Latest results of the Pierre Auger Observatory

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OPEN Questions about UHECR

What is their source?
What is their nature?
How are they accelerated?
How do they propagate?
The Pierre Auger Observatory, main characteristics

Update of results, towards the understanding of UHECR’s?

  Spectrum
  Update of Anisotropies studies at intermediate and large scale
  Update of Mass composition studies (Fd and Sd)

Summary
The Pierre Auger Observatory in Argentina

Surface detectors
1660 Cherenkov stations
1.5 Km spaced on a hexagonal grid
Can detect shower up to 90°
100% duty cycle

Fluorescence detectors
4 building with 6 telescopes each
Telescope f.o.v. 30 x 30
~15 % duty cycle

Completed in 2008
Progressive data taking starting in 2004

Aiming at understanding the origin of Ultra High Energy Cosmic Rays,
the PAO associates the widest detection surface (3000 km²)
together with the highest precision ever achieved
Auger Hybrid concept: more than 2 detectors!

SD provides:
• Huge aperture (100% duty cycle) easily calculable
• Large angular acceptance (showers up to 80°)
• Robust detectors
• Good angular resolution

FD provides:
• Fluorescence light emitted in proportion to energy deposit: -> Near calorimetric energy measurements
• A direct view of shower maximum (composition)
• Precise directions (hybrid method).
• But duty cycle is only 10-15%

Optimisation of Auger's hybrid data
- FD calibrates SD energy scale that is used on the large statistic of SD events
- minimise (when possible) use of simulations in the production of key scientific output
  (SD energy spectrum, composition(~ minimal use))
- Various cross-check (directions, energy thresholds...)

Lateral profile by SD

Longitudinal profile by FD

S(1000)

RMS($X_{max}$)

$E_{Cal} = \int_{0}^{\infty} dX \frac{dE}{dX}$
Present status of the Pierre Auger Observatory

LOW ENERGY EXTENSION ($10^{17} - 3 \times 10^{18}$ eV)

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Combined Spectrum features (both SD arrays + hybrid)

SD Spectrum in 4 declination ranges

20σ flux suppression $\rightarrow$ GZK ?
Ankle $\rightarrow$ Transition G to XG?

No indication of a declination-dependent flux

Interpretation needs composition at the highest energies
Anisotropies of arrival direction can give some key hints.
Anisotropy searches

Motivation: Structure in the distribution of arrival directions
   —> a hint to track the nature and origin of UHECRs

Large scale anisotropies:

- **Transition** from Galactic to Extragalactic
  —> significant change in the large scale angular distribution of CR
- **Galactic:** diffusion & escape of galactic CRs below EeV energies might generate dipole pattern
- **Extragalactic:** Small dipole due to our motion (Compton-Getting effect, expected below 1%)

Point sources anisotropies:

- Largest energies: above GZK a light composition component would arrive with small deflection from the source → trace source population
Reconstruction of a dipole in Right Ascension

Observed dipole: \((l, b) = (233^\circ, -13^\circ) \sim 125^\circ\) from GC

Disfavors Galactic origin \(>8\) EeV

Previous results for \(E \geq 8\) EV

- \(r_1^\alpha = 0.046 \pm 0.013\) \(p\)-value 0.001
- \(\phi^\alpha = 86^\circ \pm 16^\circ\)

\(\theta < 60^\circ\) \(\Rightarrow 2012\)

- \(r_1^\beta = 0.044 \pm 0.010\) \(p\)-value \(6.4 \times 10^{-5}\)
- \(\phi^\beta = 95^\circ \pm 13^\circ\)

\(\theta < 80^\circ\) \(\Rightarrow 2013\)

Update with more relaxed selection and 3 more years (\(\approx 20\%\) more statistics)

E > 8 EeV
Dipole 6.5\% amplitude

Flux map above 8 EeV- Galactic coordinates
Rayleigh analysis

Centaurus-A

Excess of events over random scanning in energy and angle

Minimum: \( f_{\text{min}} = 2 \times 10^{-4} \) for \( E_{\text{th}} = 58 \text{ EeV}, \Psi = 15^\circ \)

Brightest Swift AGN

Small excess of events scanning in energy, distance, angle and Luminosity

Minimum: \( f_{\text{min}} = 2 \times 10^{-6} \) for \( E_{\text{th}} = 58 \text{ EeV}, \Psi = 18^\circ, \text{L} > 10^{44}\text{erg/s} \)

–> Post-trial probabilities at the level of the percent

“New” approach developed

Maximum likelihood technique building smoothed maps of flux weighted sources from gamma ray catalogs

–> Interesting deviations from isotropy

Stay tuned next week at ICRC
Fe shower develop higher in atmosphere
-> lower $X_{\text{max}}$ (~100 g.cm$^{-2}$ avrg)

Observables sensitive to composition:
- Depth of shower maximum ($<X_{\text{max}}>$);
- Elongation rate ($d<X_{\text{max}}>/d\log E$);
- RMS of $X_{\text{max}}$ (distribution at fixed energy:)
Mass composition over 3 decades in energy- $X_{\text{max}}$

- From a clean hybrid data set (strong anti-bias cuts), detector independent measurement
- Latest Hadronic interaction MCs tuned including new Sybill 2.3
- New extended low energy range data down to $10^{17}$ with HEAT FOV

In agreement with TA when folded from the detector effect (as done in TA)
Mass composition - from $X_{\text{max}}$ to $\ln A$

\[
\langle X_{\text{max}} \rangle \simeq \langle X_{\text{P}} \rangle - D_p \langle \ln A \rangle
\]
\[
\sigma(X_{\text{max}})^2 \simeq \sigma_f^2 + D_p^2 \sigma(\ln A)^2
\]
\[
\langle \ln A \rangle = \sum f_i \ln A_i
\]
\[
\sigma(\ln A)^2 = \langle (\ln A)^2 \rangle - \langle \ln A \rangle^2
\]

$D_p$ elongation rate  \( <\sigma_i> \) mass-averaged fluctuations

Average composition
\[
\langle \ln A \rangle = 4 \text{ pure Fe}
\]
\[
\langle \ln A \rangle \sim 2 \text{ 50%Fe 50% p}
\]
\[
\langle \ln A \rangle = 0 \text{ pure p}
\]

Dispersion of masses at ground
(source or propagation)
\[
\sigma(\ln A)=0 \text{ pure p or Fe}
\]
\[
\sigma(\ln A) \sim 4 \text{ 50%Fe 50% p}
\]

- $<\ln A>$ minimum in ankle region
- Energy evolution common to all models $<\ln A>$ increasing from light to medium
- The mix include intermediates species

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Mass Fraction from $X_{\text{max}}$

Fitted fraction and quality with intermediate species: $p$, $Fe$, $N$ and $He$

- Presence of $Fe$ disfavored in the middle energy range
- Best $p$-values for Sybill 2.3
- Statistics at high energy needed to check the trend —> need to use SD data
Mass composition from SD: from the risetime $t_{1/2}$ to the Delta method

Rise time in PMT Traces from individual Water tanks $\rightarrow$ The Delta Method

The rise time (time of 1/2 total signal) is sensitive to the muon to em signal, thus to the composition

The observable $\Delta_s$ is the average deviation of risetime within an event from the expected average rise time (from benchmark) after accounting for measurement uncertainties.
Mass composition from SD

Evolution of $<X_{\text{max}}>$ from SD with energy

$\Delta s$ calibrated with $X_{\text{max}}$ from Hybrid events
Systematics 11-14 g.cm$^{-2}$

Evolution of $<\ln A>$ from SD with energy

This SD analysis has 517 events above $10^{19.5}$ eV whereas the FD measurements have 37 events in this energy range

Not enough resolution for an event by event mass estimation
Upgrade needed to go further

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The Pierre Auger Observatory has provided wealthy data starting to give us some hints on the origin of cosmic rays.

Promising statistical mass composition studies at the highest energy

Hard work to improve detector capabilities and give definitive answers to open key questions.

See G. Cataldi’s talk on Saturday for more details

Thank you
BACKUP SLIDES
INVISIBLE ENERGY

Now estimated from Auger data M. Tueros ICRC #0705

Previously from simulation H. M. J. Barbosa et al., Astropart. Phys. 22 (2004) 159

→ reduction of the dependence on the hadronic interaction models and mass composition

$E_{\text{inv}}$ from SD signal and parameterised with an analytical function of the calorimetric energy ($E_{\text{cal}}$)

$E_{\text{inv}} / E = 15\% \div 10\%$ lower at the higher energies

$E$ increased by 4%

$\Delta E / E < 3\%$

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<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute fluorescence yield</td>
<td>3.4%</td>
</tr>
<tr>
<td>Fluorescence spectrum and quenching parameters</td>
<td>1.1%</td>
</tr>
<tr>
<td><strong>Sub total (Fluorescence Yield)</strong></td>
<td><strong>3.6%</strong></td>
</tr>
<tr>
<td>Aerosol optical depth</td>
<td>3% ± 0%</td>
</tr>
<tr>
<td>Aerosol phase function</td>
<td>1%</td>
</tr>
<tr>
<td>Wavelength dependence of aerosol scattering</td>
<td>0.5%</td>
</tr>
<tr>
<td>Atmospheric density profile</td>
<td>1%</td>
</tr>
<tr>
<td><strong>Sub total (Atmosphere)</strong></td>
<td><strong>3.4% ± 6.2%</strong></td>
</tr>
<tr>
<td>Absolute FD calibration</td>
<td>9%</td>
</tr>
<tr>
<td>Nightly relative calibration</td>
<td>2%</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>3.5%</td>
</tr>
<tr>
<td><strong>Sub total (FD calibration)</strong></td>
<td><strong>9.9%</strong></td>
</tr>
<tr>
<td>Folding with point spread function</td>
<td>5%</td>
</tr>
<tr>
<td>Multiple scattering model</td>
<td>1%</td>
</tr>
<tr>
<td>Simulation bias</td>
<td>2%</td>
</tr>
<tr>
<td>Constraints in the Gaisser-Hillas fit</td>
<td>3.5% ± 1%</td>
</tr>
<tr>
<td><strong>Sub total (FD profile rec.)</strong></td>
<td><strong>6.5% ± 5.6%</strong></td>
</tr>
<tr>
<td><strong>Invisible energy</strong></td>
<td><strong>3% ± 1.5%</strong></td>
</tr>
<tr>
<td>Statistical error of the SD calib. fit</td>
<td>0.7% ± 1.8%</td>
</tr>
<tr>
<td>Stability of the energy scale</td>
<td>5%</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>14%</strong></td>
</tr>
</tbody>
</table>

FD uncertainties propagate to the SD energies

TOTAL ≈ 14%

~ independent of energy
Mass composition - $X_{\text{max}}$

Change from a mixed/light composition to a heavier one
Mass Fraction from $X_{\text{max}}$

Method: Fit in different energy bins the $X_{\text{max}}$ profile from hybrid data with $X_{\text{max}}$ profile from individual species (averaged shapes from MC)

Test of 3 models: EPOS-LHC, QGSJet II-4 and Sibyll 2.1

Example of profile fit for the E-range $10^{17.8}$ - $10^{17.9}$ eV

$p$-Value from maximum-likelihood fit