Recent Results from the Pierre Auger Observatory

Alan Watson
University of Leeds, UK
Bristol, UK: Conference on Very High Energy Interactions, January 1963

Important names in ground-based gamma-ray astronomy: Jelley, Galbraith, Porter, Hillas and Weekes
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Wednesday, October 30, 13
Measurement of the angular resolution of an extensive air shower array using a Cherenkov light detector

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Received 2 October 1990

We describe a method which has been used to evaluate the pointing accuracy and angular resolution of the South Pole air shower array. It makes use of coincidences between the air shower array and a very simple air Cherenkov detector of small aperture. The alignment of the array is shown to be known to be within $\pm 0.2^\circ$ for the zenith direction and $\pm 0.5^\circ$ for the azimuth direction. Additionally the angular resolution has been measured at energies below 200 TeV, lower than those at which the subarray comparison technique can be applied. At higher energies conclusions drawn previously from subarray comparisons are confirmed: the angular resolution, as described by the root mean square uncertainty in zenith angle, of showers produced by primaries of 200 TeV is found to be $0.8^\circ$ for showers incident at about 20$^\circ$ from the vertical.

Cherenkov Light Detector: Pair of pmts and a Fresnel lens

5 citations
Visit to Whipple: April – May
1994 Smithsonian Visiting Fellow
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Observing Markarian 421 with Julie McHenry
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Observing Markarian 421 with Julie McHenry

Over 70 citations
SAGENAP Committee

Three awful meetings in 1997 - 98

Trevor was one of the Auger Champions
Outline

• The Auger Observatory

• Mass Composition and influence of hadronic interactions on interpretation

• Spectrum

• Some conclusions
Flux of Cosmic Rays

1 particle m⁻² s⁻¹

11 Decades in Energy

Air-showers

'Knee'
1 particle m⁻² per year

Ankle
1 particle km⁻² per year

LHC

25 decades in intensity

S Swordy
(Univ. Chicago)

10/30/13

Wednesday, October 30, 13
1390 m above sea level: 875 g cm\(^{-2}\)
400 PhD scientists from 18 countries

~ area of Rhode Island

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Auger

$< 60^\circ$ 31645 km$^2$ sr yr

$> 60^\circ$ 8027 km$^2$ sr yr

Telescope Array and HiRes

TA 4580 km$^2$ sr yr

14787 events above $10^{18.2}$ eV

HiRes 3650 km$^2$ sr yr

307 events above $10^{19}$ eV
The Auger energy scale is determined from the data and does not depend on a knowledge of interaction models or of the primary composition – except at level of few %.

Zenith Angle $\sim 48^\circ$  
Energy $\sim 7 \times 10^{19}$ eV

The detector signal at 1000 m from the shower core – $S(1000)$
- determined for each surface detector event

$S(1000)$ is proportional to the primary energy
Some Longitudinal Profiles measured with Auger

\[ 1000 \text{ g cm}^{-2} = 1 \text{ Atmosphere } \sim 1000 \text{ mb} \]

rms uncertainty in \( X_{\text{max}} = 20 \text{ g cm}^{-2} \) from stereo-measurements
Excellent check on the Energy

**E = 7.1\pm 0.2 \times 10^{19} \text{ eV} - X_{\text{max}} = 752 \pm 7 \text{ g/cm}^2**
Mass Composition
How we try to infer the variation of mass with energy

Energy per nucleon is crucial

Need to assume a model

$dX_{\text{max}}/\log E = \text{elongation rate}$

$< 2\% \text{ above } 10 \text{ EeV}$
after Tanguy Pierog
\[ \sim 30 \text{ g cm}^{-2} \]
Change from a mixed/light composition to a heavier one, Sigma relatively small
(RMS of 50% p and 50% Fe would be higher than proton-only fluctuations)
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Extensive Cross-checks and Verifications

Zenith and declination dependencies

For detailed discussion of method see paper by de Souza at Rio ICRC
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Elongation Rate Compatibility?
(a) fit to a horizontal line (constant composition).

(b) fit to a broken line (changing composition).

<table>
<thead>
<tr>
<th></th>
<th>Auger</th>
<th>HiRes</th>
<th>TA</th>
<th>Yakutsk</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Slope</td>
<td>$-1.0 \pm 0.3$</td>
<td>$-1.0$</td>
<td>$-1.0$</td>
<td>$-1.0$</td>
</tr>
<tr>
<td>Second Slope</td>
<td>$1.3 \pm 0.1$</td>
<td>$1.3$</td>
<td>$1.3$</td>
<td>$1.3$</td>
</tr>
<tr>
<td>$\lg(E_{\text{break}}/\text{eV})$</td>
<td>$18.43 \pm 0.04$</td>
<td>$18.65 \pm 0.07$</td>
<td>$18.26 \pm 0.14/-\infty$</td>
<td>$18.62 \pm 0.14$</td>
</tr>
<tr>
<td>$\langle \ln(A) \rangle_{\text{break}}$</td>
<td>$0.75 \pm 0.05$</td>
<td>$0.26 \pm 0.10$</td>
<td>$0.05 \pm 0.22/-\infty$</td>
<td>$0.08 \pm 0.15$</td>
</tr>
<tr>
<td>$\chi^2/ndf$</td>
<td>7.4/9</td>
<td>1.23/6</td>
<td>3.37/6</td>
<td>4.22/8</td>
</tr>
</tbody>
</table>
Cosmic Ray Energy Spectrum: Does the spectrum terminate?

Greisen-Zatsepin-Kuz’m’min – GZK effect (1966)

\[ \gamma_{2.7 K} + p \rightarrow \Delta^+ \rightarrow n + \pi^+ \text{ or } p + \pi^0 \]
and

\[ \gamma_{\text{IR}/2.7 K} + A \rightarrow (A - 1) + n \]

Sources must lie within about 100 Mpc

Approach introduced by Auger Collaboration:-

Calibrate the surface detector measurements with a sample of hybrid events

Many surface events at various angles combined using a very well-established method – the constant intensity approach
Post Rio ICRC July 2013

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Thanks to Alex Schulz
$\gamma_1 = -3.28 \pm 0.03 \quad \gamma_2 = 2.685 \pm 0.05 \quad \gamma_3 = 4.6 \pm 0.7$

$E_A = 5.04 \quad E = 4.27 \text{ EeV}$

$\gamma_1 = -3.23 \pm 0.01 \quad \gamma_2 = 2.63 \pm 0.02 \quad \gamma_3 = 4.7 \pm 0.2$
At ICRC in Rio there was some speculation that the differences might be a N-S effect.

Likely?

Would depend on source distribution and particular sources

BUT

Different ‘invisible energy’ corrections used
Different assumptions about mass composition
Different fluorescent yields used

Key test would be to look at overlap region of sky - statistics

With inclined showers Auger Observatory sees up to declination $+36^0$
Spectrum in a band of $\delta \in [0, 45^\circ]$
Origin Models

1. Cen A a major source?
   - might lead to N/S differences (role of M87?)
   - but only at high declinations

2. Galactic Source (Dermer and Holmes, 2005 and Calvez et al 2010)
   GRB within our galaxy $10^5$
   needs extensive magnetic field

Final Remarks:-

**Hadronic models** presently available do not fit data

**Mass composition** appears to become heavier as energy increases

No evidence of dependence on Declination for $\delta < 30^\circ$

**Spectrum** shows evidence of steepening at $\sim 40$ EeV

**Steepening at highest energies** may be due to limit reached by accelerators

Sensible in context of heavy-nuclei: need to know mass better

**N-S differences** at highest energies will be settled by JEM-EUSO (despite relatively poor energy resolution) and by OVERLAP STUDIES

but look rather improbable – unless at $\delta > \sim 40^\circ$
Arrival Direction Distributions
Events above 50 EeV
Events above 50 EeV

New results from TA do not contradict this effect
Amplitudes and Phases from Auger
Amplitudes and Phases from Auger
A and S: 
Candia et al. 2003

Gal: 
Calvez et al. 20110

C-G Xgal: 
Kachelreiss and Serpico 2006
Remember Von Neumann’s elephant
Hadronic Interactions
ONE example of a problem with extrapolation of particle physics
One example of a problem with extrapolation of particle physics.

Can models match both FD and SD?

- Find simulations which match measured FD profile, for each event.
- Compare the ground signals between the simulations and data.
- Rescale muon content so that simulated ground showers best-match observed ones.

Typical example: model ground signal is too low.
• Uses latest Hadronic Event Generators
  – EPOS-LHC and QGSJET-02-4
  – models tuned to LHC data

• Allows for mixed composition
  – p, He, N, Fe

• 411 Golden Hybrid Events
  – $10^{18.8}$ to $10^{19.2}$ eV
- Find simulated events that match the FD shower, for
  - 4 different primaries (p, He, N, Fe)
  - QGSJET-II-04 and EPOS-LHC
- **Simulated ground signal is too low; discrepancy grows with zenith angle**
  - For both models and for all composition mixes that fit $X_{\text{max}}$ distribution

![Graph showing energy scale uncertainty for different models and composition mixes.](Image) 

**S(1000) observed**

**S(1000) predicted**

Hatched band is 14% FD systematic uncertainty

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This is only ONE example of how the data and the models disagree: others from indirect measurement of muon content.
Some Longitudinal Profiles measured with Auger

$1000 \text{ g cm}^{-2} = 1 \text{ Atmosphere} \sim 1000 \text{ mb}$

![Graphs showing the relationship between slant depth and $dE/dX$ for Auger measurements.](image-url)
Some Longitudinal Profiles measured with Auger

1000 g cm\(^{-2}\) = 1 Atmosphere ~ 1000 mb

rms uncertainty in \(X_{\text{max}}\) = 20 g cm\(^{-2}\) from stereo-measurements
Allard and Parizot 2010
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Invisible Energy Correction

The Auger Collaboration have adopted 50/50 proton/iron in making the invisible energy correction
Allard and Parizot 2010