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Telescope Array Measurements of the UHECR Energy Spectrum

DOUGLAS BERGMAN[1] FOR THE TA/TALE COLLABORATION.

[1] *Dept. of Physics & Astronomy, University of Utah, Salt Lake City, Utah 84112 USA*

bergman@physics.utah.edu

Abstract: The Telescope Array experiment is a hybrid of Surface Detectors (SDs) and Fluorescence Detectors (FDs). The two components can be used separately and together in making measurements of the primary cosmic ray flux spectrum. The SD spectrum currently has the largest amount of data, as it has nearly 100% duty cycle. We will present the SD spectrum using four years of data. The FD spectrum covers a larger energy range than the SD spectrum, and its energy scale is used to set the energy scale of the SD spectrum. However, the geometry of the FD reconstruction is not as precise as the SD. The FD spectrum from all three FD sites in TA is shown including data from the first four years of operation. Finally, combining FD and SD measurements on an event-by-event basis, we measure a hybrid spectrum. This has the best resolution, but the smallest statistics of the three spectral measurements. We again show a hybrid spectrum from the first four years of TA operation.

Keywords: Cosmic Rays, Extensive Air Shower Array, Energy Spectrum

1 Introduction

The existence of cosmic rays with energies above 10^{18} eV provided the first evidence of extragalactic cosmic ray accelerators. The measurements of the energy spectrum of these ultra-high energy cosmic rays (UHECRs), the spectral slopes and the energies of the break points constrains models what these cosmic accelerators are.

Telescope Array (TA) is the largest cosmic ray detector in the Northern Hemisphere. It is a hybrid detector consisting of 507 scintillation surface detectors (SDs) covering nearly 700 km^2 combined with three fluorescence detector (FD) sites consisting of 38 telescopes which image cosmic ray air showers which occur over the SD array. The two components to the experiment can be used separately or together to measure the spectrum of UHECRs, and it's important to perform all three measurements to be able to compare the systematic uncertainties inherent in each.

The SD spectrum measurement has the highest statistical power given the nearly 100% duty cycle of the SD array, however, the determination of the energy of a extensive air shower (EAS) produced by a cosmic ray is indirect since only a small fraction of the shower is sampled and the sampling occurs late in the development of the shower. The energy determination then tends to be very dependent on models of early shower development including the multiplicity and elasticity of the first few interactions and the number of hadrons early in the shower. It is more practical therefore to set the energy scale of the SD by comparison to the bolometric measurement of the FDs. The FD measurement of the spectrum, with each of the three sites acting independently, in "monocular" mode, provides a larger dynamic range of energy measurements and a bolometric measurement of the EAS energy, but the duty cycle is only $\sim 10\%$ due to its operation being restricted to moonless nights. The geometrical reconstruction of the EAS is also poorer than with the SD alone. The "hybrid" measurement combines the bolometric measurement of the FD with the geometrical precision of the SD at the cost of the duty cycle and reduced dynamic range of each method.

For the monocular and hybrid measurements of the spectra presented here, two separate analyses were performed and these separate analyses are combined appropriately to allow us to present a TA monocular spectrum and a TA hybrid spectrum. The existence of two analyses stems from the fact that the northern FD site, Middle Drum (MD), differs from the two souther FD sites, Black Rock Mesa (BRM) and Long Ridge(LR), in both the design of its mirrors and in its data-acquisition system. MD uses refurbished mirrors from the High Resolution Fly's Eye (HiRes) experiment whereas BRM and LR use newly built equipment. The reuse of HiRes mirrors at MD provides a direct connection between the MD monocular spectrum measurement and the HiRes measurement.

2 SD Measurement

A SD measurement of the UHECR has been published previously [1]. The measurement relies on the use of Monte Carol (MC) simulation of events to calculate the acceptance of CR air-showers as a function of energy and zenith angle, and this is used to calculate the effective aperture of the detector. This method avoids the use of a constant-intensity-cut method to determine the relationship between the density of charged particles at 800 m from the shower core ($S(800)$) and the zenith angle. Rather, a MC generated lookup table is used. To ensure the validity of the look-up table, extensive comparisons between data distributions and those produced by the MC simulation are made. The quality of the comparisons allows the extension of the range of the validity of the aperture calculation well off the 100% plateau to lower energies: the measurement goes down to $\log_{10}(E/\mathrm{eV}) = 18.2$ where the acceptance is approximately 8%. The energy scale of the $S(800)$ measurement is adjusted by comparison with events seen simultaneously by each of the three FD sites. The FD measurements are bolometric and thus largely free of model dependence. This requires a 27% downward adjustment in the $S(800)$ energy scale.

An updated spectrum including data from the first five years of TA operation, from May 2008 to May 2013, is shown in Figure 1. In addition to the spectrum points, a fit to a broken power law is shown. The two breaks correspond to the features known as the "Ankle" and the "GZK Cutoff". The significance of the break at the GZK Cutoff is 5.7σ

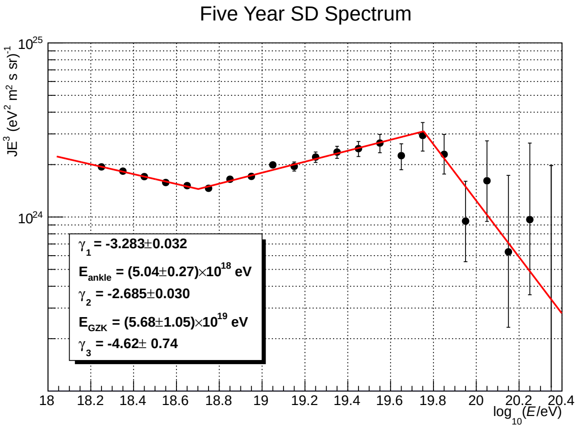

Fig. 1: The spectrum of cosmic rays as measured by the surface detector of TA [1]. A broken power law fit to the data is also shown.

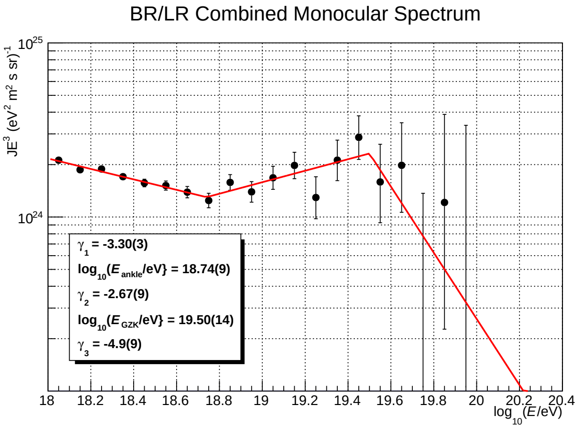

Fig. 2: The spectrum of cosmic rays as measured by the FADC fluorescence detectors of TA. A broken power law fit to the data is also shown.

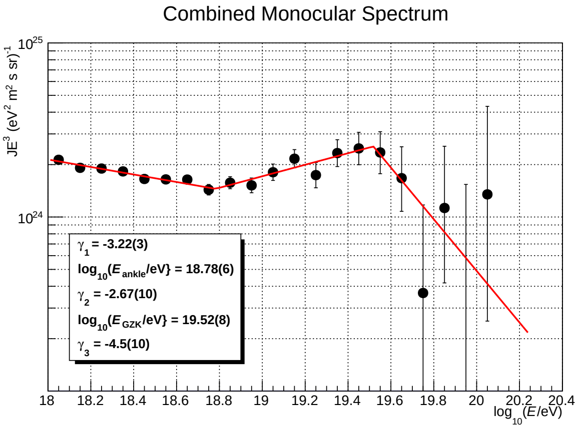

Fig. 3: The monocular spectrum of cosmic rays as measured by the combination of all the fluorescence detectors of TA. The two component spectra are also shown as open points. The broken power law fit to the BR/LR spectrum is also included.

with 68.1 events expected above the cutoff while only 26 events were observed.

The position of the GZK Cutoff can also be determined from the $E_{1/2}$ method suggested by Berezinsky *et al.*, where the energy at which the integral flux drops to half of what would be expected with no cutoff is taken as the figure of merit. TA measures $\log_{10}(E_{1/2}/\mathrm{eV}) = 19.74 \pm 0.08$. This compares with the expectation for a proton-only composition under a wide array of input spectral indices of $log_{10}(E_{1/2}/\mathrm{eV}) = 19.72$.

3 Monocular Measurements

Monocular FD measurements of air showers use the time-of-arrival of light in different pixels to determine the geometry of the air shower, its distance from the detector and its angle. This results in a quite precise determination of the plane including the line of the core of the shower and the detector itself, but a less precise measurement of the angle of the shower within that plane. Because the detector can trigger on and reconstruct showers only if it receives enough light, the range at which a shower of a given energy can be reconstructed grows with energy as the showers become brighter. The changing aperture requires a MC simulation for its determination. As was the case for the SD analysis, extensive comparisons are made between data distributions and simulated distributions to verify the veracity of the MC simulation. These comparisons include the distance to the shower, the angle within the shower-detector plane, the brightness of showers and the duration of showers.

The two southern FD sites, Black Rock Mesa (BRM) and Long Ridge (LR), are essentially identical in design and use an FADC data acquisition system. The northern FD site, Middle Drum (MD), consists of refurbished HiRes telescopes and uses a sample-and-hold data acquisition system. Because of the different instrumentation, separate analyses were performed for BRM & LR and for MD. The MD analysis in particular was identical to that performed by the HiRes Collaboration for the HiRes-I site. This measurement [2] provides a direct link to HiRes results.

The combined spectrum from BRM and LR is shown in Figure 2. To make the combined spectrum, the data and exposures from the two sites must be added together in the appropriate way. All the events which were seen by only one site are added together at the observed energy, while events seen by both sites are added in at the geometric mean of the two energy measurements. Likewise the exposures for seeing events at either one of the sites (but not both) is added, and then the exposure for seeing events at both sites is added to the previous sum. A fit to the exposure as a function of energy is used to reduce the binwise systematic uncertainty in the flux measurement from finite MC statistics. This analysis has been submitted for publication[3]. More details of this analysis can be found in Poster 0476[4].

To provide a single monocular measurement of the UHECR energy spectrum, we have combined the BRM/LR measurement with the previously published measurement from MD. We have again combined the data by considering events seen by only one of the analyses directly and adding the events extant in both analyses at the geometric mean of the measured energies. Because of the differences in the analyses it was not straightforward to calculate the combined exposure directly, rather we measured the fraction of MD events seen in the BRM/LR analysis as a function of energy, and used this to estimate the overlap in exposures. The result of the combination is shown in Figure 3.

The combined monocular spectrum is shown together with the SD spectrum in Figure 4. The monocular spectrum

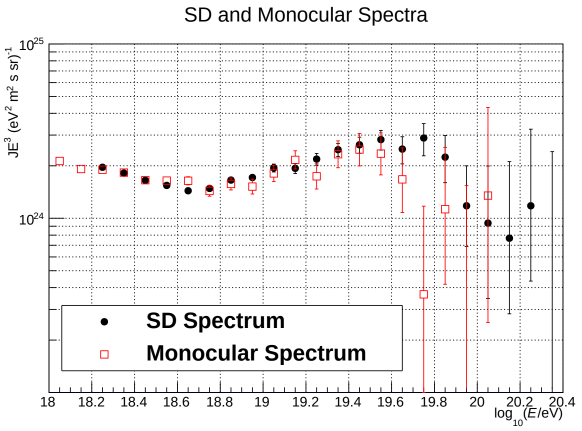

Fig. 4: The monocular spectrum of cosmic rays as measured by the combination of all the fluorescence detectors of TA shown in comparison with the SD spectrum.

shows remarkable agreement with the SD spectrum with largely independent systematic errors apart from overall energy scale. The two spectra agree in the overall flux level, the spectral slopes before and after the ankle and the general position of the ankle. The statistics in the monocular spectrum become sparse in the GZK region, so that detailed comparisons cannot be made, but the existence of the cutoff itself is evident in both spectra.

4 Hybrid Measurements

Using information from both the SD and FD when reconstructing events provides the best geometrical resolution but comes at the cost of reduced exposure and dynamic range. As was the case for monocular analyses, separate analyses were done for events using BRM & LR data and those using MD data due to the differences in instrumentation and data acquisition. Both of these analyses are described more fully in poster presented in this conference. The BRM/LR analysis is presented in poster 358[5]. The MD analysis is presented in poster 794[6].

To provide a single hybrid measurement of the UHECR energy spectrum, we have combined the two hybrid measurements in the same way as we did for the monocular measurements: add event seen only by one analysis, add events seen by both analyses at the geometric mean; add the two independent exposures and subtract the intersection as estimated from the fraction of MD data seen also in the BR/LR analysis. The combined hybrid energy spectrum is shown in Figure 5.

The comparison of all three TA spectra is shown in Figure 6. The close agreement between the three spectra confirms our use of the FD energy scale to set the SD energy scale. The energy scale is set by comparing event-by-event energies and provides one number for renormalizing the SD energy scale using $S(800)$. It is therefore gratifying to see the agreement is the spectra that result. In addition the agreement between monocular and hybrid spectra validates the quality of the geometrical reconstruction in monocular analyses and the SD acceptance calculation used in hybrid mode.

5 Non-broken power law fits

Rather than rely solely on broken power law fits, one can fit to a combination of two power-laws with a variable

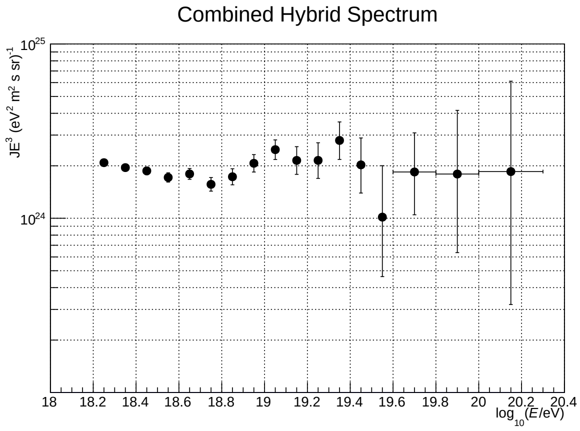

Fig. 5: The spectrum of cosmic rays as measured in hybrid mode by the combination of data from all of the fluorescence detectors of TA.

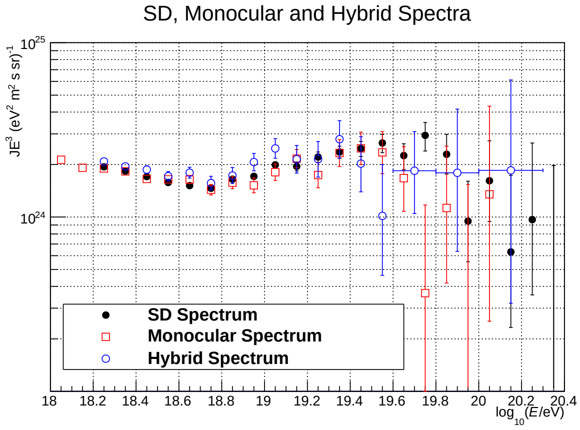

Fig. 6: The three cosmic ray energy spectra measured by TA on one plot for comparison.

transition range using the formula

$$J(E) = ((AE^{\gamma_1})^{1/R} + (BE^{\gamma_2})^{1/R})^R \qquad (1)$$

$$= AE^{\gamma_1}\left(1 + \left(\frac{BE^{\gamma_2}}{AE^{\gamma_1}}\right)^{1/R}\right)^R \qquad (2)$$

Fitting the SD spectrum only up to $10^{19.2}$ eV, we find a very sharp transition at the ankle, consistent with being instantaneous given the tenth-of-a-decade binning. This shown in Figure 7 as the red line. The sharpness of the fit is difficult to explain with either a dip model or with a component change model. In a separate fit to the energy range above the ankle, we find that the transition at the GZK Cutoff is much more gradual, taking most of a decade in energy to occur.

We have also fit the SD spectrum to a dip model using a proton propagation code. This is detailed in another presentation at this conference[7]. The best fit, with a source spectral slope of -2.39 and an evolution parameter of 4.2 is shown in Figure 8.

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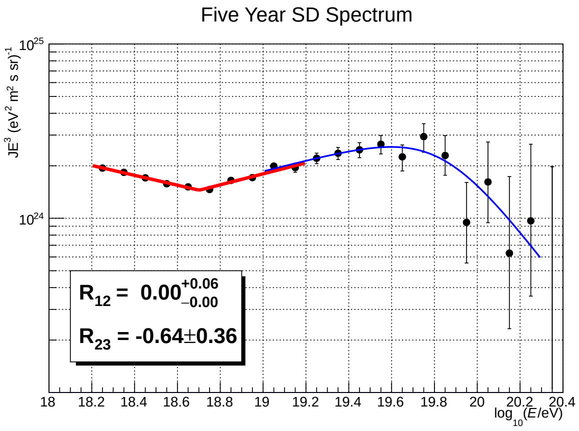

Fig. 7: The SD spectrum fit with a variable-transition power-law fit. The slopes in the fit have been fixed to the values found in the broken power-law fits, which the normalization and transition speed have been allowed to vary. The spectrum has been fit separately in two regions. The fit to the Ankle transition has been made over the region $\log_{10}(E/\mathrm{eV}) = 18.2$–$19.2$ and is shown in red. The fit to the GZK Cutoff has been made over the region $\log_{10}(E/\mathrm{eV}) = 18.8$–$20.2$ and is shown in blue.

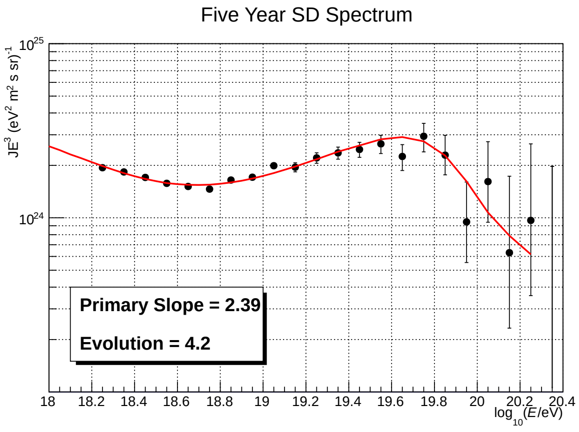

Fig. 8: The SD spectrum fit with a proton-only, uniform source, propagation model. The best fit values are shown: the source spectral slope is -2.39 with a source evolution parameter of 4.2.

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