Ultra High Energy Cosmic Radiation: Experimental and Theoretical Status

- (Very short) introduction on Cosmic Ray experimental situation and current understanding
- Large scale magnetic fields and their effects on UHECR.
- Ultra-High Energy Cosmic Rays and secondary γ-rays and neutrinos: detection prospects with different experiments.

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The structure of the spectrum and scenarios of its origin

- Supernova remnants
- Wind supernovae
- AGN, top-down ??

The graph shows the energy per nucleus $E$ (GeV) on the x-axis and the intensity $I(E)$ in units of $m^2 s sr GeV^{-1.5}$ on the y-axis. The data points represent different elements like $p$ (protons) and $Fe$ (iron) with energy spectra deviating at the knee and ankle regions. The power-law index $\gamma$ is indicated at various points, with $\gamma = 2.7$ and $\gamma = 3$. The graph includes data from experiments like Tevatron, KASCADE, and LHC-Grande.
Atmospheric Showers and their Detection

Fly's Eye technique measures fluorescence emission. The shower maximum is given by

$$X_{\text{max}} \sim X_0 + X_1 \log E_p$$

where $X_0$ depends on primary type for given energy $E_p$.

Ground array measures lateral distribution. Primary energy proportional to density 600m from shower core.
Lowering the AGASA energy scale by about 20% brings it in accordance with HiRes up to the GZK cut-off, but not beyond.

May need an experiment combining ground array with fluorescence such as the Auger project to resolve this issue.
Southern Auger Site

Pampa Amarilla; Province of Mendoza
3000 km$^2$, 875 a/cm$^2$, 1400 m
Lat.: 35.5° south

Surface Array (SD):
1600 Water Tanks
1.5 km spacing
3000 km$^2$

Fluorescence Detectors (FD):
4 Sites (“Eyes”)
6 Telescopes per site (180° x 30°)
First Auger Spectrum!!

107% AGASA exposure
Statistics as yet insufficient to draw conclusion on GZK cutoff

Deviation from best fit power law
Comparison of Experimental Spectra

HiRes 1
HiRes 2
AGASA
Auger

Flux (m$^2$ sr s eV$^{-1}$)

log(E/eV)

Connolly et al., astro-ph/0606343
The Ultra-High Energy Cosmic Ray Mystery consists of (at least) Three Interrelated Challenges

1.) electromagnetically or strongly interacting particles above $10^{20}$ eV loose energy within less than about 50 Mpc.

2.) in most conventional scenarios exceptionally powerful acceleration sources within that distance are needed.

3.) The observed distribution seems to be very isotropic (except for a possible interesting small scale clustering)
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background

\[ E_{\text{th}} = \frac{2m_N m_\pi + m_\pi^2}{4\epsilon} \approx 4 \cdot 10^{19} \text{ eV} \]

\[ \epsilon \approx \frac{\pi/m_\pi}{(E_{\text{lab}}/\text{GeV})^2 + 1} \]

⇒ sources must be in cosmological backyard

Only Lorentz symmetry breaking at \( \Gamma > 10^{11} \) could avoid this conclusion.
What the GZK effect tells us about the source distribution (in the absence of strong magnetic deflection)

Observable spectrum for an $E^3$ injection spectrum for a distribution of sources with overdensities of 1, 10, 30 (bottom to top) within 20 Mpc, and otherwise homogeneous.

**1st Order Fermi Shock Acceleration**

The most widely accepted scenario of cosmic ray acceleration

Fractional energy gain per shock crossing $\sim u_1 - u_2$ on time scale $\sim r_L / u_2$

This leads to a spectrum $E^{-q}$ with $q > 2$ typically.

When the gyroradius $r_L$ becomes comparable to the shock size $L$, the spectrum cuts off.
A possible acceleration site associated with shocks in hot spots of active galaxies.
Arrival Direction Distribution $>4\times10^{19}$eV zenith angle $<50$deg.

- Isotropic on large scales $\rightarrow$ Extra-Galactic
- But AGASA sees clusters in small scale ($\Delta\theta<2.5$deg)
  - 1 triplet and 6 doublets (2.0 doublets are expected from random)
  - Disputed by HiRes
Cosmic rays above $\sim 10^{19}$ eV are probably extragalactic and may be deflected mostly by extragalactic fields $B_{XG}$ rather than by galactic fields.

However, very little is known about about $B_{XG}$: It could be as small as $10^{-20}$ G (primordial seeds, Biermann battery) or up to fractions of micro Gauss if concentrated in clusters and filaments (equipartition with plasma).

Transition from rectilinear to diffusive propagation over distance $d$ in a field of strength $B$ and coherence length $\Lambda_c$ at:

$$E_c \equiv 4.7 \times 10^{19} \left( \frac{d}{10 \text{ Mpc}} \right)^{1/2} \left( \frac{B_{\text{rms}}}{10^{-7} \text{ G}} \right) \left( \frac{\Lambda_c}{1 \text{ Mpc}} \right)^{1/2} \text{ eV}$$

In this transition regime Monte Carlo codes are in general indispensable.
A particle is registered every time a trajectory crosses the sphere around the observer. This version to be applied for individual source/magnetic field realizations and inhomogeneous structures.

Main Drawback: CPU-intensive if deflections are considerable because most trajectories are “lost”. But inevitable for accurate simulations in highly structured environments without symmetries.
Effects of a single source: Numerical simulations

A source at 3.4 Mpc distance injecting protons with spectrum $E^{2.4}$ up to $10^{22}$ eV. A uniform Kolmogorov magnetic field, $\langle B^2(k) \rangle \sim k^{-11/3}$, of rms strength 0.3 $\mu$G, and largest turbulent eddy size of 1 Mpc.

Conclusions:
1.) Isotropy is inconsistent with only one source.
2.) Strong fields produce interesting lensing (clustering) effects.
The Universe is structured

Observations (2dF survey) simulations
The Sources may be immersed in Magnetized Structures such as Galaxy Clusters.
Smoothed rotation measure:
Possible signatures of ~0.1μG level on super-cluster scales!

Theoretical motivations from the Weibel instability which tends to drive field to fraction of thermal energy density

2MASS galaxy column density
Xu et al., astro-ph/0509826
Some results on propagation in structured extragalactic magnetic fields

Scenarios of extragalactic magnetic fields using large scale structure simulations with magnetic fields reaching few micro Gauss in galaxy clusters.

Sources of density $\sim 10^{-5}$ Mpc$^{-3}$ follow baryon density, field at Earth $\sim 10^{-11}$ G.

Magnetic field filling factors


The simulated sky \textit{above} $4 \times 10^{19}$ eV with structured sources of density $2.4 \times 10^{-5}$ Mpc$^{-3}$: $\sim 2 \times 10^5$ simulated trajectories \textit{above} $4 \times 10^{19}$ eV.
The simulated sky above $10^{20}$ eV with structured sources of density $2.4 \times 10^{-5}$ Mpc$^{-3}$: $\sim 2 \times 10^5$ simulated trajectories above $10^{20}$ eV.
Spectra and Composition of Fluxes from Single Discrete Sources considerably depend on Source Magnetization, especially for Sources within a few Mpc.

Source in the center; weakly magnetized observer modelled as a sphere shown in white at 3.3 Mpc distance.
With field = blue
Without field = red
Injection spectrum = horizontal line

Iron primaries
proton primaries
Composition for iron primaries
Importance of deflection obvious from comparing energy loss/spallation time scales with delay times.

Horizontal line = straight line propagation time
Low delay-time spike at ~50 EeV due to spallation nucleons produced outside source field.

Energy loss times for helium (solid), carbon (dotted), silicon (dashed), and iron (dash-dotted).
Scenario of Berezinsky et al.: The ankle at \(5 \times 10^{18}\) eV levels out at the 2nd knee where it is dominated by heavy Galactic nuclei. The ankle at \(5 \times 10^{18}\) eV is due to pair production of extragalactic protons on the CMB. Requires >85% protons at the ankle.
A significant iron admixtures does not reproduce the ankle in the absence of magnetic fields.

Experimental situation on chemical abundances is unsettled.

Allard et al., astro-ph/0505566, 0508465
Injection of mixed composition (solar metallicity) with spectrum \( E^{-2.2} \) up to \( 10^{21} \) eV and a source density \( \sim 2.4 \times 10^{-5} \) Mpc\(^{-3}\).

**Conclusion:** In the absence of fields, flux observed above \( 10^{19} \) eV requires too hard an injection spectrum to fit the ankle and too many nuclei are predicted at the ankle (Allard et al., astro-ph/0505566).
accelerated protons interact:

\[ p + \gamma \rightarrow X + \pi^\pm \rightarrow \text{neutrinos} \]

\[ \pi^0 \rightarrow \gamma - \text{rays} \]

during propagation ("cosmogenic") or in sources (AGN, GRB, ...)

=> energy fluences in γ-rays and neutrinos are comparable due to isospin symmetry.

Neutrino spectrum is unmodified, γ-rays pile up below pair production threshold on CMB at a few $10^{14}$ eV.

Universe acts as a calorimeter for total injected electromagnetic energy above the pair threshold. => neutrino flux constraints.
Propagation of nucleons, photons, electrons, and neutrinos

In one dimension propagation is governed by Boltzmann equations for differential spectrum of species $i$, $n_i(E)$:

$$\frac{\partial n_i(E)}{\partial t} = \Phi_i(E) - n_i(E) \left[ \int_{-1}^{1} d \mu \frac{1 - \mu \beta_i \beta_i'}{2} \sum_j \sigma_{i \rightarrow j} \left|_{s = \epsilon(E' (1 - \mu \beta_i \beta_i')} \right. \right]$$

$$+ \int dE' \int d \epsilon n_b(\epsilon) \sum_{i} \frac{1 - \mu \beta_i \beta_i'}{2} n_j(E') \left. \frac{d \sigma_{i \rightarrow j}(s, E')}{dE} \right|_{s = \epsilon(E' (1 - \mu \beta_i \beta_i')},$$

where:

$\Phi_i(E)$ = injection spectrum,

$n_b(\epsilon)$ = diffuse background neutrino or photon density at energy $\epsilon$,

$\mu = \cos{(\text{angle between background and in-particle})}$,

$\beta$ = particle velocities,

$\sigma_{i \rightarrow j}$ = cross sections for processes $i \rightarrow j$,

$s$ = center of mass energy.

Background spectrum between $\sim 10^{-3}$ eV and $\sim 10$ eV
propagated particles between 100 MeV and $10^{16}$ GeV (GUT scale)
transport equations (including cosmology, i.e. redshift-distance relation) solved by implicit methods.
Processes taken into account

Nucleons:
- (multiple) pion production: \( N\gamma \rightarrow N(n\pi) \) with subsequent pion decays: leads to “GZK-effect”.
- pair production by protons: \( p\gamma \rightarrow pe^+e^- \): relevant below GZK threshold (similar to triplet pair production below)
- Neutron decay: \( n \rightarrow pe^-\bar{\nu}_e \)

Electromagnetic channel:
- pair production and inverse Compton scattering: \( \gamma\gamma \rightarrow e^+e^- \) and \( e\gamma \rightarrow e\gamma \): leading order processes with
  \[
  \sigma_{PP} \simeq 2\sigma_{ICS} \simeq \frac{3}{2} \sigma_T \frac{m_e^2}{s} \ln \frac{s}{2m_e^2} \quad (s \gg m_e^2).
  \]

- double pair production: \( \gamma\gamma \rightarrow e^+e^-e^+e^- \): dominates at highest energies with
  \[
  \sigma_{DPP} \simeq \frac{43\alpha^2}{24\pi^2} \sigma_T \quad (s \gg m_e^2).
  \]

- triplet pair production: \( e\gamma \rightarrow ee^+e^- \): dominant at highest energies with
  \[
  \sigma_{TPP} \simeq \frac{3\alpha}{8\pi} \sigma_T \left( \frac{28}{9} \ln \frac{s}{m_e^2} - \frac{218}{27} \right) \quad (s \gg m_e^2),
  \]
  with fractional energy loss \( \eta \) of leading \( e \)
  \[
  \eta \simeq 1.768 \left( \frac{s}{m_e^2} \right)^{-3/4} \quad (s \gg m_e^2).
  \]

- synchrotron loss of electrons and positrons in cosmic magnetic fields: \( eB \rightarrow e\gamma \):

Energy loss given by
\[
\frac{dE}{dt} = -\frac{4}{3} \sigma_T \frac{B^2}{8\pi} \left( \frac{2m_e}{\eta} \right)^4 \left( \frac{E}{m_e} \right)^2.
\]
Neutrino flux upper limit for transparent sources limited by primary cosmic rays: Waxman-Bahcall bound

quasar evolution

Armengaud and Sigl
No source evolution
Application: Flux calculations in Top-Down scenarios

a) Assume mode of $X$-particle decay in GUTs

Example: $X \rightarrow l + q + q$ hadronic jets

b) Determine hadronic quark fragmentation spectrum extrapolated from accelerator data within QCD:

- modified leading log approximation (Dokshitzer et al.)
- with and without supersymmetry versus older approximations (Hill). More detailed calculations by Kachelriess, Berezinsky, Toldra, Sarkar, Barbot, Drees: results not drastically different.

Fold in meson decay spectra into neutrinos and $\gamma$-rays.

c) Fold in injection history and solve the transport equations for propagation.
A typical example:

In general, the ratio of γ-rays to nucleons is too high to explain highest energy cosmic rays without overproducing GeV γ-ray background.

\[ X \rightarrow q + q, \ m_x = 2 \times 10^{13} \text{GeV}, \ B = 10^{-12} \text{G}, \]

homogeneous sources with \( \dot{\rho}_x \propto t^{-3} \)
Putting Everything Together: Cosmic Rays, Gamma-Rays, Neutrinos, Magnetic Fields

Numerous connections:

Magnetic fields influence propagation path lengths. This influences:

- spallation of nuclei and thus observable composition, interpretation of ankle production of secondary gamma-rays and neutrinos, thus detectability of their fluxes and identification of source mechanisms and locations.
Discrete Source in a magnetized galaxy cluster injecting protons up to $10^{21}$ eV

In a magnetic field $B$, pairs emit synchrotron photons of typical energy

$$E_{\text{syn}} \simeq 6.8 \times 10^{11} \left( \frac{E_e}{10^{19} \text{eV}} \right)^2 \left( \frac{B}{0.1 \mu \text{G}} \right) \text{eV}.$$ 

For proton spectra steeper than $\sim E^{-2}$, the sub-GeV photon flux is dominated by synchrotron photons from pair production. Pairs produced by protons appear below $\sim 10^{17}$ eV which in $\sim 0.1$ G fields ends up in synchrotron photons below $\sim 1$ GeV.

Furthermore, the EGRET limit on $\gamma$-rays from clusters around 100 MeV gives the limit

$$\beta \lesssim 2.17 - 0.1 \log_{10}(\eta/0.01)$$

on the low energy proton spectrum $E^{-\beta}$ contributing a fraction $\eta$ to the CR flux at $10^{19}$ eV to avoid overproduction from $pp \rightarrow \pi \rightarrow \gamma$ processes.
Source at 20 Mpc, $E^{2.7}$ proton injection spectrum with $4 \times 10^{42}$ erg/s above $10^{19}$ eV

Note that the 3d structure of the field matters and leads to further enhancement of GeV γ-ray fluxes. Γ-rays from pp interactions neglected.
The source magnetic fields can give rise to a GeV-TeV γ-ray halo that would be easily resolvable by instruments such as HESS.

In case of previous example, γ-rays above 1 TeV:
The GZK neutrino flux can also be enhanced by magnetic fields.
Short Advertisement: CRPropa a public code for UHE cosmic rays, Neutrinos and γ-Rays

Sources:
- discrete
- continuous

Injection:
- single E
- power law

Propagation:
- Interactions
- Neutral secondaries
- Deflections in 3D
- Redshifts in 1D

Observers:
- Origin of coordinates
- Spheres around the sources
- Small spheres in the box

Conclusions

1.) The origin of very high energy cosmic rays is one of the fundamental unsolved questions of astroparticle physics. This is especially true at the highest energies, but even the origin of Galactic cosmic rays is not resolved beyond doubt.

2.) Acceleration and sky distribution of cosmic rays are strongly linked to the in part poorly known strength and distribution of cosmic magnetic fields.

3.) Sources are likely immersed in magnetic fields of fractions of a microGauss. Such fields can strongly modify spectra and composition even if cosmic rays arrive within a few degrees from the source direction.

4.) Secondary $\gamma$-ray and neutrino fluxes from discrete magnetized sources can also be enhanced considerably. This can be relevant for neutrino telescopes and $\gamma$-ray detectors such as GLAST, HESS, MAGIC.

5.) Pion-production establishes a very important link between the physics of high energy cosmic rays on the one hand, and $\gamma$-ray and neutrino astrophysics on the other hand. All three of these fields should be considered together. Strong constraints arise from $\gamma$-ray overproduction.