PROCEEDINGS OF SCIENCE

Energy Spectrum Measured by the Telescope Array Surface Detectors

Jihyun Kim,[a,*] Dmitri Ivanov[a] and Gordon Thomson[a] on behalf of the Telescope Array Collaboration

[a] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah Salt Lake City, Utah 84112-0830, USA*

E-mail: jihyun@cosmic.utah.edu

The Telescope Array (TA) experiment is a hybrid observatory designed to study ultra-high energy cosmic rays (UHECRs). As the largest UHECR observatory in the Northern Hemisphere, the TA experiment covers a 700 km^2 area on the ground in Millard County, Utah, USA. The TA surface detector (SD) consists of 507 plastic scintillation counters arranged on a square grid with 1.2 km spacing. Furthermore, the skies over the array are viewed by three fluorescence detector (FD) stations positioned around its periphery, which observe the development of cosmic ray showers in the atmosphere. Over the past 16 years, the TA experiment has maintained stable operation, ensuring data collection with high efficiency. This stability and high statistical precision have allowed us to observe three distinct spectral breaks in the TA SD energy spectrum: ankle, shoulder, and cutoff. In this presentation, we will report the latest TA SD energy spectrum and update our findings on the anisotropy of the energy spectrum.

7th International Symposium on Ultra High Energy Cosmic Rays (UHECR2024)
17-21 November 2024
Malargüe, Mendoza, Argentina

*Speaker

PoS(UHECR2024)037

1. Introduction

Ultra-high energy cosmic rays (UHECRs) are extremely energetic particles, with energies exceeding 10^{18} eV, that travel through space and reach Earth. These particles provide a unique and powerful probe into the universe, offering insights into high-energy astrophysical processes. The study of UHECRs traditionally focuses on three main observables: their mass composition, arrival directions, and energy spectrum. It is essential to analyze these observables to gain a deeper understanding of the nature and origins of UHECRs, as well as the mechanisms driving their propagation through the universe.

Studying the energy spectrum is important as its spectral features provide valuable information about the sources of UHECRs and their propagation. One notable feature is the high-energy cutoff at $\sim 10^{19.8}$ eV, first predicted by Greisen, Zatsepin, and Kuzmin [1, 2], known as the GZK cutoff. This suppression arises from interactions between cosmic ray protons and cosmic microwave background photons, leading to photo-pion production, which effectively limits the distance high-energy protons can travel. The High Resolution Fly's Eye (HiRes) was the first to observe this cutoff [3], and the result was subsequently confirmed by the Telescope Array (TA) experiment [4]. In the southern hemisphere, the Pierre Auger Observatory (Auger) [5] also detected a similar flux suppression at slightly lower energies.

In this work, we investigate the spectral features of UHECRs by analyzing the most recent data from the Telescope Array surface detector array. Our goal is to gain a deeper understanding of the UHECR energy spectrum and provide further insight into the underlying processes that shape it.

2. Telescope Array

The Telescope Array (TA), situated in the western Utah desert, USA, at coordinates 39.3°N, 112.9°W, is the largest UHECR observatory in the northern hemisphere. It is designed to observe an extensive air shower, a cascade of millions of subatomic particles initiated when a single UHECR collides with a nucleus in the Earth's atmosphere. At an elevation of 1400 meters above sea level, it is strategically positioned to capture extensive air showers at their maximum development. TA operates as a hybrid detector, combining surface array and air-fluorescence detection techniques. The surface detector (SD) array comprises 507 scintillation counters, arranged in a grid with 1.2 km spacing, spanning an area of approximately 700 km^2. Each SD unit contains two layers of plastic scintillators to record particle footprints as the air shower reaches the ground [6]. In addition, three fluorescence detector (FD) stations, equipped with 38 telescopes, monitor the sky above the SD array, covering an elevation range of 3°–31°. These telescopes capture ultraviolet emissions produced as extensive air showers propagate through the atmosphere [7].

3. Telescope Array Surface Detector Event Reconstruction

The reconstruction of extensive air showers recorded by surface detectors follows these steps. First, the core position is identified, and the arrival direction of the primary particle is determined using the positions and timing information from the SD counters when they are hit by secondary particles. This process employs a modified Linsley shower-shape function fit [8]. Next, the

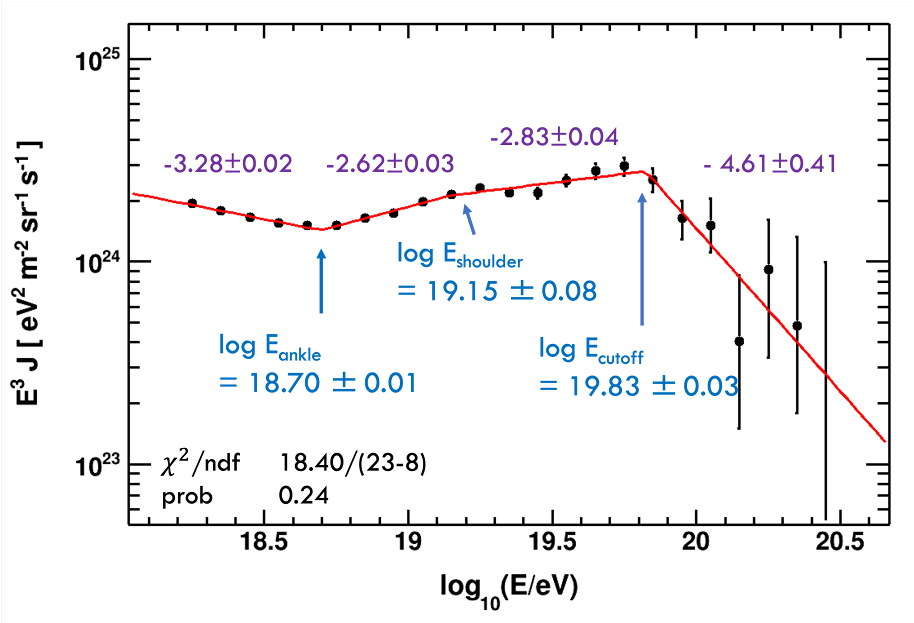

Figure 1: Energy spectrum using 16-year SD data. The data points are represented by black points with error bars, while a fit to the broken power law is shown with the red solid line. The fit is performed using a thrice-broken power law, which includes three breakpoints (E_{ankle}, E_{shoulder}, and E_{cutoff}) and four spectral indices (p_1, p_2, p_3, and p_4). The fit results are overlaid on the plot.

lateral distribution of shower particles is fitted using the same functional form as the AGASA experiment [9, 10]. From this fit, we extract the particle density at a reference distance of 800 meters from the shower axis, $S(800)$. This distance is optimized based on the altitude of the TA site and detector separation while minimizing systematic uncertainties associated with different cosmic-ray primaries.

To estimate the energy of the primary particle, we use a high-statistics SD Monte Carlo simulation with the CORSIKA software package [11], incorporating the QGSJET-II-03 hadronic interaction model [12] under the assumption of proton primaries. The initial energy estimate, E_{TBL}, is determined from $S(800)$ and the reconstructed $\sec(\theta)$, where θ is the event's zenith angle. To minimize potential biases from hadronic interaction models in simulations, we calibrate this initial energy estimate against calorimetric energy measurements from the FD. Using hybrid events observed by both the SD and FD, we derive a scaling factor of 1.27 for the SD vs. FD energies. Applying this scaling factor, the final energy estimate is obtained as $E_{\text{Final}} = E_{\text{TBL}}/1.27$.

As a check on this Monte Carlo-based method of energy reconstruction, we also applied the constant intensity cut (CIC) reconstruction method [13]. The comparison confirmed that the energy spectra obtained using the CIC method are consistent within 2% uncertainties [14].

4. Spectral Features Measured by Telescope Array Surface Detectors

In this section, we show the features in the energy spectrum measured by SD array over 16 years from May 11, 2008, to May 10, 2024. The event selection criteria employed for this analysis are as follows: (1) each event must include at least five SD counters, (2) the reconstructed primary zenith angle must be less than 45°, (3) the reconstructed event core must be more than 1200 meters from the edge of the array, (4) both the geometry and lateral distribution fits must have χ^2/degree of freedom value less than 4, (5) the angular uncertainty estimated by the geometry fit must be less than 5°, and (6) the fractional uncertainty in $S(800)$ estimated by the lateral distribution fit must be less than 25%. The total number of events that satisfy these selection criteria and have energies greater than $10^{18.2}$ eV is 40,583.

Figure 1 shows the energy spectrum and its fit to the broken power law. The data points are represented by black points with error bars, while a fit to the broken power law is shown with the red solid line. The fit is performed using a thrice-broken power law, which includes three breakpoints (E_{ankle}, E_{shoulder}, and E_{cutoff}) and four spectral indices (p_1, p_2, p_3, and p_4). The first break point, the ankle feature, is found at $E_{\text{ankle}} = 10^{18.70\pm0.01}$ eV with spectral indices of $p1 = -3.28 \pm 0.02$ and $p2 = -2.62 \pm 0.03$ before and after the ankle, respectively. The second break point, the softening feature, referred to as the shoulder, is obtained at $E_{\text{shoulder}} = 10^{19.15\pm0.08}$ with the spectral index of $p3 = -2.83 \pm 0.04$ after the shoulder. The third break point, the cutoff feature, occurs at $E_{\text{cutoff}} = 10^{19.83\pm0.03}$ eV with the spectral index of $p3 = -4.61 \pm 0.41$ after the cutoff. The fit results are overlaid on the plot.

We estimate the statistical significance of the observed cutoff at $10^{19.83}$ eV. If no cutoff feature were present, the expected number of events above this energy would be 173.7, whereas the observed number is significantly lower at 97. This discrepancy corresponds to a chance probability of 1.6×10^{-10}, equivalent to a statistical significance of 6.3σ.

Similarly, we evaluate the statistical significance of the observed shoulder feature at $10^{19.15}$ eV. In the absence of this feature, the expected number of events between the shoulder and the cutoff, from $10^{19.15}$ eV to $10^{19.83}$ eV, would be 2156.4, while the observed number is 1921. This difference corresponds to a chance probability of 1.3×10^{-7}, equivalent to a statistical significance of 5.2σ. This observation closely aligns with findings from Auger, which detected a softening feature—referred to as the instep—at $10^{19.11\pm0.03}$ eV [15]. After applying a +9% overall energy rescaling [16, 17], this feature shifts to approximately $10^{19.15}$ eV. The agreement between TA and Auger confirms the consistency of this softening feature in both the northern and southern hemispheres.

5. Declination Dependence in the Cosmic Ray Spectrum

In 2017, while investigating differences in energy spectra measured by TA and Auger, it was first identified a declination dependence in the energy spectrum in TA data between the lower and higher declination bands, divided at $\delta = 24.8°$ [18]. Recently, we revisited the declination dependence with a new methodology [19] compared to previous studies.

We compare the energy spectrum measurements from TA and Auger to assess their level of agreement or disagreement under the null hypothesis that both spectra originate from the same parent distribution. To achieve this, we perform a simultaneous fit to both TA and Auger spectrum measurements into a thrice-broken power law with three breakpoints, using the binned log-likelihood method described in Eq. 40.16 in Particle Data Group [20].

The TA's event selection criteria for this study are identical to those used in the common declination investigations conducted by the TA and Auger Joint Spectrum Working Group: (1) each event must involve at least five SD counters, (2) the reconstructed primary zenith angle must be

PoS(UHECR2024)037

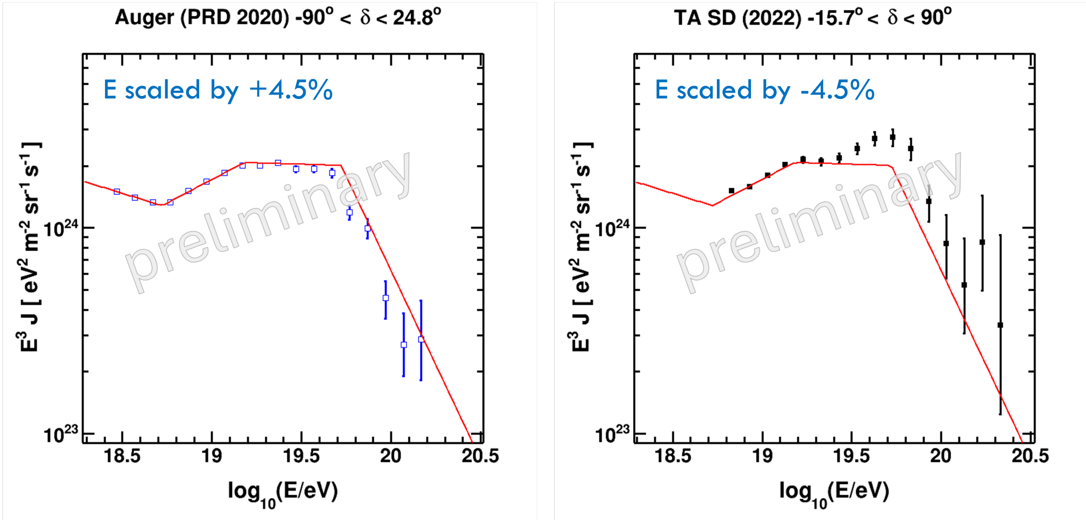

Figure 2: Energy spectra measured by Auger and TA in their full apertures. Auger spectrum data points after +4.5% energy rescaling on the left panel and the black squares on the right panel represent the TA spectrum data points after −4.5% energy rescaling on the right panel. The red lines indicate the same broken power law function from the simultaneous fit to these two spectra.

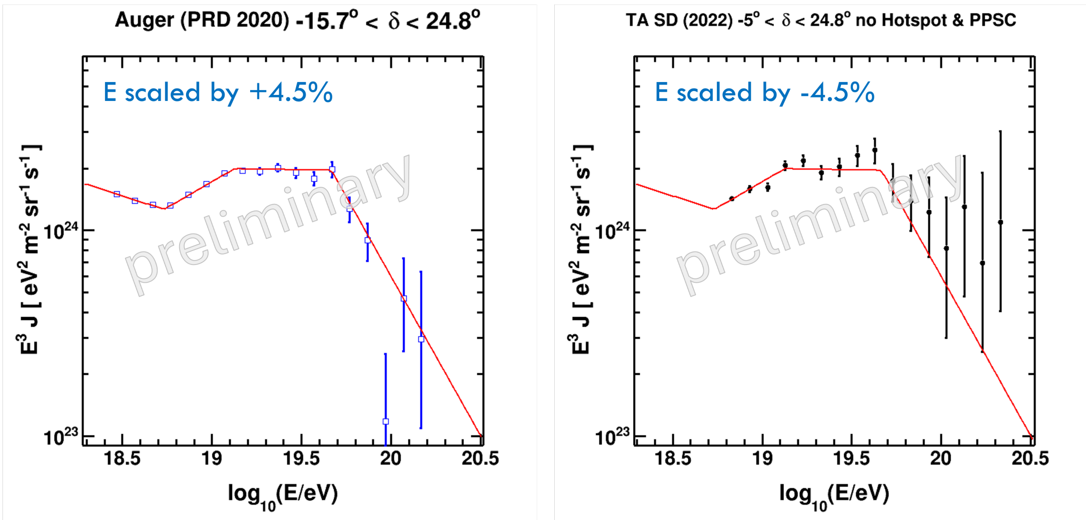

Figure 3: Energy spectra in the common sky with *a priori* cuts applied to TA data. The markers and lines used in this figure follow the same conventions as those in Figure 2.

less than 55°, (3) both the geometry and lateral distribution fits must have a χ^2/degree of freedom less than 4, (4) the angular uncertainty estimated by the geometry fit must be less than 5°, (5) the fractional uncertainty in $S(800)$ estimated by the lateral distribution fit must be less than 25%, and (6) the counter with the largest signal must be surrounded by four working counters—one to the north, east, south, and west on the grid, although these counters do not need to be immediate neighbors of the largest signal counter.

The key difference from the selection criteria introduced in Section 4 is that the zenith angle cut is extended to 55°, allowing us to maximize the overlap in the observable sky down to a declination of $-15.7°$. However, to ensure good energy and angular resolution, a minimum energy cut is applied at $10^{18.8}$ eV. (These selection criteria are also applied to the data sets used in anisotropy studies.) This analysis uses 14 years of TA SD data with $E \geq 10^{18.8}$ eV and Auger data with $E \geq 10^{18.4}$ eV from [15, 17].

Figure 2 shows the simultaneous fit results for both TA and Auger across their full apertures. The blue squares in the left panel represent the Auger spectrum data points after a +4.5% energy rescaling, and the black squares in the right panel indicate the TA spectrum data points after a −4.5% energy rescaling. This overall energy rescaling follows the study conducted by the Joint Spectrum Working Group, which demonstrated that the two spectra agree well in the ankle region [16]. The red lines indicate the same broken power law function obtained from the simultaneous fit, which yields a total log-likelihood sum of 130.33 with 26 degrees of freedom, corresponding to a Poisson probability of 7.5×10^{-16}. We observed a difference in ultra-high energy cosmic ray spectrum between the northern and southern skies with a significance of 8σ.

This finding is validated by examining the common sky observed by both experiments. We apply *a priori* cuts to isolate causes of an apparent discrepancy: the rapidly declining TA exposure at its southernmost edge and the excesses of events extending down into the common sky. The TA's exposure drops rapidly at its southernmost edge, below the declination of $\delta = -5°$. (See Figure 3 in [19].) The two medium-scale anisotropies in the arrival direction distribution—the Hotspot and Perseus-Pisces Supercluster (PPSC) excess [21–23]—extend down into the common sky. They lie close to the northernmost edge of Auger's exposure, where its exposure also drops rapidly. (See Figures 3 and 4 in [19].) For the most direct comparison possible of the spectrum measurements by TA and Auger within this band, we implement *a priori* cuts to the TA data by excluding events from these regions of the sky.

Figure 3 displays the simultaneous fit results for the common sky with the application of *a priori* cuts to the TA data. The fit yields a total log-likelihood sum of 40.12 with 26 degrees of freedom, resulting in a Poisson probability of 3.8×10^{-2}. We observed a difference between these spectrum measurements with a significance of 1.8σ, which shows that there is no statistically significant difference between the spectra. This consistency strengthens confidence in the validity of the simultaneous fit result for two spectra in their full aperture.

6. Summary

Over the past 16 years, the Telescope Array (TA) experiment has demonstrated consistent and reliable operation, facilitating high-precision data collection. Building on this stable performance, we have conducted a thorough validation of our Monte Carlo simulations by directly comparing them with observed data. This careful validation ensures the reliability of our simulation framework for UHECR studies, which supports the reconstruction of cosmic ray events and the calculation of the detector aperture and the exposure.

The robustness of energy reconstruction of the Telescope Array Surface Detector has been demonstrated through three independent methods: (1) a direct comparison between the FD and SD energies, (2) consistency checks using Monte Carlo thrown and reconstructed energies, and (3) a comparison between the energy calculated using the constant intensity cut method and the standard

TA reconstruction energy. The agreement across these methods shows the linearity of the TA SD energy reconstruction process.

We presented key spectral features observed in the 16-year data measured by the TA SD array, including the ankle at $10^{18.70\pm0.01}$ eV, the shoulder at $10^{19.15\pm0.08}$ eV, and the high-energy cutoff at $10^{19.83\pm0.03}$ eV. The statistical significance of the observed shoulder feature at $10^{19.15}$ eV is estimated to be 5.2σ, and that of the observed cutoff at $10^{19.83}$ eV is estimated to be 6.3σ. These features provide essential insights into the origin and propagation of cosmic rays at the highest energies.

We also presented evidence of a significant difference in the cosmic ray energy spectrum between the northern and southern hemispheres. A simultaneous spectral fit analysis was performed, incorporating both the TA and Auger spectra. When considering the full aperture of both experiments, the fit yielded an 8.0σ significance difference. We validated the methodology by examining the common sky seen by both observatories. To enable the most direct comparison of the spectrum measurements by TA and Auger within this band, we implemented *a priori* cuts to the TA data and performed a simultaneous spectral fit. The result, obtained as 1.8σ, indicates that there is no statistically significant difference between the spectra in the common sky. These findings suggest a difference in the cosmic ray energy spectrum between the northern and southern skies.

References

[1] K. Greisen, *End to the cosmic-ray spectrum?*, *Phys. Rev. Lett.* **16** (1966) 748.

[2] G.T. Zatsepin and V.A. Kuz'min, *Upper limit of the spectrum of cosmic rays*, *J. Exp. Theor. Phys. Lett.* **4** (1966) 78.

[3] HiRes collaboration, *First observation of the Greisen-Zatsepin-Kuzmin suppression*, *Phys. Rev. Lett.* **100** (2008) 101101 [astro-ph/0703099].

[4] Telescope Array collaboration, *The Cosmic Ray Energy Spectrum Observed with the Surface Detector of the Telescope Array Experiment*, *Astrophys. J. Lett.* **768** (2013) L1 [1205.5067].

[5] Pierre Auger collaboration, *Observation of the suppression of the flux of cosmic rays above 4×10^{19}eV*, *Phys. Rev. Lett.* **101** (2008) 061101 [0806.4302].

[6] Telescope Array collaboration, *The surface detector array of the Telescope Array experiment*, *Nucl. Instrum. Meth. A* **689** (2013) 87 [1201.4964].

[7] H. Tokuno et al., *New air fluorescence detectors employed in the Telescope Array experiment*, *Nucl. Instrum. Meth. A* **676** (2012) 54 [1201.0002].

[8] M. Teshima et al., *Properties of 10**9-GeV - 10**10-GeV Extensive Air Showers at Core Distances Between 100-m and 3000-m*, *J. Phys. G* **12** (1986) 1097.

[9] S. Yoshida et al., *Lateral distribution of charged particles in giant air showers above EeV observed by AGASA*, *J. Phys. G* **20** (1994) 651.

[10] M. Takeda et al., *Energy determination in the Akeno Giant Air Shower Array experiment*, *Astropart. Phys.* **19** (2003) 447 [astro-ph/0209422].

[11] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz and T. Thouw, *CORSIKA: a Monte Carlo code to simulate extensive air showers.*, Forschungszentrum Karlsruhe GmbH (Feb., 1998).

[12] S. Ostapchenko, *QGSJET-II: Towards reliable description of very high energy hadronic interactions*, *Nucl. Phys. B Proc. Suppl.* **151** (2006) 143 [hep-ph/0412332].

[13] J. Hersil, I. Escobar, D. Scott, G. Clark and S. Olbert, *Observations of Extensive Air Showers near the Maximum of Their Longitudinal Development*, *Phys. Rev. Lett.* **6** (1961) 22.

[14] Telescope Array collaboration, *Highlights from the Telescope Array Experiment*, *PoS* **ICRC2023** (2024) 008.

[15] Pierre Auger collaboration, *Measurement of the cosmic-ray energy spectrum above* $2.5{\times}10^{18}$ *eV using the Pierre Auger Observatory*, *Phys. Rev. D* **102** (2020) 062005 [2008.06486].

[16] Telescope Array, Pierre Auger collaboration, *Joint analysis of the energy spectrum of ultra-high-energy cosmic rays as measured at the Pierre Auger Observatory and the Telescope Array*, *PoS* **ICRC2021** (2021) 337.

[17] Pierre Auger, Telescope Array collaboration, *Measurement of UHECR energy spectrum with the Pierre Auger Observatory and the Telescope Array*, *PoS* **ICRC2023** (2024) 406.

[18] Telescope Array collaboration, *Declination Dependence of the Telescope Array Surface Detector Spectrum*, *PoS* **ICRC2017** (2018) 496.

[19] Telescope Array collaboration, *Observation of Declination Dependence in the Cosmic Ray Energy Spectrum*, 2406.08612.

[20] Particle Data Group collaboration, *Review of particle physics*, *Phys. Rev. D* **110** (2024) 030001.

[21] Telescope Array collaboration, *Indications of Intermediate-Scale Anisotropy of Cosmic Rays with Energy Greater Than 57 EeV in the Northern Sky Measured with the Surface Detector of the Telescope Array Experiment*, *Astrophys. J. Lett.* **790** (2014) L21 [1404.5890].

[22] Telescope Array collaboration, *Indications of a Cosmic Ray Source in the Perseus-Pisces Supercluster*, 2110.14827.

[23] Telescope Array collaboration, *Telescope array surface detector medium-scale anisotropy analyses*, in *UHECR 2024 Proceedings*, 2024.