Cosmic particles

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Where particle physics is born

Victor Hess

Carl Anderson and a Wilson chamber

Bruno Rossi, the coincidence technique
## An exciting field and a lot of ambitions

<table>
<thead>
<tr>
<th>In space (satellites, ISS,...)</th>
<th>At the South Pole</th>
<th>Under water</th>
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</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Satellite Image" /></td>
<td><img src="image2.png" alt="South Pole Image" /></td>
<td><img src="image3.png" alt="Water Image" /></td>
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Array of detectors over huge surfaces up to thousands of km²
(Pierre Auger Observatory, Telescope Array)

Cherenkov Telescopes in Africa, Arizona, Canarie
A flux of particles over many energy decades

Nature is generous in energy but parsimonious in events
A flux of particles over many energy decades

Nature is generous in energy but parsimonious in events

- Origin and propagation of CRs
- Fundamental physics
  - Spectral features
  - Mass composition
  - Arrival directions

A single power-law

- Knee: $E \sim 10^{15}$ eV
- Ankle: $E \sim 10^{18.5}$ eV
- Cut-off: $E > 10^{19.5}$ eV

~ 1 particle per km$^2$ per century

Tevatron, LHC (14 TeV)
A flux of particles over many energy decades

Nature is generous in energy but parsimonious in events

- Origin and propagation of CRs
- Fundamental physics
  - Spectral features
  - Mass composition
  - Arrival directions

What do we know?
What can we still learn?
Sources of cosmic rays

Galactic sources
Low energy up hundreds TeV

Extragalactic sources
High energies, above $10^{17}$-$10^{18}$ eV

Transition between galactic and extragalactic components
between $\sim 10^{17}$ - $10^{18.5}$ eV
Cosmic rays from our Galaxy

Measurements from balloons and satellite-borne experiments

Nature and origin
~ 98% are protons, helium
< 2% electrons, nuclei

Similar spectral index for all primaries, similar origin
What are we still looking for?
How do we do it?

Acceleration mechanism? Sources and propagation?
Non-astrophysical origin of cosmic rays?

Higher we go in energy less we know
How can we learn more?

Many detection technique and many experiments

Low energy (GeV - TeV):
- **direct detection (balloon, satellites)**

High energy (> tens of TeV):
- **indirect detection (ground-based exp.)**
Looking closer to our Galaxy

- Gamma-ray observations (satellites, ground-based Cherenkov)
- Flux of primary cosmic-rays, spallation products, isotopes and antiparticles

Evidence of a Pevatron in the Galactic center
Proton and helium spectra

With 30 months of AMS-02 data, the hardening of the proton and helium spectra is confirmed.

Proton

Helium

Propagation, re-acceleration, new sources?

A. Oliva for the AMS coll., parallel session
The electron/positron fluxes

Study of cosmic ray propagation (see also B/C ratio)
Rise in the $e^+/e^-$ ratio observed by Pamela and AMS

Hints for Dark Matter or not-well modeled astrophysical origin?
Moving to very-high and ultra-high energies

Extensive-Air-Showers and Ground-based detectors
**Ground-based detectors**

using the atmosphere as a calorimeter

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### Fluorescence Telescopes

- Longitudinal shower development
- Calorimetric energy
- 10-15% duty cycle

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**Surface array detector**

- Particle density at ground
- (hadronic interaction models)
- 100% duty cycle
The investigation tools

Not a lab experiment: a few inputs (mostly models) and observables to combine

From extensive air-showers:

- Evolution of the electromagnetic cascade
- Maximum of the shower (X_{\text{max}})
- Number of muons

Different detectors access to a different piece of information

Energy
Mass
hadronic signal
Two observatories for UHECRs

hybrid design and full sky coverage

**Telescope Array**
Millard County, Utah, USA, 1400 m a.s.l.

- 507 Scintillators (3 m² surface)
- 38 Fluorescence Telescopes

**Pierre Auger Observatory**
Malargüe, Argentina, 1400 m a.s.l.

- 1660 Water Cherenkov Detectors
- 27 Fluorescence Telescopes
The high-energy spectrum

V. Verzi, Cosmic Rays: Rapporteur talk, ICRC 2015

\[ J(E) \times E^{2.5} \, [m^{-2} \cdot s^{-1} \cdot sr^{-1} \cdot eV^{1.5}] \]

- Knee
- 2nd Knee?
- Ankle
- Galactic
- Extragalactic
- Flux suppression
The end of the spectrum?

Galactic/Extragalactic transition? propagation?

E_{\text{max}} at the source? propagation (GZK)?

Ankle

Galactic
Extragalactic

$J(E) \times E^{2.5} \text{ [m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{eV}^{1.5}]$
The end of the spectrum?

1. Energy Spectrum
2. Mass composition
3. Anisotropy (astronomy for UHE protons!)
4. Cosmogenic photons and neutrinos
1. Energy spectrum above $10^{18}$ eV: some details

- **Ankle** position in good agreement
Are Northern and Southern skies different?

- **Ankle** position in good agreement
- **Flux suppression** at different energies (different skies?)

\[ \log_{10}(E/\text{eV}) = a + b \cdot \log_{10}(E) \]

\[ \text{Syst. on energy scale:} \]
- 14% for Auger, 21% for TA

\[ \delta < 26^\circ: \log_{10}(E/\text{eV}) = 19.62 \pm 0.06 \]
\[ \delta > 26^\circ: \log_{10}(E/\text{eV}) = 19.84 \pm 0.03 \]
2. Mass composition:

Change in composition and break point at $E \sim 10^{18.3}$ eV

Auger&TA joint work: TA uncertainties too large to distinguish between the Auger-mix and a light composition
3. Anisotropy at UHE ($E \gtrsim 55$ EeV)

No significant deviation from isotropy at small angular scale. Maximum significance at intermediate angular scales.

Telescope Array

Max significance: $5.1\sigma$ (pre-trial)
post-trial: $3.4\sigma$
$E_{\text{thr}} > 57$ EeV, $\psi = 20^\circ$

($N_{\text{obs}} = 24$, $N_{\text{bg}} = 6.88$)

Pierre Auger Observatory

Largest excess: pre-trial $4.3\sigma$, 69% post-trial probability)

$E_{\text{thr}} > 54$ EeV, $\psi = 12^\circ$
$N_{\text{obs}} = 14 / N_{\text{bg}} = 3.23$

J. Aublin for the Auger Coll., ICRC 2015

K.Kawata for the Telescope Array Collab., ICRC 2015
Test of air-shower models at UHE

From two Independent analyses using the signal in the Auger surface stations

Muon deficit in simulations from 30% to 80% at $10^{19}$ eV
What’s next?

TA extension to ~ 3000 km²

- Hot-spot at > 5 σ
- Statistics for mass composition and energy spectrum at highest energies

AugerPrime

- Muon content and mass composition
- Origin of the flux suppression
- Search proton flux (test astronomy for future detectors)
- Hadronic models and EAS physics

Scintillator, 3.8 m², 1 cm thick

Water Cherenkov Station

SDE
Still a lot to learn!

Very active field in all the energy ranges

- Many high-quality observations lead to precise measurements, unexpected results and open questions

- New experiments and upgrades taking data in the next years

A multi-messenger approach to constrain scenarios

The UHECRs a unique laboratory for astrophysics and for particle physics beyond LHC
Backup
Interpretation of results

Same $X_{\text{max}}$ and $\sigma(X_{\text{max}})$ but different mixtures fit the $X_{\text{max}}$ distribution with a $N$-components model.
Inferring the fraction of chemical components

Fit of the $X_{\text{max}}$ distribution with simulation templates (4-components)

Are Auger and TA results in tension?

1) Construct a model of $X_{\text{max}}$ distribution describing the Auger data

2) Pass the “Auger-like” composition through the TA simulation, reconstruction and analysis chain

Auger:
- 8 years
- hybrid (at least one surface detector station)
- 24 telescopes
- PRD 90 (2014) 12, 122005

TA:
- 5-year hybrid data sample
- hybrid (at least three surface detector station)
- Middle Drum telescopes (MD)
- APP 64 (2014) 49

M. Unger et al. for the Pierre Auger and Telescope Array Collaborations, ICRC 2015
The Scintillator Surface Detector

- $S_\mu$ from WCD and SSD signals
- $\sigma[S_\mu(800)] / \langle S_\mu(800) \rangle \sim 15\% \text{ (iron)} - 20\% \text{ (proton)}$
- resolution $X_{\text{max}} \sim 30 \, \text{g/cm}^2$

- faster sampling (120 MHz)
- enhanced trigger and monitor capabilities

$S_{\mu,\text{WCD}} = a S_{\text{WCD}} + b S_{\text{SSD}}$
The end of the galactic component?

The classical model (not the only possible interpretation)
Large Scale Anisotropy (E ≳ 10 EeV)

Joint analysis Auger and Telescope Array

O. Deligny, for the Pierre Auger and Telescope Array Collaborations, ICRC 2015

zenith range
[0-55°] for TA
[0-80°] for Auger

Energy threshold
~10^{19} eV

$$\omega(\mathbf{n} ; b) = \omega_{\text{TA}}(\mathbf{n}) + b \omega_{\text{Auger}}(\mathbf{n})$$

b: empirical factor absorbing systematics

Dipole amplitude: (6.5 ± 1.9)%
Direction: (93° ± 24°, -46° ± 18°)

The full sky coverage
**Combined fit: spectrum and mass composition**

**Model:** identical sources (uniformly distributed) accelerating p, He, N, Fe

**Fit parameters:** injection flux, spectral index, energy cut off, mass fractions

Best fit with very hard spectra ($\gamma \leq 1$)

Prevailing intermediate mass at the source
Astrophysical interpretation of the results

Combined fit of spectrum and mass composition

Fit of the mass assuming pure proton at source

**Auger ICRC2015**

best fit: \( \gamma = \frac{R_{\text{cut}}}{0.94^{+0.09}_{-0.10}} \times 10^{18.67\pm0.03} \)

**Telescope Array ICRC2015**

best fit: \( p = 2.21^{+0.10}_{-0.15}, \quad m = 6.7^{+1.7}_{-1.4} \)
UHE photons

✓ top-down models disfavored
✓ GZK flux region within reach
\( \nu \) selected as inclined showers with large em component (time spread of SD signals)

- Waxman-Bahcall landmark reached
- cosmogenic model with pure p composition at the source and strong FRII evolution disfavored

![Graph showing Neutrino single flavour limits (90% C.L.)](graph)

**Cosmogenic \( \nu \) models**
- \( p \), Fermi-LAT best-fit (Ahlers '10)
- \( p \), Fermi-LAT 99\% CL band (Ahlers '10)
- \( p \), FRII & SFR (Kampert '12)
- Fe, FRII & SFR (Kampert '12)
- \( p \) or mixed, SFR & GRB (Kotera '10)

**Waxman-Bahcall '01**

\( E^2 \, dN/dE \) [GeV cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\)]

\( E_\nu \) [eV]

\( 10^{17} \) to \( 10^{21} \)
IceCube Mass Composition + Systematics
Neutrino bounds on UHECRs sources

The IceCube collaboration, arXiv:1607.05886

Search for high energy neutrino-induced events with deposited energy from $> 10^6$ GeV to $> 10^{11}$ GeV.

2 events found at $7.7 \times 10^5$ GeV and $2.6 \times 10^6$ GeV. The hypothesis of cosmogenic origin is rejected at $> 99\%$ CL.

sources with $m = 3.5$, $z_{\text{max}} = 2$ disfavored!

i.e. sources of UHECRs must evolve more slowly than the SFR otherwise a proton-dominant composition is excluded.
AMS-02: A TeV Multi-purpose Spectrometer

Separates hadrons from leptons, matter from anti-matter and able to do CRs chemical and isotopic composition in GeV to TeV range.

Multiple and Independent Measurement of Charge (Z), Energy (β, p, E) and Charge Sign (±).
Some recent results from AMS-02

- At $E > 10$ GeV/n the B/C ratio measures the energy dependence of the escape path-length of CRs from the Galaxy
- Energy spectrum of particles injected by the source is different from observed spectrum

Need 10% precision @1 TeV/n to discriminate between break models (#1124 Kunz)
Mass composition measurements (Auger)

Depth of shower maximum (Xmax) proportional to the lnA.
Mass inferred from the first two moments of the Xmax distribution

Break-point @ E \sim 10^{18.3} \text{ eV}: Mass composition from intermediate to light primaries at low energy and to intermediate/heavy at high energy