Energy Spectrum Measured by the Telescope Array Experiment in $10^{15.6}$ eV to $10^{20.3}$ eV Range

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Image Credit: Brett Abernethy
Abstract


The Telescope Array (TA) experiment is the largest fluorescence detector array, allowing the measurement of an energy spectrum covering three orders of magnitude in energy. After seven years of steady operation, one advantage of monocular analysis of the fluorescence detectors is a lower energy threshold for detection.

1. Introduction

The energy spectrum of cosmic rays has been measured by the Telescope Array (TA) experiment. The TA experiment is the largest fluorescence detector array and has measured the energy spectrum covering three orders of magnitude in energy. After seven years of steady operation, one advantage of monocular analysis of the fluorescence detectors is a lower energy threshold for detection.

Japan, USA, Korea, Russia, Belgium
Telescope Array Experiment (TA)

- Largest cosmic ray detector in the Northern hemisphere
  ~ 700 km² at Utah, USA
- Fluorescence detector + Surface detector array

**Surface Detector Array**
507 Scintillator, 1.2 km spacing

**Fluorescence Detector at BRM and LR stations**
Spherical segment mirror (6.8 m²) + 256 Photomultiplier tube (PMTs)/camera, 12 newly designed telescopes

**Fluorescence detector at MD station**
Refurbished from HiRes experiment, Spherical mirror 5.2 m², 256 PMTs/camera, 14 telescopes
Telescope Array Experiment (TA)

Surface detector array (SD)  Fluorescence detector (FD)
7 Years Steadily Operation

Surface detector array (SD)   Fluorescence detector (FD)

~100% duty operation          Clear moonless night
                               ~10% duty operation

Mar’08  Feb’11  Jun’15

Observation Time [hr]

61904.0 hrs  97.7 %

62032.9 hrs  96.0 %

60390.1 hrs  95.2 %

Mar’08  Jun’15  Nov’07  Jun’15

Observation Time [hr]

7784.0 hrs  11.6 %

5587.0 hrs  9.8 %
... to Observe Extensive Air Shower (EAS) induced by Ultra-High Energy Cosmic Ray (UHECR)

Image credit: ASPERA_Novapix_L.Bret
Observed UHECR Event

Surface detector array (SD)

- Observe lateral density distribution
- Charge density at 800 m, $S_{800}$ as energy indicator

Fluorescence detector (FD)

- Observe longitudinal development
- Reconstruct calorimetric energy

Figure 1: UHECR event observed by the fluorescence detector. The top figure shows the PMT pointing directions and the brightness of signal (point size) and timing (point color). The bottom figure shows a sum of selected PMT waveforms as a function of slant depth (black plot), compared with the reconstructed result by the inverse Monte Carlo reconstruction (histograms). The inverse Monte Carlo method can reproduce the obtained signal at the camera.
Energy Estimation by TA SD

A look-up table made from Monte Carlo simulation

Event energy $E_{\text{TBL}}$ = function of $S_{800}$ and zenith angle, $\sec(\theta)$

$E_{\text{TBL}}$ is rescaled by the FD reconstructed energy to estimate final energy of SD, $E_{\text{SD,final}}$

$E_{\text{SD,final}} = E_{\text{TBL}}/1.27,$

<20% resolution above $10^{19}$ eV
Aperture, Exposure Calculation

Detailed Monte Carlo used for aperture calculation in all measurement of TA. Exposure = Aperture × live-time.

FD aperture needs to assume mass composition.

Use the proton fraction measured by the HiRes/MIA experiment with 20% uncertainty [Astrophys. J. 622 (2005) 910].
Energy Spectrum from TA FD and SD

Ankle at $\log E = 18.72 \pm 0.02$, 
Suppression at $\log E = 19.78 \pm 0.05$

<table>
<thead>
<tr>
<th>Item</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescence</td>
<td>11%</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>11%</td>
</tr>
<tr>
<td>Calibration</td>
<td>10%</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>9%</td>
</tr>
<tr>
<td>Total</td>
<td>21%</td>
</tr>
</tbody>
</table>
Uncertainty attributed to Proton Fraction Assumption

- Change the proton fraction by the uncertainty of HiRes/MIA of ±20%, and recalculate aperture of FD.
- Calculated the energy spectrum with those aperture.
Comparison with Other Measurements

Consistent with the HiRes result in a broad energy range

Consistent with TA MD result

8.5% difference with Auger result around ankle, however consistent within systematics uncertainty.
Discrepancy on the Suppression

Even if we correct the energy difference, the suppression shows large discrepancy above $10^{19.5}$ eV.

Possible reasons of discrepancy: fluorescence yield, atmospheric model, missing energy correction, detector: scintillator or water-tank, Northern/Southern hemisphere.

TA×4: fourfold statistics at the suppression

Water-tank Scintillator on Water-
installed at TA site Tank (AugerPrime)

Further Lower Energy = TALE (Telescope Array Low-energy Extension)

Enlarge field of view of FD in elevation to observe lower energy showers down to $10^{15.6}$ eV.

- $> 10^{17.4}$ eV Fluorescence dominated
- $< 10^{17.4}$ eV Cherenkov dominated
Resolution and Exposure as a Function of Energy
Energy Spectrum in $10^{15.6}$ eV to $10^{20.3}$ eV
TALE + TA FD + TA SD

$E^3 \times J$ [eV$^2$ × m$^{-2}$ × sr$^{-1}$ × s$^{-1}$]

- TA SD 7 year (ICRC 2015)
- BR-LR Mono 7 year (ICRC 2015)
- TALE Bridge (ICRC 2015)
- TALE Čerenkov (ICRC 2015)

Preliminary
Combined Spectrum and Fitted Result

\[ \log(E(\text{eV})) = 16.34 \pm 0.04 \]
\[ \log(E(\text{eV})) = 17.30 \pm 0.04 \]
\[ \log(E(\text{eV})) = 18.72 \pm 0.02 \]
\[ \log(E(\text{eV})) = 19.80 \pm 0.05 \]
Comparison with other Measurements
Summary and Future Plans

TA measured the energy spectrum over 4.7 orders of magnitude in $10^{15.6}$ eV to $10^{20.5}$ eV range.

4 features seen: low energy ankle at $10^{16.34}$ eV, 2nd knee at $10^{17.30}$ eV, ankle at $10^{18.72}$ eV, suppression at $10^{19.80}$ eV.

Large discrepancy with Pierre Auger above $10^{19.3}$ eV, which cannot be resolved by rescaling energies of the experiments.

TAx4 will provide us fourfold statistics at the suppression.

Activities to understand the suppression discrepancy.