Recent Results from the Telescope Array Experiment

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The Telescope Array Experiment (TA) is the northern hemisphere's largest detector of ultra-high-energy cosmic rays (UHECRs). Built to measure the UHECR chemical composition, arrival-direction anisotropy, and energy spectrum for $E > 1$ EeV, TA's instrumentation includes both an array of scintillator-based particle counters and three fluorescence detector stations overlooking the ground array. This presentation highlights recent composition, spectrum, and anisotropy measurements based on UHECR data collected since TA operations began in 2007, including preliminary results for $E > 10$ PeV from the newly commissioned TA Low-energy Extension (TALE). The expected impact of planned expansions to the experiment will also be described.

1 Introduction

Ultra-high-energy cosmic rays (UHECRs) are subatomic particles that have been accelerated elsewhere in the cosmos to energies in excess of 10^{18} eV. Primary UHECR particles incident on Earth's atmosphere undergo inelastic collisions with gas nuclei, producing extensive air showers. These cascades of secondary particles produce ultraviolet light (via fluorescence emissions of excited nitrogen as well as the Cherenkov mechanism) en route to the ground, where the shower's electromagnetic and muonic footprint can be several kilometers wide in the case of the most energetic primary interactions.

The cosmic-ray flux is a steeply falling function over many orders of magnitude in energy, so that a detector with very large exposure is necessary for any experimental investigation of especially the highest-energy UHECRs' properties. The Telescope Array (TA) experiment is the northern hemisphere's largest UHECR detector, built on over 700 km^2 centered at approximately 39.3° N, 112.9° W in west-central Utah. The original TA instrumentation consists of 38 ultraviolet telescopes located at three fluorescence detector (FD) stations, operating since 2007, and 507 surface detectors (SDs) located every 1.2 km on a square grid, operating since 2008. The SD array and each FD station operate independently, as well as allowing hybrid SD+FD or stereoscopic FD+FD observation of individual showers.

Telescope Array's design facilitates the study of several distinct but interrelated aspects of the nature of UHECRs, and we present some recent highlights of these investigations here. After a brief review of the data analysis in Section 2, we report measurements of an intermediate-scale anisotropy we call the *hotspot* (Section 3), a proton-dominated chemical composition at all energies $E > 10^{18.2}$ eV (Section 4), and the differential energy spectrum manifesting four distinct spectral features in the range $15.9 \leq \log_{10}(E/\text{eV}) < 20.5$ (Section 5). Finally, we preview the present and future operations to enlarge the TA scientific program in Section 6.

2 Data analysis

The principle underlying TA data analysis is the reconstruction of the air shower properties responsible for the observed signal. The shower trajectory is first determined from an appropriate combination of signal timing and/or detector geometry, which enables the reconstruction of shower energy and, in the case of FD observations, the longitudinal development. The details of the analysis depend on whether the data being analyzed originated in SD or FD observation [1, 2].

A shower observed via direct detection of secondary particles by SDs has its impact position and zenith angle θ determined from the respective distribution of signal sizes and times. The observed signals are then projected onto a lateral distribution model, from which the shower density 800 m from the axis (s_{800}) is interpolated. A lookup table provides an estimate, determined from Monte Carlo simulation and calibrated to the FD energy scale via common events, of the primary shower energy for the observed combination of s_{800} and θ.

In the case of a shower observed via atmospheric fluorescence, the pattern of illuminated photomultiplier tubes (PMTs) constrains the shower trajectory to a plane including the position of the FD. Within this shower-detector plane, the shower's inclination angle and impact parameter determine the relative timing of the signals observed in each PMT.

An inverse-Monte Carlo technique determines the energy and atmospheric slant depth of shower maximum (X_{max}) by varying the longitudinal profile parameters of simulated showers, until reaching the best agreement in detector response between simulation and data.

3 Anisotropy above 57 EeV

Based on five years of SD observation, a directional excess in the flux of UHECRs with $E >$ 57 EeV has been observed in the constellation Ursa Major [3]. Given the exposure of the SD array, the expected number of events within a 20° radius was 4.5, but 19 were observed, a 5.1σ excess (see Fig. 1). The chance probability of our observing an excess of this size from an isotropic flux, given intermediate-scale event oversampling in 5° steps from 15° to 35°, is 3.7×10^{-4}, for a post-trials significance of 3.4σ. Preliminary analysis including a sixth year of data increases the significance of the observation to 4.0σ.

4 Mass composition

It is possible to estimate the mean mass of primary cosmic rays as a function of energy by comparison of the observed X_{max} distribution to model predictions for known compositions. Using the hybrid combination of data from the SD array and the Middle Drum FD (consisting of equipment refurbished from the High Resolution Fly's Eye experiment), we find our observations compatible with a predominantly protonic composition at all energies $E > 10^{18.2}$ eV regardless of the choice of hadronic interaction model used in simulation [4].

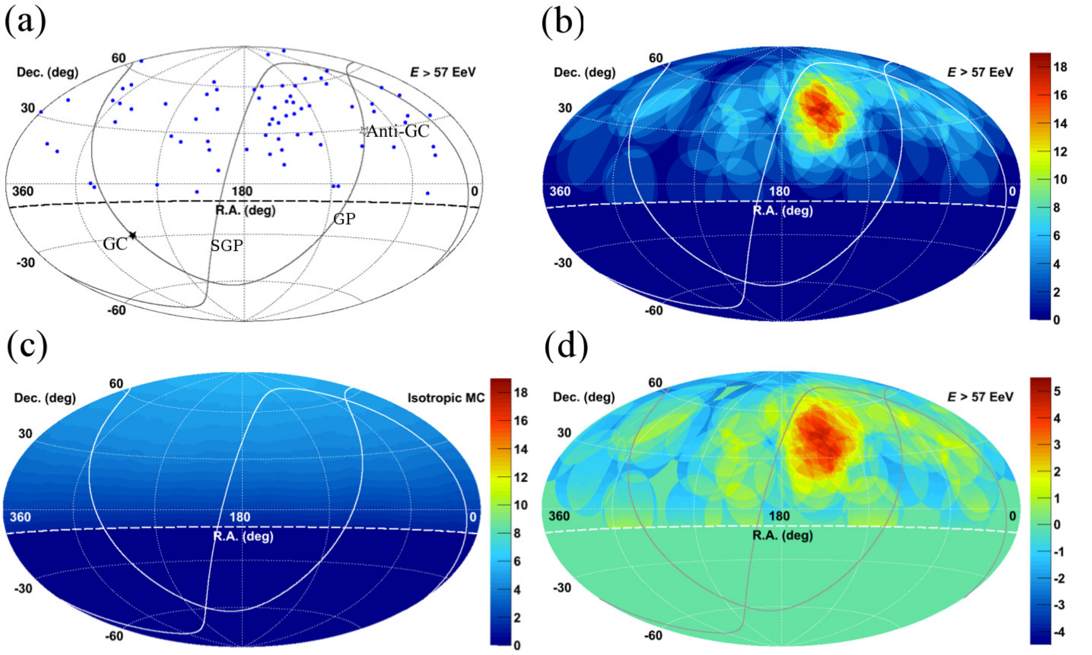

Figure 1: Anisotropy above 57 EeV: (**a**) arrival directions; (**b**) arrival directions with 20° oversampling; (**c**) expected number of events assuming isotropic null hypothesis; (**d**) Li-Ma significance of excess.

5 Energy spectrum

Using six years of data from the SD array, we observe two features in the UHECR spectrum: a hardening *ankle* at $10^{18.70\pm0.02}$ eV and a suppression above $10^{19.74\pm0.04}$ eV compatible with the *GZK cutoff* predicted for protons. The suppression represents a 6.59σ deficit relative to a spectrum maintaining the post-ankle spectral slope without cutoff.

The newly commissioned TA Low-energy Extension (TALE) includes ten FD telescopes observing at higher elevation angles than the main FD configuration, complemented by an array of closely-spaced ($\sim$ 400 m) SDs, to reduce the energy threshold for shower detection [5]. A preliminary analysis using fluorescence and Cherenkov light seen by the TALE FD extends the observed spectrum to below 10 PeV and reveals two additional spectral breaks.

6 Future operations

A number of operations are being pursued to upgrade Telescope Array in the coming years. A quadrupling of the TA exposure above 10^{19} eV (TA×4) will be accomplished by adding another 500 SDs with greater spacing, overlooked by two additional FD stations. The detection threshold will be pushed further down into the PeV decade via a Non-Imaging Cherenkov Experiment (NICHE [6]) cross-calibrated with TALE events. Progress continues toward UHECR detection via bistatic radar (TARA [7]), and we are exploring claims of a connection between thunderstorms and high-energy radiation with a lightning-mapping array (TALMA). The science program at Telescope Array continues to grow increasingly expansive and robust.

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