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Energy Spectrum of Ultra-High-Energy Cosmic Rays Measured by The Telescope Array

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The Telescope Array (TA) is a hybrid cosmic ray detector using air fluorescence detectors (FDs) and an array of surface detectors (SDs) which covers $700\,\mathrm{km}^2$ in Utah. The TA Low-energy Extension (TALE) also consists of FDs with larger elevation angles and an infill SD array with 400 m spacing, which extends the observable energy range down to 4 PeV. In this contribution we present the spectrum from the TA SD, which has the largest statistics, the FD monocular spectrum, the FD-SD hybrid spectrum, and the lower energy spectrum obtained by TALE. We discuss the declination dependence of the energy spectrum in the northern sky.

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1. TA detectors

The Telescope Array experiment is located in Millard County, Utah (USA) at a 39.3° N latitude and ~ 1400 m altitude above sea level ($\sim 860\,\mathrm{g/cm^2}$). The TA detectors have been fully operational since May 2008.

The TA SD array is composed of 507 particle counters arranged in a square grid with 1.2 km spacing to cover a total area of about 700 $\mathrm{km^2}$ (Figure 1). Each detector unit consists of two layers of plastic scintillators of 3 $\mathrm{m^2}$ in area and one photo-multiplier tube (PMT) for each layer [1]. Scintillation light in each layer is collected with wavelength-shifting fibers and directed to the PMTs. Signals from the PMTs are sampled at 50 MHz frequency and digitized with 12-bit FADC. The SD data acquisition system is triggered by a coincidence, within 8μs window, of neibouring three SDs with signals greater than 3 MIPs (minimum-ionizing particles) equivalent in their both layers. The SD array is fully efficient for cosmic rays with energies greater than $10^{18.8}$ eV [2].

The fluorescence detectors are installed in three sites, Black Rock (BR, 12 telescopes), Long Ridge (LR, 12 telescopes), and Middle Drum (MD, 14 telescopes), viewing the sky above the SDs. The 24 BR and LR telescopes were newly developed for TA, and the MD telescopes are refurbished HiRes-1 detectors. One BR/LR telescope is comprised of a cluster of photo-tubes (or a "camera"), and a reflecting mirror of an area $6.8\,\mathrm{m^2}$. Each BR/LR camera has 16×16 2-inch hexagonal tubes covering $15.5^\circ \times 18^\circ$ of the sky. A telescope triggering signal is generated when five adjacent tubes in a camera are fired by incident photons, and waveform data of all the cameras are recorded in a station [3, 4]. An MD telescopes has a $5.2\,\mathrm{m^2}$ mirror and a camera of 256 pixels using 40mm Philips tubes. These telescopes are operated with the same electronics and data acquisition system of the HiRes-1 experiment. The total FD fields of view are $108^\circ, 108^\circ$ and 114° in azimuth and $3^\circ \sim 31^\circ$ in elevation. The operational duty cycle of SD is at $\sim 98\%$, and the FD duty factor is $\sim 11\%$, which reduces to $\sim 9\%$ after good weather cut.

The TA low energy extension (TALE) consists of fluorescence telescopes viewing higher altitudes at the MD site, and an infill array of scintillation counters at distances 1.5 to 3 km away from the MD. The TALE infill array is operational synce May 2013, and there are currently ~ 100 active counters at May 2017. TALE FD has 10 fluorescence telescopes with 256 pixels per telescope that use a 10MHz FADC readout system. TALE FD looks higher into the sky and extends the field of view of the TA MD from 31° to 57° in elevation.

The absolute calibration of the TA FDs is obtained by performing an absolute calibration of few "standard" PMTs that are installed in each camera using the CRAYS (Calibration using RAYleigh Scattering) system in the laboratory [5]. The calibration of the TA FDs was carried out by measuring the *absolute* gains of dozens of the standard PMTs that are installed in each camera using the *CRAYS* (Calibration using RAYleigh Scattering) system in the laboratory [5]. The other PMTs in the cameras are *relatively* calibrated to the standard ones by using Xe flash lamps installed at the center of each mirror [6, 7].

2. Event Reconstruction

The phototubes of the TA fluorescence detectors measure the number of photons emitted at different altitudes in the atmosphere, which are proportional to energy losses of shower particles

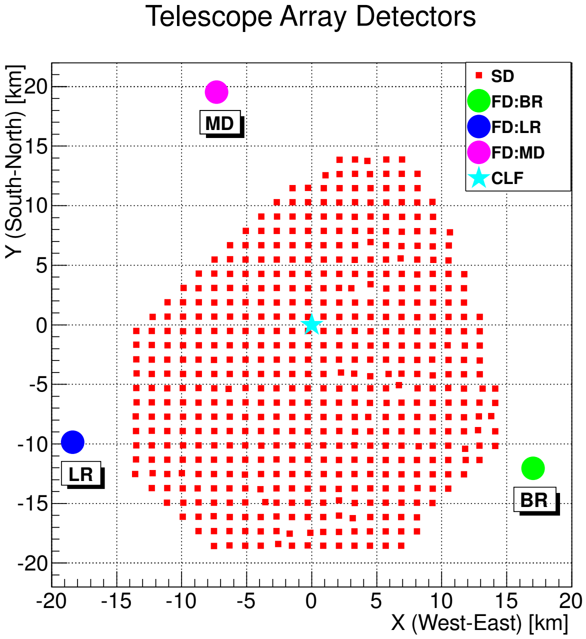

Figure 1: Layout of the TA detectors.

and therefore the number of charged particles in the shower. We use the efficiency of fluorescence photon emission in the air (the *fluorescence yield*) from [8], and assume the wavelength spectrum measured by the FLASH experiment [9]. The longitudinal development of the shower, i.e. the number of particles at different atmospheric depth is well described by the Gaisser-Hillas function,

$$N(X) = \left(\frac{X - X_0}{X_{\max} - X_0}\right)^{\frac{X_{\max}-X_0}{\lambda}} \exp\left(-\frac{X - X_{\max}}{\lambda}\right) \tag{2.1}$$

and we estimate the *calorimetric energy* of the shower by integrating the fitted $N(X)$ and multiplying the average energy loss by charged particles in the atmosphere. We need a correction to the calorimetric energy to determine the primary energy of the cosmic ray taking into account a fraction of energies at $\sim 10\%$ carried away by neutral particles like neutrinos. The systematic uncertainty in the energy determination is about 20 %. The details of the TA-FD event reconstruction are given in our previous publications e.g. [10, 11, 12, 13].

The particle counters of the SD array measure the lateral distribution of charged particles in an air shower at the ground. The lateral distribution of particles as a function of distance from the shower core is fitted to an assumed function known from previous experiments and confirmed in the TA data [14],

$$\rho(r) \propto \left(\frac{r}{R_M}\right)^{-1.2} \left(1 + \frac{r}{R_M}\right)^{-(\eta-1.2)} \left[1 + \left(\frac{r}{1000\mathrm{m}}\right)^2\right]^{0.6} \tag{2.2}$$

as shown in Figure 3, where R_M denotes a characteristic length of particles' lateral spread (the Moliére unit). We use the particle density at a distance of 800 m from the core, the so called

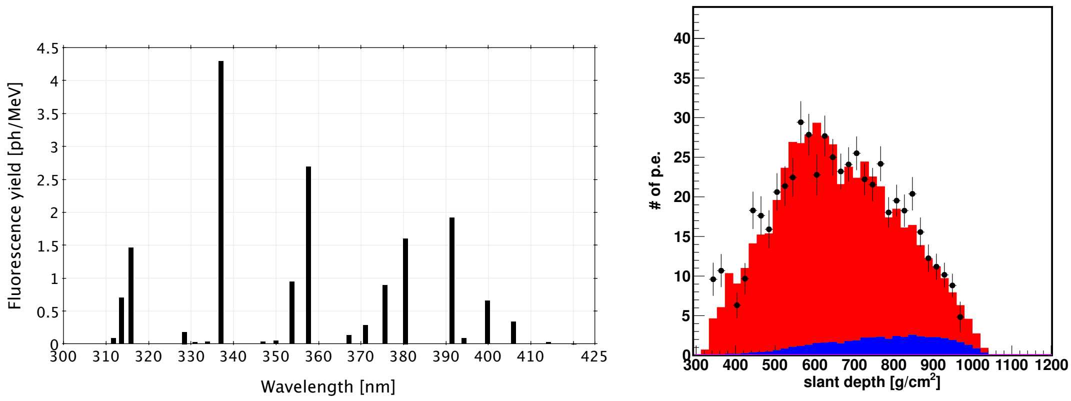

Figure 2: Left: Spectrum of fluorescence photons in the atmosphere used in TA-FD analysis [9]. Right: An example of the longitudinal fit of the shower development from the TA FDs

$S800$ parameter, to estimate of the shower energy. The distance 800 m is optimized for the altitude of the site and detector separation, and also to minimize the systematic uncertainty coming from different cosmic ray primary types. The first estimate of the energy is given from $S800$ and the shower inclination angle (zenith angle) θ using an energy conversion table obtained from the TA-SD Monte Carlo (MC) [15]. There is however a rather large systematic uncertainty in the energy calculated based on the present knowledge of high energy particle interactions employed in the shower MC simulation. The energies determined from the FD data are less dependent on MC because of the substantially calorimetric measurement. We make an event-by-event comparison of shower energies independently obtained by SD and FD for *hybrid events*, which are observed by the both detectors. The result is shown in Figure 3, and it is found that there is a linear correlation in the energies determined from the SD and FD data, with a scaling factor $\langle E_{\mathrm{SD}}/E_{\mathrm{FD}}\rangle_{\mathrm{h}} = 1.27$. We use this scaling factor for final determination of shower energies for not only the hybrid events but also those detected on by SD alone.

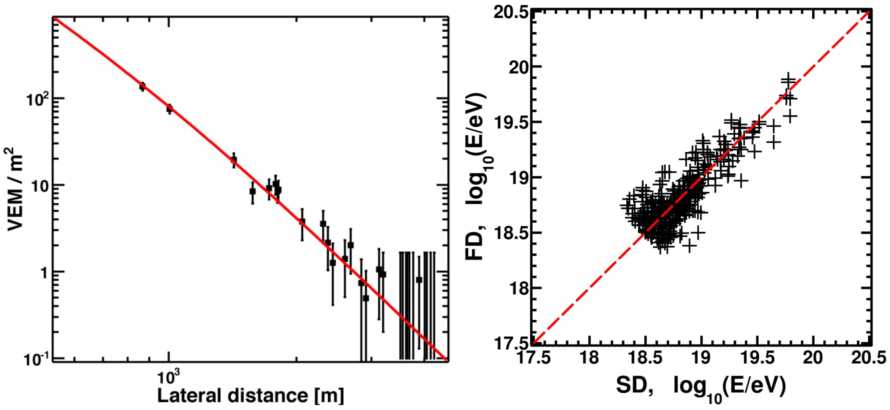

Figure 3: An example of lateral distribution of shower particles measured with the TA SD

3. TA 9-year spectrum

We have accumulated shower events in 9-year observation since May 2008. The total exposure amounts to $8 \times 10^3\,\mathrm{km}^2\,\mathrm{sr\,yr}$ to cosmic rays with energies greater than 10^{19} eV (Figure 4).

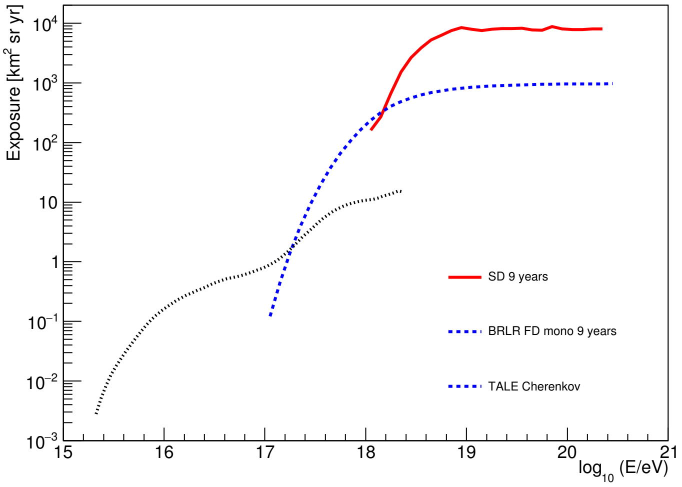

Figure 4: TA 9-year exposure as function of energy

The TA 9-year energy spectra obtained from the SD data is shown in Figure 5. We emphasize that the northern hemisphere measurements of ultra-high energy cosmic ray spectrum by the High Resolution Fly's Eye [16] and the Telescope Array are consistent. A suppression of the cosmic ray intensity is clearly seen, and from the SD data a piece-wise power law fit indicates a change in the spectral index $E^{-\gamma}$ from $\gamma = 2.69 \pm 0.02$ to 4.63 ± 0.49 at $E_{\mathrm{sup}} = 10^{19.81 \pm 0.04}$ eV. We observed 26 events above E_{sup}, while an expectation of 80 in the absence of the suppression. The probability of observing $N_{\mathrm{obs}} = 26$ with $N_{\mathrm{exp}} = 80$ is 2.2×10^{-12} from the Poisson statistics, which corresponds to $6.92\,\sigma$.

The fluorescence data gives an energy spectrum above $10^{17.2}$ eV, and in agreement with the SD data in the overlap region [17]. The TALE FD has an even more lower threshold, and the energy spectrum in a PeV region was obtained [18]. Note that the evaluation of detector aperture and invisible energy correction is sensitive to chemical composition of cosmic rays in particular in the PeV region. Here we used a composition model that reproduces the X_{max} distribution of the TALE FD data.

We examined a declination dependence of the energy spectrum of cosmic rays in the TA sky. We divided the SD data set into two, of higher declination ($\delta > 26°$) and lower declination ($\delta < 26°$) bands [19]. The lower-declination energy spectrum for $\delta < 26°$ is in good agreement with the Auger data of the same declination band allowing an energy shift within the uncertainties quoted by the both experiments [20]. Note that the TA "hotspot" is not included in this region [21]. However we found different suppression energies in the two bands, $10^{19.59 \pm 0.06}$ eV for $\delta < 26°$ and $10^{19.85 \pm 0.03}$ eV for $\delta > 26°$. This is a hint of spectrum anisotropy of cosmic rays in the northern and southern skies [19, 22, 23]

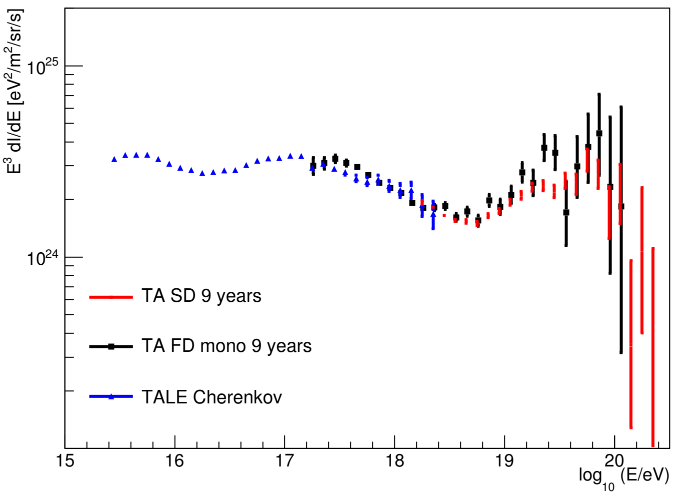

Figure 5: TA 9-year energy spectrum

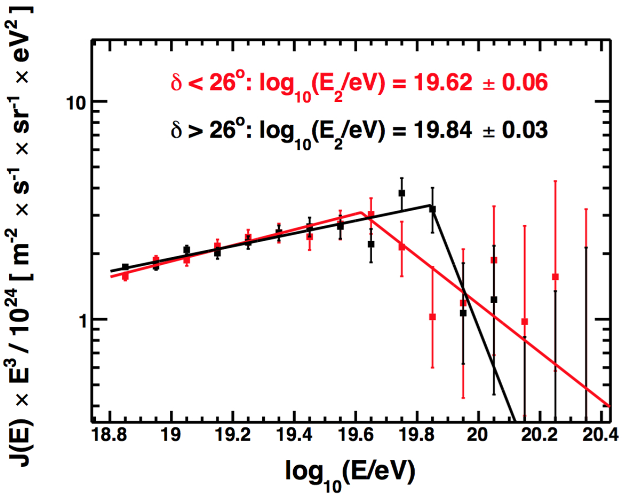

Figure 6: Declination dependence of the TA energy specrum

4. Summary

We present an update of the measurements of cosmic-ray energy spectrum with the Telescope Array detectors. The three types of detectors, TA SD, TA FD, and TALE FD data gives energy spectrum of 4.7 decades in energies. All three data are in agreement, and also consistent with the HiRes data measured in the northern hemisphere. The TA spectrum in declinations below $\delta = 26^\circ$ is consistent with the Auger data, however the break energy is different from that of the higher-declination spectrum. The origin of the declination dependence is still unknown, and the "TA $\times$ 4" project is highly expected to confirm the spectrum anisotropy with huge statistics and to explore the extreme energy universe.

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