Gamma ray signatures of UHECR sources

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Overview of the talk

(1) CR spectrum extends up to extreme energies → > 10^{20} eV

which are the sources of UHECRs? can we do CR astronomy?

(2) UHECRs need to be accelerated… (generalized Hillas criterium)

if acceleration limited by radiative losses → GAMMA RAYS

(3) …and have to propagate to the observer

GZK suppression → GAMMA RAYS (unavoidable!)
Which are the sources of UHECRs?
Who is accelerating UHECRs?
The Hillas plot

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

\[ 2 R_L(E, B) < L_{acc} \]

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

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)
In many cases, acceleration of UHECRs MUST be accompanied by radiation!

Aharonian et al, 2002; Derishev et al, 2003; Neronov et al, 2005

If you want to accelerate particles you need strong EM field
→ radiative losses may become important
→ radiation is expected to show up at gamma ray energies

**BUT…**

1) Is acceleration limited by energy losses or escape?
2) Which EM energy loss? (synchrotron, curvature…)
3) Are there strong radiation fields within the accelerator? (p-gamma losses)

**Need for more detailed studies**
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 \(\sim 10^{20}\) eV.

\[\begin{align*}
\lambda (\text{Mpc}) & \quad \text{10\,\sim\,20 Mpc}
\end{align*}\]
AUGER results

AUGER collaboration, PRL, 2008

\[ \gamma = 2.69 \pm 0.06 \quad \gamma = 4.2 \pm 0.4 \]

Single power law rejected with significance > 6 sigmas
Propagation: the beginning of CR astronomy?

The value of the intergalactic magnetic field is unknown!!!

Sigl et al. 2004
Dolag et al. 2005
Das et al. 2008
Propagation: the beginning of CR astronomy?

The value of the intergalactic magnetic field is unknown!!!

Correlation with nearby AGNs?
(Auger, Science, 2007)

Sigl et al. 2004
Dolag et al. 2005
Das et al. 2008

Cronin, 2005
A new possibility: searching for UHECR accelerators in gamma rays

Ferrigno et al., 2005; *SG* and Aharonian, 2005, 2007; 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?
THIS RADIATION IS UNAVOIDABLE!
Electromagnetic cascade initiated by a UHECR

*SG* and Aharonian, 2005, 2007

\[ \epsilon_b E_{e/\gamma} \gg m^2 c^4 \quad : \quad e \Rightarrow \gamma \Rightarrow e \ldots \]

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

Gould & Rephaeli, 1978

**NO MAGNETIC FIELD!!!**

One leading particle!!!

Lots of particles
The case of the unmagnetized Universe

Ferrigno, Blasi and De Marco, 2005

Ideal case: $B = 0 \text{ G} \rightarrow$ 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

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

Part I: energy losses

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

\[ E_e = 5 \cdot 10^{18} E_{p,20} \text{ eV} \]

The cascade is suppressed if:

\[ B \geq 10^{-9} G \]
What does “unmagnetized” mean? 
Part II: deflection

SG & Aharonian, 2007
Aharonian et al., 1994

@ 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

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

CAUTION! This is NOT included is the public code CRPropa!(Armengaud et al, 2006)
Three different regimes

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

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

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

low energy electrons are isotropized, no energy losses

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

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

*SG & Aharonian, 2007*

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

proton interaction length

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

\textit{SG} & Aharonian, 2007

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

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

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

\textit{SG} & Aharonian, 2007

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

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

Aharonian, 2001
Regime 1: one-dimensional cascade

*SG* & Aharonian, 2007

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

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

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

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

(Ferrigno, Blasi and De Marco, 2005)

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

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

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

EM cascade might be observed @ TeV energies by Cherenkov telescopes

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

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2007

$B_{\text{ISO}} \leq \frac{B}{B_{\text{syn}}} \sim 10^{-9} \text{ G}$
Regime 2: giant pair halo

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2007

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

\[ \geq 20 \text{ TeV} \]
Regime 2: giant pair halo

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2007

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

\[ \geq 20 \text{ TeV} \]

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20 TeV
Regime 2: giant pair halo

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2007

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

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2007

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

You

1 TeV

conservative (!!!) estimate of the halo size

$\theta_{\text{hc}} \geq 10^\alpha \left( \frac{l_{\text{halo}}}{20 \text{Mpc}} \right) \left( \frac{D}{100 \text{Mpc}} \right)^{-1}$

$LARGER \ THAN \ THE \ HESS \ FIELD \ OF \ VIEW!$
Regime 2: giant pair halo

Aharonian, Coppi & Völk, 1994; SG & Aharonian, 2007

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

In the publicly available code CRPropa (Armengaud et al. 2007) this effect is not taken into account. EM cascade is always treated as a 1-D process.

**Estimate of the halo size**

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

\[ \geq 20 \text{ TeV} \]

\[ 20 \text{ TeV} \]

LARGER THAN THE HESS FIELD OF VIEW!
Regime 3: synchrotron gamma ray emission

$SG$ and Aharonian, 2005, 2007

If a $\sim nG$ magnetic field is present, the cascade is suppressed at its first (one particle) step!

If $B \geq B_{\text{syn}} \sim 10^{-9} \text{G}$

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

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

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

10 ÷ 20 Mpc

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

- Steady UHECR source
- Magnetized region
- $B \sim 1$ nG
- $10 \div 20$ Mpc

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

$p + \gamma_{\text{CMB}} \rightarrow p(n) + \pi's$
$
\pi \rightarrow \mu \rightarrow e$
$E_e \sim 10^{19}$ eV

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

steady UHECR source

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

Electrons immediately cool via synchrotron emission!

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

10 ÷ 20 Mpc

super clusters?
bigger than the interaction loss length!

B \sim 1 \text{ nG}

magnetized region
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!!!}

the Universe is transparent to GeV photons

super clusters?
bigger than the interaction loss length!

10 \div 20 \text{ Mpc}
New way to identify UHECR sources!

- Steady UHECR source
- Magnetized region
- $B \sim 1 \text{ nG}$
- 10 ÷ 20 Mpc super clusters? bigger than the interaction loss length!
- 10$^{20}$ eV proton → NO DEFLECTION!!!
- The Universe is transparent to GeV photons
- You don't see this!
New way to identify UHECR sources!

steady UHECR source

magnetized region

B \sim 1 \text{ nG}

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

the Universe is transparent to GeV photons

super clusters?
bigger than the interaction loss length!

you don't see this

POINT LIKE and STEADY GeV source!!!
New way to identify UHECR sources!

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

you don't see this

the Universe is transparent to GeV photons

POINT LIKE and STEADY GeV source!!!

UHE neutrinos \Rightarrow E^2_{\nu} F_{\nu} \sim 1 \frac{E eV}{km^2 yr} \quad @E_{\nu} = 5 \times 10^{18} eV

AUGER?
New way to identify UHECR sources!

Although synchrotron photons are produced in an extended region of size ~ 10-20 Mpc, the gamma ray emission is POINT LIKE (and STEADY)!!!

UHE neutrinos \( \Rightarrow E_\nu^2 F_\nu \sim 1 \frac{EeV}{km^2 yr} \) @ \( E_\nu = 5 \times 10^{18} eV \) AUGER?
Quantitative estimates: angular size

$SG$ and Aharonian, 2005, 2007

for $B = 1$ nG

$v_{\text{syn}} \approx \left( v_p + v_e \right) \left( \frac{l_p}{D} \right) \approx 0.5^\circ$ @ 100 Mpc

comparable with the GLAST angular resolution!

GLAST $\Rightarrow$ $D \geq 100$ Mpc

HESS $\Rightarrow$ $D \geq 1$ Gpc

HESS large field of view $\Rightarrow$ imaging of closer sources?
Quantitative estimates: total energy

*SG* and Aharonian, 2005, 2007

Condition for detectability:

\[ L_{\text{UHECR}} > 10^{44} \left( \frac{D}{100 \text{Mpc}} \right)^2 \frac{\text{erg}}{\text{s}} \]

\[ \delta \approx 2.0 \div 2.3 \]

Beaming can reduce the energy by a factor:

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

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 nG the formation of the synchrotron source seems to be UNAVOIDABLE.

If $B \ll 0.5 \text{ nG}$, no synchrotron!

If $B >> 50 \text{ nG}$, absorption!
Speculation: detecting sources outside the horizon

SG and Aharonian, 2005, 2007

Extremely powerful accelerator @ a Gpc or more...

no CR above $\sim 5 \times 10^{19}$ eV $\Rightarrow$ energy losses

no CR below $\sim 5 \times 10^{19}$ eV $\Rightarrow$ deflection

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

Detectability condition: $L_{UHECR} > 10^{44} \left( \frac{D}{Gpc} \right)^2 \left( \frac{\theta_b}{10^o} \right)$ erg/s
Variations: confinement in a cluster of galaxies

Rordorf et al, 2004; Atoyan & Dermer, 2008

CygA: $4 \times 10^{46}$ erg/s in CRs, $B = 20 \, \mu G$, photo-pair production included

Confinement
Bohm? age

Rordorf $\rightarrow$ X-rays photo-pair

photo-pion

(z = 0.056)
Conclusions

- Which are the sources of UHECRs? Can we do CR astronomy?
- Gamma ray expected both during UHECR *acceleration* and *propagation*
- Gamma rays from propagation are **UNAVOIDABLE!!!**

1. \[ \frac{B}{B_{\text{ISO}}} \sim 10^{-12} \text{ G} \rightarrow \text{one-dimensional cascade} \]
   
   TeV point sources → Cherenkov telescopes

2. \[ B_{\text{ISO}} \leq \frac{B}{B_{\text{syn}}} \sim 10^{-9} \text{ G} \rightarrow \text{giant pair halo} \]
   
   very extended TeV sources → detection very difficult

3. \[ B \geq B_{\text{syn}} \rightarrow \text{no cascade} \]
   
   GeV/TeV point like or (reasonably) extended → FERMI/Cherenkov