PROCEEDINGS OF SCIENCE

Telescope Array Surface Detector Medium-scale Anisotropy Analyses

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Ultra-high energy cosmic rays (UHECRs) are highly energetic charged particles originating from extragalactic sources, with energies exceeding 10^{18} eV. Elucidating the origin of UHECRs is a critical scientific objective. One approach is analyzing their arrival direction distribution for evidence of anisotropy. The Telescope Array (TA) experiment, the largest UHECR observatory in the Northern Hemisphere, has detected evidence of two medium-scale anisotropies: the TA Hotspot in the constellation of Ursa Major and an excess in the direction of the Perseus-Pisces supercluster. This presentation will detail an oversampling analysis using TA surface detector data to identify event excesses. We will present the latest findings regarding the TA Hotspot and the Perseus-Pisces supercluster excess.

7th International Symposium on Ultra High Energy Cosmic Rays (UHECR2024)
17-21 November 2024
Malargüe, Mendoza, Argentina

*Speaker

PoS(UHECR2024)097

1. Introduction

Ultra-high energy cosmic rays (UHECRs) are extremely energetic charged particles with energies exceeding 10^{18} eV, originating from outer space. When a single UHECR interacts with a nucleus in the atmosphere, it produces secondary particles and dissipates its energy. These secondary particles, in turn, produce additional secondary particles. This cascade of millions of subatomic particles, triggered by the primary UHECR, is referred to as an extensive air shower. By observing the properties of this air shower, we reconstruct the characteristics of the primary particle, including its energy and arrival direction.

Elucidating the origin of UHECRs is a critical scientific objective. One approach is analyzing their arrival direction distribution for evidence of anisotropy. Studies of anisotropy in the arrival directions can reveal patterns that provide insights into the sources of UHECRs. The task is challenging due to the pervasive cosmic magnetic fields that bend UHECR trajectories, but there have been significant efforts to understand their origins.

In 2014, the Telescope Array (TA) experiment reported an anisotropy in the arrival directions of UHECRs with energies greater than 5.7×10^{19}, referred to as the TA Hotspot [1]. By analyzing five years of data collected with the TA surface detector array, an excess of events was identified in the Ursa Major constellation using an oversampling method with an angular scale of 20°. The Li-Ma method [2] revealed a maximum local significance of 5.1σ excess in arrival direction distribution at the position $(146.7°, 43.2°)$ in equatorial coordinates. Monte Carlo simulations estimated the post-trial significance of this excess to be 3.4σ. There have been discussions proposing sources of the Hotspot, including M82 and Mrk 180 [3], Mrk 421 [4], and galaxy filaments associated with the Virgo cluster [5]. However, none of them were conclusive, and additional data are required to further understand the nature of the TA Hotspot.

More recently, the Telescope Array reported the observation of another excess of events with energies greater than $10^{19.4}$ eV. The new excess in slightly lower energy events were identified while examining discrepancies in the energy spectra between TA and the Pierre Auger Observatory. Investigations into the arrival directions of these events uncovered the new excess aligned with the Perseus-Pisces supercluster (PPSC), now referred to as the PPSC excess [6–8].

This work presents updated analyses of both the TA Hotspot and the PPSC excess using the most recent data collected over 16 years (from May 11, 2008, to May 10, 2024) by the Telescope Array surface detector array.

2. Telescope Array

The Telescope Array, located in the western desert of Utah, USA, at coordinates 39.3°N, 112.9°W, is the largest UHECR observatory in the northern hemisphere. Positioned at an altitude of 1400 meters above sea level, it is optimally placed to observe the maximum development of extensive air showers. TA functions as a hybrid experiment, integrating ground array and air-fluorescence detection methods. The surface detector (SD) array consists of 507 detectors spaced 1.2 km apart, covering approximately 700 km^2. Each SD unit is equipped with two layers of plastic scintillators to sample the air shower footprint upon reaching the ground [9]. Additionally, three fluorescence detector (FD) stations, comprising 38 telescopes, oversee the atmosphere above the SD array, covering an elevation range of 3°–31°. These telescopes detect ultraviolet light emitted during the extensive air showers induced by a UHECR primary as they develop through the atmosphere [10].

3. Medium-scale Anisotropy Analysis Methods

We perform oversampling searches to explore medium-scale scale anisotropies within a data set. These oversampling calculations are conducted at grid points in equatorial coordinates. At each grid point, we add up the number of events within a specified medium-scale angular window for the data, denoted as $N_{\rm on}$. By definition, we also get $N_{\rm off} = N_{\rm tot} - N_{\rm on}$, where $N_{\rm tot}$ is the total number of events in the data set.

Subsequently, we conduct the same calculation by using 10^5 cosmic ray events generated under the assumption of an isotropic flux, considering the geometrical exposure $g(\theta) = \sin\theta\cos\theta$ as a function of zenith angle (θ), given that the detection efficiency for this energy range is approximately 100% regardless of zenith angle θ. Using these isotropic background events, we define $\alpha = N_{\rm iso,on}/N_{\rm iso,off}$ as the exposure ratio of *on* to *off*. By comparing the oversampling of observed data to the isotropic background events, we calculate the Li-Ma statistical significance of the deviation from the isotropic background expectation at each grid point using the following equation [2]:

$$S_{\rm LM} = \sqrt{2}\left[N_{\rm on}\ln\left(\frac{(1+\alpha)N_{\rm on}}{\alpha(N_{\rm on}+N_{\rm off})}\right) + N_{\rm off}\ln\left(\frac{(1+\alpha)N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]^{1/2}. \quad (1)$$

In the following sections, we provide more details on the data sets and oversampling methods for the TA Hotspot and the PPSC excess, respectively.

4. Telescope Array Hotspot

In the initial report on the TA Hotspot [1], we applied the following event selection criteria: (1) each event had to include at least four SD counters, (2) the zenith angle of the event's arrival direction had to be less than 55°, and (3) the reconstructed energy had to exceed 5.7×10^{19} eV. This energy threshold was based on the active galactic nuclei correlation analysis results from the Pierre Auger Observatory [11], and was chosen to avoid introducing a free parameter in the scanning phase space.

The oversampling calculations were performed at grid points in equatorial coordinates, using 0.1° steps in right ascension (0°–360°) and declination (−10°–90°). The angular window size for each grid point was initially set to 20°, based on the medium-scale anisotropy measurements conducted by the AGASA collaboration [12, 13], to avoid introducing arbitrary scanning parameters. However, subsequent analyses included parameter scans over angular window sizes, revealing that the strongest excess signal occurred with a 25° window. In recent updates, the angular window has been fixed at 25° for consistency.

With the historical evolution of TA Hotspot analyses in mind, we analyze 16 years of data collected by the TA SD array. This dataset, consisting of events with energies greater than 5.7×10^{19} eV, includes a total of 228 events. Using an oversampling analysis with a 25° radius, we determine

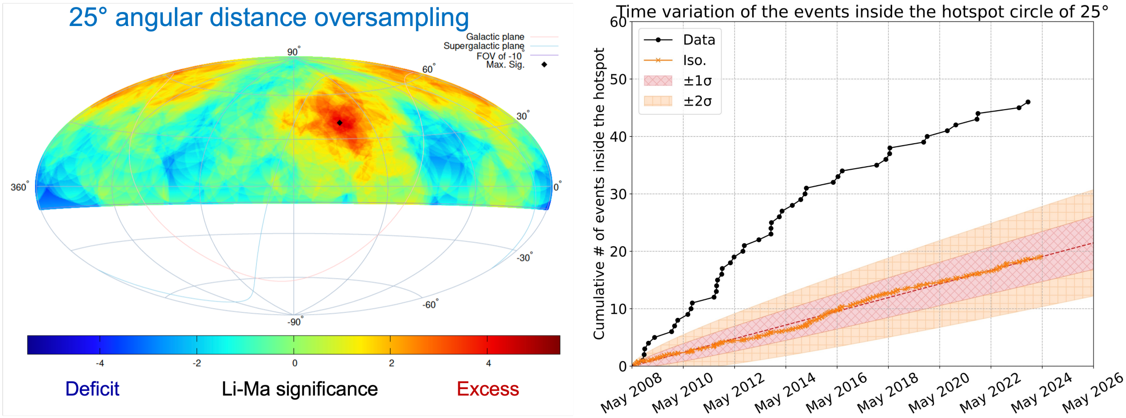

Figure 1: The sky map of the TA Hotspot using Hammer projection and the growth of the Hotspot. (Left) The Li-Ma significance using a 25°-circle angular window is shown in equatorial coordinates for 16 years of SD events with energies greater than 5.7×10^{19} eV. The black diamond indicates the maximum Li-Ma significance position measured at (144.0°, 40.5°). The color code indicates an excess (red) and a deficit (blue) of events compared to isotropy. **(Right)** The black dots represent the cumulative number of events falling inside the Hotspot circle of 25° from the most significant excess to the isotropy at (144.0°, 40.5°). The orange X's indicate the cumulative number of isotropic background expectations. The estimated isotropic event rate is depicted with the red dashed line, showing $\pm1\sigma$ (pink) and $\pm2\sigma$ (orange) deviations from the linear increase rate.

the maximum Li-Ma significance to be 4.9σ at the coordinates $(144.0°, 40.5°)$ in equatorial coordinates. Within this 25°-radius circle, 46 out of the 228 events are observed, compared to an expectation of 19.1 events under an isotropic distribution.

The left panel of Figure 1 presents the sky map of the TA Hotspot in equatorial coordinates using a Hammer projection. The color code indicates an excess (red) and a deficit (blue) of events compared to isotropy. The black diamond marks the location of the maximum Li-Ma significance $(144.0°, , 40.5°)$. To estimate how frequently such an excess might occur randomly within an isotropic UHECR sky, we generate Monte Carlo event sets. Each simulated set contains the same number of cosmic ray events as data distributed isotropically, taking into account the geometrical exposure of the TA SD array. We identify successes as cases where the maximum Li-Ma significance equals or greater than the observed value ($S_{\mathrm{MC}} \geq S_{\mathrm{obs}}$). The probability of finding such an excess by chance anywhere in the given field of view is calculated to be 2.1×10^{-3}, which is equivalent to $\sim 2.9\sigma$.

The right panel of Figure 1 illustrates the growth of events within the Hotspot. The black dots represent the cumulative number of events within the 25° circle from the maximum Li-Ma significance measured at $(144.0°, 40.5°)$, while the orange X's indicate the cumulative number of expected background events under an isotropic distribution. The estimated isotropic event rate is shown as a red dashed line, with $\pm1\sigma$ (pink) and $\pm2\sigma$ (orange) bands representing statistical deviations from the expected linear increase. This visualization highlights the deviation of the observed excess from the isotropic expectation, as well as its statistical fluctuations over time.

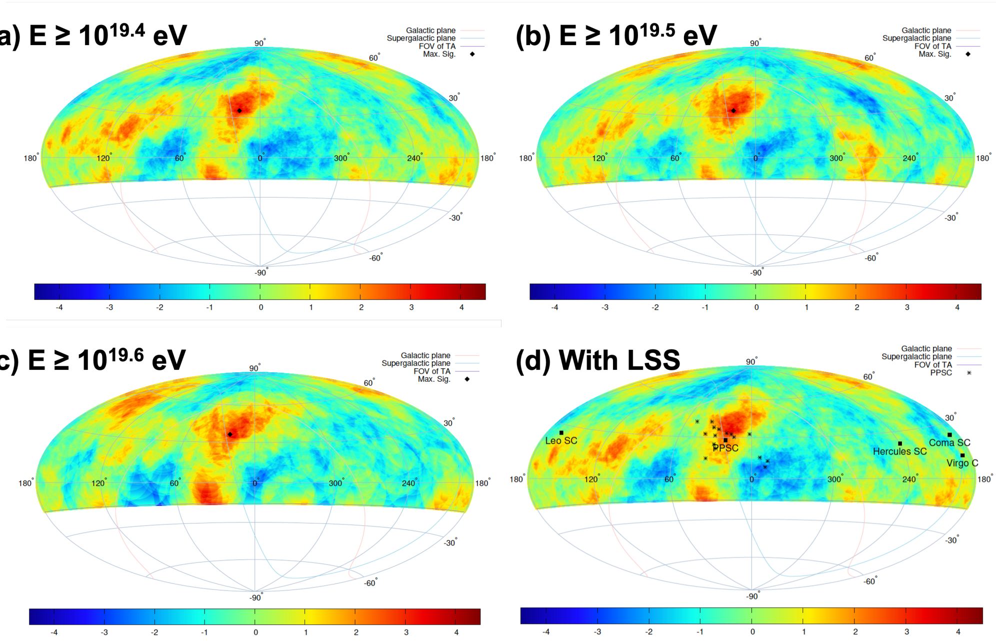

Figure 2: The sky maps of the Perseus-Pisces Supercluster (PPSC) excess using Hammer projection. The Li-Ma significance using a 20°-circle angular window is shown in equatorial coordinates for different energy thresholds: (a) $E \geq 10^{19.4}$ eV, (b) $E \geq 10^{19.5}$ eV, and (c) $E \geq 10^{19.6}$ eV. The black diamonds indicate the maximum Li-Ma significance positions for each energy threshold. Additionally, (d) shows the nearby major large-scale structures (LSS) overlaid with the Li-Ma significance map for $E \geq 10^{19.4}$ eV. The color code indicates an excess (red) and a deficit (blue) of events compared to isotropy.

5. Perseus-Pisces Supercluster Excess

A new excess in slightly lower energy events, with energies greater than $10^{19.4}$ eV, was identified during an investigation into the energy spectra mismatch observed between the TA and Pierre Auger data for energies above $10^{19.5}$ eV [14, 15]. One part of this investigation aimed to determine whether the Hotspot extends to lower declinations at somewhat lower energies. To maintain consistency with the original Hotspot analysis [1], we employed angular windows of 20° for the oversampling analysis, avoiding the introduction of a free parameter during the scanning phase space [6]. This approach resulted in the identification of additional excesses in the distribution of arrival directions.

The event selection criteria adopted for the PPSC excess study are identical to those used in the energy spectra mismatch study between TA and Auger. This consistency enables the investigation of both spectrum and anisotropy at lower energy levels while maintaining good energy and angular resolution: (1) each event must involve at least five SD counters, (2) the reconstructed primary zenith angle must be less than 55°, (3) both the geometry and lateral distribution fits must have a χ^2/degree of freedom less than 4, (4) the angular uncertainty estimated by the geometry fit must be less than 5°, (5) the fractional uncertainty in $S(800)$ estimated by the lateral distribution fit must be less than 25%, and (6) the counter with the largest signal must be surrounded by four working counters—one to the north, east, south, and west on the grid, although these counters do not need to be immediate neighbors of the largest signal counter.

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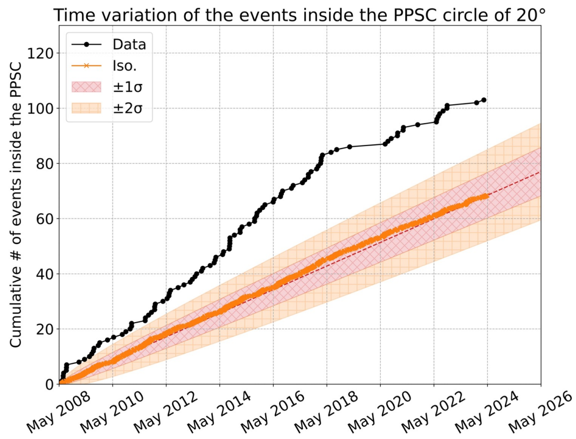

Figure 3: The growth of the Perseus-Pisces Supercluster excess. The black dots represent the cumulative number of events with energies greater than $10^{19.4}$ eV falling inside the PPSC excess circle of 20° from the most significant excess to the isotropy at (17.9°, 35.2°). The orange X's indicate the cumulative number of isotropic background expectations. The estimated isotropic event rate is depicted with the red dashed line, showing $\pm1\sigma$ (pink) and $\pm2\sigma$ (orange) deviations from the linear increase rate.

Over the course of 16 years of TA SD data, we observed 1186, 767, and 464 events with energies greater than $10^{19.4}$ eV, $10^{19.5}$ eV, and $10^{19.6}$ eV, respectively. The oversampling calculations are conducted at grid points in equatorial coordinates, with 0.1° increments in right ascension (0°–360°) and in declination (−15.7°–90°). The results of the oversampling analysis are as follows: the Li-Ma significances are found to be 3.7σ at (17.9°, 35.2°), 3.9σ at (19.2°, 35.2°), and 3.7σ at (21.8°, 36.2°) for $E \geq 10^{19.4}$ eV, $E \geq 10^{19.5}$ eV, and $E \geq 10^{19.6}$ eV, respectively. Consistent excesses are observed in the direction of the PPSC within angular distances of 7.7°, 7.4°, and 8.3° for each energy threshold. The sky maps for the PPSC excess at each energy threshold are shown in Figure 2.

To investigate whether similar excesses are seen near other major supercluster locations, we consider all structures similar to the PPSC within TA's field of view and within 150 Mpc, the GZK horizon for proton primaries. These structures include the Virgo cluster (17 Mpc), PPSC (70 Mpc), Coma supercluster (90 Mpc), Leo supercluster (135 Mpc), and Hercules supercluster (135 Mpc). The locations of these superclusters are overlaid on the excess map in Figure 2 (d). No such excess is observed at any of these other major structures. The PPSC stands out as a unique and significant structure in TA's field of view because it is the closest supercluster to us, aside from the Local supercluster, and is located near the Local Void [16, 17], where the magnetic field strength is expected to be weaker than in other cosmic web structures. This makes the excess in the data in the direction of the PPSC noteworthy.

We generate multiple Monte Carlo event sets, each containing the same number of events as the data, and isotropically throw events according to the TA SD acceptance to estimate the likelihood of this result occurring by chance. We then perform the same oversampling analysis using the Li-Ma method on each Monte Carlo set. We count as successes the number of sets where the point of maximum Li-Ma significance is at least as significant as in the data, and also occurs at least as close to the PPSC as in the data: ($S_{\mathrm{MC}} \geq S_{\mathrm{obs}}$) and ($\theta_{\mathrm{mc}} \leq \theta_{\mathrm{obs}}$). The resulting chance probabilities for having an excess as significant and as close to the PPSC as in the data are 3.1σ,

3.2σ, and 3.0σ for $E \geq 10^{19.4}$ eV, $E \geq 10^{19.5}$ eV, and $E \geq 10^{19.6}$ eV, respectively. We also calculate the chance probabilities for having excesses as significant and as close to any of the nearby major structures considered. The results are 2.5σ, 2.6σ, and 2.4σ for $E \geq 10^{19.4}$ eV, $E \geq 10^{19.5}$ eV, and $E \geq 10^{19.6}$ eV, respectively. Based on these findings, we conclude that there is a possible cosmic ray source in the direction of the PPSC.

Figure 3 shows the growth of events within the PPSC excess for $E \geq 10^{19.4}$ eV. The black dots represent the cumulative number of events within the 20° circle centered on the maximum Li-Ma significance at (17.9°, 35.2°), while the orange X's represent the cumulative number of background events expected under an isotropic distribution. The estimated isotropic event rate is depicted as a red dashed line, with $\pm 1\sigma$ (pink) and $\pm 2\sigma$ (orange) bands illustrating statistical deviations from the expected linear growth of isotropic distribution. This plot emphasizes the observed excess events in comparison to the isotropic expectation over time.

6. Summary

By analyzing data collected over 16 years by the Telescope Array surface detector array, we revisit the medium-scale anisotropies observed in the data. We present evidence for a persistent Hotspot at the highest energies ($E \geq 5.7 \times 10^{19}$ eV) near the Ursa Major constellation, with a local significance of 4.9σ and a global significance of 2.9σ. Additionally, we update the new excess of events at slightly lower energies ($E \geq 10^{19.4}$ eV) in the direction of the Perseus-Pisces supercluster, with a local significance of 3.7σ and a chance probability of 3.1σ for an excess occurring this close to the PPSC. These findings are in agreement with previous observations of medium-scale anisotropies, suggesting a potential correlation between UHECR arrival directions and large-scale cosmic structures, which could offer insights into the distribution of sources or the effects of intergalactic magnetic fields. The continued expansion of the Telescope Array experiment, TA×4, will significantly enhance data collection, playing a vital role in uncovering the origin of UHECRs. Ongoing observations are crucial for further probing the nature and stability of both the TA Hotspot and the PPSC excess feature.

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