Ultra-High-Energy Cosmic-Ray Hotspot Observed with the Telescope Array Surface Detectors

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The Telescope Array (TA) collaboration has reported on an indication of the excess flux of ultra-high energy cosmic rays (UHECRs) with $E > 57$ EeV, located near the Ursa Major cluster [1]. Corresponding sky region was called the "hotspot". In the present work we test this result using the latest data collected by the TA SD array. As a result, the number of events in the hotspot increases to 24, while expected background is 6.88 with the first 5-year and the additional 2-year data. The statistical significance of the hotspot for the seven year dataset remains at the same level of 3.4σ as for 5 year initial sample.

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1. Introduction

The origin of ultra-high-energy cosmic rays (UHECRs), which reach energy 10^{20} eV, remains the mysteries in modern astrophysics. The main obstacles in identifying the origin of UHECRs are low statistics of observed events and the loss of directional information induced by bending in magnetic fields, since the cosmic rays are charged particles. The deflection angle for a 60 EeV proton from a source at a distance of 50 Mpc is estimated to be a few degrees assuming intergalactic magnetic field (IGMF) strength of 1 nG. In addition, the estimated deflection by the Galactic magnetic field (GMF) ranges from a few to 10 degrees.

Until recently the UHECR distribution in arrival directions observed by many experiments seemed to be isotropic, with the significance of any anisotropy being less than 3σ. The TA collaboration has reported a cluster of UHECRs, with $E > 57$ EeV, called "hotspot", in the 5-year observation period from 2008 May to 20013 May [1]. This hotspot is centered near the Ursa Major cluster, and extends to $> \sim 10°$ angular scale. The chance probability of this hotspot in an isotropic cosmic-ray sky was calculated to be 3.7×10^{-4} (3.4σ). In this paper, we will update this result by adding the latest data collected by the TA SD array.

2. Analysis

The Telescope Array (TA) is the largest cosmic-ray detector in the northern hemisphere. It consists of a scintillator surface detector (SD) array [2] and three fluorescence detector (FD) stations [3]. The TA SD array consists of 507 plastic scintillation detectors, 3 m^2 each, and located on a 1.2 km square grid. The array has an area of $\sim$700 km^2, which is seven times larger than the AGASA experiment.

We analyzed the SD data recorded between 2008 May 11 and 2015 May 11. The total number of observed events (N_{tot}) is 109, with cuts in energy $E > 57$ EeV and the zenith angle $\theta < 55°$. The event distributions for $E > 57$ EeV is shown in Figure 1 in the horizontal coordinate system.
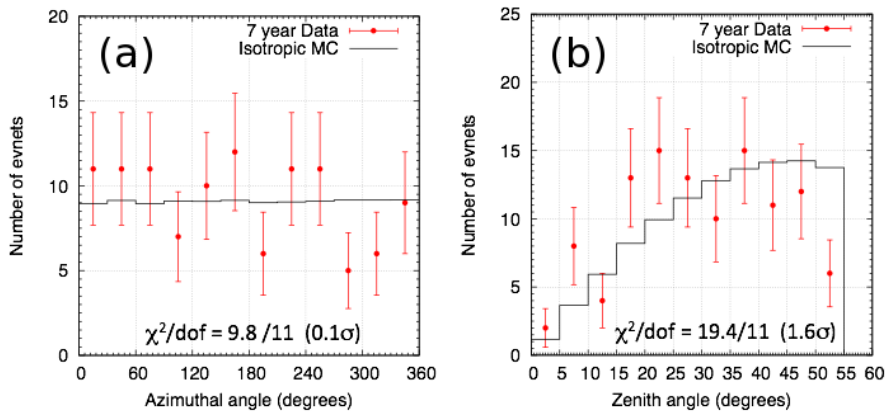
Figure 1: Azimuthal angle (a) and zenith angle (b) distributions of UHECR with $E > 57$ EeV observed by the TA SD array for 7 years. The closed circles and the solid histograms show the experimental data and the isotropic MC simulation, respectively, assuming the TA geometrical exposure.

The observed azimuthal angle and zenith angle distributions above 57 EeV are in good agreement with the isotropic MC simulations assuming geometrical exposure. The anisotropy analysis follows exactly the procedure adopted in Ref. [1]. Namely, for each point in the sky map grid, the cosmic ray events are summed over a 20°-radius circle. This gives the number of "signal" events, N_{on}, for this point. To estimate corresponding background, N_{bg}, we generate 100,000 Monte Carlo events assuming isotropic flux and TA SD geometrical exposure. The generated MC events are also summed over a 20°-radius circle producing N_{off}, and N_{off} is normalized to the total number of observed events, i.e. $N_{bg} = (109/100,000)N_{off}$. Then, we calculate the statistical significance of the excess of events at each grid point using Li-Ma equation [4].

3. Results

Figure 2 (a) shows a sky map of arrival directions of the 109 cosmic-ray events with $E > 57$ EeV in equatorial coordinates. The blue and red points show the directions of the UHECRs for the 5-year and the latest 2-year observation periods, respectively. Figure 2 (b) shows corresponding significance map of the excess. The maximum excess in our FoV appears centered at R.A. (α) $= 148.5°$, Dec. (δ) $= 44.6°$ with a statistical significance of $S_{MAX} = 5.1\sigma$ ($N_{on} = 24, N_{bg} = 6.88$). This is 1.5° away from the center position found in the previous search.

As a next step, we estimate the probability of such a hotspot appearing by chance anywhere in the isotropic sky in exactly the same way as in the previous report [1]. We generated 1 million MC data sets, each having 109 events within our FoV (i.e., we reproduced the statistics of the experimental data), assuming a uniform distribution over the TA SD exposure. The maximum of the significances (S_{MAX}) was calculated for each MC dataset in the same way as for the data using 20° oversampling radius.

We found that there were 134 instances of $S_{MAX} > 5.1\sigma$. This yields a chance probability of the observed hotspot in the isotropic cosmic-ray sky of 1.3×10^{-4}, equivalent to a one-sided probability of 3.6σ. When we adopted the 20° oversampling radius, we knew that it would approximately fit the hotspot. To correct for this knowledge we recalculate the chance probability using five oversampling radii, 15, 20, 25, 30, and 35 degrees. Then the chance probability becomes 3.7×10^{-4}, equivalent to 3.4σ, which is the same level as the previous estimation [1].

As an alternative approach, we searched for UHECRs excess using only 6-th and 7-th year data. This time we can use 20° circle centered at $(\alpha, \delta) = (146.7°, 43.2°)$, which is the maximum significance position determined by first 5-year data. As a result, we found four events against 2.31 expected background. The probability of this marginal excess in the isotropic sky is estimated to be 20%.

4. Discussion

The TA UHECR energy spectrum above $10^{18.2}$ eV shows a steepening around 5.7×10^{19} eV [5], which is consistent with theoretical expectation from the Greisen-Zatsepin-Kuzmin (GZK) cutoff [6, 7]. If UHECRs are protons and we observe genuine GZK-effect, the sources of observed events should be in the local universe, within sphere of 100 Mpc. The angular distance between the hotspot center and the supergalactic plane in the vicinity of the Ursa Major cluster is $\sim 17°$. It
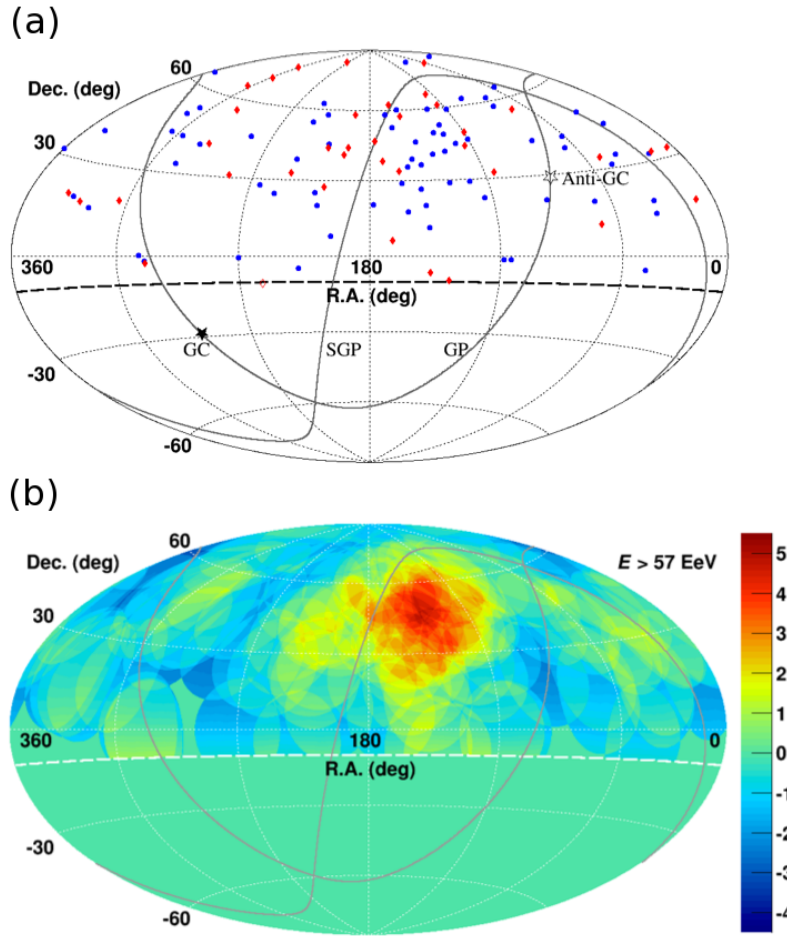
Figure 2: Aitoff projection of the UHECR maps in equatorial coordinates. The solid curves indicate the galactic plane (GP) and supergalactic plane (SGP). (a) The blue points show the directions of the UHECRs with $E > 57$ EeV for the first 5-year observation. The red diamonds show the directions of the UHECRs for the latest 6-th and 7-th year observation period. The red open diamond shows an event at $\delta < -10°$ that was not included in this analysis. The closed and open stars indicate the Galactic center (GC) and the anti-Galactic center (Anti-GC), respectively; (b) Significance map for the 7-year observation using the 20° oversampling radius. The maximum significance is 5.1σ.

is possible that the hotspot direction is physically associated with a filament of the local large scale structure connecting us and Virgo [8]. The several prominent sources around the hotspot, such as the blazar Mrk 421, Mrk 180 and starburst galaxy M82 have been suggested as the candidates of its origin [9, 10]. In either case, the mass composition of UHECRs and the magnetic bending by the IGMF and GMF play very important role in the identification of the hotspot origin. The X_{max} distribution for events with $E > 10$ EeV measured by the TA FD suggests largely proton composition [11]. However, the statistics of the UHECRs with $E > 57$ EeV measured by the TA FD is still very low. The current TA aperture is obviously not adequate, if we want to resolve the UHECR anisotropy firmly. In order to collect data at a faster rate, we are now planning to build the TA extension, which will increase the area of the TA SD array by a factor of 4, and also add additional FD stations.

5. Summary

The TA collaboration reported on an indication of the UHECR hotspot near the Ursa Major cluster using 5-year data [1]. In this paper, we tested this indication using the latest additional two years of data collected by the TA SD array. Our observations are summarized in Table 1. Using the data up to 2015 May 11, the number of events in the hotspot increases to 24 events against an expected background 6.88. The chance probability calculated in the same way as in the previous report remains the same, 3.4σ. As an alternative approach, we searched for UHECR excess using only the latest 2-year data, within the $20°$-radius circle centered at $(\alpha, \delta) = (146.7°, 43.2°)$, which is the maximum significance position determined by first 5-year data. As a result, we found four events against 2.31 background. The probability of this excess in the isotropic sky is estimated to be 20%. The TA will continuously observe UHECRs to verify the TA hotspot. Besides, we will promote the TA$\times$4 project [12], which will extend the size of the TA SD by a factor of 4, to collect data faster.

Date (YYYY.MM.DD)	N_{tot}	N_{on}	N_{bg}	S_{MAX} (σ)	Position (α, δ)	Chance Prob. (σ)	Ref.
2008.05.11 - 2013.05.04	72	19	4.49	5.1	146.7°, 43.2°	3.4	[1]
2008.05.11 - 2014.05.11	87	23	5.49	5.5	148.4°, 44.6°	4.0	This work
2008.05.11 - 2015.05.11	109	24	6.88	5.1	148.4°, 44.6°	3.4	This work

Table 1: Summary of the hotspot observation by the TA SD array.

Acknowledgments

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