Energy Spectrum Measured by the Telescope Array Surface Detector

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OUTLINE

• Ultra High Energy Cosmic Rays (UHECR)
• Greisen-Zatsepin-Kuzmin GZK suppression
  – HiRes\(^1\)-AGASA\(^2\) contradiction
• Telescope Array (TA)
• TA Surface Detector (SD)
• TA SD Event Reconstruction
• TA SD Monte-Carlo (MC) Simulation
• Energy Spectrum Result
• Conclusions

\(^1\)HiRes: High Resolution Fly’s Eye (UHECR) experiment
\(^2\)AGASA: Akeno Giant Air Shower Array (UHECR experiment)
Cosmic Rays

- Cosmic Rays
  - First discovered by V. Hess
  - Mostly charged particles
  - Flux = steeply falling power law \( \rightarrow \) UHECR (\( E > 10^{18} \text{ eV} \)) are rare

- \( E > 10^{18} \text{ eV}, \) UHECR
  - Sources unknown
  - Produce extensive air showers in atmosphere (Auger)
  - Secondary particles reach the ground \( \rightarrow \) Sparsely spaced ground array detectors (Rossi)
  - Volcano Ranch saw a first \( 10^{20} \text{ eV} \) event (Linsley).
Extensive Air Showers

- **Hadronic core**
  - Baryons, $\pi$, $K$

- **Electromagnetic component**
  - Started by $\pi^0 \rightarrow 2\gamma$ decays
  - Pair production
  - Bremsstrahlung
  - Ionization & Excitation losses
    - Produce Fluorescence and Cherenkov light
  - Compton scattering

- **Muon component**
  - Due to charged $\pi$ and $K$ decays
  - Muons are long-lived, penetrating, and reach the ground level
Extensive Air Showers (Contd.)

- Fluorescence detectors register fluorescence light due to the excitation of N\textsubscript{2} molecules by the electromagnetic component.
- Ground Arrays register secondary particles from electromagnetic and muonic component.
GZK Suppression

- A well known fact from accelerator experiments of ~0.5 GeV gamma + stationary proton:

  \[
  \gamma + p \rightarrow \Delta^+ \rightarrow n + \pi^+
  \]

  \[
  \gamma + p \rightarrow \Delta^+ \rightarrow p + \pi^0
  \]

- Cosmic Microwave Background
  - 2.7 K ~2 x 10^{-4}eV
  - $10^{20}$eV protons should lose energy (efficiently) due to this photopion production → strong suppression in cosmic ray flux near $10^{20}$eV (Greisen, Zatsepin, Kuzmin)
GZK Suppression (Contd.)

• But early ground array experiments reported seeing \( E \geq 10^{20} \text{ eV} \) events
  – Volcano Ranch, SUGAR, Yakutsk

• Fly’s Eye reported \( 3 \times 10^{20} \text{eV} \)
  – Largest particle energy ever measured
  – Used Air-fluorescence technique
    • pioneered by University of Utah experiment

• The experiments were too small to conclusively rule out the GZK suppression
  – few tens of square kilometers
  – small \((\text{Area} \times \text{Solid Angle} \times \text{Observation Time})\) factors for measuring flux at \( E > 10^{19} \text{ eV} \)
AGASA

- Akeno, Japan
- 1st experiment large enough to measure flux above $10^{19}$ eV
- Area ~ 100 km$^2$
- ~1 km spacing
- 111 plastic scintillation counters
- 13 years of operation, 1991-2004
- ~120 km$^2$ sr aperture above $10^{19}$ eV
AGASA: No GZK effect

- 11 “super-GZK” events in AGASA data
- Flux limited by the rate at which sources can produce UHECR?
- GZK suppression ??

Dotted line = spectrum by uniform sources, propagated through cosmic microwave background
HiRes

- Dugway Proving Grounds, UT
- Two-site fluorescence detector
  - Spherical mirrors, 4.2m²
  - 256 photomultiplier tubes / mirror
  - Each tube ~1 degree cone of the sky
- HiRes1
  - 1 ring of 21 mirrors
  - 3 – 17 degree elevations
- HiRes2:
  - 12.6 km South-West of HiRes1.
  - 2 rings x 42 mirrors
  - 3 – 31 degree elevations
- 9 years of operation 1997 – 2006
  - 10% duty cycle
- Aperture ~7.5x10³ km² sr at 10²⁰ eV
HiRes: GZK Cutoff Exists

- Fluorescence detector
  - First to observe GZK effect
    - Chance probability > 5 σ
HiRes vs AGASA

• Combine HiRes and AGASA experiments
  – AGASA-like array of scintillation counters
  – HiRes – like fluorescence detectors

• **Telescope Array** experiment
  – Deployed in 2007
  – Measure UHECR anisotropy, mass composition
  – Measure UHECR energy spectrum:
    • Using fluorescence detectors only
    • Using surface detectors only
      – large statistics above $10^{19}$ eV
      – *This work*
    • Using surface and fluorescence detectors (hybrid)
The Telescope Array (TA) Collaboration

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• 140 collaborators, 26 schools, 5 countries
• US, Japan, Korea, Russia, Belgium
• Many former HiRes & AGASA members
TA SD Spectrum Group

• Prof. Gordon Thomson - Faculty Supervisor
  – Dr. Benjamin Stokes - Post Doc
    • Detailed CORSIKA Monte-Carlo simulation of the TA SD
    • Circumvent problems due to approximations in CORSIKA
    • Solve computational performance issues
    • Simulate UHECR as they exist in nature
    • Include TA SD details: response, electronics, and calibration
  – Dmitri Ivanov - Graduate Student
    • Parsing and handling raw data, calibration
    • GEANT- 4 simulation of the detector response
    • Event reconstruction and quality cuts
    • Monte-Carlo validation (comparison with data)
    • Energy spectrum calculation and interpretation
Telescope Array
Hybrid detector
Millard County, UT
39.3° N, 112.9° W,
Alt. 1400m
~880g/cm²

507 Surface Detector (SD) counters, 1.2km apart, cover 680km²

3 Communication Towers (CT): BR, LR, SK
3 Fluorescence Detectors (FD): BR, LR, MD
TA Surface Detector (TA SD)

- Powered by solar cells; radio readout.
- Calibration using atmospheric muons.
- Energy deposition by secondary cosmic ray particles measured in VEM units (Vertical Equivalent Muon)
  - Energy deposited by a vertical minimum-ionizing muon
Exterior Parts

1. Wireless antenna
2. GPS receiver
3. Battery & electronics box
4. Solar panel
5. Iron roof
6. Supporting metal frame
Sensitive Parts

1. Stainless steel box
2. Two layers of 1.5m x 2m plastic scintillators, 1.2cm thick each
3. Wavelength Shifting Fiber (WLS)
4. Photomultiplier Tube (PMT)
   - Operate at ~1000 V
   - Gain ~ $2 \times 10^6$
   - One PMT for each (upper, lower) scintillator layer
5. Tyvek sheet
6. WLS (cross-sectional view)
7. WLS Grooves
8. Separator plate
VEM Definition

- **GEANT4 simulation:**
  - Minimum ionizing energy occurs at vertical muon (kinetic) energy of ~300 MeV
  - Most probable value of dE/dX for a vertical 300 MeV muon is 2.05 MeV

- **1 VEM = 2.05 MeV**
- Varies slowly with increasing (kinetic) energy of muon
Electronics

- Energy deposition in each counter is read out by two PMTs
  - upper, lower scintillator layers
- PMT output recorded by 12 bit 50 MHz Flash-Analog-to-Digital-Converter (FADC)
- Waveforms (signal vs time) reported to the communication towers

Typical waveform reported by a counter
(signal from an extensive air shower)
Trigger and Data Acquisition

- Trigger issued by **Communication Towers (CT)** when:
  - 3 adjacent counters
  - ≥ 150 FADC counts each
  - Upper/lower layer coincidence
  - Within 8µS

- Data acquisition ↔ request waveforms from counters:
  - ≥ 15 FADC counts each
  - Upper/lower layer coincidence
  - ± 32 µS of the trigger time

- Hybrid Trigger
  - FDs can send commands that prompt data acquisition
    - just like normal CT trigger

Acceptable trigger patterns (up to rotations by 90°)
VEM Calibration

- Convert signal from [FADC] to [VEM]
- **Minimum Ionizing Particle (MIP)** pulses
  - ~700 Hz at a counter
  - Histogrammed over 10 minute periods by each counter
- Peak $P_{\text{MIP}}$ of the histogram related to FADC counts per VEM (separately for each layer):
  - $P_{\text{MIP}} \approx FADC_{\text{VEM}} \sec(30^\circ)$
    - $30^\circ$ is the effective zenith angle of particles
    - Detailed simulations of atmospheric particles give answers within 1.5%
VEM Calibration (Contd.)

• $FADC_{VEM}$ (color) plotted versus counter X, Y position
  – a randomly chosen 10 min monitoring cycle
• Typically, $FADC_{VEM} \approx 40$ FADC counts VEM$^{-1}$
Event Reconstruction

- Circle = a counter
- Color = counter time
- Circle size proportional to the log of the counter pulse height (in VEM)
- Star = shower impact position
- Arrow = projection of the event direction on the ground (the “u-axis”)
- Geometry reconstructed from the counter time
- Energy estimated from the lateral distribution of counter signals

After pattern recognition
  - Pick out counters that are part of the event (remove random muons)
Geometry Reconstruction

- Event direction is found by minimizing:

\[ \chi^2 = \sum_{i=1}^{nSDs} \left( \frac{(t_i - T_0 - T_{\text{Plane}} - T_D)^2}{T_S^2} + \frac{(\vec{R} - \vec{R}_{\text{COG}})^2}{(180\text{m})^2} \right) \]

- 6 parameters in the final fit:
  - Zenith and azimuthal angles
  - Core X, Core Y, Core time
  - Curvature of the front

- \( T_0 \) - Time of the core hitting ground
- \( T_{\text{Plane}} \) - Time of the shower front plane
- \( T_D \) - Time delay (next slide)
- \( T_S \) - Fluctuation of the time delay
- \( \vec{R} \) - Fitted (2D) core position
- \( \vec{R}_{\text{COG}} \) - 2D core position found from the center of gravity of charge
Time Structure of the Shower Front

\[ T_D = a \left(1 - \frac{l}{12 \times 10^3 \text{m}}\right)^{1.05} \left(1.0 + \frac{s}{30 \text{m}}\right)^{1.35} \rho^{-0.5} \]

\[ T_S = (1.56 \times 10^{-3} \mu\text{S}) \left(1.0 - \frac{l}{12 \times 10^3 \text{m}}\right)^{1.05} \left(1.0 + \frac{s}{30 \text{m}}\right)^{1.5} \rho^{-0.3} \]

- \( T_D \) = Counter delay time due to the shower front curvature
- \( T_S \) = Fluctuation of the shower front time at the counter
- \( a \) = Curvature parameter
- \( l \) = Counter distance from the core along the (3D) shower axis
- \( s \) = Counter perpendicular distance from the shower axis
- \( \rho \) = Charge (pulse height) density at the counter, VEM m\(^{-2}\)

- Started with AGASA-Linsley formula
- Empirically adjusted using TA SD data only
- Tested that it works for Monte-Carlo also
Time Fit

- Counter time plotted vs distance along the u-axis (points with error bars = data)
- Solid line = fit expectation time for counters on the u-axis
- Dashed line = fit expectation for counters 1km off the u-axis
- Dotted line = fit expectation for counters 2km off the u-axis

(A 1D illustration of a multi-dimensional fit)
Test the time fit formulas derived from the TA SD data.

Each entry = counter, plots are **over all counters and over all events**.

Normalized residual = \((\text{counter time} - \text{fit time}) / T_S\)

Plotted versus (perpendicular) distance from the shower axis.

Data and Monte-Carlo fit in the same way.
Lateral Distribution Fit

- Counter signal versus perpendicular (lateral) distance from the shower axis
- Fit to the AGASA Lateral Distribution Function (LDF)
- Determine the Signal Size at 800m (S800) from the shower axis

AGASA LDF:
\[ \rho = A \left( \frac{s}{91.6\text{m}} \right)^{-1.2} \left( 1 + \frac{s}{91.6\text{m}} \right)^{-(\eta(\theta)-1.2)} \left( 1 + \left[ \frac{s}{1000\text{m}} \right]^2 \right)^{-0.6} \]
\[ \eta(\theta) = 3.97 - 1.79 \left[ \sec(\theta) - 1 \right] \]

\[ \sigma_\rho = \sqrt{0.56 \rho + 6.3 \times 10^{-3} \rho^2} \]

uncertainty on charge density \( \rho \) determined empirically from the TA SD data

3 fit parameters: A, Core X, and Core Y
Lateral Distribution Fit Residuals

- Each entry = counter, plots are over all counters and over all events
- Normalized residual = \(\frac{\text{counter } \rho - \text{fit } \rho}{\sigma_{\rho}}\)
- Plotted versus (perpendicular) distance from the shower axis
- Data and Monte-Carlo fit to the AGASA LDF in the same way
Energy Determination, Step 1/2

- A look-up table made from the Monte-Carlo
- Event energy \( E_{\text{TBL}} \) is a function of reconstructed S800 and sec(θ)
- Energy reconstruction \( \leftrightarrow \) interpolation between S800 vs sec(θ) contours of constant values of \( E_{\text{TBL}} \)

\[
Y = \log_{10}[S800 \text{ (VEM m}^{-2}\text{)]}
\]

\[
X = \sec(\theta)
\]

\[
Z = \log_{10}(E/\text{eV})
\]

- \( \log_{10}[S800 \text{ (VEM m}^{-2}\text{)]} \)
- \( 10^{17.8} \text{ eV} \)
- \( 10^{20.5} \text{ eV} \)

\( E_{\text{TBL}} = f[S800, \sec(\theta)] \)
Energy Determination, Step 2/2

- Energy scale locked to the TA FD to reduce the systematic due to the model
- Used well-reconstructed events seen in common by the TA SD and TA FD:
  - $\text{TA SD} \cap [\text{BR U LR U MD}]$
  - $E_{\text{FINAL}} = \frac{E_{\text{TBL}}}{(1.27 \pm 0.02)}$
- Energy scale systematic uncertainty is now same as that of the TA FD, which is 21%
- TOP figure: $E_{\text{FINAL}}$ vs $E_{\text{FD}}$ scatter plot
- BOTTOM figure: histogram of $E_{\text{FINAL}} / E_{\text{FD}}$ ratio
List of Quality Cuts

• Remove events reconstructing with bad resolution, otherwise may “miss” important features in the energy spectrum.

• Quality cuts:
  1. $N_{SD} \geq 5$: minimum number of counter / event
  2. $\theta < 45^\circ$: maximum zenith angle
  3. $D_{\text{Border}} \geq 1200\text{m}$: minimum core distance from the edge of the array
  4. $\chi^2 / \text{d.o.f.} < 4$: maximum $\chi^2$ per degree of freedom of time and LDF fits.
  5. $\sigma_G < 5^\circ$: maximum pointing direction uncertainty (from the time fit)
  6. $\sigma_{S800} / S800 < 0.25$: maximum fractional uncertainty of S800 (from the LDF fit)

• Next page shows the effects on the energy resolution of incrementally applying cuts 1 through 6
Effect of Quality Cuts

- Used a detailed Monte-Carlo to develop quality cuts

- No cuts
- 1
- 1,2
- 1,2,3
- 1-4
- 1-5

Reconstructed Energy vs True (Generated) Energy

Final with all cuts
Angular Resolution

- Determined from the Monte-Carlo
- Cumulative distribution \((f = \text{fraction of events})\) of the opening angle between the true and reconstructed event directions \((\delta)\)
- Quoted 68% confidence limits: 
  - values of \(\delta\) that contain 68% of events \((f = 68\%)\)

\[
\begin{align*}
\text{2.4°} & \quad 10^{18} - 10^{18.5} \text{ eV} \\
\text{2.1°} & \quad 10^{18.5} - 10^{19} \text{ eV} \\
\text{1.4°} & \quad 10^{19} - 10^{20.5} \text{ eV}
\end{align*}
\]
Energy Resolution

- Determined from the Monte-Carlo
- Histogram (natural logarithm) of reconstructed over generated (true) energies
- Use the root-mean-square (RMS) of the distribution to determine the energy resolution in percent of the true energy

$10^{18} - 10^{18.5} \text{ eV}$

$10^{18.5} - 10^{19.0} \text{ eV}$

$10^{19.0} - 10^{20.5} \text{ eV}$
Reconstruction Summary

• Two fits:
  – Time fit $\rightarrow$ event geometry
  – Lateral distribution fit $\rightarrow$ S800 (Signal 800m from shower axis)
  – Fitting procedure and formulas adjusted using data only $\rightarrow$ avoid model dependences

• Energy determination:
  – Reconstructed (S800, $\text{sec} \, \theta$) + Monte-Carlo $\rightarrow$ initial estimate of energy
  – FD energy scale(1/1.27 rescaling of look-up table values) $\rightarrow$ reduce model dependence
  – Quality cuts $\rightarrow$ improve resolution
TA SD Monte-Carlo Approach

• Simulate UHECR as they exist in nature
  1. Primary particle type
     – Proton, mass composition measurement by HiRes
  2. Energy spectrum
     – previously measured by HiRes
  3. Angular distribution
     – Isotropic in local sky
  4. Shower impact parameter
     – Distributed randomly in a large circular area surrounding the Telescope Array experiment
Generated Energy Distribution

- Generated MC energy histogram displayed using format:
  - \( 0.1 \log_{10}(E/eV) \) bins
  - Each bin content
  - divided by the (linear) bin size in energy
  - Multiplied by \( E^3 \) (energy of the bin center)
  - Normalized so that the first bin is unity

- Solid line = HiRes spectrum, parameterized by a broken power law function
Generated Angular Distribution

- **Zenith Angle**
  - $\sin(\theta) \cos(\theta)$
  - Distribution: $\theta_{GEN}$ [Degree]

- **Azimuthal Angle**
  - Flat distribution
  - Distribution: $\phi_{GEN}$ [Degree]
Generated Impact Position

- Random point inside a circle
  - radius = 25 km
  - centered at the Central Laser Facility (CLF)
  - Encircles entire experiment
TA SD Monte-Carlo Procedures

• Simulate Extensive Air Showers
  – Use CORSIKA:
    • QGSJET-II high energy hadronic model
    • EGS4 electromagnetic model
    • FLUKA low energy hadronic model
  – Include atmospheric muon flux
  – Simulate detector response to secondary particles by GEANT4
    • Including $\gamma$, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, p, n
  – Use real-time detector calibration and life-time
  – Simulate the trigger and electronics
  – Write events in the same format as data, reconstruct with the same programs, apply same quality cuts

• Validate the Monte-Carlo by comparing the distributions of reconstructed variables with data
DATA / MC Comparisons

Points with error bars = DATA histograms
Solid line = MC histograms normalized to the data histograms by area

1 to 2 % agreement between the DATA and MC in most variables
Next Step: Aperture

- Calculated from the MC
- Including:
  - Effects of quality cuts
  - Effects of energy resolution

\[ \alpha_i = A_{\text{GEN}} \Omega_{\text{GEN}} \left( \frac{N_{\text{REC}}^{\text{MC}}}{N_{\text{GEN}}^{\text{MC}}} \right)_i \]

- MC generation aperture, 4626 km² sr
- Number of MC events reconstructing in the \( i \)th energy bin
- Number of MC events generated in the \( i \)th energy bin

(Efficiency plateaus at \( E \sim 10^{19} \) eV)
Measured UHECR Flux

- 2008/05/11 – 2011/04/25 (T ~ 3 yr)
- Systematic uncertainties
  - 21% on energy scale (controlled by the FD) → ~35% on J
  - 2% due to the acceptance (14% below $10^{18.2}$ eV)
  - 2% due to the resolution unfolding

\[
J_i = \frac{(N_{\text{DATA}}^\text{REC})_i}{(N_{\text{MC}}^\text{REC})_i} \frac{\Delta E_i}{A_{\text{GEN}} \Omega_{\text{GEN}} T}
\]
Comparison with HiRes

- Different detection techniques, excellent agreement
- Both experiments clearly see the ankle feature near $10^{18.7}$ eV
- TA SD confirms the existence of the break at $10^{19.7}$ eV
Comparison with AGASA

- Clear disagreement
- (RIGHT) Accounting for AGASA – TA energy scale difference
  - Doesn’t explain discrepancy above $10^{19.7}$ eV
TA SD Flux Fit

• Differential flux is described by the **Broken Power Law** formula (*BPL*):

\[ J(E) = K \times \begin{cases} 
E^k, & E < E_{\text{ANK}} \\
E_{\text{ANK}}^{k-l} E^l, & E_{\text{ANK}} \leq E < E_{\text{GZK}} \\
E_{\text{ANK}}^{k-l} E_{\text{GZK}}^{l-m} E^m, & E \geq E_{\text{GZK}}
\end{cases} \]

• 6 Fit parameters:
  – \( K \) = normalization factor
  – \( k, l, m \) (negative) spectral indices
  – \( E_{\text{ANK}} \) – 1\(^{\text{st}}\) break point
  – \( E_{\text{GZK}} \) – 2\(^{\text{nd}}\) break point
TA SD Flux Fit (Contd.)

\[
E^3 J / 10^{24} \text{ m}^2 \text{s}^{-1} \text{sr}^{-1} \text{eV}^2
\]

\[
\log_{10}(E/\text{eV})
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K)</td>
<td>(2.25 \pm 0.06 \times 10^{-30} \text{ eV}^{-1} \text{m}^{-2} \text{s}^{-1} \text{sr}^{-1})</td>
</tr>
<tr>
<td>(E_{\text{ANK}})</td>
<td>(10^{18.70 \pm 0.03} \text{ eV})</td>
</tr>
<tr>
<td>(E_{\text{GZK}})</td>
<td>(10^{19.68 \pm 0.09} \text{ cV})</td>
</tr>
<tr>
<td>(k)</td>
<td>(-3.27 \pm 0.03)</td>
</tr>
<tr>
<td>(l)</td>
<td>(-2.68 \pm 0.04)</td>
</tr>
<tr>
<td>(m)</td>
<td>(-4.2 \pm 0.7)</td>
</tr>
</tbody>
</table>
Measured GZK cutoff

- Quantify position of the break by $E_{1/2}$ (Berezinsky et. al)
  - Integral flux becomes $\frac{1}{2}$ of the flux obtained by linear extrapolation beyond the GZK break
- TA SD measures
  - $\log_{10}(E_{1/2}) = 19.69 \pm 0.10$
- Berezinsky calculates for proton primaries propagating in cosmic microwave background
  - $\log_{10}(E_{1/2}^{\text{THEORY}}) = 19.72$
- TA SD measurement fits the extra-galactic proton model
Significance of the GZK cutoff

• Assume no GZK cutoff and extend the broken power law fit beyond the break
• Apply this extended flux formula to the actual TA SD exposure, find the number of expected events and compare it to the number of events observed in $\log_{10} E$ bins after $10^{19.7} \text{eV}$ bin:
  - $N_{\text{EXPECT}} = 54.9$
  - $N_{\text{OBSERVE}} = 28$

$$\text{PROB} = \sum_{i=0}^{28} \text{Poisson}(\mu = 54.9; i) \approx 4.75 \times 10^{-5}$$

$(3.9\sigma)$
Recent - UHECR 2012

- Fits to extragalactic proton model made by V. Berezinsky
  - UHECR-2012 Conference, Feb. 2012, CERN
- Both TA and HiRes consistent with model of extragalactic proton propagation in Cosmic Microwave Background
Conclusions

• Telescope Array combined measurement techniques used by the AGASA and HiRes experiments
  – Fit formulas derived starting with AGASA functions, tuned to fit the TA SD data
  – DATA / MC analysis used, just like in HiRes experiment (excellent control of systematic uncertainties)
  – Energy scale locked to the FD to avoid large systematic uncertainties due to the hadronic models
• Existence of the GZK cutoff is verified, for the first time, by an array of scintillation counters
• Measurement suggests extra-galactic proton interpretation (Berezinsky et. al.)
Fin
Comparison with Pierre Auger Observatory

- ~20% energy scale difference
  - Comes from the FD
- Same power laws (within fitting errors)
- Position of the second break ($E_{\text{GZK}}$) different
- Most recent Auger result (ICRC-2011)
  - Auger ~27% lower
  - After taking energy scale into account
Compare with other CR experiments

(T.K Gaisser, T. Stanev, 2009)