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Search for the large-scale cosmic-ray anisotropies using the TA and TALE surface detector arrays

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Abstract. Origins of ultra-high-energy cosmic rays (UHECRs) are still largely unknown. In particular, the "2nd knee" around 10^{17} eV could be related to a transition of origins from the galactic to extra-galactic sources. In this scenario, one would expect the large-scale anisotropies of UHECRs to change over the 2nd knee region. We search for large-scale anisotropies using data taken from surface detector (SD) arrays of the Telescope Array experiment (TA), the largest cosmic-ray detector in the northern hemisphere, and from its low energy extension, the Telescope Array Low-energy Extension (TALE). In this contribution, we report on preliminary results in the search for the large-scale cosmic-ray anisotropies with 11-years TA SD and two-years TALE SD data.

1 Introduction

Deciphering origins of ultra-high-energy cosmic rays (UHECRs) is one of the most important question in a field of astroparticle physics. Since the cosmic rays are charged particles, they are deflected by the galactic and extragalactic magnetic fields. With small deflections of UHECRs by galactic and intergalactic magnetic fields, $\sim 5^\circ Z(E/50\,\mathrm{EeV})^{-1}$ where Z is the charge of nuclei [1], a small-intermediate scale anisotropy is predicted at the highest energies. The deflections by magnetic fields are enlarged at lower energies below 10 EeV, resulting in a large-scale anisotropy, which can be approximated as a dipole [2–4].

In 2017 the Pierre Auger Collaboration reported the observation of a significant large-scale anisotropy in the arrival directions of cosmic rays above 8 EeV, indicating a significant dipole structure of 4.7% amplitude in a projection of the right ascension with a 5.2σ significance [5]. An enhancement of the dipole amplitude above 4 EeV and results down to 0.03 EeV are also reported [6, 7]. These results are agreement with an extragalactic origin of UHECRs. The Telescope Array Collaboration reported a consistent result with both the Auger reported dipole and isotropic distribution due to the current statistics [8].

In this proceedings we search for an energy dependence of a dipole structure at lower energy below 8 EeV using the Telescope Array experiment, and from its low energy extension.

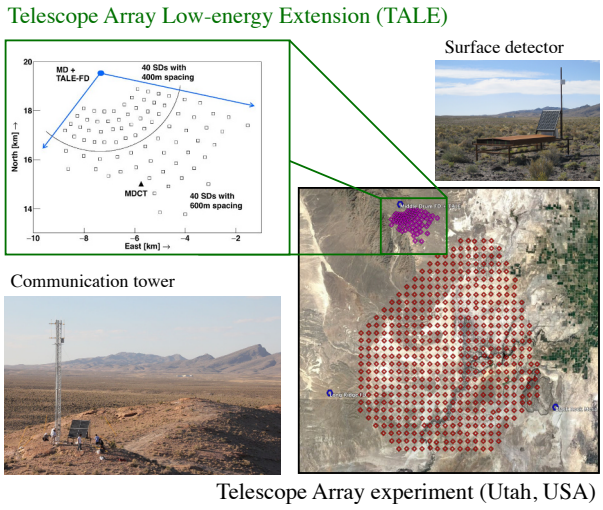

Figure 1. The detector configuration of TA SD and TALE SD. The square grid is used in the TA SD deployment, while the hybrid detection efficiency is maximized for the arrangement of TALE SD. The picture of communication tower and individual surface detector are displayed.

2 Telescope Array experiment (TA) and Telescope Array Low-energy Extension (TALE)

The Telescope Array experiment (TA) is the largest cosmic-ray detector in the Northern hemisphere, located near the city of Delta, Utah, USA (39.30° North and 112.91° West at ~1400 m above sea level [9]. The surface detector array (SD) consists of 507 plastic scintillators of 3 m^2 area deployed in a square grid with a 1.2 km spac-

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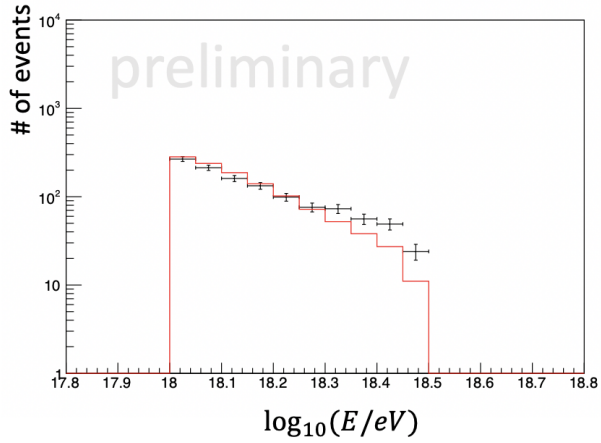

Figure 2. Energy distribution of TALE SD during two-years data (black plots) and the MC prediction using proton of QGSJetII-04 model under the assumption of isotropic distribution (red histogram)

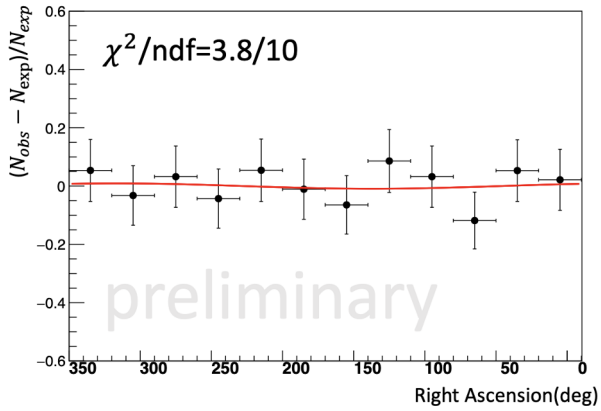

Figure 3. Residual intensities vs right ascension from two-years of TALE SD data (black points). The red curve shows a fitted result by $r_\alpha \cos(\alpha + \phi_\alpha)$

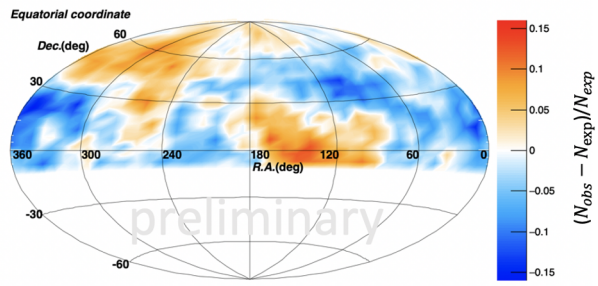

Figure 4. Skymap of residual intensities with TALE SD in equatorial coordinates using a top-hat function of 45° over-samplings

ing. The total effective area is approximately 700 km^2. Additional surface detectors, designed to provide a four-fold increase in effective area, named TAx4, are now being deployed and partly in operation [10]. Total 80 additional SDs with 600 m and 400 m spacings are installed to be sensitive to lower energies below 3 EeV than TA SD, named Telescope Array Low-energy Extension (TALE). The total effective area of TALE is 21 km^2. Figure 1 shows the detector configuration of TA SD and TALE SD. The TA SD and TALE SD are overlooked by fluorescence detectors, which are used for determination of the calorimetric energy of UHECR from energy deposited in the atmosphere during its development [11]. The obtained energy is calibrated to the calorimetric energy measured by the fluorescence detectors by a factor of 1/1.27 for TA SD [12] and of 1/1.08 for TALE SD.

3 Large-scale anisotropy search with TALE around 2 EeV

Since the TALE SD data taking was started from 2019, two years data from October 2nd, 2019 to September 28th 2021 are used for the large-scale anisotropy search around 2 EeV. The obtained result is compared to time dependent detailed detector simulation under assumptions of the isotropic distribution and primary proton of QGSJetII-04, which is the post-LHC interaction model. We found no significant non-uniformities in the sidereal time and anti-sidereal time distributions.

Figure 2 shows the reconstructed energy distribution of TALE SD, compared to the Monte Carlo (MC) expectation with the normalization to the total number of the observed events with the TALE SD. The total 1122 events are recorded in the energy range from 1 EeV to 3 EeV with TALE SD data during two-years data. Figure 3 shows residual intensities as a function of the right ascension with a fitted curve by a formula of $r_\alpha \cos(\alpha+\phi_\alpha)$ where α is the right ascension, r_α and ϕ_α are amplitude and phase of the dipole structure, respectively. The fitted amplitude is 0.009±0.040 with a phase of 327°±267°. The obtained amplitude is consistent with the isotropic distribution. Also we found no significant non-uniformities in the sidereal time and anti-sidereal time distributions.

Figure 4 shows residual intensities measured with the TALE data in equatorial coordinates using a top-hat funtion of 45° over-samplings. There is no significant dipole structure seen under the limited statistics.

4 Large-scale anisotropy search with TA around 6 EeV

As the TA SD data taking is continued over 11 years, the 11-years data from May 2008 to May 2019 are analyzed for the large-scale anisotropy around 6 EeV. There were 8810 events surviving in a range from 4 EeV to 8 EeV as shown in Figure 5, compared to the time-dependent detailed MC simulation using primary proton of QGSJetII-03 under the assumption of isotropic distribution. We confirmed no significant non-uniformities in the sidereal time and anti-sidereal time distributions.

Figure 6 shows residual intensities of 11-years TA SD data below 8 EeV in equatorial coordinates with a fitted curve of the dipole component. The fitted amplitude is 0.044±0.016 with a phase of 225°±20°. The χ^2/ndf

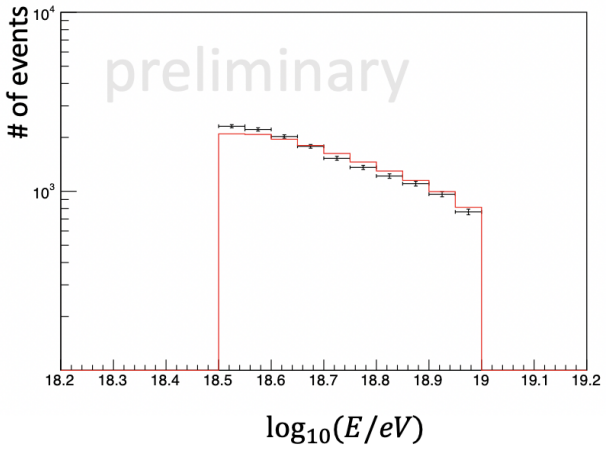

Figure 5. Energy distribution measured by the TA SD during 11 years (black points), compared to the time dependent detailed MC simulations (red histogram)

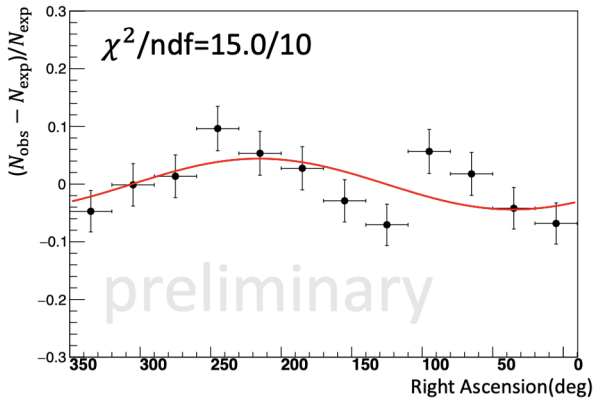

Figure 6. Residual intensities vs right ascension analyzed from 11-years of TA SD data of residual intensities. The red curve shows a fitted result by $r_\alpha \cos(\alpha + \phi_\alpha)$

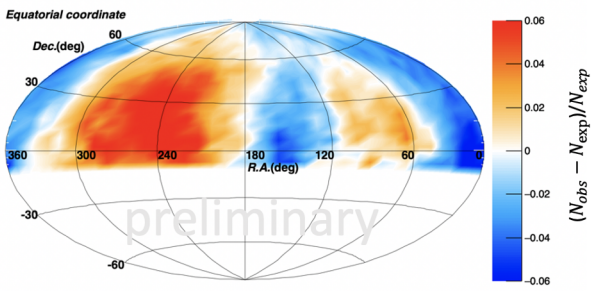

Figure 7. Preliminary residual intensities of 11-years TA SD data below 8 EeV in equatorial coordinates

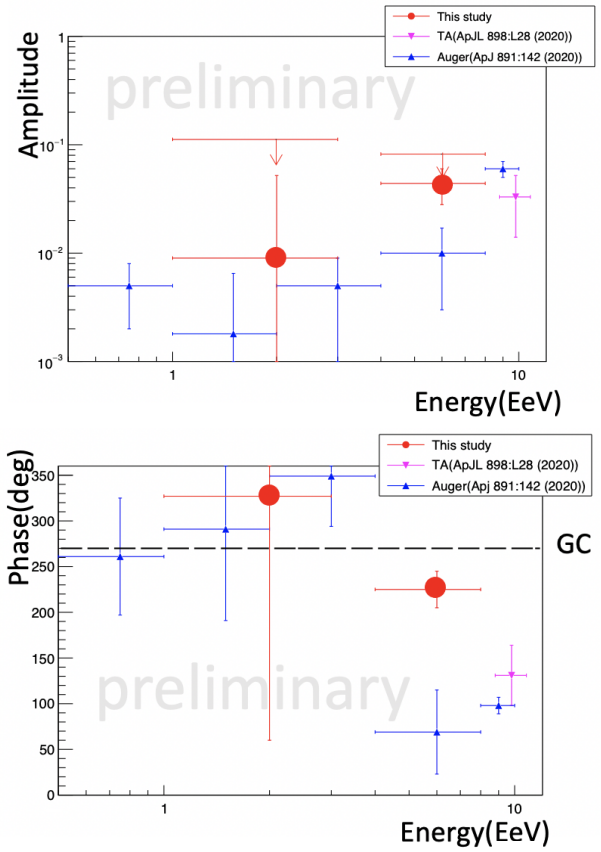

Figure 8. The measured amplitude with their upper limits of 99% confidence level and phase using both TALE SD and TA SD. The obtained results are compared with the result reported from Pierre Auger Collaboration [6, 7]

against the isotropic distribution is 21.5/12. Figure 7 shows a skymap of the residual intensities in equatorial coordinates. Although a small enhancement toward the galactic center of ~266° is seen in Figure 6 and Figure 7, the measured amplitude is not significant due to the current statistics.

Because of no significant results reported from the dipole search using both TALE SD and TA SD, the upper limits of 99% confidence level are evaluated. The measured amplitudes with their upper limits and phases are indicated in Figure 8, compared to the already reported result for the Pierre Auger Collaboration [6, 7]. The upper limits of TALE and TA are consistent with the Auger result. Further statistic of UHECR is required for the detailed check with these results.

5 Summary

The large-scale anisotropies below 8 EeV were searched using data-sets of TALE SD during two years data and TA SD during 11 years. Since there are no significant results seen in the current limited statistics, the upper bounds on the amplitude of dipole structure are derived from this results of TALE SD and TA SD. Further data-taking of these

SD arrays are essential to understand the origin and nature of UHECRs.

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References

[1] J. Bray, A. Scaife, Astrophys. J. **861**, 3 (2018), 1805.07995

[2] D. Harari, S. Mollerach, E. Roulet, Phys. Rev. D **92**, 063014 (2015), 1507.06585

[3] A. di Matteo, P. Tinyakov, Mon. Not. Roy. Astron. Soc. **476**, 715 (2018), 1706.02534

[4] B. Eichmann, T. Winchen, JCAP **04**, 047 (2020), 2001.01530

[5] A. Aab et al. (Pierre Auger), Science **357**, 1266 (2017), 1709.07321

[6] A. Aab et al. (Pierre Auger), Astrophys. J. **868**, 4 (2018), 1808.03579

[7] A. Aab et al. (Pierre Auger), Astrophys. J. **891**, 142 (2020), 2002.06172

[8] R.U. Abbasi et al. (Telescope Array), Astrophys. J. Lett. **898**, L28 (2020), 2007.00023

[9] T. Abu-Zayyad et al. (Telescope Array), Nucl. Instrum. Meth. **A689**, 87 (2013), 1201.4964

[10] E. Kido et al. (Telsecope Array), EPJ Web Conf. **210**, 06001 (2019)

[11] H. Tokuno et al., Nucl. Instrum. Meth. **A676**, 54 (2012), 1201.0002

[12] T. Abu-Zayyad et al. (Telescope Array), Astrophys. J. **768**, L1 (2013), 1205.5067