Cosmic Ray in the Northern Hemisphere: Results from the Telescope Array Experiment

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Abstract. The Telescope Array Experiment is the largest extensive air-shower cosmic-ray detector in the northern hemisphere. TA combines three fluorescence detectors and a scintillation counter surface detector. The physics goals of TA are to measure the spectrum, composition, and arrival direction anisotropy of ultrahigh energy cosmic rays. We will present the latest results from Telescope Array.

1. Introduction
The Telescope Array (TA) experiment [1] is located in the desert of Millard County, Utah. The physical layout of the experiment is shown in figure 1. Three fluorescence detectors (FDs) shown by the green squares, are sited at the edge of a central ground array 507 scintillation surface detectors (SDs) marked by the Black squares. The ground array is arranged in a square grid pattern with a nearest-neighbor separation of 1.2 km, covering a total of 700 km$^2$. Each FD station views approximately 30$^\circ$ in elevation and 110$^\circ$ in azimuth, inward onto the surface array. Overall, the telescope array detector systems constitute a very large, homogenous, sampling calorimeter. The total mass of the active volume is of the order of $10^{13}$ kg. It is a non-compensating calorimeter with an $e/h$ ratio of about 1.1.

2. TA Surface Detectors
The active component of a TA SD counter is made of two layers of plastic scintillators, with a total collection area for particles of 3.0 m$^2$. Extruded grooves in the plastic carry wavelength-shifting optical fibers that collect and concentrate the scintillation light into two photo-multiplier tubes (PMTs), one for each layer. Each SD is powered entirely by a solar-panel battery power unit, and exchanges data over a 2.4 GHz wireless network. The SD counters are self-calibrated at ten-minute intervals using distribution of pulse heights from minimum-ionizing cosmic muons. Each PMT is continuously sampled at 40 million samples per second (40 MSPS). Data is stored at a counter for pulses corresponding to at least 0.3 vertical equivalent muon (VEM) over background. An event trigger occurs when a minimum of three adjacent counters are fired with at least 3 VEM each. A typical event is shown in figure 2.

In figure 2(a), the triggered counters and the their measured densities are shown by the circles and their area, respectively. The location, signal size, and arrival time detected by each counter are used to find the core location and arrival direction of the shower, using a modified Linsley time delay function [2]. The result of this fit is illustrated in figure 2(b). The particle densities from the participating SDs are then fitted to their distance from the shower core to the AGASA lateral density function (LDF) [3], and the density at 800 meters (S800) is interpolated from
**Figure 1.** The physical layout of the Telescope Array experiment. Black squares show the location of the 507 SDs. Green squares mark the FD stations.

**Figure 2.** (a) Display of a typical air shower event captured by the TA surface detector array. Each circle represents a triggered SD unit. (b) Shower arrival times at hit SD units fitted to determine the shower arrival direction. (c) Bottom Right: Particle density vs. distance from the shower axis fitted and interpolated to obtain the density at 800 m (S800). (d) Variation of S800 with the energy and zenith angle of simulated air showers.

The fit, as shown in figure 2(c). The S800 value is then compared to the average from simulated events, shown in figure 2(d) and the energy is interpolated according to the zenith angle.

### 3. TA Fluorescence Detectors

A total of 38 fluorescence telescopes are deployed over three sites. The first two sites were constructed on Black Rock (BR) Mesa and Long Ridge (LR) at the southern flanks of the SD array. These 24 telescopes were built in Japan, based on the same optical design and 256-pixel segmentation as the HiRes experiment, but with 30% larger mirrors of 6.8 m² area. A typical event captured by the FD station at Black Rock is shown in figure 3(a). Signals are recorded by each PMT pixel at 10 MHz, those containing a three sigma excess over night-sky background are designated hit pixels, and displayed as circles in the figure. The area of each circle is proportional to the integrated pulse area.

The pointing directions of the hit pixels are used to fit for a shower-detector plane (SDP),
Figure 3. (a) Display of a typical downward air shower event captured by the FD station at Black Rock. The circles correspond to channels with pulses in excess of three sigma over background, and the area of each circle represents the integrated pulse area. (b) Illustration of the FD shower-detector plane, and the time-fit to determine the shower trajectory.

which appears as a curve in the cylindrical projection of figure 3(a). The colors of pixels indicate time progression: blue represents the earliest arrival times at the top of the event, and red represents the latest at the bottom. The event depicted was clearly a downward going air shower. Next, the shower axis is found by fitting the pixel arrival times to

$$t_i = t_0 + \frac{R_P}{c} \tan \left( \frac{\pi - \psi - \chi_i}{2} \right)$$

As illustrated in figure 3(b), The output of the fit are: (1) $R_P$, nearest distance of approach of the shower axis to the FD, (2) $\psi$, the angle made by the shower axis to the line of intersection between the SDP and the ground, and (3) $t_0$, physically corresponds to the time at which the shower passes the point of nearest approach. The inputs are the measured times $t_i$ and the angles $\chi_i$ made between the PMT pointing direction (projected onto the SDP) and the ground, measured within the shower detector plane.

Figure 4. (a) Time-fit to determine $R_P$ and $\psi$. (b) Profile-fit to determine the energy and $X_{max}$ for the shower shown originally in figure 3(a)

Figure 4(a) shows the time-fit described above for the event shown in figure 3(a). Next, the pointing directions of the PMTs are converted to slant depth and the PMT signals are then fitted to a parametric Gaisser-Hillas form [4] for the shower size vs. depth. This fit includes scattered and direct Cherenkov light in addition to the fluorescence signal. The shower-profile
fit for this same event is shown in figure 4(b). The Energy is extracted from the overall area of the curve, and the depth of the shower maximum, $X_{\text{max}}$, from the longitudinal extent of this curve. Over many showers, the $X_{\text{max}}$ values give a statistical measure of the composition.

4. TA Energy Spectrum Measurement

A priority objective for TA was to resolve the controversy in the Greisen-Zatsepin-K'uzmin [5] cut-off. Using the fluorescence technique alone, HiRes reported the first observation of the GZK cut-off in 2008 [6], whereas earlier spectrum measurements by AGASA, using a scintillation ground array alone reported a continuing spectrum [7].

The MD FD station redeployed 14 telescopes from HiRes-1, the latter having provided most of the statistical significance for the GZK cut-off. This commonality between HiRes and TA allows us to compare the results of the two experiments directly. A variant of the monocular reconstruction was used that combined the timing and profile-fits of figure 4. This profile-constrained fit (PCF) was developed to overcome the very short tracks seen by the HiRes-1 detector, which only viewed up to 17° in elevation. To make a direct comparison, this analysis of the MD monocular FD data used exactly the same simulation and PCF reconstruction codes as was used for HiRes-1. The only changes made were updates of pointing geometry of the detectors, and lowering the trigger threshold in the simulation to reflect the reduced ambient background light at the TA site. Figure 5(a) shows the monocular spectrum from the Middle Drum FD station from its first three years of observation [8], overlaid with the HiRes monocular spectrum [6]. The two results agree both in the shape and normalization. The MD monocular spectrum is also consistent with the GZK cutoff.

![Figure 5](image)

**Figure 5.** (a) TA monocular spectrum from the Middle Drum FD station from its first three years of observation, overlaid with the monocular spectra from HiRes. (b) TA surface detector spectrum with event energies scaled down by a factor of 1.27, overlaid with the monocular FD spectrum from Middle Drum.

Figure 5(b) shows the cosmic ray energy spectrum from the first three years of TA SD data, overlaid with the monocular MD FD spectrum. The FD and SD spectra are in excellent agreement, and the SD spectrum clearly shows a suppression at the expected GZK cut-off. Note that the energies of the SD events used to make Figure 5(b) were divided by a scaling factor of 1.27 obtained by comparing the reconstructed energies of hybrid events seen by both FD and SD. Figure 6(a) shows a scatter-plot of log FD energy vs. log SD energy for the coincident events, after applying the 1.27 correction factor to the SD. This plot shows a linear relationship between the two energy measurements over the 1.5 decades of energy above $3 \times 10^{18}$ eV.

The hybrid event set can be analyzed using another variant of the monocular reconstruction, where times from the SD counters can be added to those of the FD for the fit to equation 3.
The benefit of this technique is that it provides much improved resolutions over that obtained by monocular reconstruction: angular resolution of $\sim 0.6^\circ$ for hybrid compared to $\sim 5 - 8^\circ$ for monocular, and $X_{\text{max}}$ resolutions of $\sim 30 \, \text{g/cm}^2$ for hybrid over that of $\sim 50 - 60 \, \text{g/cm}^2$ for monocular. Figure 6(b) shows a preliminary hybrid spectrum from the Middle Drum FD data overlaid with the SD spectrum. Again the two are in excellent agreement.

Figure 6. (a) Scatter-plot of the log FD energy vs. log SD energy (rescaled by 1.27) for hybrid events above $3 \times 10^{18} \, \text{eV}$. (b) The hybrid FD spectrum from Middle Drum overlaid with the (energy-rescaled) SD spectrum.

5. Composition and Anisotropy

Since 2009, there has been a discrepancy in the $X_{\text{max}}$-based composition results between the AUGER and HiRes collaborations. AUGER claims to see a trend toward heavier composition at above $10^{19} \, \text{eV}$ [9], whereas HiRes results are entirely consistent with proton composition [10]. Figure 7 shows the first TA composition result based on $X_{\text{max}}$ from stereo events, where the shower trajectory can be determined from the intersection of the two SDPs. In Figure 7(a), the distribution of $X_{\text{max}}$ for TA stereo events is compared to those of iron and proton events simulated with CORSIKA using the QGSJET-II hadronic model. Figure 7(b) shows the plot of mean $X_{\text{max}}$ vs. log energy for the same stereo data set. The accompanying curves show the predictions (folding in detector response and trigger selection) of CORSIKA simulations with different hadronic interaction models. The TA data, like that for HiRes, is again consistent with a predominately protonic composition, especially when compared to QGSJET models. Composition studies based on the width of the $X_{\text{max}}$ distributions, and on the width of the shower profiles as well as those using hybrid events are nearing completion.

The anisotropy searches in TA are based on the SD data. After the first three years, our data is entirely consistent with isotropy. A search was made in TA data against the claim made by the AUGER collaboration in the 2007 Science article [11], where 8 of 13 AUGER events above $5.7 \times 10^{19} \, \text{eV}$ were seen to be within $3.1^\circ$ of Active galactic nuclei in the Veron-Cetty catalog [12] with $z < 0.018$. For the northern sky, the prediction for TA was 15 correlations out of 20 TA events above $5.7 \times 10^{19} \, \text{eV}$, with five accidental background coincidences. Of the 20 events, eight were seen to be in coincidence with AGNs. This result is not a particularly significant departure ($p = 0.13$) from the null hypothesis. More TA data are needed.

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Figure 7. (a) Distribution of shower maximum depth ($X_{\text{max}}$) of TA stereo data compared to CORSIKA simulation for proton and iron, based on the QGSJET-II hadronic interaction model. (b) Plot of mean $X_{\text{max}}$ vs. log energy for the same TA stereo data set.

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