The Cosmic Ray Energy Spectrum Observed with the Surface Detector of the Telescope Array Experiment

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The Telescope Array (TA) collaboration has measured the energy spectrum of ultra-high energy cosmic rays for energies above 1.6×10^{18} eV in its first three years of operation. The spectrum shows a dip at an energy of 5×10^{18} eV and a steepening at 5×10^{19} eV which is consistent with the expectation from the GZK cutoff. Here we use a new technique that involves generating a complete simulation of the TA surface detector. The procedure starts with shower simulations using the CORSIKA Monte Carlo program where we have solved the problems caused by use of the "thinning" approximation. This simulation method allows us to make an accurate calculation of the acceptance of the detector for the energies concerned.

INTRODUCTION

One of the most powerful tools for studying the origin of cosmic rays is their energy spectrum, which shows several features that reveal important information about the cosmic rays, their sources, and their propagation across cosmological distances. One example is the high-energy ($4-6\times10^{19}$ eV) suppression in the spectrum which was predicted by Greisen [1] and by Zatsepin and Kuz'min [2] in 1966, and is called the GZK cutoff. Both sets of authors predicted a strong suppression in the spectrum due to the interaction of cosmic rays with photons of the cosmic microwave background radiation. The authors also pointed out that a spectrum suppression is expected for cosmic protons (by photo-pion production) as well as heavier nuclei (by spallation) so long as the particles travel more than 50 Mpc from their sources. If cosmic rays are protons there should also be a dip in the spectrum, caused by e^+e^- pair production in the same interactions, at an energy of about 5×10^{18} eV [3]. Heavy nuclei do not naturally cause such a dip. Hence the existence of a high-energy suppression would indicate that cosmic rays of these energies are of extragalactic origin, and that their propagation over cosmological distances imposes structures in their energy spectrum. This is the theory that is being tested by the Telescope Array and other experiments.

The AGASA experiment [4][5], comprising of a surface detector of 111 scintillation counters, was the first to be large enough to test this theory, but they did not observe the suppression. The first experiment to observe the GZK cutoff was the High Resolution Fly's Eye (HiRes) experiment [6], which consisted of fluorescence detectors located atop two desert mountains in western Utah. The cutoff energy reported by HiRes was $(5.6\pm0.5\pm0.9)\times10^{19}$ eV, which is consistent with a suppression of protons. They also observed the ankle structure: a hardening of the spectrum, at the energy (4×10^{18} eV) expected for cosmic protons. HiRes also published measurements of the shower maximum slant depth (X_{max}) that indicated a predominately light composition above 2×10^{18} eV [7]. A somewhat different picture is seen by the Pierre Auger Observatory (PAO), located in Argentina. The PAO consists of a surface detector (SD) of 1600 water tanks, accompanied by four fluorescence detectors located at the SD corners. The PAO also observes the high-energy suppression, but at $(2.9\pm0.2)\times10^{19}$ eV [8][9]. They see the ankle also, but their X_{max} results may indicate that the composition is heavy [10]. The straightforward interpretation of the PAO results is that the ankle would need to be explained by some other mechanism involving heavy nuclei.

The Telescope Array (TA) experiment, also in western Utah, is the largest experiment studying ultrahigh energy cosmic rays in the northern hemisphere. It consists of a surface detector of 507 scintillation counters [11], plus 38 fluorescence telescopes [12][13] located at three sites overlooking the SD. TA combines the experimental techniques of AGASA and HiRes, in order to achieve the best possible control over systematic errors and biases. Moreover, scintillation counters are sensitive mostly to the electromagnetic component of cosmic ray showers, rather than the muonic component which is poorly predicted by shower Monte Carlo programs. Hence TA results can shed light on the AGASA - HiRes - PAO disagreements.

This paper reports on a measurement of the cosmic ray spectrum above 1.6×10^{18} eV made by the TA SD over approximately three years of observation between May 11, 2008 and April 25, 2011. For this study, we used an analysis method that while standard for fluorescence detectors, is being implemented for the first time on a surface array. Instead of restricting our analysis to a domain where we expect 100% efficiency, as previous experiments have done, the TA SD detector aperture is calculated using extensive air showers generated in detail by the CORSIKA simulation package [14], accompanied by a full GEANT simulation of the detector [15]. Another important aspect of this technique is the validation of the simulation by comparisons of key distributions from the data to those obtained from the Monte Carlo (MC) simulation, as is currently standard practice in experimental high-energy physics. Moreover, our study overcomes the inability of "thinned" simulated showers (e.g. as used in CORSIKA and AIRES [16]) to reproduce the particle density and arrival time fluctuations far from the core. The solution applied is a novel dethinning technique that replicates a non-thinned simulation [17] at the core distances where most of the detector data is collected.

THE TA SURFACE DETECTOR

Each counter of the TA SD consists of two layers 1.2 cm thick plastic scintillator, each 3 m^2 in area. Photons produced by ionizing particles passing through the counters are collected by wavelength shifting fibers, and read out by photomultiplier tubes, one for each layer. A histogram of pulse heights, triggered by a coincidence between the two layers, within an individual SD, is collected every 10 minutes. This histogram is dominated by single muons with a count rate of $\sim$ 700 Hz. Each 10-minute histogram is used to calibrate each scintillator to the pulse height of a minimum ionizing particle (MIP) and later to a vertical equivalent muon (VEM) to a 1% accuracy. The SD array trigger requires at least three adjacent counters with pulse areas over 3 MIP to fire within 8 μsec. A 50 MHz FADC readout system then saves the signal traces for all counters in the array with more than 0.3 MIP. The VEM calibration is applied in the offline analysis, and two fits are used to reconstruct the properties of the cosmic ray:

first a fit to counter times, using the modified Linsley shower-shape function [18], is made to determine the arrival direction, and core position of the event; second, a lateral distribution fit, using the AGASA function [4][5], is used to find $S(800)$, the density of shower particles at a lateral distance of 800 m from the core. The energy is then estimated by using a look-up table in $S(800)$ and zenith angle determined from a Monte Carlo simulation.

APERTURE

In the ultrahigh energy regime, computer-time requirements make it impossible to follow every particle when simulating showers. An approximation called thinning is used in programs like CORSIKA and AIRES to reduce computational load by only performing a small, statistically representative sample of the air shower simulation. Thinned showers can be used for simulation of fluorescence detectors, because the fluorescence light comes mostly from near the shower axis where the particle density is extremely high, and the fluctuations in the signal are dominated by the Poisson nature of fluorescence photon statistics. But for surface detectors, which operate far from the shower core, the number of shower particles is low and the thinning approximation fails to represent the intrinsic density fluctuations within the shower. To simulate the TA SD accurately, we have developed a procedure called "dethinning," where we statistically regenerate each group of thinned particles from its weighted representative [17].

The Monte Carlo simulation of TA SD has the goal of making an accurate representation of the data and our detectors. Our shower library consists of shower simulations generated by CORSIKA using QGSJET-II-03 [19] to model high-energy hadronic interactions, FLUKA [20][21] to model low-energy hadronic interactions, and EGS4 [22] to model electromagnetic interactions. Events are chosen from our shower libraries according to the spectrum previously measured by the HiRes collaboration [6]. For this library, proton showers were used exclusively because both the HiRes composition results [7] and the preliminary TA composition result [23] are consistent with QGSJET-II-03 protons. A complete representation of calibration and ontime for each surface counter as a function of time is also included. Direct comparisons between data and Monte Carlo show that the result closely resembles the data [24]. Figure 1 shows a comparison of the $S(800)$ of cosmic ray showers. The excellent agreement between the data and simulation exemplifies the accuracy of our simulation and the resulting efficiency calculation of the SD.

The selection criteria employed in our analysis are as follows:

1. Each event must include at least five counters.

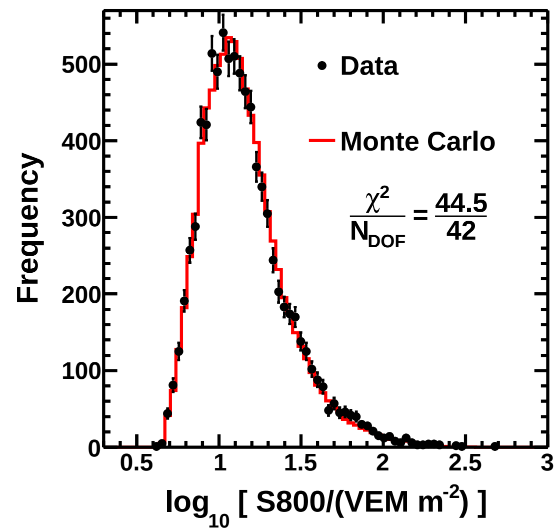

FIG. 1. Data and MC comparison of the event $S(800)$ distributions. The reduced χ^2 is 1.06, indicating a good agreement.

2. The reconstructed primary zenith angle must be less than 45°.

3. The reconstructed event core must be more than 1200 m from edge of the array.

4. Both the timing and lateral distribution fits must have $\chi^2/d.o.f. < 4$.

5. The angular uncertainty estimated by the timing fit must be less than 5°.

6. The fractional uncertainty in $S(800)$ estimated by the lateral distribution fit must be less than 25%.

Figure 2 shows the efficiency of reconstruction calculated from the TA SD Monte Carlo Program. The values of aperture and exposure, for this data set, corresponding to the 100% efficiency region are 890 km^2 sr and 2640 km^2 sr yr, respectively. For energies above $10^{18.2}$ eV (where the efficiency falls to 10% of its plateau) we can accurately simulate all air showers, both well- and poorly-reconstructed. The resolution of the TA SD energy determination is better than 20% above 10^{19} eV.

The uncertainty in energy scale of the Monte Carlo simulation of an SD is large, and possible biases associated with the modeling of hadronic interactions are difficult to determine. However, the energy scale uncertainty is experimentally well controlled for a fluorescence detector (FD) since the energy measurement is calorimetric. We therefore correct our energy scale to the TA FD using events seen in common between the FD and SD. The observed differences between the FD and SD events are well described by a simple proportionality relationship, where the SD energy scale is 27% higher than the FD.

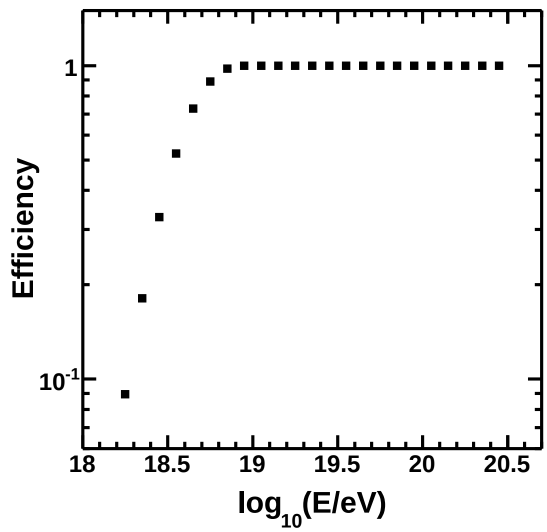

FIG. 2. Efficiency as a function of energy. Both trigger and reconstruction effects are included.

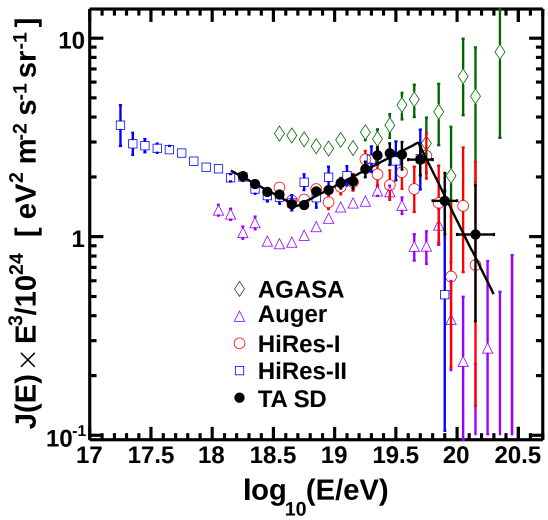

FIG. 4. Cosmic ray flux multiplied by E^3. Solid line shows the BPL fit to the TA SD data.

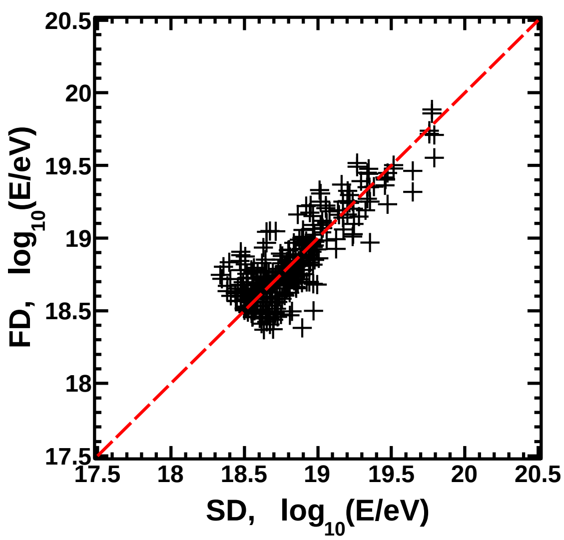

FIG. 3. Energy comparison between the TA SD and FD *after* the 27% normalization has been applied to the SD.

Figure 3 shows a scatter plot of FD vs SD energies, where the latter have been rescaled. Events from all three FD stations were included in this plot.

SPECTRUM

Figure 4 shows the spectrum measured by the TA SD, where the differential flux, $J(E) = \mathrm{d}^4N(E)\,/\,\mathrm{d}E\,\mathrm{d}A\,\mathrm{d}\Omega\,\mathrm{d}t$ is multiplied by E^3, and plotted against $\log_{10}E$. The ankle structure and the suppression at the highest energies are clearly visible. A fit to a broken power law (BPL) is also shown. The fit finds the ankle at an energy of $(4.9 \pm 0.3) \times 10^{18}$ eV and the suppression at $(4.8 \pm 0.1) \times 10^{19}$ eV. The power exponents for the three regions (below the ankle, between the breaks, and above the suppression) are -3.33 ± 0.04, -2.68 ± 0.04, and -4.2 ± 0.7 respectively. Also shown in Figure 4 are the spectra reported by AGASA [5], HiRes (monocular mode) [6], and PAO (combined hybrid and SD) [9]. The agreement between the HiRes and TA SD, where very different detection techniques were used, is remarkable.

A linear extrapolation of the power law below the suppression predicts 54.9 events above the break; whereas only 28 TA events were observed. This difference corresponds to a Poisson probability of 4.75×10^{-5}, or 3.9 standard deviations significance. $E_{1/2}$ is the energy at which the integral spectrum falls to 1/2 of its expected value in the absence of the GZK cutoff. Under a wide range of assumptions about the spectrum of extragalactic sources, $E_{1/2}$ should be $10^{19.72}$ eV for protons [25]. HiRes reported $\log E = 19.73 \pm 0.07$ [6], and we measure 19.69 ± 0.10.

While this is not a 5σ observation, it provides independent confirmation of the GZK cutoff observed by HiRes [6]. Furthermore, the energy of the cutoff is consistent with the interpretation that the composition is protonic

Reference [24] includes a description of systematic uncertainties in the SD spectrum measurement. The largest source of systematic uncertainty in the spectrum is that of the energy scale. Since the SD energy scale is fixed to that of the TA fluorescence detectors, we take the systematic uncertainty in the SD energy to be 22% [26], the same as the FD. This propagates into a 37% uncertainty in the flux.

CONCLUSIONS

We have measured the spectrum of cosmic rays in the energy range $10^{18.2} - 10^{20.3}$ eV using the surface detector of the Telescope Array experiment. In the analysis, we have introduced the new technique of calculating the surface detector aperture using Monte Carlo simulation. This technique includes a dethinning process that enables the simulation of air showers with excellent detail. We found that the energy scale of the SD determined from simulations can be reconciled with the calorimetric scale of fluorescence detectors by a simple renormalization of 27%. Two features are seen in the spectrum, the ankle and the high-energy suppression. Fitting the spectrum to a broken power law shows a definite break at and energy of $(4.8 \pm 0.1) \times 10^{19}$ eV, which is consistent with the GZK cutoff energy expected for protons. An extended spectrum beyond the GZK energy is ruled out with a statistical significance of 3.9σ. Our result is in excellent agreement with that of the HiRes experiment where fluorescence detectors were used. This result demonstrates that there is no difference between measurements of the cosmic ray spectrum using a fluorescence detector and a surface scintillation array once the energy scales are normalized.

In summary, by combining the two techniques used by the AGASA and HiRes experiments, we have now obtained a consistent energy spectrum for ultra-high energy cosmic rays from both a surface detector and fluorescence telescopes. The spectrum obtained by our experiment demonstrates spectral features, a dip and a cutoff, consistent with the interaction of extra-galactic protons with the cosmic microwave background (GZK process).

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