Cosmic Rays at Extreme Energies
The Pierre Auger Observatory

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Lecture 1
Outline

• Lecture 1
  *The High End of the Cosmic Ray Spectrum*

• Lecture 2
  *Extended Air Showers Detection*

• Lecture 3
  *The Observatory and its First Results*
The Cosmic Ray Spectrum

![Cosmic Ray Flux Vs. Energy]

![Equivalence c.m. energy $\sqrt{s_{pp}}$ (GeV)]

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Outstanding Issues

Acceleration Mechanism

GZK

Composition

Point Sources
The Magnetic Mirror

Energy exchange
Drift ↔ Revolution

\[ v_{||}^2(z) = v_{||}^2(0) - v_{\perp}^2(0) \left[ \frac{B(z)}{B(0)} - 1 \right] . \]

Inhomogeneous B field
Spiral trajectories around field lines
High gradient regions acting like walls
Fermi Mechanism - 2nd Order

Scattering by $B$-field

Stochastic process:

$$\Delta E \propto \beta^2 E$$

Expect:

Slow, inefficient

$$E'_1 = \gamma E_1 (1 - \beta \cos \theta_1)$$

$$E_2 = \gamma E'_2 (1 + \beta \cos \theta_2)$$

$$\left\langle \frac{\Delta E}{E} \right\rangle_{\theta_1, \theta_2} \approx \frac{4}{3} \beta^2$$
Fermi Mechanism - 1st Order

As before, scattering by $B$-field irregularities

Momentum gain:

$$\frac{\delta p}{p} = +\frac{2U_1}{c} \quad \text{head-on acceleration}$$

$$\frac{\delta p}{p} = -\frac{2U_2}{c} \quad \text{tail-on deceleration}$$

$$\rightarrow \frac{\delta p}{p} = 2\left(U_1 - U_2\right)/c > 0 \quad \text{net gain}$$

Expect:

*fast, efficient*

Shock compression ratio
A General Argument - I

Just a couple of units:
1 pc = 3.2 light yr
1 EeV = 10^{18} eV = 0.16 J

To get accelerated: *No early escape from the source*

\[
\text{Source size } > \left( \frac{R_{\text{Larmor}}}{kpc} \right) = \left( \frac{1}{Z} \right) \cdot \left( \frac{E}{1EeV} \right) \cdot \left( \frac{ZB}{\mu G} \right)
\]

To get accelerated: *Synchrotron loss < energy gain*

\[
dE/dt \propto B^2 \quad dE/dt \propto B
\]

\[(\text{Greisen}, 1965)\]
A General Argument - II

\[ W_B = \frac{B^2}{4\pi} \frac{4}{3} \pi R^3 \propto \gamma^5_{\text{particle}} \]

Ex. \( 10^{20} \text{ eV} \rightarrow W_B > 10^{57} \text{ erg} \)

Such humongous source should be a strong radio emitter (like \( 10^{41} \text{ erg s}^{-1} \))

\[ \rightarrow \text{Easy to detect!} \]
Maximum Energy

Simple estimate of max. energy (Hillas):

\[ E_{\text{max}} = Ze\beta BL \]

\( \beta \): Plasma speed  
\( B \): Mag field  
\( L \): Source size
Spectral Index, Time Constant

Power law spectrum

\[ N(E) \propto E^{-x} \]

Fermi 2nd order:

\[ x = 1 + \frac{\tau_{acc}}{\tau_{esc}} \gg 1 \]
\[ t_{acc} > 10^8 \text{ yr! KO} \]

Fermi 1st order:

\[ x = \frac{R + 2}{R - 1} \sim 2 \]
\[ t_{acc} \sim 1 \text{ month! OK} \]
Compact sources

Just meaning: *Non* electromagnetic acceleration

Various mechanisms proposed:

*Black hole accretion disks*

*Gamma ray bursts*

*Topological defects (monopoles, cosmic strings, ..)*

*UHE \(\nu\)’s from decays of high mass particles*
Cosmic Microwave Background

Penzias, Wilson & the Antenna

The CMB spectrum (by FIRAS)
CMB Photons

Peak energy $\sim k_B T = 0.6$ meV
Density $\sim 400$ cm$^{-3}$

Possible CR interactions:
$G(reisen), Z(atepsin), K(uz’min)$

\[
\begin{aligned}
    p + \gamma(2.7K) &\rightarrow n + \pi^+ \\
    p + \gamma(2.7K) &\rightarrow p + \pi^0
\end{aligned}
\]

$(G, Z&K - 1965)$

$E_{\text{thresh}} \sim 6 \times 10^{19}$ eV \hspace{1cm} \text{En.loss} \sim 20\% \hspace{1cm} \text{int}$

\[
\begin{aligned}
    p + \gamma(2.7K) &\rightarrow p + e^+ + e^-
\end{aligned}
\]

$E_{\text{thresh}} \sim 1 \times 10^{18}$ eV \hspace{1cm} \text{En.loss} \sim 0.1\% \hspace{1cm} \text{int}$

The moral:

*CR’s above threshold bound to lose energy*
The GZK Cutoff

So UHECR’s just can’t propagate beyond, say, 50 Mpc!

Then we should find a suitable source just ‘round the corner’.

But where?
The High End of the CR spectrum

~ x 2 effect

~ 2-3 σ issue..

Systematics Dominates

Statistics Dominates
Composition Issues

Spectrum

Depth of Shower Maximum in Air vs. E

Galactic? Extra-Galactic
More on Composition

Proton/Iron Discrimination tied to Intra/Extra-Galactic origin
Opening a New Window?

Effect of Extra-Galactic Magnetic Field on CR trajectories Simulation

\[ E = 10^{18} \text{ eV} \quad \text{and} \quad E = 10^{20} \text{ eV} \]

![Simulation Diagrams]

Clearly, around \( 10^{20} \text{ eV} \) a new astronomy is feasible… …if Cosmic Rays of that energy are actually observed
No deflection @ High E

Little deflection from extragalactic mag field

$B$ not well known $\leq 10^{-9} \, G$

Constant field region: $B$, size $l$, $\text{var[defl]} = \sigma^2$

Assuming random walk through $N$ regions

$$\theta(E) \approx 0.04 \text{mrad} \left( \frac{d}{\lambda} \right)^{1/2} \frac{1}{\lambda BE}$$

$\lambda : \text{Mpc}, \ B : \text{nG}, \ E : 10^{20} \text{eV}$

$\rightarrow$ Negligible deflection
The Known Matter (< 21 Mpc)
Anisotropies, Point Sources?

Controversial results…
Issues at stake:

Detection Technique
Angular Resolution
Statistics!

AGASA

HIRES
Cosmic Rays Detection

Airborne conventional detectors: $E < 10^{14} \text{ eV}$
*Not suitable to deal with small fluxes*

$E > 10^{14} \text{ eV}$: $E$(xtensive) $A$(ir) $S$(showers)

*Different techniques:*

- *Ground arrays (scintillators, water Cherenkov)*
- *Air Cherenkov telescopes*
- *Fluorescence detectors*
EAS - I

10 km

LOW ENERGY NUCLEONIC COMPONENT
DISINTEGRATION PRODUCT NEUTRONS DEGENERATE TO "SLOW" NEUTRONS

ELECTROMAGNETIC OR "SOFT" COMPONENT
MESON OR "HARD" COMPONENT
NUCLEONIC COMPONENT

ENERGY FEEDS ACROSS FROM NUCLEAR TO ELECTROMAGNETIC INTERACTIONS
SMALL ENERGY FEEDBACK FROM MESON TO NUCLEONIC COMPONENT

N, p • HIGH ENERGY NUCLEONS
n, p • DISINTEGRATION PRODUCT NUCLEONS
• NUCLEAR DISINTEGRATION
EAS - II
Data & MCarlo

Inelastic $\sigma(p,\text{air})$

Tevatron LHC

A 10 EeV Extensive Air Shower (EAS)

100 billion particles at sea level
- photons, electrons (99%), muons (1%)
- Ground Array stations
EAS development

Next slides from R. Engel’s simulations
See for example:

R. Engel

EAS

Lectures given at ISAPP 2005 Summer School
http://www.isapp2005.to.infn.it
EAS-I

Atmospheric depth:

\[ \int_{h}^{\infty} \rho(l) \, dl = X(h) \]

- Shower particles: mainly e^\pm, \gamma
- 80 – 95% of primary energy converted to ionization energy
- Up to \(10^{11}\) charged particles
EAS-II

Detailed MC simulation: 10 showers
zenith angle 35°, QGSJET

\[ N_{\text{max}}^A = N_{\text{max}}, \quad X_{\text{max}}^A \sim \lambda_e \ln(E_0/A) \]
EAS-III

Proton $10^{19}$ eV

21336 m
EAS-IV

Iron $10^{15}$ eV

24928 m
EAS-V

Gamma $10^{13}$ eV

24713 m

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EAS - Profiles

(Heck, 2004)

Longitudinal

Lateral
EAS - Electron Lateral Distribution

![Graph showing EAS - Electron Lateral Distribution](image)
EAS - Muons vs Electrons
EAS – The Movie