The Pierre Auger Observatory: Progress and Perspectives

“Declassified Results” ??

UHE Cosmic Rays, Photons and Neutrinos
KITP, Santa Barbara, CA
May 4, 2005

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The Pennsylvania State University
EXECUTIVE SUMMARY
I. OBJECTIVES, SCOPE, AND METHODOLOGY
II. BACKGROUND
III. FINDINGS AND RECOMMENDATIONS
A. The Department's Declassification Program
B. Department Exemptions From Declassification and Referrals to Other Agencies
APPENDIX A: DECLASSIFICATION EXEMPTION CATEGORIES
APPENDIX B: AGENCY COMMENTS
First Auger Spectrum

Total acceptance is $6.4 \times 10^{15} \text{ m}^2 \text{ sr} \text{ s}$

Auger data from April 22 to June 23

$\Phi(E) (\text{eV}^{-1} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1})$

- **AUGER - ultra preliminary !!!**
- AGASA data ($E - 20\%$)
- HiRes 1 Monocular

$log_{10} E (\text{eV})$
First Auger Sky Map
Outline

- Detection techniques and Results
  - AGASA
  - HiRes
  - A hybrid observatory

- Recent and Future Developments
  - The Auger Observatory
  - Telescope Array, other proposed efforts
  - Current status and prospects
Pierre Auger Discovers Extensive Air Showers (1938)

Auger, Maze and Grivet-Meyer, Comptes rendus, Académie des Sciences 206, 1721 (1938)

<table>
<thead>
<tr>
<th></th>
<th>1ère partie</th>
<th>2ème partie</th>
<th>3ème partie</th>
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</thead>
<tbody>
<tr>
<td>Nombre de compteurs</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Distance extrême en mètres</td>
<td>0,20</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Ecran de plomb (cm)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Coïncidences par heure (fortuites déduites)</td>
<td>6,7</td>
<td>2,1</td>
<td>0,7</td>
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</tbody>
</table>

\[ \Rightarrow 10^{11} \text{ eV} \]

cosmic ray
Techniques for UHECR Detection

- UHECR generate cascades (showers) in the atmosphere
- $10^{20}$ eV yields $10^{11}$ particles at maximum

- Shower front particles can be directly detected on the ground
- Showers excite nitrogen fluorescence, detectable on dark nights

100 billion particles at sea level
photons, electrons (99%), muons (1%)

Ground Array stations
Techniques for UHECR Detection

1. **Generic Method** (Auger): Detect the particles directly
   - Haverah Park: 12 km$^2$: 270 km$^2$ yr sr
   - Yakutsk: 25 km$^2$: 490 km$^2$ yr sr
   - AGASA: 100 km$^2$: 2000 km$^2$ yr sr
   **BUT primary energy estimate is MODEL DEPENDENT**
   \[ \Delta E/E \sim \pm 25\% \]

2. **Fluorescence Light** gives **CALORIMETRIC** measure of energy of primary particle.
   \[ \Delta E/E \sim \pm 20\% \]
   - Fly’s Eye: 930 km$^2$ yr sr monocular
   - \hspace{1cm} 151 km$^2$ yr sr stereo
   - HiRes: 5000 km$^2$ yr sr monocular
   - \hspace{1cm} 2500 km$^2$ yr sr stereo
Akeno Giant Air Shower Array

AGASA (Akeno, Japan)
100 km² ground array
AGASA Spectrum

The graph shows the AGASA spectrum with energy on the x-axis and the value of $J(E) E^3$ on the y-axis. The data points are represented by black circles with error bars, and the dotted line is labeled "Uniform sources."
HiRes (Dugway, Utah)
2 $N_2$ fluorescence sites
Absorption Length of Atmosphere was set to 15 km
Absorption Length of Atmosphere was changed to 25 km...

GZK cutoff seen?
HiRes vs AGASA

AGASA energies overestimated by 20%?

Energy reconstruction dependent on particle physics extrapolated by several decades...
(AGASA estimate: ±25% systematic)
HiRes vs AGASA

HiRes profile fits sometimes poor...

Fluorescence yield poorly understood

Atmospheric attenuation needs to be understood and corrected for daily
AGASA UHECR Sky Map

- > $10^{20}$ eV
- $4 - 10 \times 10^{19}$ eV
- Galactic Plane
- Supergalactic Plane
- Clustering within 2.5°
- 0.9% probability
HiRes UHECR Sky Map

HiRes 2004: point sources ruled out above $10^{19.5}$ eV in HiRes-I mono data

HiRes 2005: point sources ruled out above $4 \times 10^{19}$ eV in an analysis of 57 AGASA + 27 HiRes stereo events
Results so far suggest:

- There are events with energies beyond $10^{20}$ eV; seen by AGASA, Fly’s Eye and HiRes
  - BUT we are not sure of the fluxes
- The arrival directions seem rather isotropic
  - BUT there may be clusters

Major problem is that flux above $10^{20}$ eV is

$\sim 1$ km$^{-2}$ century$^{-1}$ sr$^{-1}$

Need much larger, hybrid detector $\Rightarrow$ Auger!
Hybrid Operation
Auger Observatory

• 10 years × 3000 km² yields 300 - 500 events >10²⁰ eV

• SOURCES? Two Observatories Necessary
Auger Hybrid Detector
Surface Detectors
Surface Detector Deployment
A tank was opened at the ‘end of project’ party on 31 July 1987. The water shown had been in the tank for 25 years but was quite drinkable!
Unique Problems
Unique Problems
Near Vertical Shower

$\Theta = 13^\circ$

$E = 1.6 \times 10^{19}\text{eV}$
Near Vertical Shower

FADC Traces

- 458 m
- 846 m
- 1072 m
- 1204 m
- 1283 m
- 1677 m

1 µs
UHE Auger Event

May 21, 2004
34 tanks
E = 1.2 \times 10^{20} \text{ eV}
preliminary!
\theta = 59^\circ
Shower Reconstruction

NKG-type LDF used: 

\[ S(r) = k \left( \frac{r}{r_0} \right)^{-\beta} \left( 1 + \frac{r}{r_0} \right)^{-\beta} \]

\( r_0 = 700 \text{ m} \)

\( \beta = 1.777 \)

\( \beta = 1.621 \)

\( \delta\beta = 0.156 \)

\( \beta \text{ effect minimized for } S(1000) \)

\( 10^{19} \text{ eV p shower} \)

\( \beta \) effect minimized for \( S(1000) \)
S(1000) = \left( \frac{7.8E_0}{\sqrt{1+11.8(\sec \theta - 1)^2}} \right)^{0.95}

AGASA Energy Conversion

E = a \times 10^{17} \cdot S(600)^b

- a = 2.03
- b = 1.02
- p, QCDjet
- a = 2.07
- b = 1.03
- p, QGSjet
- a = 2.24
- b = 1.00
- Fe
- a = 2.30
- b = 1.03
- p, Sibyll
- a = 2.19
- b = 1.01
- Fe
- a = 2.17
- b = 1.03
- p, QGSjet
- a = 2.15
- b = 1.01
- Fe
- a = 2.34
- b = 1.04
- p, Sibyll
- a = 2.24
- b = 1.02
- Fe

S(600) = 500 m\(^{-2}\)
Extremes ~30%
Fluorescence Detector
Fluorescence Detector

- Fluorescence detector at Los Leones
- Segmented spherical mirror
- Aperture box
- shutter
- Filter UV pass
- Safety curtain
- Corrector lens (aperture x2)
- 440 PMT camera
- 1.5° per pixel
- Segmented spherical mirror
Fluorescence Event

\[ \theta = 15^\circ \]

\[ E = 2.5 \times 10^{18} \text{ eV} \]
FD Calibrations

Pierre Auger Observatory  Central Laser Facility  SD Tank
Golden Hybrid Event

2-Telescope Golden Hybrid Event #668949

Los Leones
Stereo Hybrid Event

Platinum Event #673411 (10 tanks in fit)
Hybrid Reconstruction

- 0-25 degrees
- 25-45 degrees
- 45-60 degrees

Clear correlation between SD and FD energy estimates
Hybrid Reconstruction

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<thead>
<tr>
<th></th>
<th>δR (m)</th>
<th>δχ₀ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono</td>
<td>921</td>
<td>8.05</td>
</tr>
<tr>
<td>Hybrid</td>
<td>21</td>
<td>0.24</td>
</tr>
</tbody>
</table>
Auger Status April 05

- 793 surface detectors deployed (749 fully functional)
- 3 fluorescence detector buildings completed, 1 under preparation (15 telescopes fully instrumented)
Auger Deployment

Pierre Auger Project Schedule Chart
Updated 07-Apr-05

- Actual Complete Tanks Deployed
- Expected Tanks Deployed
- Actual Complete Electronics
- Expected Electronics/Water Deployed
- Actual FD Telescopes
- Expected FD Telescopes
Exposure of Auger
Simulated Auger Spectrum w/GZK Cutoff

20 months with full Auger Observatory
## Performance Targets of Auger

### Fully Efficient at $10^{19}$ eV (threshold $\sim 10^{18}$ eV)

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Tanks struck</th>
<th>$\Delta E/E$</th>
<th>$\sigma(\theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{19}$</td>
<td>$&gt;6$</td>
<td>25%</td>
<td>$\sim 3^\circ$</td>
</tr>
<tr>
<td>$10^{20}$</td>
<td>$&gt;12$</td>
<td>15%</td>
<td>$\sim 1^\circ$</td>
</tr>
</tbody>
</table>

10% of events to have fluorescence detections
Top-Down Exotics

e.g. TD model:
– UHE flux $\nu$ dominated
– spectrum can extend beyond $10^{20}$eV
– possible constraints from $\gamma$ flux

**Horizontal Showers**

**Far inclined showers** (~ thousand per year)
- Flat and thin shower front
- Narrow signals
- Time alignment

**Deep inclined showers** (~ one per year?)
- Curved and thick shower front
- Broad signals
- Soft \(\mu\) s + e.m.
Far Shower

Ground particle densities for $10^{20}$ eV p, 100 km injection altitude, $\theta = 80^\circ$
Deep Shower

Ground particle densities for $10^{19}$ eV p, 3 km injection altitude, $\theta = 80^\circ$
Geomagnetic distortion of the ground spot, at 80° and 86°; affects acceptance vs. energy.
January 6, 2002: 8 tanks triggered (7 radioed information):

- Tank signals: 5.6, 6.3, 6.8, 7.5, 16, 21, 35 v.e.m.
- $\theta = 82.9 \pm 1.2^\circ$, $\phi = 130.4 \pm 1.3^\circ$ (w/ magnetic corrections)
- $E > 10^{19}$ eV

Far shower
(not neutrino!)
Best fit $83^\circ$ seems to require $> 10^{19}$ eV; (but then would have expected more tanks fired)
Neutrino Spectrum

- 0.3 event / year ($\nu_e$ or $\nu_\mu$)
- 1 event / year / decade ($\nu_\tau$)
- 90% $\nu_\tau$ limit after 5 years

$\nu$ events / year:
- AGN: 24
- TD: 1.8
- GRB: 0.4
- GZK: 1.5
Haverah Park as a Prototype

- Haverah Park Array (also water Cherenkov counters) operated from 1974 to 1987; covered a 12 km² area.
- 8000 events with $\theta > 60^\circ$ recorded; not analyzed until now (simulation tools previously inadequate to the task)
  - Shower reconstruction highly dependent on detailed understanding of detector orientation and position, including effects due to vertical relief.
  - New analysis of HP data shows that near horizontal showers can be reconstructed (see M. Ave et al., PRL 85, 2244 (2000), astro-ph/0003011).
- Two HP events ($60^\circ$ and $75^\circ$):
Results from Highly Inclined HP Events

- Arrival direction from relative timing, energy reconstruction from muon signals in tanks, composition sensitivity from muon harvest.
- Reconstruction somewhat model dependent, requiring detailed understanding of detector response.
- Estimated resolution:
  - Zenith angle: 1.5° at 60°, 5° at 85°.
  - Energy: 20% @ 10^{19} eV to 50% at 10^{20} eV.
- Integral spectrum compared to expectations:
  - Promising for Auger!
Telescope Array

- Utah 2004-2008
- 3 N₂ fluorescence detectors
- 576 scintillators
- 830 km² (1/4 of one Auger site)
- Resolve AGASA/HiRes differences
- Possible low-energy extension (TALE) using HiRes telescopes and AGASA infill

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Conclusions

- Highest energy cosmic rays: origin is still a complete mystery!
- Large increases in data, and fresh particle physics input, are needed.
- Promising new experimental efforts.
- Auger Argentina site completion targeted for 2006; Northern site (UT, CO) under discussion.
- Expect definitive measurement of UHE spectrum, sensitivity to point sources, composition, potential for new neutrino frontier.