Anisotropy and point sources searches in the Telescope Array data

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Abstract: The first two years of the Telescope Array surface detector data are analysed for anisotropy. First, we calculate the angular correlation function of the cosmic ray events at energies larger 10 and 40 EeV and show that there is no significant clustering either at small or large angular scales. We then test previously existing claims for correlation with putative classes of point sources of UHECR.

Keywords: Telescope Array AGN sources correlations autocorrelations

1 Introduction

The Telescope Array (TA) is a hybrid detector of ultra-high energy cosmic rays (UHERCs) located in the Northern hemisphere (Utah, USA) which is fully operational starting from March 2008. It currently consists of 507 scintillator detectors covering the area of approximately 680 km^2. This area is overlooked by 38 fluorescence telescopes arranged in 3 towers. The surface detector of TA is the largest surface detector to date observing the Northern hemisphere.

UHECRs provide the highest-energy window into the Universe. Detection of their anisotropy is one of the main scientific goals of the Telescope Array. Such anisotropy is a key to identifying the UHECR sources. When detected, it will also be an important step in understanding the chemical composition of UHECR and the parameters of the intergalactic medium such as magnetic fields and photon background radiation.

Observation of the cutoff in the highest-energy part of the cosmic ray spectrum [1] together with theoretical arguments [2, 3] strongly suggest that the UHECR propagation length at high energies becomes substantially shorter than the size of the Universe, and therefore their sources must be within at most a few hundred Mpc from Earth. Since the matter is distributed non-uniformly at these scales, one generally expects the UHECR flux to be anisotropic, showing both point sources and variations at large angular scales.

Numerous attempts at detection of the UHECR anisotropy were made previously. Early studies suggested clustering of the UHECR events at small angular scale [4, 5]. On the basis of small-scale correlations, different classes of putative sources of UHECR were suggested (see, e.g., Refs. [6, 7, 8, 9]. In particular, the Pierre Auger Observatory (PAO) has claimed correlations of UHECRs with the nearby active galactic nuclei (AGN) [8, 9] which was not confirmed by observations in the Northern hemisphere [10].

At larger angular scales evidence for correlations with the supergalactic plane was claimed [11] but not confirmed by other authors [4, 12, 13]. Also, an anisotropy in the PAO data was reported [14] (see, however, Ref. [15]) but was not confirmed by the HiRes data in the Northern hemisphere [16].

In this paper we present the search of an anisotropy in the recent Telescope array data. We concentrate on small-scale clustering and correlations with AGN.

2 Data

This analysis is based on the data collected during 28 months of the surface detector operation in the period from March 2008 till September 2010. With the zenith angle cut of 45°, this data set contains 655 events with energies

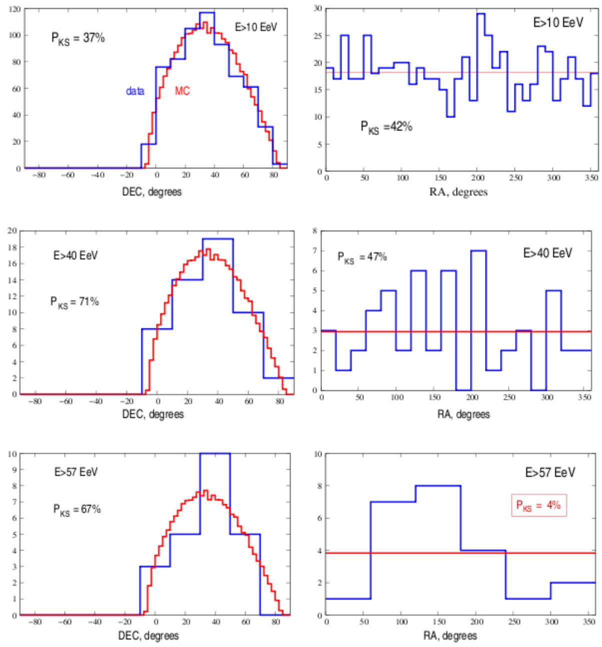

Figure 1: Comparison between the data (blue lines) and the Monte-Carlo simulations (red lines) at energies 10 EeV, 40 EeV and 57 EeV (top, middle and bottom rows, respectively). Plots show the distribution of events in declination (right column) and right ascension (left column). The compatibility of the two distributions by the Kolmogorov-Smirnov test is given as P_{KS}.

higher 10 EeV, 35 events with energies higher than 40 EeV and 15 events with energies higher than 57 EeV.

For the correlation studies it is crucial to have dataset with good energy and angular resolutions. Above 10 EeV and cut on zenith angle ZA$< 45°$, the angular resolution of TA events is better than $1.5°$, while the energy resolution is about 20%.

Correlation analysis requires good knowledge of the exposure function that corresponds to the data set used. In the case of the TA surface detector, and for the data set with energies $E > 10$ EeV, the exposure is very well approximated by the geometrical one. The approximation becomes better at higher energies.

Fig. 1 shows the comparison between the distributions in the declination (left column) and right ascension (right column) of the events in the Monte-Carlo simulations based on the geometrical exposure (red line) and in the data (blue line) with energy thresholds $E > 10$ EeV, $E > 40$ EeV and $E > 57$ EeV (top, middle and bottom rows, respectively). The $E > 10$ EeV and $E > 40$ EeV sets are compatible with geometrical exposure. This also indicates the absence of strong deviation from isotropy in these sets. The highest-energy set has the distribution in right ascension which is mildly incompatible with that in the simulated set: the probability that the two distributions are the same is 4% according to the Kolmogorov-Smirnov (KS) test. This may be interpreted either as a fluctuation, or as an indication that the UHECR distribution is not isotropic (see Sect. 3.2).

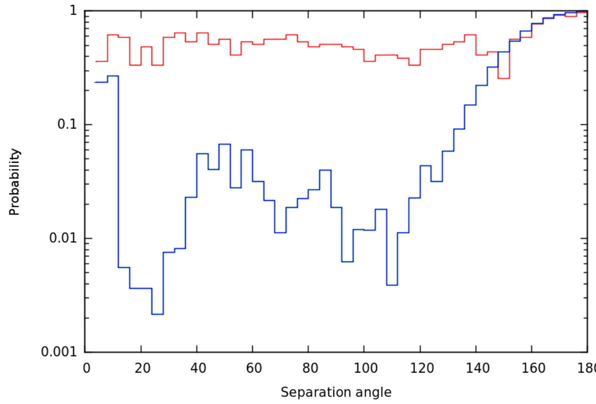

Figure 2: Autocorrelation function $P(\delta)$ for $E > 40$ EeV (upper red line) and $E > 57$ EeV (lower blue line).

3 Testing autocorrelations and correlations with AGN

3.1 The Method

Our analysis is based on the calculation of the angular correlation function as in [5, 6, 8]. The statistical significance of the correlation is estimated by testing the hypothesis that the highest energy cosmic rays and candidate sources are uncorrelated. The procedure is as follows. For a given set of sources and the angle δ, we count the number of pairs source-cosmic ray separated by the angular distance less or equal to δ, thus obtaining the data count, $N(\delta)$. We then replace the real data by a randomly generated Monte-Carlo set of cosmic rays and calculate the number of pairs in the same way, thus obtaining the Monte-Carlo count. We repeat the latter procedure many times calling successful those tries when the Monte- Carlo count equals or exceeds the data count. The number of successful tries divided by the total number of tries gives the probability $P(\delta)$ that the excess count in the data occurred by chance. The smaller is this probability, the stronger (more significant) is the correlation. The validity of this straightforward approach does not depend on the completeness of the catalog of the candidate sources on the condition that simulated sets of events correctly represent the detector exposure.

3.2 Autocorrelations

Clustering was observed in the AGASA data [4] at the angular scale of $2.5°$. Here we perform a blind test of this result using the TA data. Following the analysis of AGASA, we fix two energy thresholds $E > 10$ EeV and $E > 40$ EeV. We then count the number of pairs of cosmic ray events separated by less than $2.5°$ and compare to the expected number of pairs in case of the uniform distribution.

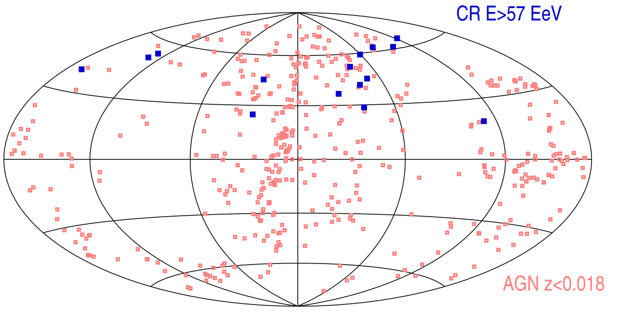

Figure 3: Sky map of the TA cosmic ray events (blue symbols) with $E > 57$ EeV and nearby AGNs from the VCV catalogue (red symbols) in the equatorial coordinates.

In the event set with $E > 10$ EeV we find 311 such pairs while 323 are expected for the uniform distribution. No excess is observed. In the event set with $E > 40$ EeV we find 1 pair while 0.838 are expected for the uniform distribution. The probability of this or larger excess is $\sim 57\%$. We conclude that no significant clustering is observed in the TA data at the angular scale of $\delta = 2.5°$.

We then extend the search and check for an excess at any angular scale from 0 to 180°. The results are presented in Fig. 2 for two data sets with the energy thresholds 40 EeV and 57 EeV, respectively. For the dataset with $E > 57$ EeV $P(\delta)$ reaches rather low values, but there is no statistical significance here to support the deviation from isotropy.

3.3 Correlations with AGN

Pierre Auger Observatory has reported correlation [8, 9] between UHECRs with energy higher than 57 EeV and nearby (closer than 75 Mpc) AGNs from the Veron-Cetty & Veron 2006 (VCV) catalog [18]. The correlation was observed at an angle $\delta = 3.1°$. In the control data set, the number of correlating events was 9 out of 13 [19], which corresponds to about 69% of events. We report on the blind test of this correlation with the TA data.

Unlike PAO, the TA exposure is peaked in the Northern hemisphere, so that different AGNs are in the TA field of view. The distribution of the AGNs over the sky is not uniform because of the large scale structure. In addition, the VCV catalog is not complete; due to the observational bias it tends to represent more completely the objects in the Northern hemisphere. For this reason, different (larger) fraction of events is expected to correlate in the TA data under the assumption that AGNs are sources of the observed UHECRs. Given the distribution of nearby VCV AGNs over the sky and assuming equal intrinsic AGN luminosities in UHECR, we estimated this fraction to be 73% for TA.

We are fixing the setup for testing AGN hypothesis as follows:

- Active galaxies from AGN, QSO and BL Lac sections of VCV catalog (as in Ref. [8, 9]) with the cut on redshift $0 < z \leq 0.018$. (Additional cut $z > 0$ leaves 465 objects out of 472. Some of the objects with z=0 are stars in NED database.)

- Cosmic rays with energy cut $E > 57$ EeV.

- Correlation signal should be read out at the 3.1° angular separation.

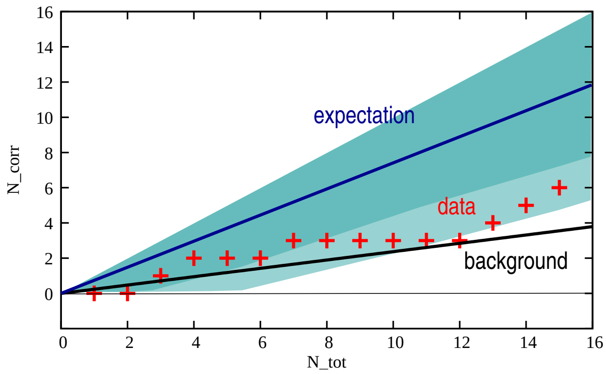

Figure 4: The number of TA events with $E > 57$ EeV correlating with VCV AGNs as a function of the total number of events. The expectation according to the original PAO claim is shown by the blue line together with the 1- and 2-sigma significance bands. The black line shows the average number of random coincidences.

The TA events with energies $E > 57$ EeV are shown in Fig. 3 (larger blue dots) together with the nearby AGNs from the VCV catalog (smaller red dots). The vertically oriented overdensity of AGN in the middle of the plot corresponds to the Supergalactic plane.

Fig. 4 shows the number of TA events correlating with AGNs as a function of the total number of events with $E > 57$ EeV ordered according to the arrival time. The black line represents the average number of random coincidences (background) calculated by Monte-Carlo simulation. The blue line shows expected number of correlating events as derived from the PAO correlation. Shaded regions represent 1- and 2-sigma deviations from the expectation. As is seen from Fig. 4, present TA data are compatible with both isotropic distribution and the AGN hypothesis.

4 Summary

In this paper we presented the search for anisotropy and point sources in the TA data collected over the period of about 2 years. We have examined autocorrelations at small angular scales. No significant autocorrelations (clustering) at small scales were found. We have also checked correlations with nearby AGNs as claimed by PAO. Out of 15 observed events with $E > 57$ EeV 6 correlate within 3.1° with positions of nearby AGNs form the VCV catalog, while 3.6 are expected in average from random coincidences (probability 16%). The data are compatible with both isotropy and the expectation from the AGN correlation.

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