PROCEEDINGS OF SCIENCE

# Telescope Array extension: TA×4

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The Telescope Array (TA) aims to explore the origin of highest energy cosmic rays using Surface Detectors (SDs) and Fluorescence Detectors (FDs) located in Utah, USA. The SD array consists of 507 scintillation detectors arranged on a square grid of 1.2-km spacing, covering approximately 700 km$^2$. The FD telescopes, located at three sites, look over the surface array. Using the first six years of data collected by the surface detectors, we found a cluster of cosmic rays with energies greater than $5.7\times10^{19}$ eV that we call the hotspot. With enhanced statistics, we expect to observe the structure of that hotspot along with other possible excesses, point sources along with the correlations with extreme phenomena in the nearby universe. We plan to quadruple the area of the TA SD array to approximately 3,000 km$^2$, by adding 500 surface detectors with 2.08-km spacing. Two FD stations will be constructed viewing the new SD array. This TA extension that we call TA×4 will greatly accelerate the pace at which we will reach the goals we have set above, and will enhance TA's cosmic ray energy spectrum measurements and composition studies at the highest energies. At this conference, we present our plan for TA×4.

*The 34th International Cosmic Ray Conference,*
*30 July- 6 August, 2015*
*The Hague, The Netherlands*

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## 1. Introduction

TA is the largest Ultra-High Energy Cosmic Ray (UHECR) observatory in the northern hemisphere (Section 2), It aims to explore the origin and nature of UHECRs by a hybrid technique combining SDs and FDs with an aperture significantly larger than those of the previous generation of experiments. Recent results from TA have yielded important results of the physics of UHECRs (Section 3). Firstly, a flux suppression of cosmic rays at energies greater than $5.4\times10^{19}$ eV using the first four-year data has been confirmed [1]. Secondly, an indication of a cluster of arrival directions of cosmic rays with energies greater than $5.7\times10^{19}$ eV has been found near the super-galactic plane (SGP) [2]. Thirdly, the composition measurement based on shower maximum depth ($X_{\rm max}$) from the initial five years of data has been consistent with a light, largely protonic, composition [3].

The above results support a scenario in which cosmic rays are accelerated at sources that are distributed similarly to visible matter in the universe, and propagate with energy loss from interactions with cosmic microwave background photons. In this picture, a suppression of cosmic ray flux, known as the GZK cut-off, is expected at the highest energies. And because of the high rigidity of protons at these energies, the arrival directions of the cosmic rays should follow the distribution of matter inside the GZK horizon, and exhibit observable anisotropy.

Based on the TA results, we propose to quadruple the acceptance of the current TA detector in the trans-GZK energy region, in order to accelerate the pace of the studies listed in the preceding paragraphs. We will summarize this paper in Section 5.

## 2. Telescope Array

TA is located in the West Desert in Millard County, Utah, USA (latitude 39.3° N, longitude 112.9° W, altitude $\sim$1400 m). It observes extensive air showers (EAS) induced by the UHECRs with energies greater than $\sim10^{18}$ eV for the measurement of the energy spectrum, arrival direction and mass composition.

TA uses a surface detector array of 507 scintillation counters to measure the lateral distribution and arrival times of secondary particles on the ground. They are deployed on a square grid of 1.2-km spacing, and covers approximately 700 km$^2$ [4]. Each SD has two 1.2-cm thick layers of plastic scintillator each 3 m$^2$ in area. Signal light produced in the scintillators by secondary charged particles from an air shower is collected by wavelength shifting optical fibers. These are placed in extruded grooves on each scintillator. The fibers then gather the photons and channel them to a photomultiplier tube (PMT), one for each layer. The resulting electronic waveforms are digitized by 12-bit FADCs at a sampling rate of 50 MHz.

To measure the longitudinal development of the EAS in the atmosphere, the FD stations were built at three sites on the periphery, looking inward over the SD array. The Middle Drum (MD) FD site is located to the north of the SD array, and is instrumented with 14 refurbished telescopes from the High-Resolution Fly's Eye (HiRes) experiment [5]. These telescopes view from 3°-31° above the horizon and 114° in azimuth. The Black Rock Mesa (BRM) and Long Ridge (LR) FD sites are located to the southeast and southwest of the SD array, respectively. They are each instrumented with 12 new telescopes [6].

The TA is operated by an international collaboration of researchers from Japan, USA, Russia, Belgium and Korea. Hybrid observation with both surface detectors and fluorescence detectors started in March 2008.

## 3. Recent TA results

Here we summarize the recent TA results of energy spectrum, arrival directions and mass composition of UHECRs.

### 3.1 Energy spectrum

Figure 1 shows the energy spectrum measured from the first six years of TA surface detector array data. A piece-wise power-law fit to the data points found two breaks at 5.0×$10^{18}$ eV and 5.6×$10^{19}$ eV, corresponding to the ankle and the GZK cutoff expected for protons, respectively. An extended spectrum beyond the GZK cutoff energy is ruled out with a statistical significance of $6.6\sigma$.

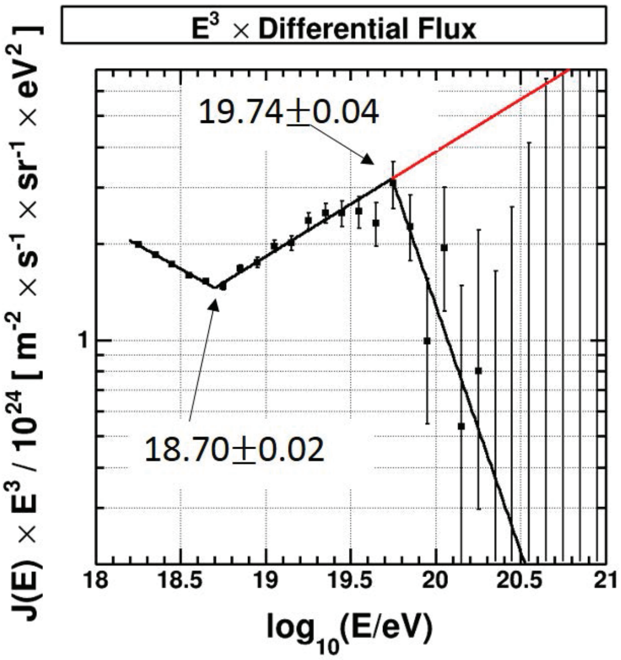

**Figure 1:** Cosmic-ray flux multiplied by $E^3$ using the TA SD data collected for a period of six years. The solid line shows the fit of a piece-wise power-law model to the TA SD data (black filled circles).

The TA spectrum shown above is well described by a calculation of the propagation of proton cosmic rays with energies greater than $10^{18.2}$ eV from the sources with spectral index of 2.2 and strong evolution of the source density with redshift [7].

### 3.2 Arrival directions

We have searched for intermediate-scale anisotropy in the arrival directions of UHECRs with energies greater than 5.7×$10^{19}$ eV in the northern sky using data collected over a five-year period between May 2008 and May 2013 by the surface detectors. We reported a cluster of events that we call the hotspot, which was found by oversampling 20-degree-radius circles [2]. The hotspot had an excess of $5.1\sigma$, as given by Li-Ma statistics, and is centered at R.A. = 146.7°, Dec. = 43.2°. The center of the hotspot was about 19° off of the super-galactic plane (SGP). The probability of a cluster of events of $5.1\sigma$ significance, appearing by chance in an isotropic cosmic-ray sky, was estimated to be $3.7\times10^{-4}$ ($3.4\sigma$). We have updated this analysis by adding the data collected between May 2013 and May 2014. With six years of data, the hotspot has grown to a $5.55\sigma$ excess, as shown in Figure 2. The new center of the hotspot is about 17° off of the SGP. The probability of the hotspot of $5.55\sigma$ excess, appearing by chance in an isotropic cosmic-ray sky, is estimated to be $3.1\times10^{-5}$ ($4.0\sigma$).

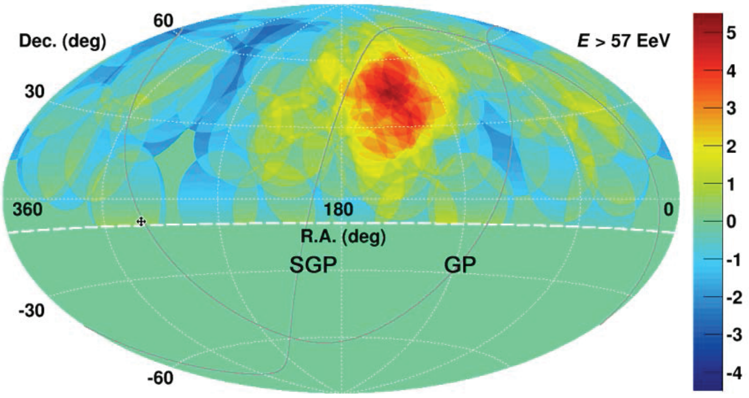

**Figure 2:** Aitoff projection of significance map, in equatorial coordinates, of the UHECRs with energies greater than $5.7\times10^{19}$ eV observed by the TA surface detector for a period of six years. The significance at each direction was calculated by summing the number of observed events over a 20° radius circle and comparing to the fluctuation in the number of background events expected from an isotropic arrival distribution. The solid curves indicate the galactic plane (GP) and super-galactic plane (SGP). Our field of view is shown by the region above the dashed curve at declination = $-10°$.

### 3.3 Mass composition

TA uses the distribution of the shower maximum depth ($X_{\max}$) to determine the mass composition. The result from events simultaneously observed by the MD FD and surface detectors (hybrid events) for five years was reported in [3]. The energy evolution of the average $X_{\max}$ was compared with the MC data with energies greater than $10^{18.2}$ eV as shown in Figure 3. The result is in agreement with a light, largely protonic, composition.

## 4. TA×4

The TA results are consistent with a picture of cosmic rays from extragalactic objects dominated by protons, and interacting with cosmic microwave and infrared background photons [7]. Subjected to relatively small deflections of highest-energy cosmic rays, their arrival directions should be correlated with nearby matter distribution in the universe, and are, therefore, expected to be anisotropic. To accelerate this study, we propose to quadruple the acceptance of the current TA detector in the trans-GZK energy region and above.

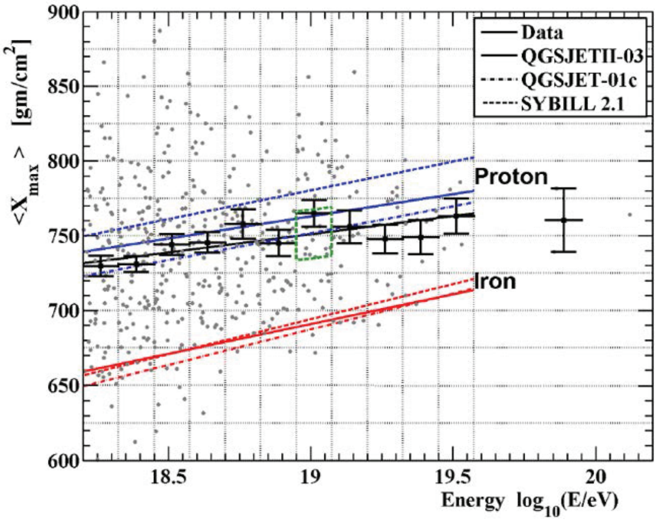

**Figure 3:** The plot of $X_{\rm max}$ values (grey points) for each data as a function of energy, overlaid are QGSJET-01c (dot-dashed line), QGSJETII-03 (solid line), and SIBYLL 2.1 (dashed line) hadronic models. Black data points with error bars represent the data average $X_{\rm max}$ values, in 12 energy bins (of width $\log_{10}(E/eV)$ = 0.125), that are plotted as a function of bin energy. The black rail is a fit to these binned values. Colored lines are fits to MC. Blue is proton and red is iron. The green hashed box indicates the total systematic error on average $X_{\rm max}$.

The current TA surface detector consists of 507 detectors on a square grid of 1.2-km spacing, covering approximately 700 km$^2$. For an aperture extension, we plan to fabricate 500 more surface detectors and deploy them on a square grid of 2.08-km spacing to the east of the current TA site. The new surface detector is composed of two sub-arrays, and covers three times the area of the current TA surface detector. Combined with the current SD, the total area will be increased to approximately 3,000 km$^2$, quadrupling the acceptance from that of the existing TA surface array (see Figure 4). Our plan for TA×4 is to construct new SD counters using the existing TA design.

We also plan to install two additional FD stations consisting of refurbished HiRes-II telescopes, one each at the MD and BRM sites. These telescopes will view from 3°-31° above the horizon and the azimuthal fields of view are shown by fan shapes pictured in Figure 4. The primary purpose of the additional FDs is to provide the energy cross-calibration for the new sparse SD arrays, and also to maximize the hybrid detection aperture of TA.

The proposal for the SD extension of TA×4 from Japan was approved in April 2015 [8], and will be in effect over a period of five years between April 2015 and March 2020. We plan to deploy all surface detectors by helicopter in a period of a few months in the autumn of 2017. The existing TA detectors will continue to operate during this time. The operation of the full TA×4 will begin in December 2017. Upon the expected approval for the proposal of two additional FD stations from US in 2016, we plan to start construction of the first FD at the MD site in 2016 and start its observation in 2017. We will then construct the second FD at the BRM site in 2017 and start its observation in 2018. Including data already taken, we expect to have accumulated in total the equivalent of 19 years of the current TA SD data and 16.3 years of the current TA hybrid data by May of 2020 as shown in Table 1.

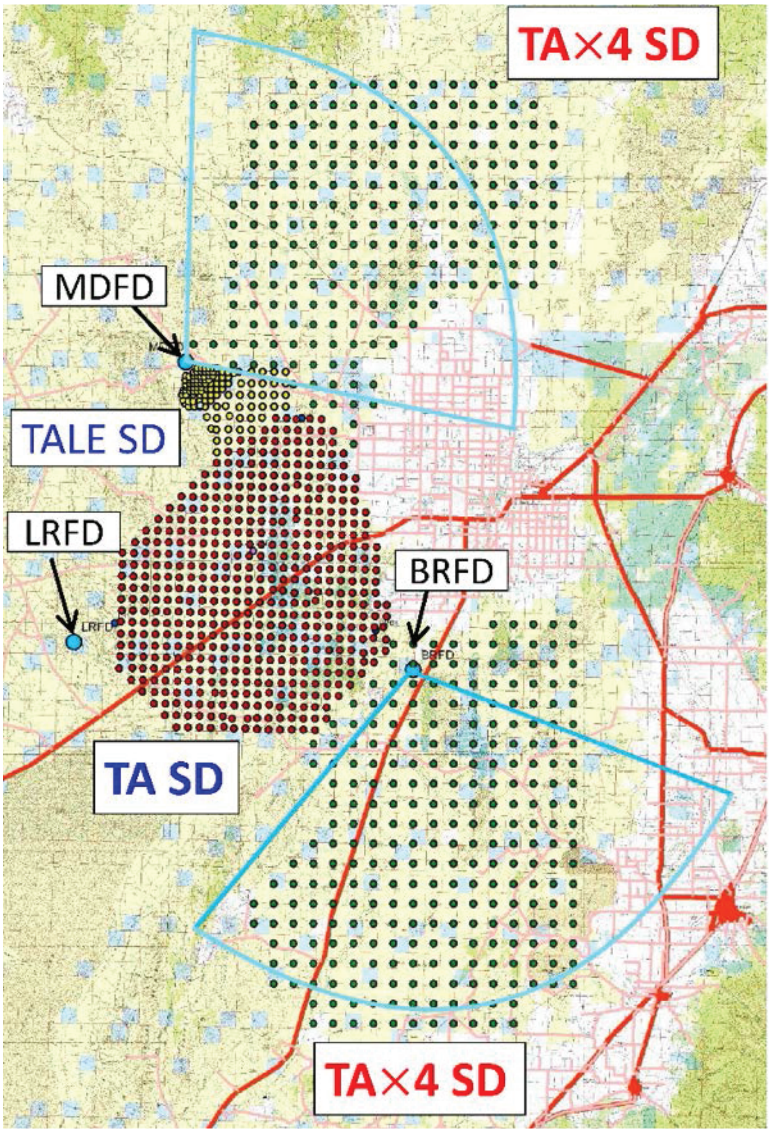

**Figure 4:** The layout of TA×4. The array of 507 SDs (red filled circles) constitutes the current TA SD array. The three blue filled circles are the TA FD stations (MD to the north, LR to the west, and BRM to the east of the TA SD array). The array of SDs (yellow circles) to the north of the TA SD array is the TALE SD array. The two new SD sub-arrays (green filled circles) to the east of the TA SD array form TA×4. New FD stations with refurbished HiRes telescopes will be installed at the MD and BRM sites. Fan shapes show the field of view of the two new telescope stations.

The main physics objectives of the TA×4 program are as follows:

- Confirmation of the hotspot at a post-trial significance greater than $5\sigma$ and search for its origin
- Studies of the fine structure of the hotspot and search for other excess spots
- Searches for correlations of UHECR arrival directions with astronomical objects and with cosmological structures

| JFY | construction or observation | surface detector (SD) | | hybrid (HYB) | |
|---|---|---|---|---|---|
| | | TA SD (=1) (=1) | additional SD (=3) | TA HYB (=1) | additional HYB (=3) |
| 2008-2014 | observation | 7 | 0 | 7 | 0 |
| 2015 | construction | 1 | 0 | 1 | 0 |
| 2016 | construction | 1 | 0 | 1 | 0 |
| 2017 | construction/(2/3) observation(1/3) | 1 | 1 | 1 | 0.3 |
| 2018 | observation | 1 | 3 | 1 | 2 |
| 2019 | observation | 1 | 3 | 1 | 2 |
| subtotal | | 12 | 7 | 12 | 4.3 |
| total | | 19 | | 16.3 | |

**Table 1:** The plan for data accumulation by TA×4. JFY is the abbreviation for the Japanese Fiscal Year that starts in April. The amounts of the SD and hybrid data are shown in units of (existing) TA 1-year SD data and TA 1-year hybrid data, respectively. Since the duty cycle of FD is about 10%, the number of hybrid events is about 10% of SD events.

- Search for point sources of highest-energy cosmic rays
- Establishing definitive spectral features of the flux suppression in the highest energy region, which will give astrophysical picture of the origin of UHECRs
- Determination of mass composition around the flux suppression, which is important to understand the origin of the flux suppression and nature of the cosmic-ray sources. As seen in figure 3, the statistics of events already collected by TA with energies greater than $10^{19}$ eV is not enough to settle these questions.
- Setting flux limits or measuring UHE gamma rays and neutrinos, which are key to understanding the cause of the flux suppression

## 5. Summary

The Telescope Array (TA) is the largest experiment studying the origin and nature of ultra-high energy cosmic rays in the northern hemisphere. From the SD data collected for the first six years, TA has confirmed the flux suppression above $5.6\times10^{19}$ eV, consistent with GZK cutoff, with a statistical significance of $6.6\sigma$. TA has also observed the ankle at $5.0\times10^{18}$ eV. From the arrival directions of cosmic rays with energies greater than $5.7\times10^{19}$ eV, we found an evidence for a cluster of events that we call the hotspot with a post-trial significance of $4.0\sigma$ by oversampling $20^\circ$ radius circles. The hotspot is located near the Ursa Major galaxy cluster situated in the super-galactic plane. From the SD and FD hybrid data collected for a period of five years, the measurement of $X_{\max}$ of cosmic rays with energies above $10^{18.2}$ eV is consistent with a light, largely protonic, composition.

These TA results support a picture where UHECRs are extra-galactic in origin, dominated by protons, and their arrival directions can be correlated with nearby super-galactic clusters or matter distribution in the universe. With enhanced statistics, we expect to observe the structure of that hotspot, other excess spots, point sources, and the correlations with extreme phenomena in the nearby universe. Therefore, we propose to expand the aperture of the TA SD by a factor of four by building 500 additional counters, based on the current TA SD design, but deployed on a square grid with 2.08-km spacing. Coupled with additional two FD sites, the expanded TA×4 will achieve by 2020 the equivalent of 19 and 18.5 years of SD and hybrid exposures of the current TA, respectively. In April 2015, the proposal for the SD part of TA×4, which is a five-year plan for the construction and observation of additional SDs, was approved in Japan.

**Acknowledgments:** TA×4 is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Promoted Research (15H05693) "Extended Telescope Array Experiment - Nearby Extreme Universe Elucidated by Highest-energy Cosmic Rays." The Telescope Array experiment is supported by the aid from the University of Tokyo, the Inter-University Research Program of the Institute for Cosmic Ray Research, and Scientific Research (S) (19104006); by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0649681, PHY-0703893, PHY-0758342, PHY-0848320, PHY-1069280, PHY-1069286, PHY-1404495 and PHY-1404502; by the National Research Foundation of Korea (2007-0093860, R32-10130, 2012R1A1A2008381, 2013004883); by the Russian Academy of Sciences, RFBR grants 11-02-01528a and 13-02-01311a (INR), IISN project No. 4.4502.13, and Belgian Science Policy under IUAP VII/37 (ULB). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles, and George S. and Dolores Dor*é* Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management, and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions. An allocation of computer time from the Center for High Performance Computing at the University of Utah is gratefully acknowledged.

## References

[1] T. Abu-Zayyad *et al.*, Astrophysical Journal Letters, 768 (2013) L1 (5pp).

[2] R.U Abbasi *et al.*, Astrophysical Journal Letters, 790 (2014) L21 (5pp).

[3] R.U Abbasi *et al.*, Astroparticle Physics 64 (2015) 49-62.

[4] T. Abu-Zayyad *et al.*, Nuclear Instrumentation and Methods A689 (2012) 87-97.

[5] D.C. Rodriguez, The telescope array middle drum monocular energy spectrum and a search for coincident showers using high resolution fly ’ s eye HiRes-1 monocular data (Ph.D. thesis), University of Utah, 2011. URL:http://www.cosmic-ray.org/thesis/rodriguez.html.

[6] H. Tokuno *et al.*, Nuclear Instrumentation and Methods A676 (2012) 54-65.

[7] E. Kido *et al.*, at this conference.

[8] Grants-in-Aids for Scientific Research on Specially Promoted Research (15H05693) by the Japan Society for the Promotion of Science with the title of "Extended Telescope Array Experiment -Nearby Extreme Universe Elucidated by Highest-nergy Cosmic Rays" for a period of five years between April 2015 and March 2020.