way to identify UHECR sources!

steady UHECR source

B ~ 1 nG

magnetized region

10\textsuperscript{20}eV proton ⇔ NO DEFLECTION!!!

the Universe is transparent to GeV photons

POINT LIKE and STEADY GeV source!!!

10 ÷ 20 Mpc

super clusters?
bigger than the interaction loss length!

you don't see this

New way to identify UHECR sources!
New way to identify UHECR sources!

steady UHECR source

B \sim 1 \text{nG}

magnetized region

10^{20}\text{eV} \text{proton} \Rightarrow \text{NO DEFLECTION!!!}

the Universe is transparent to GeV photons

you don't see this

POINT LIKE and STEADY GeV source!!!

10 \div 20 \text{Mpc}

\text{UHE neutrinos} \Rightarrow E_{\nu}^2 F_{\nu} \sim 1 \frac{EeV}{km^2 \text{yr}} \quad @ \quad E_{\nu} = 5 \cdot 10^{18} \text{eV}

ANITA, AUGER?
New way to identify UHECR sources!

Although synchrotron photons are produced in an extended region of size \( \sim 10\text{–}20\) Mpc, the gamma ray emission is POINT LIKE (and STEADY)!!!

10\(^{20}\) eV proton ⇒ NO DEFLECTION!!!

the Universe is transparent to GeV photons

UHE neutrinos ⇒ \( E_\nu^2 F_\nu \sim 1 \frac{EeV}{km^2 \text{ yr}} \) @ \( E_\nu = 5 \cdot 10^{18} \text{ eV} \)

ANITA, AUGER?
Quantitative estimates: angular size

SG and Aharonian, 2005, 2006

\[ \theta_{\text{syn}} \approx (\theta_p + \theta_e) \left( \frac{l_p}{D} \right) \approx \frac{\text{frac of degree}}{\text{degree}} @ 100 \text{ Mpc} \]

for \( B = 1 \text{ nG} \)

comparable with the GLAST angular resolution!

GLAST \( \rightarrow D \geq 100 \text{ Mpc} \)

HESS \( \rightarrow D \geq 1 \text{ Gpc} \)

HESS large field of view \( \rightarrow \) imaging of closer sources?
Quantitative estimates: total energy

SG and Aharonian, 2005, 2006

\[ \text{D}=100 \text{Mpc} \quad B=1 \text{nG} \quad L_{\text{UHECR}}=2 \times 10^{44} \text{erg/s} \]

\[ L_{\text{UHECR}} > 8 \times 10^{43} \div 2 \times 10^{44} \left( \frac{D_L}{100 \text{ Mpc}} \right)^2 \text{erg/s} \]

\[ \delta = 2.0 \div 2.3 \]

Beaming can reduce the energy by a factor:

\[ f_b = \frac{4 \pi}{\omega} \sim 100 \left( \frac{\theta}{10^\circ} \right)^{-1} \]

AGN Jets

\[ E_{\text{jet}} \sim 10^{47} \div 10^{48} \text{ erg/s} \]

Ghisellini & Celotti, 2001

If the source is bursting (e.g. GRB) this does not work! (time spread of the signal)
Can we constrain the magnetic field?

If the field is in the range 0.5 – 50 G the formation of the synchrotron source seems to be UNAVOIDABLE.
Speculation: detecting sources outside the horizon

SG and Aharonian, 2005, 2006

Extremely powerful accelerator @ a Gpc or more...

no CR above \( \sim 5 \times 10^{19} \text{ eV} \) \( \rightarrow \) energy losses

no CR below \( \sim 5 \times 10^{19} \text{ eV} \) \( \rightarrow \) deflection

\[
\theta_p \approx 10^\circ \left( \frac{B}{5 \times 10^{-10} \text{ G}} \right) \left( \frac{E}{5 \times 10^{19} \text{ eV}} \right)^{-1}
\]

Point-like and steady sources without counterparts might be accelerators of UHECRs located outside the CR-horizon!!!

Detectability condition:

\[
L_{UHECR} > 10^{44} \left( \frac{D}{1 \text{ Gpc}} \right)^2 \left( \frac{\theta_b}{10^\circ} \right) \frac{\text{erg}}{s}
\]
Conclusions

✓ UHECR sources: still a mystery

✓ CR astronomy? → Intergalactic magnetic field basically unknown!

✓ An exciting possibility: gamma ray counterparts

✓ Three different scenarios:

1. \( B \ll 10^{-12} \, \text{G} \) → 1D cascade \( 2 \times 10^{43} \, \text{erg/s} @ 100 \, \text{Mpc} \)

2. \( 10^{-12} \, \text{G} \leq B \ll 10^{-9} \, \text{G} \) → giant pair halo UNDETECTABLE!

3. \( B \geq 10^{-9} \, \text{G} \) → no cascade BUT SYNCHROTRON!!!

\( \text{point like \& steady emission} \rightarrow 10^{44} \, \text{erg/s} @ 100 \, \text{Mpc} \)

✓ Constraint on the magnetic field!

✓ Powerful accelerators located outside the horizon?