Recent Results from Telescope Array

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Abstract. The results from the Telescope Array for thee-year observations are presented. The energy spectra of ultra high energy cosmic rays measured by using the data of the fluorescence detectors, surface detectors and hybrid mode of both detectors are in good agreement. We found two break points, at $10^{18.69}$ eV as the "ankle" structure and at $10^{19.68}$ eV as a flux suppression. The results of the composition study with the longitudinal development observed by the fluorescence detectors show proton-dominated hypothesis. No significant anisotropies in the arrival directions observed by surface detectors are found.

1. Introduction

The Telescope Array (TA) experiment is the largest Ultra-High Energy Cosmic Ray (UHECR) observatory in the northern hemisphere, located in the west Utah desert. This is a hybrid UHECR detector using two types of detectors: three stations of Fluorescence Detectors (FDs) and 507 Surface Detectors (SDs) (Figure 1). The main subjects of TA are to clarify the origin of UHECR as a follow-up to the AGASA [1] and HiRes [2] experiments.

Each of the SD consists of two layers of plastic scintillator. TA SD array covers a ground area of approximately 700 km^2 on a grid of 1.2 km spacing [3]. Three FD stations (Middle Drum (MD), Black Rock Mesa (BR), and Long Ridge (LR)) are located surrounding the SD array. The MD station consists of the 14 refurbished HiRes-I telescopes [4]. The BR and LR stations are constructed newly for the TA experiment. Here, the preliminary results from the TA three-year observations about energy spectra, mass composition and anisotropies are presented.

2. Shower analysis

2.1. Shower reconstruction with FD data

The FDs observe photons emitted along the track of air showers passing through the atmosphere. Due to the fact that the amount of the fluorescence lights which is the main component of light emission is proportional to the energy deposit, the energy deposit profile along the shower axis can be reconstructed from FD data. The calorimetric energy of the air shower is obtained by integrating the longitudinal profile. By taking into account the missing energy which is carried away by the neutrinos, the energy of the primary particle is obtained.

The analysis procedure for the MD data is almost identical to that of HiRes experiment [5]. For the BR/LR data analysis, new analysis procedure which is called an Inverse Monte Carlo method has been developed [6]. The observed charges at each PMT are compared with that produced by the simulated showers with all of the effects such as Cherenkov lights, shadowing by structures, non-uniformity of the PMT surface and other calibration factors. The systematic uncertainty of the energy determination is estimated to be 21% [6].

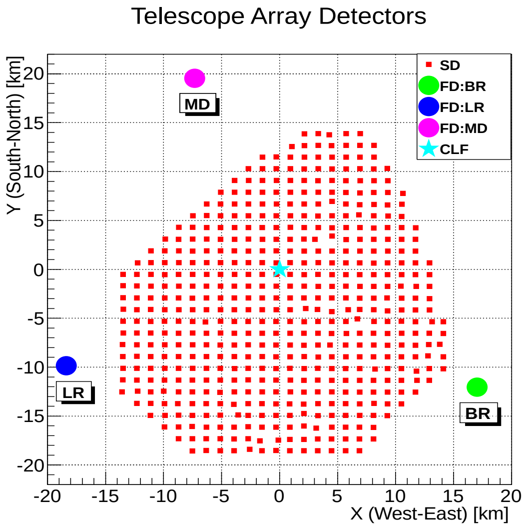

Figure 1. Overview of the TA detectors.

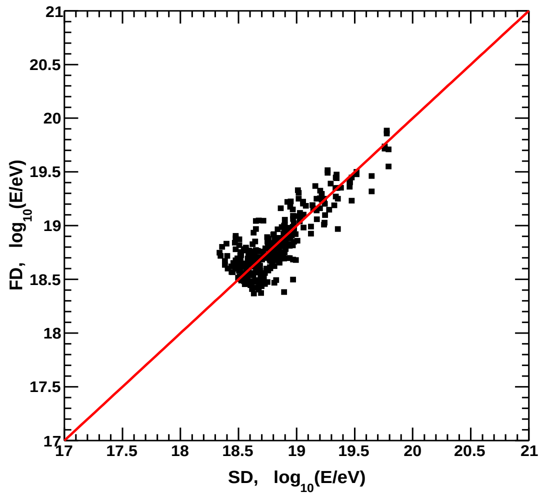

Figure 2. The scatter plot of the energies determined by FDs (MD monocular, BR/LR hybrid) and SD (rescaled by 1/1.27).

2.2. Shower reconstruction with SD data
The SDs observe shower particles at the ground. The basic idea of energy reconstruction is to use the charge density at the distance of 800m from shower core (S_{800}) as an energy estimator. The lateral distribution function which we used is an AGASA formula, and the reconstruction procedures are tuned with the TA SD data [7]. In order to take into account the atmospheric attenuation, we constructed the lookup table which consists of S_{800} and zenith angle for each primary energy by using a CORSIKA based Monte Carlo (MC) simulation code developed for TA [8].

Since the TA is operated as a hybrid detector, the energy scales of FD and SD can be compared by using the hybrid event. The scatter plot of the energies of well-reconstructed hybrid events is shown in Figure 2. This result shows that the energy of SD is 27% larger than that of FD. Sine we use the energy scale experimentally determined by FD, the SD energy is used with 27% renormalization.

3. Energy Spectra
The energy spectra above 10^{18} eV from the TA observations (MD monocular mode [5], BR/LR hybrid mode [6], and SD [7]) are shown in Figure 3. All of the three TA spectra are in good agreement. It is also important that the MD data, which were obtained from the refurbished HiRes-1 detectors and were analyzed with the identical procedures used in HiRes, is fully consistent with the HiRes-1 and HiRes-2 results. We applied a broken-power-law fit with two bending points to the SD spectrum. We found two break points, at $10^{18.69}$ eV as the “ankle” structure and at $10^{19.68}$ eV as a flux suppression. Above second bending points, we obtained 28 events for data and 54.9 events for expectation from continued spectrum. The significance of the suppression is evaluated as 3.9 σ.

4. Mass Composition
The difference of the primary nuclear types appears in the longitudinal developments of the air showers. In particular, the depth of maximum of air showers, X_{max}, is used as an estimator.

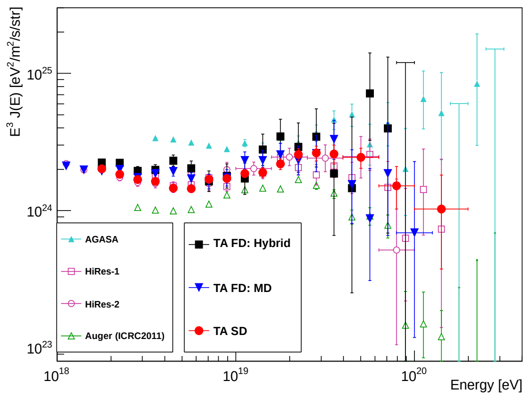

Figure 3. Energy spectra measured by TA data, MD monocular mode (filled triangle), BR/LR hybrid mode (filled square) and SD (filled circle).

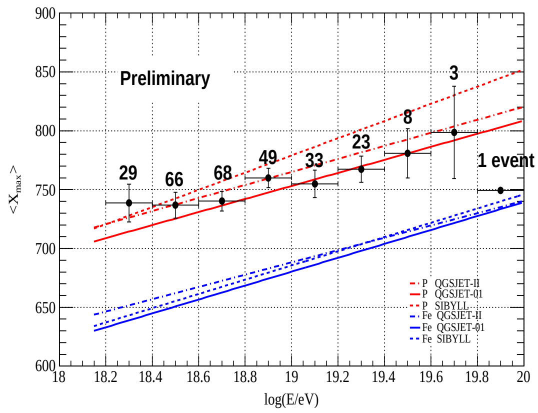

Figure 4. Averaged X_{max} measured by TA FD. Lines are expected values obtained from MC data for which applied same analysis procedure as that for the data.

Here we used BR/LR stereo events, observed simultaneously with two FDs, because the shower geometry can be determined more accurately than that of the monocular mode. Since field of view (FOV) of the FD is limited, the distribution of the observed X_{max} should be different from the prediction by air shower MC. Therefore, we constructed the MC data set which is generated by CORSIKA with detector simulation, and applied the same analysis procedure for real data. Here the prediction from MC data set includes all of the bias of FOV and analysis procedure.

The averaged X_{max} of the observed showers are shown in Figure 4 [9]. The TA data is consistent with the proton-dominated composition of UHECR. The distributions of X_{max} in each energy bin are also compared with the expectation from MC and checked by KS tests. By this analysis, the TA data are also compatible with proton primary predictions [9]. In the higher energies ($E > 10^{19.4}$ eV), TA data are compatible with the predictions both for proton and iron, but the statistics are still limited.

5. Anisotropies

The anisotropies of the UHECR are the powerful methods to know the origin of the UHECR. We used the TA SD data observed from May 2008 to April 2011, of zenith angles smaller than 45° and angular accuracies $\sim 1.5°$. There are 854 events above 10 EeV, 49 events above 40 EeV and 20 events above 57 EeV, respectively (Figure 6).

Firstly, we checked the correlations with the AGN objects, which reported by PAO [10]. The search condition is same as PAO; 57 EeV of threshold energy, 3.1 degrees of correlation angle, VCV catalog [11] with 0.018 of maximum redshift. We found 8 correlated events out of 20 events, while the number of chance correlation with the isotropic distribution is 5 [12]. Therefore, the AGN hypothesis by PAO is not supported by the TA SD data.

Secondly, we examined a correlation with large-scale structure (LSS), as a matter distribution in the universe. We constructed the expected density map by using 2 Mass Galaxy Redshift Catalog taking into account an smearing angle as a deflection effect by the galactic and extra-galactic magnetic field with an assumption on the proton primary [13]. The compatibilities of the LSS hypothesis with the TA events are investigated with the KS test for three energy thresholds, above 10 EeV, 40 EeV and 57 EeV respectively (Figure 7). The compatibilities for the events above 40 EeV and 57 EeV are rather higher, but not statistically significant from the isotropy hypothesis. Therefore, there are no evidences of the correlations with any astronomical objects in the present TA SD data.

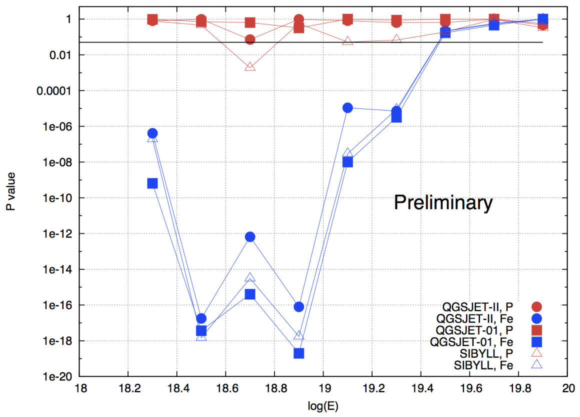

Figure 5. The compatibilities of the X_{max} distributions between observed data and MC obtained by KS test for various energy bins.

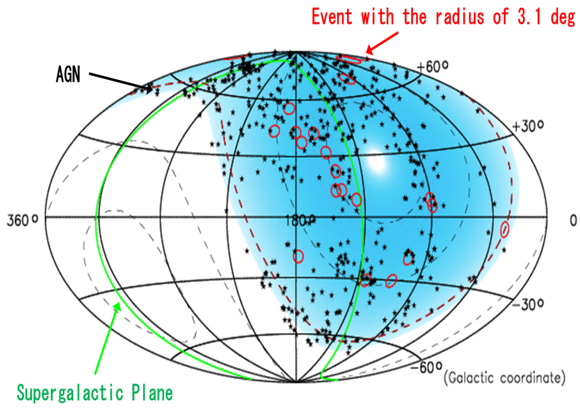

Figure 6. Observed 20 events above 57 EeV in galactic coordinates. Black points are the AGNs in the VCV catalog [11].

6. Conclusion

Here, the preliminary results from the TA three-year observations about three types of energy spectra, mass composition study with averaged X_{max} and distribution of X_{max}, and the search of three types of anisotropies are presented. The energy spectra measured by MD monocular mode, BR/LR hybrid mode and SD are in good agreement. By the result of the broken-power-law fit, we found two break points, at $10^{18.69}$ eV as the "ankle" structure and at $10^{19.68}$ eV as a flux suppression. The significance of the suppression from continuous spectrum is 3.9σ. We also measured the composition by using X_{max} observed by FDs. The TA data is consistent with the proton-dominated composition. In addition, we investigated the correlations between the arrival directions observed by TA SD and astronomical objects. No significant anisotropies are found in the present TA data.

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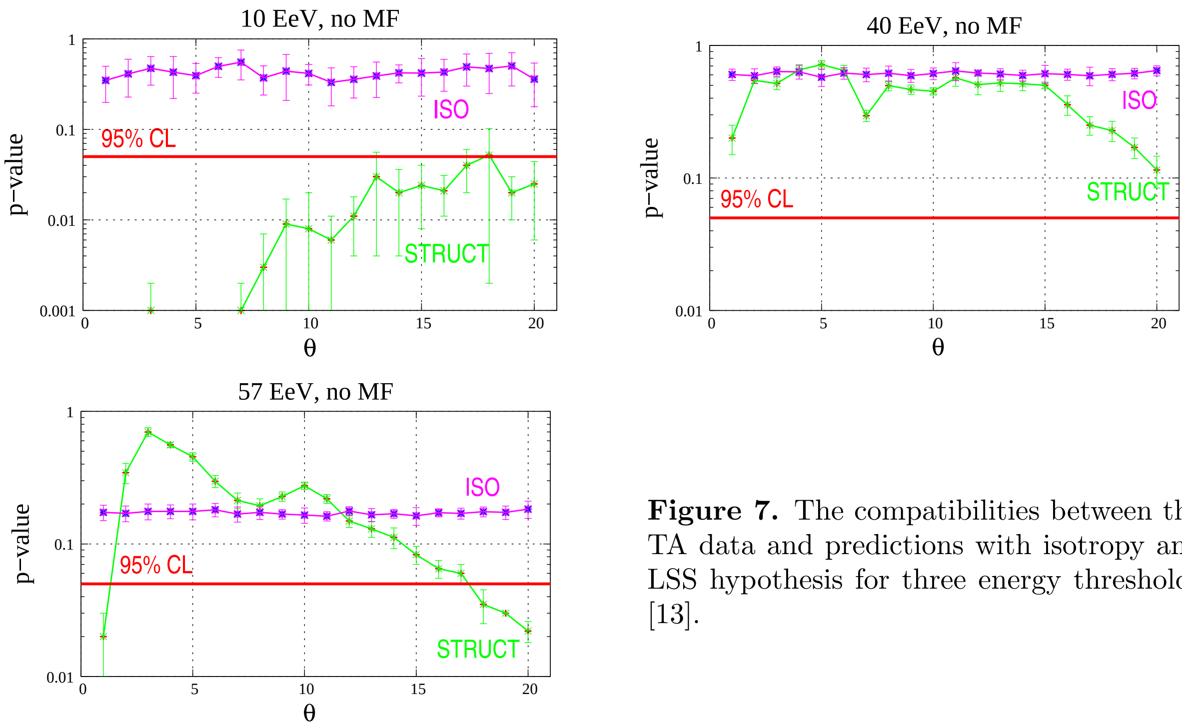

Figure 7. The compatibilities between the TA data and predictions with isotropy and LSS hypothesis for three energy thresholds [13].

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