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Search for Large-scale Anisotropy on Arrival Directions of Ultra-high-energy Cosmic Rays Observed with the Telescope Array Experiment

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Telescope Array Collaboration

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Abstract

Motivated by the detection of a significant dipole structure in the arrival directions of ultra-high-energy cosmic rays above 8 EeV reported by the Pierre Auger Observatory (Auger), we search for a large-scale anisotropy using data collected with the surface detector array of the Telescope Array Experiment (TA). With 11 yr of TA data, a dipole structure in a projection of the R.A. is fitted with an amplitude of $3.3\% \pm 1.9\%$ and a phase of $131° \pm 33°$. The corresponding 99% confidence-level upper limit on the amplitude is 7.3%. At the current level of statistics, the fitted result is compatible with both an isotropic distribution and the dipole structure reported by Auger.

Unified Astronomy Thesaurus concepts: Cosmic rays (329); Ultra-high-energy cosmic radiation (1733); Cosmic ray sources (328); Cosmic ray showers (327); Cosmic ray detectors (325); Cosmic ray astronomy (324); Extragalactic astronomy (506); Extragalactic magnetic fields (507)

1. Introduction

Clarifying the origin and nature of the ultra-high-energy cosmic rays (UHECRs) has been a decades-long endeavor (Dawson et al. 2017; Alves Batista et al. 2019). There are a number of challenges in identifying sources, including the uncertainty in the chemical composition of cosmic rays with energies above 10 EeV ($\equiv 10^{19}$ eV) and the existence of galactic and extragalactic magnetic fields that scramble directional information.

The origin of UHECRs above 50 EeV would be significantly restricted to nearby sources due to interactions with the cosmic microwave background radiation via pion production for protons or via photodisintegration processes for heavier nuclei, known as the GZK cutoff (Greisen 1966; Zatsepin & Kuzmin 1966). With small deflections of UHECRs by galactic and intergalactic magnetic fields, $\sim 5° Z (E/50 \, \text{EeV})^{-1}$ where Z is the charge of nuclei (Bray & Scaife 2018), a small-intermediate scale anisotropy[38] is predicted at the highest energies. On the other hand, the distance to sources and deflections by magnetic fields are enlarged at lower energies around 10 EeV, resulting in a large-scale anisotropy, which can be approximated as a dipole (Harari et al. 2015; di Matteo & Tinyakov 2018; Eichmann & Winchen 2020). Full-sky anisotropy measurements from both hemispheres are also essential to understand the large-scale anisotropy.

The two largest observatories, the Telescope Array Experiment (TA; Tokuno et al. 2012; Abu-Zayyad et al. 2013a) and Pierre Auger Observatory (Auger; Pierre Auger Collaboration 2015), are currently in operation and observing UHECRs from the Northern and Southern hemispheres, respectively. There are indications of a number of intriguing intermediate-scale anisotropies at the highest energies ($E > 30$ EeV), such as the hotspot reported by TA (Abbasi et al. 2014) and the result of the flux pattern correlation analysis from Auger (Aab et al. 2018a) and TA (Abbasi et al. 2018). However, no conclusive results are reported and the origins of UHECRs are still unknown.

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 an obvious dipole structure of 4.7% amplitude in a projection of the R.A. with a 5.2σ significance (Pierre Auger Collaboration et al. 2017). An enhancement of the dipole amplitude above 4 EeV and results down to 0.03 EeV are also reported (Aab et al. 2018b, 2020). These results are consistent with an extragalactic origin of UHECRs. The dipole anisotropy of R.A. over a broad energy range is reported by a variety of experiments, as summarized in Mollerach & Roulet (2018).

In this Letter we investigate the existence of a dipole structure using TA data. TA detects UHECRs from the Northern hemisphere, providing us with an independent check of the large-scale anisotropy reported by Auger.

2. 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) (Abu-Zayyad et al. 2013a). The surface detector array (SD) consists of 507 plastic scintillators of $3 \, \text{m}^2$ area deployed in a square grid with a 1.2 km spacing. The total effective area is approximately $700 \, \text{km}^2$. Additional surface detectors, designed to provide a fourfold increase in effective area, named TAx4, are now being deployed and are partly in operation (Kido 2019). The TA SD is overlooked by fluorescence detectors, which are used for determination of the calorimetric energy of an air shower from energy deposited in the atmosphere during its development (Tokuno et al. 2012).

The arrival direction of UHECR as measured by the TA SD is determined from the relative difference in arrival time of the shower front at each surface detector (which are time-synchronized using GPS modules). The energy estimator of the TA SD is the particle density measured at a distance of 800 m from the air shower axis, called S_{800}. The S_{800} parameter is converted to the primary energy as a function of zenith angle based on a Monte Carlo simulation using the CORSIKA software package (Heck et al. 1998). The obtained energy is calibrated to the calorimetric energy measured by the fluorescence detectors using a scaling factor of 1/1.27 (Abu-Zayyad et al. 2013b). The typical resolution of the TA SD is $1°0 \sim 1°5$ in arrival direction and $10\% \sim 15\%$ in primary energy (Abu-Zayyad et al. 2013b), and the systematic uncertainty in the energy scale is quoted as 21% (Abbasi et al. 2016).

3. Data Set and Methodology

TA SD data recorded over 11 yr from 2008 May to 2019 May were analyzed for a study of the large-scale anisotropy. To avoid potential penalties from scanning, we use an a priori energy threshold of 8.8 EeV, equivalent to 8 EeV used by Auger, taking into account the 10% energy scale difference between TA and Auger calibrated from a common hardening feature of both energy spectra around 5 EeV (Verzi et al. 2017). There were 6032 events surviving this cut above a primary energy of 8.8 EeV, with zenith angles below $55°$ and the same quality cuts used in the TA spectrum analysis

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[38] In this research field, we define a small angular scale anisotropy as less than $5°$, intermediate scale as $10°$ to $35°$, and large scale as $>40°$.
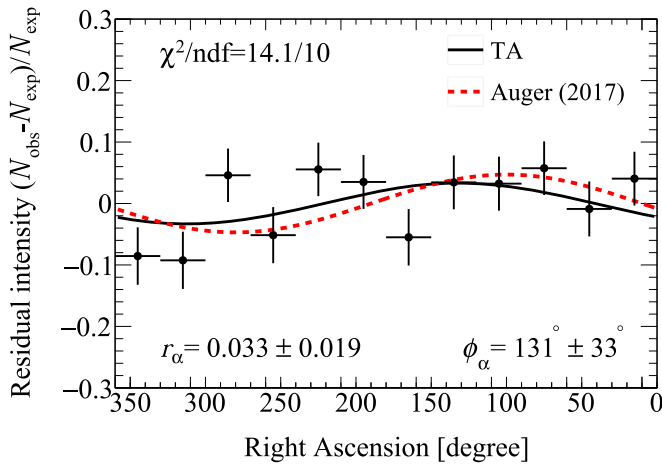
Figure 1. Residual intensities of UHECRs with energies above 8.8 EeV observed with 11 yr of TA data as a function of the R.A. The black curve is the TA fitted dipole result and the red dashed curve is the Auger reported dipole result.

(Abu-Zayyad et al. 2013b). In this data set, TA SD is capable of measuring UHECRs injected in a decl. band from $-15°$ to $90°$.

As the trigger efficiency of the TA SD at 8.8 EeV is not 100%, the obtained R.A. distribution is compared with the expected distribution assuming an isotropic UHECR sky from a time-dependent Monte Carlo (MC) simulation including calibration constants, live time and dead time of each surface detector station, and TA SD trigger efficiencies. A sidereal time distribution (366.25 cycles/year) of the simulation has a small amplitude of 0.4%. The residual intensity is defined as $(N_{obs} - N_{exp})/N_{exp}$, where N_{obs} is the number of events observed by TA and N_{exp} is the expected number estimated from the simulation. The number of total events in the MC simulation is normalized to the number of events in the TA data above 8.8 EeV.

We also check for possible decl. band dependence in common with Auger with $\delta < 24°.8$, where δ is the decl., and a higher decl. band with $\delta \geqslant 24°.8$. These decl. bands were defined in Verzi et al. (2017).

4. Results

4.1. Dipole Structure in R.A.

Figure 1 shows the residual intensity as a function of R.A. between 11 yr of TA SD data and the isotropic expectation calculated from the MC simulation. The residual intensity is fitted to $r_\alpha \cos(x - \phi_\alpha)$, where r_α is the amplitude of the dipole and ϕ_α is the phase. The obtained dipole structure has an amplitude of $3.3\% \pm 1.9\%$ with a phase of $131° \pm 33°$. The TA SD data points are also compared with an isotropic distribution and the dipole structure reported from Auger, which has a 4.7% amplitude with a phase of $100°$. The χ^2/ndf against the isotropic distribution is $17.1/12$ with a probability of 14%, and that against the Auger dipole is $15.9/12$ with a probability of 20%. With current statistics, the obtained TA SD result is consistent with both hypotheses.

Since there is no significant dipole structure, an upper limit is evaluated for a chance probability of 1% that a fluctuation of an isotropic source distribution would yield an amplitude greater than the measured value. The obtained 99% confidence-level upper limit on amplitude is 7.3% for TA data above 8.8 EeV.

4.2. Systematic Uncertainty

When we change to an assumption of 100% trigger efficiency and of uniform exposure to calculate the expected number of events from each R.A. bin, we have a dipole shifted by the amplitude of -0.4% and the phase of $+5°$. This gives a possible spurious dipole due to time-dependent detector conditions.

A modulation related to the atmospheric condition is seen in the TA SD data. When an empirical energy correction as a function of the atmospheric density at the ground is applied, the fitted dipole result is changed by -1.1% in amplitude and $-23°$ in phase. The correction method related to the atmospheric condition is being investigated and validated. These systematic uncertainties are smaller than the current statistical uncertainty of 1.9% in amplitude in the TA SD data.

The anti-sidereal time distribution (364.25 cycles/year) is also tested for a systematic study. The fitted amplitude is $1.8\% \pm 1.8\%$, being consistent with a uniform distribution.

4.3. Residual Intensity Sky Map

To investigate the dipole structure, the residual intensity sky map is calculated with a $45°$ radius cylindrical smoothing function, usually known as a top-hat function, applied to the arrival directions of UHECRs as used in Auger (Pierre Auger Collaboration et al. 2017). Figure 2 shows the residual intensity sky map of UHECRs measured by TA with energies above 8.8 EeV in equatorial and galactic coordinates. Even with our limited statistics, a similar dipole structure is seen in the common decl. $\delta < 24°.8$ band shared with Auger.

4.4. Decl. Dependence

Figure 3 shows the residual intensities and fitted results in the higher decl. band above $24°.8$ and the decl. band in common with Auger below $24°.8$. If we assume the three-dimensional dipole structure reported by Auger, with 6.5% amplitude at $100°$ in R.A. and $-24°$ in decl. (Pierre Auger Collaboration et al. 2017), the expected amplitudes are evaluated to be 3.8% in the higher decl. band and 5.7% in the common decl. band with Auger. These expectations are indicated by the curves in the plots of Figure 3. An offset parameter is added to the fitting function as we divide the data into two sets without a renormalization in each data set.

The obtained results are still inconclusive. The fitted function in the higher decl. band has an amplitude of $2.1\% \pm 2.4\%$ at $178° \pm 66°$. The χ^2/ndf against the isotropic distribution is $21.2/12$ with a probability of 5%, and that against the reported dipole from Auger is $23.1/12$ with a probability of 3%. The dipole structure in the common decl. band with Auger is fitted by an amplitude of $6.3 \pm 3.0\%$ at $115° \pm 28°$, which is consistent with the one reported by Auger. Also the χ^2/ndf against the isotropic distribution is $10.8/12$ with a probability of 55%, and that against the Auger result is $6.8/12$ with a probability of 80%. The fitted parameters and corresponding upper limits at 99% confidence level in these bands are summarized in Table 1,

5. Discussion

Due to the limited statistics with the TA data, the obtained amplitudes are compatible with an isotropic distribution at a 2σ significance level. However, focusing on the common decl.

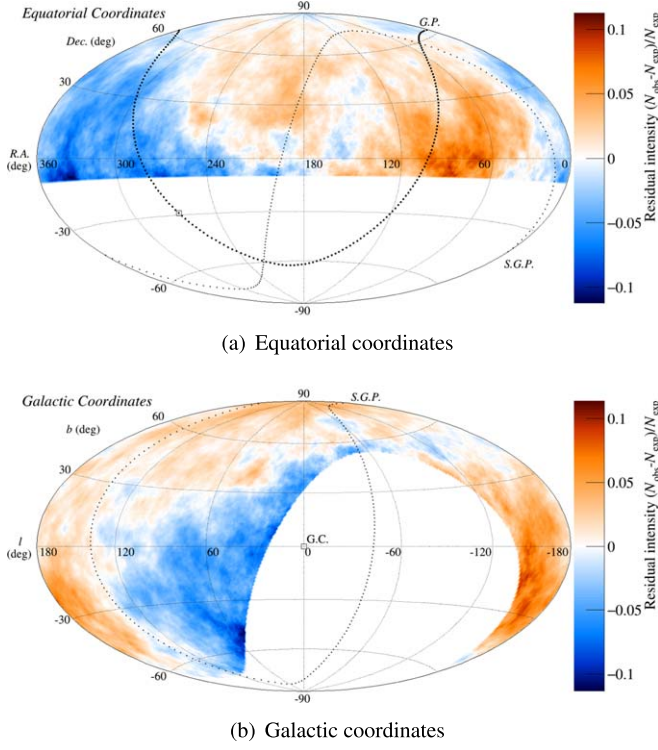(a) Equatorial coordinates

(b) Galactic coordinates

Figure 2. Sky map of residual intensities between TA data and an isotropic distribution shown in the Equatorial and the Galactic coordinates. The arrival directions are oversampled with a 45° radius cylindrical function. The galactic plane (G.P.) and the supergalactic plane (S.G.P.) are shown as thick and thin dotted curves, respectively. The galactic center (G.C.) is indicated by the open square.

band with Auger and the sky map of residual intensities in Figure 2, the fitted phase is apart from the galactic center of 266° in R.A., supporting an extragalactic origin of UHECRs reported from Auger. In the higher decl. band, probabilities of 5% against the isotropic distribution and of 3% against the Auger reported dipole might be influenced by additional components of the anisotropy, possibly related to local sources and magnetic fields.

Further data-taking with TA and TA × 4 will be essential to differentiate between the isotropic and the dipole structure hypotheses, and capable to investigate an energy dependence of the dipole amplitude reported from Auger (Aab et al. 2018b). Continuing the full-sky anisotropy searches from both hemispheres is of the upmost importance to clarify the origin and nature of UHECRs.

6. Conclusions

We report on a follow-up search for the dipole structure reported by Auger using 11 yr of TA SD data from the northern sky. We see results consistent with both an isotropic source distribution and the dipole structure reported by Auger. Therefore, we have evaluated a 99% confidence-level upper limit of $r_\alpha^{\mathrm{UL}} = 7.3\%$ above 8.8 EeV on the amplitude of a dipole structure in a projection of the R.A. Although the residual intensity sky map shows a similar dipole structure to Auger, further statistics from TA are required to distinguish the two hypotheses. Further data collection by TA and the on-going upgrade of TA × 4 will be essential for further studies.
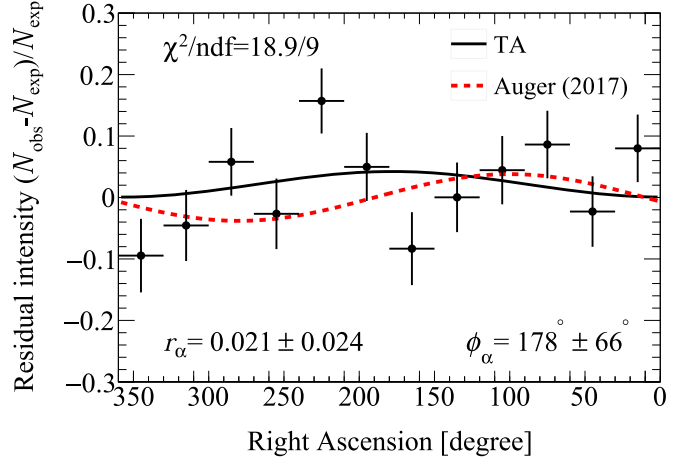
(a) Higher declination band, $\delta \geq 24.8°$
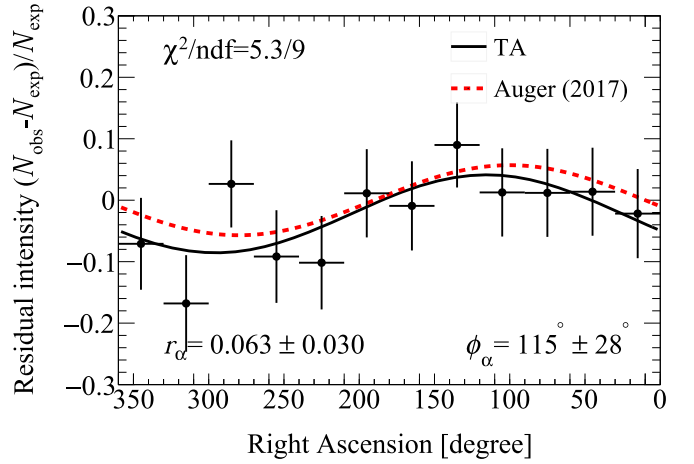
(b) Common declination band with Auger, $\delta < 24.8°$

Figure 3. Residual intensity in R.A. in (a) the higher decl. band, $\delta \geqslant 24°.8$, and (b) the common decl. band with Auger, $\delta < 24°.8$. The solid black curve is the fit to the TA SD data, and the red dashed curve is the expected dipole structure from the Auger result, 3.8% amplitude in the higher band and 5.7% amplitude in the common band.

Table 1
Summary of the Median Energy, Number of Events, the Dipole Fitted Results and the Corresponding Upper Limits (UL) Amplitude at 99% Confidence Level in All Bands, in the Higher decl. Band, $\delta \geqslant 24°.8$, and in the Common decl. Band with Auger, $\delta < 24°.8$

	E_{med} (EeV)	N	r_α (%)	ϕ_α (°)	r_α^{UL} (%)
All	13.0	6032	3.3 ± 1.9	131 ± 33	7.3
$\delta \geqslant 24°.8$	⋯	3778	2.1 ± 2.4	178 ± 66	6.7
$\delta < 24°.8$	⋯	2254	6.3 ± 3.0	115 ± 28	12.9

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