Observation of ultra-high energy cosmic rays with the Telescope Array experiment

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Ultra-high energy cosmic ray (UHECR)

• Cosmic ray: charged particles from outside of the Earth
• Spectrum is power-law shape.
  - Suggests the generation with particle acceleration on astrophysical objects
• Acceleration and propagation information of cosmic rays is obtained from the spectrum.
• Due to low flux,

Origin of UHECRs is unrevealed.
Possible sources of UHECR

- The source candidates are gamma ray burst, active galactic nuclei etc.
- Observation of spectrum and arrival direction anisotropy is necessary.
- Since cosmic rays are deflected by galactic and extragalactic magnetic fields, observation of mass composition is also needed.

At objects above the lines, particles can be accelerated up to $10^{20} \text{ eV}$
Method of UHECR observation

- UHECR is observed by using cascade reaction of primary cosmic rays with atmospheric particles, which is called air shower.
- Using air shower MC, spectrum and arrival direction of primary cosmic rays are reconstructed.

**Surface detector (SD)**
samples charged particles on the ground.

**Fluorescence detector (FD)**
measures fluorescence light generated by air shower propagation in the sky.

**MC air shower propagation**

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Atmospheric depth (g/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1000</td>
</tr>
<tr>
<td>2</td>
<td>2000</td>
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<td>3</td>
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<tr>
<td>8</td>
<td>8000</td>
</tr>
<tr>
<td>9</td>
<td>9000</td>
</tr>
<tr>
<td>10</td>
<td>10000</td>
</tr>
</tbody>
</table>

**Altitude (km)**

- 1000 km
- 2000 km
- 3000 km
- 4000 km
- 5000 km
- 6000 km
- 7000 km
- 8000 km
- 9000 km
- 10000 km

**Number of particles**

- e⁺ (× 100)
- e⁻ (× 100)
- μ⁺ (× 5)
- μ⁻ (× 100)

**EM are dominated**

R. Engel et al., ARNPS (2011)
Uncertainty of UHECR observation

- UHECR energy range is beyond accelerator experiments.
- Hadronic interaction models of MC use extrapolated values for cross section from lower energy data.

Muon excess issue:
- Number of muons $N_\mu$ measured by the Auger experiment shows $N_\mu^{\text{data}} \sim 1.8N_\mu^{\text{MC}}$
- Present hadronic models does not fully reproduce UHE air showers.
Telescope Array Collaboration

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Telescope Array Observatory

- An array of 507 scintillator SDs
- 3 FD stations overlooking the array
- Operational as of 2008

Largest cosmic ray observatory in the Northern hemisphere.

\[ \sim 700 \text{ km}^2 \]

\[ \Rightarrow \lesssim \frac{1}{10} \text{ of Crete} \]
Event from 2008-10-26

<table>
<thead>
<tr>
<th>MD mono</th>
<th>BR mono</th>
<th>Stereo BR&amp;LR</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.43</td>
<td>51.50</td>
<td>50.21</td>
</tr>
<tr>
<td>73.76</td>
<td>77.09</td>
<td>71.30</td>
</tr>
<tr>
<td>7.83</td>
<td>7.67</td>
<td>8.55</td>
</tr>
<tr>
<td>-3.10</td>
<td>-4.14</td>
<td>-4.88</td>
</tr>
</tbody>
</table>

Table: Parameters for different event configurations:

- **MD FD**: MD mono event configuration.
- **LR FD**: LR mono event configuration.
- **SD**: Stereo event configuration for BR&LR.
- **BR FD**: BR mono event configuration.

Example Event

Air shower propagation in the sky.
Air shower reconstruction

- Calculate primary cosmic ray energy and geometry from particle signal size and arrival time distributions

[SD hit map for 1 event]

- SD hit signal
- Lateral distribution fit
- Convert S800 to Energy using MC

- SD energy is scaled to FD energy (calorimetric) $E_{SD}/1.27 = E_{FD}$

- $E > 10^{19} \text{ eV}$
- Angular resolution = $1.4^\circ$
- Energy resolution < 20%
TA SD Spectrum (9 yrs data)

![Graph showing fit to broken power law]

- Cutoff at highest energy corresponds to GZK cutoff (flux reduction by the reaction between cosmic ray and CMB photons).
Anisotropy results

Total events: 143
Observed: 34
Expected: 13.5

Events over-sampled using 25° circles
Excess center: RA=144.3°, Dec=+40.3°
Li Ma significance: 5.06 σ
2.96 σ chance probability
Mass composition analysis

- Estimate primary cosmic ray mass composition from the depth of the air shower maximum ($X_{\text{max}}$)

**Lighter composition propagates deeper at same energy**

**Proton**

**Iron**

**Longitudinal distribution for MC**
- Proton
- Iron
Composition results

- TA uses different analysis techniques using 3 FDs and hybrid analysis with SD.

MD hybrid

BR/LR hybrid

- Mass composition from TA observation corresponds to light component.
Study of muons from air showers

• Muon excess issue
  → Present hadronic models do not fully reproduce air showers.

• Hadronic interaction models can be tested by comparing the measured number of muons with the MC prediction.

• We analyzed lateral distribution of muons and studied air shower structure using TA SD data.
Study of muons from air showers

- Assume primary particle is proton
- \(80 – 90\%\) of TA SD signal derives from EM components.

Analysis approach:

- Search for the analysis condition where the muon purity in the SD signal becomes high using the MC
- Compare data with MC on the high muon purity condition

Analysis condition
- Energy: \(10^{18.8} \text{ eV} < E < 10^{19.2} \text{ eV}\)
- Experimental data: 7 year dataset (2008/5/11 ~ 2015/5/11), \(~3600\) events
- MC: Firstly check QGSJETII-03 proton, then other hadronic models
  \(~60000\) events
Muon analysis procedure

- EM components generated on the shower axis are attenuated faster than muons in the atmosphere.

- By using the SD in the shower forwarding direction, 60 – 70% of the signal becomes muons.

Analysis range
θ: [0°, 45°]
Φ: [-180°, 180°]
R: [500m, 4500m]

Muon ratio is expected to be larger as θ, |Φ|, R values are larger.

μ ratio in the SD signal

- SD signal (MC)

- Total Muon γ e hadron B.G.

- 60 ~ 70% at 2000~4000m
Muon analysis results (7 yrs data)

- Lateral distribution on condition $\mu$ purity 60~70% and data/MC ratio
- Data is larger than MC by more than 1.5 times, with $R$ dependence.
  
  $1.72 \pm 0.10$ (stat.) $\pm 0.40$ (syst.) $(1910 \text{ m} < R < 2160 \text{ m}) \quad (1.8\sigma)$
  
  $3.14 \pm 0.36$ (stat.) $\pm 0.72$ (syst.) $(2760 \text{ m} < R < 3120 \text{ m}) \quad (2.7\sigma)$

- Muon excess in the data is suggested. MC models need to be revised.

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### Lateral distribution

<table>
<thead>
<tr>
<th>Condition</th>
<th>Data/MC Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$30^\circ &lt; \theta &lt; 45^\circ$</td>
<td>$1.72 \pm 0.10$ (stat.) $\pm 0.40$ (syst.)</td>
</tr>
<tr>
<td>$150^\circ &lt;</td>
<td>\theta</td>
</tr>
</tbody>
</table>

### Data / MC signal ratio

- Data 7y
- MC QGSJETII-03
Summary of Results

- **Spectrum**
  - Flux suppression at the highest energy

- **Arrival direction**
  - Observation of hotspot in the northern hemisphere

- **Mass composition**
  - Compatible with a light component

- **Hadronic interaction**
  - Muon excess in the data $\rightarrow$ Information about more reliable models is obtained
Get ~20 years of TA SD data by 2020

Clarify the details of hotspot at > 57 EeV

TA SD (~3000 km²): Quadruple area

500 additional scintillator SDs

173 SDs have arrived in Utah for assembly, 77 SD is prepared in Japan.

2 FD stations (12 Telescopes)

telescopes/electronics being prepared at Univ. Utah

Site construction underway at the northern station.
TA Low Energy Extension (TALE)
Observe Galactic to Extra-Galactic Transition

- 10 FD telescopes to look higher in the sky (31-59°) to see shower development
- More dense SDs (lower energy threshold)

TALE-SD array (103 SDs, 70km²)

TALE FD

TALE Energy spectrum (Monocular)

break point: 17.04 +/- 0.052
slope before: 2.86 +/- 0.012
slope after: 3.19 +/- 0.018

TALE-FD + TA-FD(MD)

TA-SD array (507 SDs, 700km²)

TA-FD(LR)

TA-FD(BRM)

400 m spacing
40 SDs

600 m spacing
36 SDs

1.2 km spacing
27 SDs

WLAN Tower
TA SD

- Two layers of flat scintillators
- It records energy deposit when charged particles penetrate the scintillator (~2 MeV for vertical injection)
- It obtains charged particles from air showers

- From time and number density distribution of air shower particles, primary particle energy and arrival direction are reconstructed.

Signal is mainly from muons
TA Fluorescence Detectors

Middle Drum
- 14 telescopes @ station
- 256 PMTs/camera

Reutilized from HiRes-I

Long Ridge

Black Rock Mesa
- 12 telescopes/station
- 256 PMTs/camera

New Telescopes
- 6.8 m²
- ~1 m²
Telescope Array & Pierre Auger Spectra

\[ E^3 J(E) / (\text{eV}^2 \text{km}^2 \text{sr}^{-1} \text{yr}^{-1}) \]

- TA SD ICRC 2017
- Auger SD Full Sky (ICRC 2015) +16%

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

- SD data full 9 years
- Zenith angle up to 55°, loose border cut
- Geometrical acceptance; exposure 8600 km² yr sr
- Angular resolution: better than 1.5°
- Energy resolution: 20%

\[ E > 10 \text{ EeV}, \theta < 55° \]

\[ \Delta \Psi \text{ [Degree]} \]

\[ \ln \left[ \frac{E_{\text{REC}}}{E_{\text{GEN}}} \right] \]

Entries: 323733
Mean: -0.01032
RMS: 0.1888
Prob: 0
Constant: 2.834e+04
Mean: -0.005933
Sigma: 0.1797
Nearby Galaxy Clusters

- Virgo Cluster (D=20Mpc)
- Ursa Major Cluster (D=20Mpc)
- Perseus-Pisces Supercluster (D=70Mpc)
- Eridanus Cluster (D=30Mpc)
- Fornax Cluster
- Centaurus Supercluster (D=60Mpc)

Dots: 2MASS catalog Heliocentric velocity <3000 km/s (D<~45Mpc)


TA hotspot is found near the Ursa Major Cluster. TA & PAO see no excess in the direction of Virgo.
TA composition compared to QGSJet-II.3

The graph compares the TA composition to QGSJet-II.3 in terms of the ratio of (data - iron)/(proton - iron) as a function of log(E(eV)).

Key points:
- Different models are represented by different markers:
  - MD Hybrid: Black circles
  - BR/LR Hybrid: Red circles
  - BR/LR/MD Stereo: Blue circles
- The log(E(eV)) axis ranges from 18 to 20.
- The lnA axis ranges from 0.0 to 4.0, with markers for p, He, N, and Fe.
Results

- Lateral distribution with various hadronic models
- Data is larger than MC for all considered models.

\[
E : 10^{18.8} \sim 19.2 \text{ eV} \\
30^\circ < \theta < 45^\circ \\
150^\circ < |\Phi| < 180^\circ \\
\]

(\text{Data 7y, QGSJETII-03, QGSJETII-04, epos1.99, sibyll2.1})
Results

- Data-MC comparison assuming iron composition

<table>
<thead>
<tr>
<th>R (m)</th>
<th>Data/MC proton</th>
<th>Data/MC iron</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1910, 2160]</td>
<td>1.72 ± 0.10(stat.) ± 0.40(syst.)</td>
<td>1.26 ± 0.07(stat.) ± 0.29(syst.)</td>
</tr>
<tr>
<td>[2760, 3120]</td>
<td>3.14 ± 0.36(stat.) ± 0.72(syst.)</td>
<td>1.74 ± 0.19(stat.) ± 0.40(syst.)</td>
</tr>
</tbody>
</table>
Correlation plots between muon purity and $N_{\text{data}} / N_{\text{MC}}$ in different ($\theta$, $\Phi$) conditions

- For $30^\circ < \theta < 45^\circ$, $150^\circ < |\Phi| < 180^\circ$, muon purity = $\sim 65\%$ and $\text{Data/MC} = 1.88 \pm 0.08(\text{stat.}) \pm 0.40(\text{syst.})$

- For $\theta < 30^\circ$, $|\Phi| < 30^\circ$, muon purity = $\sim 28\%$ and $\text{Data/MC} = 1.30 \pm 0.06(\text{stat.}) \pm 0.27(\text{syst.})$

Larger number of particles of data than that of MC with larger muon purity. Part of the discrepancy between data and MC is due to muon excess.
Discussion

• Lateral distribution of MC does not reproduce data on muon-enriched condition, and the discrepancy is partially due to muon excess.

• Lateral distribution of data is broader than MC, which possibly indicates air shower development of the data is faster than MC.

• This feature suggests
  - larger hadron interaction cross section
  - larger pion multiplicity
TA Measurement of $\sigma_{p\text{-}air}$ (inelast.)

Inelastic cross section between proton and air calculated from UHECR $X_{\text{max}}$ distribution

Hadronic interaction at $E > 10^{18}$ eV is being revealed by air shower experiments.

$\sigma_{p\text{-}air}$ (inelast.) = 567.0±70.5[Stat.] (+25,-29)[Sys.] mb

$\Lambda$: attenuation length $\Lambda \propto (\sigma_{p\text{-}air})^{-1}$

$\exp(X_{\text{max}}/\Lambda)$