Telescope Array: Latest Results and Expansion Plans

Douglas Bergman, for the Telescope Array Collaboration
Dept. of Physics and Astronomy, University of Utah, Salt Lake City UT, USA
E-mail: bergman@physics.utah.edu

Abstract. We present the latest physics results from the Telescope Array Experiment, including an update to the ultra-high energy cosmic ray spectrum, new cosmic ray composition measurements in both hybrid and stereo modes, an update on the TA hotspot, and new measurements at lower energies using the NICHE array. We also give a status update on the TA\times4 expansion currently underway.

Telescope Array (TA) is the largest cosmic ray detector in the northern hemisphere. It is located in the West Desert in the State of Utah in the United States of America. It is run by the Telescope Array Collaboration, 140 physicists from 36 institutions in 6 countries: Japan, USA, South Korea, Russia, Belgium and the Czech Republic. It is a hybrid detector consisting of 507 surface detectors (SDs) on a square grid with 1.2 km separations overlooked by three fluorescence detectors (FDs). The SDs are dual-layered scintillator particle detectors with a surface area of 3 m$^2$ covering a total area of 700 km$^2$[1]. The three FD stations consist of 38 separate Schmitt camera telescopes. Each station observes elevation angles from 3° to 31° and has azimuthal angle range of 108° for the southern two sites and 120° for the northern site[2]. In the North part of the TA site is the TA Low Energy (TALE) detector consisting of an in-fill array of SDs with smaller spacings of 600 and 400 m and overlooked by another FD with telescopes observing from 31°–59°. Directly in front of the TALE fluorescence detector is an array of 14 non-imaging Cherenkov detectors, called NICHE.

TA has measured the spectrum of ultra-high energy cosmic rays (UHECRs) using 11 years of surface detector data. The measured spectrum is shown in Figure 1. The data for the spectrum was collected between 11 May 2008 and 11 May 2019. The spectrum has been fit to a broken power law. The measured power law slopes are $-3.28 \pm 0.02$, $-2.68 \pm 0.02$ and $-4.8 \pm 0.5$, with breaks at $\log_{10}(E/eV)$ of 18.61 ± 0.01 and 19.81 ± 0.03. The data used for this spectrum have a cut on the zenith angle of included showers less that 45°. For cosmic ray energies above $10^{18.8}$ eV, the TA SD is fully efficient and a larger zenith angles can be accepted out to 55°.

The TA spectrum has some declination dependence. If one splits the 55°-zenith angle data into sets above and below 24.8° in declination and fits to a broken power-law, one finds the high energy breakpoint of the two samples are different: 19.84 ± 0.02 for the high declination sample, 19.64 ± 0.04 for the low. This difference has a 4.3$\sigma$ global significance. These two spectra and the fits are shown in Figure 2[3].

The TALE fluorescence detector allows one to measure the cosmic ray spectrum at lower energies, and to measure a combined spectrum for cosmic rays over 5 orders-of-magnitude. At the lowest energies, TALE works as an imaging air-Cherenkov detector, meaning that the observed events are dominated by direct Cherenkov light produced by shower particles. While these observations are monocular, the constraing on possible shower geometries constrain the
Figure 1. The all-particle energy spectrum of UHECRs as measured by the TA surface detector using 11-years data. The zenith angle cut used is 45°.

Figure 2. The cosmic ray spectra above and below 24.8° in declination as measured by SD with 11-years data and a zenith angle cut of 55°.

measurement greatly reducing the systematic energy uncertainty due to the geometry. The combined TALE/TA SD spectrum is shown in Figure 3. TALE also measures a spectrum with mixed Cherenkov and fluorescence signals. The spectrum calculated using this data is shown in Figure 4[4].

Figure 3. The all-particle energy spectrum of cosmic ray as measured by the TA SD and the TALE fluorescence detector in Cherenkov mode.

Figure 4. The cosmic ray spectrum as measured by the TALE FD using mixed Cherenkov-fluorescence events.

TA composition measurements use the fluorescence telescopes to measure the longitudinal development of air-showers. The location of the shower maximum is an indicator of the nuclear species of the primary cosmic ray which initiated the shower. The geometry of the shower must be well determined to reduce uncertainties about the depth of shower max, \( X_{\text{max}} \). We perform composition measurements using stereo measurements, using two or more fluorescence detectors simultaneously, and hybrid measurements, using both surface detectors and fluorescence detector. Stereo measurements have a higher energy threshold than the hybrid measurements since the shower must be visible by two detectors simultaneously but they have a large aperture at high energies because they are not constrained to the area covered by the surface detectors. When comparing the observed mean \( X_{\text{max}} \) values with expectations of H and Fe as produced by the QGSJettII-04 model, the data is on the lighter side for all energies from
$10^{18.4} \text{ eV}$ to $10^{20} \text{ eV}$\cite{5}. The resolution in measuring $X_{\text{max}}$ is 25 g/cm$^2$, while the systematic uncertainty in measuring the average value of $X_{\text{max}}$ is 15 g/cm$^2$.

The hybrid measurements have a slightly better resolution in of $X_{\text{max}}$ is 17 g/cm$^2$. We show the mean value of the $X_{\text{max}}$ distributions up to an energy of $10^{19.1} \text{ eV}$ in Figure 5. Along with predictions for H, He, N and Fe nuclei from the QGSJet II-04 model. All the data is consistent with being light nuclei\cite{7}.

![Figure 5](image1.png)  
**Figure 5.** The average value of $X_{\text{max}}$ vs energy for TA hybrid measurements along with QGSJet II-04 predictions for H, He, N and Fe nuclei. Systematic uncertainty bands are also shown for the data and for the H and He predictions indicating that the data is consistent with either of these two species.

![Figure 6](image2.png)  
**Figure 6.** The width of the $X_{\text{max}}$ distribution vs energy for TA hybrid measurements along with QGSJet II-04 predictions for H, He, N and Fe nuclei. The systematic uncertainty band for the data is also shown indicating consistency with the expected width of H nuclei.

Because of the systematic uncertainty of both the average $X_{\text{max}}$ of the data and the modeling uncertainty of location of the average $X_{\text{max}}$ for various species (the width of the $X_{\text{max}}$ distribution has a much smaller model uncertainty), we performed an analysis where we shifted the predicted QGSJet II-04 $X_{\text{max}}$ distributions by various amounts until we found the best agreement with the data distribution. We then looked at the quality of this agreement with a K-S test vs the energy of the bin for each of the single species. We find that the observed $X_{\text{max}}$ distribution is consistent with the H prediction for all energies but with about a 20 g/cm$^2$ shift. Our distribution is consistent with pure He only for energies above 10 EeV, only a very small shift is required. N and Fe primaries are only consistent at the highest energies where the data statistics limit the power of the comparison. The results of this analysis are shown in Figure 7\cite{7}.

The “TA Hotspot” continues to persist in TA data with 11-years data. There are currently 168 events with energy above 57 EeV in the TA data, 38 of which are within a 25$^\circ$ circle, where 14.2 would be expected. This is a 5.1$\sigma$ local significance, which becomes a 2.9$\sigma$ global significance after accounting for trials. The sky-map for these events is shown in Figure 8. For comparison the initial “TA Hotspot” using 5-years data had 19 events out of 72 events over 57 EeV within a circle of 20$^\circ$. The growth of the current hotspot is consistent with a steady source\cite{9}.

The Non-Imaging CHErenkov (NICHE) Array sits within the field-of-view of the TALE fluorescence detector at a distance of about 800 m. It consists of 14 counters stationed on a square grid with 100-m separation. Each counter has a 3$^\circ$ photomultiplier tube augmented with a 45$^\circ$ Winston Cone. NICHE and TALE Cherenkov can work together to perform an air-Cherenkov hybrid measurement of cosmic rays in the 1–10 PeV range. The hybrid timing fit
Figure 7. KS-test $p$-values for comparisons of shifted data to single species model (over isotropy) of the 168 TA events above predictions from QGSJettII-04. The color of the points indicates how much the prediction had to be shifted in order to get the given (best fit) comparison.

Figure 8. The sky-map of the significance (over isotropy) of the 168 TA events above 57 EeV. The significance is calculated using $25^\circ$ top-hat averaging.

has an uncertainty in measuring the in-lane angle of the shower to about 0.2°. NICHE working by itself, but with core and position information from TALE can measure the time width of the Cherenkov light at some distance from the shower core. This width varies with the distance from $X_{\text{max}}$ and so can be used to measure cosmic ray composition in the PeV range. NICHE has demonstrated this relationship experimentally for the first time[8].

TA is expanding to be a factor of 4 larger than the current area, covering 3,000 km$^2$. The new area will be covered by 500 new SD counters, similar SD counters to standard TA, but with a larger spacing of 2.08 km. This will increase the energy threshold for the detector, but will allow a much larger aperture for events in the TA hotspot. The new SDs will be overlooked by two new fluorescence detectors which will observe elevation angles from $3^\circ$–$17^\circ$. The fluorescence detector for the North lobe was deployed in 2018, and took first light 16 Feb 2018. The FD for the South lobe is currently under construction. 257 of the SDs were deployed Feb-Mar 2019 and are currently being commissioned. The remainder of the new SDs will be deployed in the Winter of 2020.

References
[1] T. AbuZayyad et al., Nucl. Inst. Meth. A 689 (2012) 87.
[2] H. Tokuno et al., Nucl. Inst. Meth. A 676 (2012) 54.
[3] D. Ivanov, PoS(ICRC2019)298.
[4] J.H. Kim, T. AbuZayyad, PoS(ICRC2019)314.
[5] D.R. Bergman, T. Stroman, PoS(ICRC2019)191.
[6] W. Hanlon, PoS(ICRC2019)280.
[7] K. Kawata et al., PoS(ICRC2019)
[8] D.R. Bergman, PoS(ICRC2019)189.
[9] K. Kawata et al., PoS(ICRC2019)055.