Search for large-scale anisotropy of ultra-high energy cosmic rays with the Telescope Array

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Abstract: The correlation between the first 5 years of the Telescope Array surface detector data and the large-scale structure of the Universe is studied. With the source distribution derived form the complete catalog of galaxies (the LSS model), the predicted cosmic ray flux is calculated by propagating ultra-high energy protons. This flux is smeared by a Gaussian function with the width θ representing typical deflections in magnetic fields. Three event subsets with a-priori chosen energy thresholds of 10 EeV, 40 EeV and 57 EeV are compared to both the LSS model and the isotropic distribution. The two lower-energy sets are found to be compatible with the isotropic distribution and incompatible with the LSS model at smearing angles smaller than $\sim 20^\circ$ and $\sim 10^\circ$ for event sets with $E > 10$ EeV and $E > 40$ EeV, respectively. The highest-energy set is compatible with the LSS model and is not compatible with isotropy at $\sim 3\sigma$ C.L. (pre-trial).

Keywords: large-scale structure, ultra-high energy cosmic rays, Telescope Array, correlations

1 Introduction

With the growth of the world set of the ultra-high energy cosmic ray (UHECR) events the lack of clear deviations from isotropy is becoming an important message by itself, encoding the information about the properties of the sources, their space distribution, cosmic magnetic fields, as well as the charge composition of the UHECRs. At small angular scales, many attempts have been made at identification of the UHECR sources by cross-correlating the observed events with various source catalogs. A number of deviations from isotropy have been reported [1, 2, 3, 4]. However, thus far none of these deviations has grown, with the increase of statistics, into an unambiguous detection. At large angular scales the situation is rather similar: none of the previously reported hints at anisotropy [5, 6, 7] has so far strengthened enough with the accumulation of events [8, 9, 10, 11].

In the absence of a solid knowledge of the kind of astrophysical objects producing the UHECRs, one may attempt extracting useful information from more general properties of the UHECR sources such as their space distribution. Indeed, regardless of the concrete nature of sources, their distribution in space is expected to follow that of other matter in the Universe (with some possible variations due to different clustering properties), provided they are sufficiently dense to be treated statistically. Knowing the source distribution and assuming some values of the UHECR propagation parameters allows one to predict the variations of the flux over the sky. The predicted flux may then be compared to observations and thus the constraints on the input parameters may be obtained.

Regardless of the UHECR composition, at highest energies their propagation distance becomes of order of a few tens to a hundred Mpc. The matter in the Universe is distributed non-uniformly at these scales forming the large-scale structure (LSS). Therefore, the UHECR flux should be anisotropic mapping out the nearby structures, with the amplitude of anisotropy increasing with energy due to decreasing propagation length and smaller deflections.

There are essentially two crucial parameters that enter this prediction: a typical deflection of UHECR (which depends on the cosmic magnetic fields and the charge composition of UHECR) and the density of sources. The latter is important because the flux will only map out the matter distribution if there are enough sources within 50-100 Mpc to populate local structures. We will assume in what follows that the density of sources is high enough that they can be treated statistically. This leaves only one free parameter — the typical deflection angle θ.

In this paper we confront the predictions for the sky distribution of the UHECR flux calculated at different values of θ with the latest set of UHECR events observed by the Telescope Array (TA) experiment in the 5 years of operation. To minimize statistical penalties, we consider three *a priori* chosen energy thresholds: 10 EeV, 40 EeV and 57 EeV. We assume pure proton composition of UHECR compatible with the results of the HiRes and TA composition studies [12, 13].

We find that the two lower-energy sets are compatible with the isotropy and incompatible with the LSS model at smearing angles smaller than $\sim 20^\circ$ and $\sim 10^\circ$ for event sets with $E > 10$ EeV and $E > 40$ EeV, respectively. This is expected since at low energies the deflections of UHECR

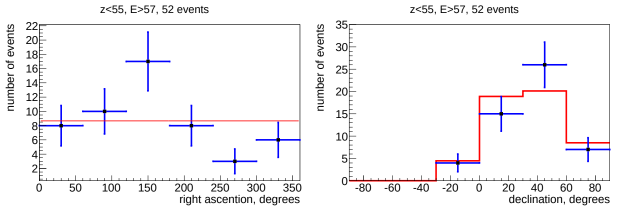

Figure 1: Distributions of events with $E > 57$ EeV in right ascension (left panel) and declination (right panel).

in magnetic fields are large. The highest-energy set is compatible with the LSS model and is not compatible with the isotropic distribution at about $\sim 3\sigma$ C.L. (pre-trial). This picture is consistent with the expectations assuming light composition of UHECR at highest energies.

2 The TA detector and the data set

TA is a hybrid UHECR detector located in the Northern hemisphere in Utah, USA ($39°17'48''$ N, $112°54'31''$ W) which has been fully operational since March 2008. It consists of 507 scintillator detectors covering the area of approximately 700 km^2 (for details see [14]). The atmosphere over the surface array is viewed by 38 fluorescence telescopes arranged in 3 stations (see [15]). In this paper we use the UHECR event set collected by the Surface Detector (SD) of the Telescope Array in the first 5 years of its operation.

The data set used in the previous TA analyses contained events with the zenith angles $< 45°$. That event set was optimized for spectrum studies. We have found, however, that relaxing the zenith angle cut to $55°$ does not lead to a significant loss of the data quality, while noticeably increasing the number of events. For the first time, in this analysis we use the event set with zenith angles up to $55°$. This set contains 2130 events with energies $E > 10$ EeV, 132 events with $E > 40$ EeV, and 52 events with $E > 57$ EeV.

By comparing the thrown and reconstructed arrival directions of simulated data sets, the angular resolution of TA events with $E > 10$ EeV was found to be approximately $1.5°$. The energy resolution of the TA surface detector at $E > 10$ EeV is close to 20% [16].

The exposure of the TA SD detector was calculated by the Monte-Carlo technique with full simulation of the detector. It follows from these Monte-Carlo simulations that the efficiency of the TA surface detector for $E > 10$ EeV and zenith angle cut of $55°$ reaches 100% and the exposure is very close to the geometrical one.

At the energy thresholds of 10 EeV and 40 EeV the distribution of the TA events in declination and right ascension is compatible with uniform. This was checked by generating a large Monte-Carlo event set corresponding to a uniform cosmic ray distribution, and comparing the distribution of the events in this set in declination and right ascension with that of the data by the Kolmogorov-Smirnov (KS) test. The highest energy events with $E > 57$ EeV show a mild deviation from isotropy. The KS probability that the distribution of right ascensions in this set is compatible with isotropy is 0.015, while for the distribution in declination this probability is 0.15. The corresponding histograms are shown in Fig. 1.

3 Method

Our analysis consists of two steps: (i) the calculation of the UHECR flux expected at different values of the typical deflection angle, and (ii) comparison of this flux to the sky distribution of the TA events. In this study we assume that the space distribution of sources follows the galaxy distribution. In principle, it is possible that UHECR are emitted by some particular type(s) of galaxies only, whose space distribution (the clustering properties) may slightly differ from the overall galaxy distribution. We neglect this difference.

The galaxy distribution in the nearby Universe is inferred from the complete galaxy catalogs containing the redshift information. Following previous TA analysis [17], in this work we use the 2MASS Galaxy Redshift Catalog (XSCz)[1] that is derived from the 2MASS Extended Source Catalog (XSC), with redshifts that have either been spectroscopically measured (for most of the objects) or derived from the 2MASS photometric measurements. The flux-limited subsample of galaxies with apparent magnitude $m \leq 12.5$ is used in UHECR flux calculations. The galaxies further than 250 Mpc are cut out and replaced by the uniform source distribution with the same mean density of sources. The resulting catalog contains 106 218 galaxies. The UHECR flux distribution is reconstructed from this flux-limited catalog by the weighting method proposed by [18] and adapted to the UHECR flux calculations by [19].

When propagating the UHECR particles from sources to the Earth we assume them to be protons and take into account all energy attenuation processes. We adopt the injection index at the source equal to 2.4 which is compatible with the UHECR spectrum observed by HiRes and TA [16] assuming proton composition and the source evolution parameter $m = 4$ [20]. The deflections of UHECR in the magnetic fields are accounted for by introducing a Gaussian smearing with the angle θ which we take distance-independent as corresponds to the hypothesis that Galactic magnetic fields dominate in the deflections. The typical deflection angle θ is treated as a free parameter. The goal of the analysis is to determine which values of θ are compatible with the space distribution of the TA events.

Figure 2 shows the flux map calculated by the above procedure for an energy threshold of 57 EeV and smearing angle $\theta = 6°$, not yet modulated with the TA exposure. Darker regions correspond to higher flux. Bands of 5 levels of gray color integrate to $1/5$ of the total flux each. One can identify the nearby structures which are marked by letters on the plot and explained in the caption.

The statistical compatibility of the predicted flux with the sky distribution of the TA events is determined by the flux-sampling test proposed in Ref. [21]. This test is performed as follows. The TA events "sample" the flux map by defining the set of flux *values* (the "data set") — the values of the flux that are read off at the positions of the events. These values follow some distribution that depends on the sky distribution of the data events. In the same way, Monte-Carlo events generated assuming a given (either uniform or tracing the LSS) UHECR distribution sample the flux map and define another set of flux values (the "MC set"). If *sky* distributions of data and MC events are the same, so should be the distributions of flux values in the data set and MC set. Conversely, if the latter two distributions are

1. We are grateful to T. Jarrett for providing us with the preliminary version of this catalog.

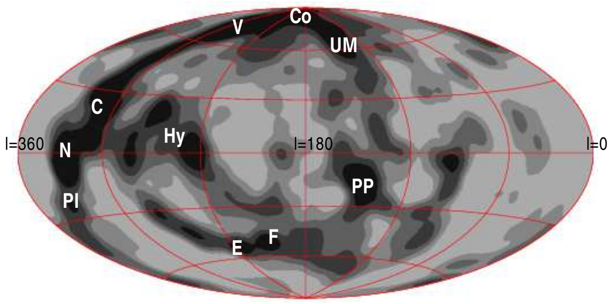

Figure 2: Sky map of expected flux at $E > 57$ EeV (Galactic coordinates). The smearing angle is $6°$. Letters indicate the nearby structures as follows: **C**: Centaurus supercluster (60 Mpc); **Co**: Coma cluster (90 Mpc); **E**: Eridanus cluster (30 Mpc); **F**: Fornax cluster (20 Mpc); **Hy**: Hydra supercluster (50 Mpc); **N**: Norma supercluster (65 Mpc); **PI**: Pavo-Indus supercluster (70 Mpc); **PP**: Perseus-Pisces supercluster (70 Mpc); **UM**: Ursa Major (20 Mpc); **V**: Virgo cluster (20 Mpc).

different, so must be the sky distributions of data and MC. The comparison of the distributions of the flux values in the data and MC sets is performed by the (binless) KS test, which returns a p-value characterizing the probability that the two sets are drawn from the same parent distribution. Small p-values, therefore, indicate incompatibility of the two distributions and imply a difference in the sky distributions of the data and MC events.

4 Results

The sky maps of the expected flux, together with the observed TA events with three energy thresholds of 10 EeV, 40 EeV and 57 EeV and the smearing angle $\theta = 6°$ are shown in Fig. 3, right column. Note that the flux maps change with the energy threshold. This is due to the energy dependence of the propagation length. The higher is the energy, the smaller is the UHECR propagation length and the larger the relative contribution of the local structures.

The p-values corresponding to these three energy thresholds are shown in the left column of Fig. 3 as a function of the smearing angle θ. Different panels correspond to different energy thresholds as indicated on the plots. The blue crosses show the p-values obtained by comparison of the data with the MC events generated isotropically, while the green pluses show the p-values resulting from comparison with the MC events generated according the structure model with the value of the smearing angle as indicated on the horizontal axis. In all cases the events sample the flux map representing the structure model with the corresponding smearing angle. The red horizontal line shows the confidence level of 95%.

At low energies $E > 10$ EeV, the data are compatible with isotropy and not compatible with the LSS model unless the smearing angle is larger than $\sim 20°$. This is expected, since even in the case of protons the regular component of the Galactic magnetic field alone produces the deflections of the UHECR at $E \sim 10$ EeV of the order of $20 - 40°$, depending on the direction.

At intermediate energies $E > 40$ EeV the situation is similar: the data are compatible with the isotropic distri-

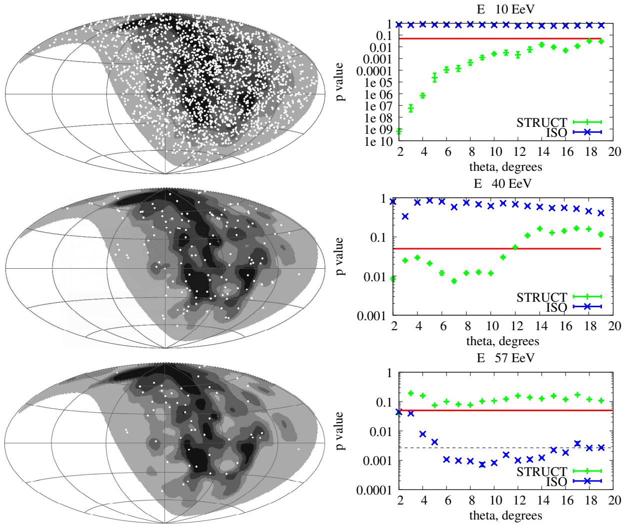

Figure 3: *Left column:* sky maps of the expected flux and observed TA events at three energy thresholds of 10 EeV, 40 EeV and 57 EeV (from top to bottom). *Right column: p*-values as a function of the smearing angle θ for the same three energy thresholds.

bution and incompatible with the LSS model unless the smearing angle is larger than $\sim 10°$.

At the highest energies $E > 57$ EeV the behavior changes. The data are compatible with the LSS model but not compatible with the isotropic distribution for most values of the smearing angle at the $\sim 3\sigma$ C.L. (pre-trial) as indicated by the dashed line on the corresponding plot. Such a behavior is consistent with the deviation from isotropy being due to the non-uniform distribution of sources that follow the large-scale structure of the Universe, and UHECR being protons with reasonably small deflections in the magnetic fields.

In interpreting the above results of the flux sampling test it is important to understand the sensitivity of the latter. In general, the sensitivity of the statistical test can be quantitatively characterized by its ability to discriminate between different hypotheses, called the statistical power. The statistical power is defined as the complement of the type-II error, which is the probability to falsely accept the null hypothesis if an alternative one is true. The closer is the statistical power to 1, the higher are chances that in a concrete realization the null hypothesis will be ruled out, if the data follow a given alternative hypothesis.

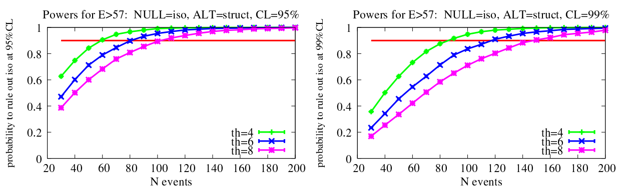

Figure 4: The statistical power of the flux sampling test (see the text for explanation) as a function of the number of events at $E > 57$ EeV and three deflection angles: $4°$, $6°$ and $8°$ as indicated on the plots. Left and right panels correspond to the confidence level of 95% and 99%, respectively.

We have calculated the statistical power of the flux sampling test in the case of the set with the energy threshold 57 EeV at smearing angles $\theta = 4^\circ, 6^\circ, 8^\circ$, as a function of the number of events varying from 20 to 200. The results are presented in Fig. 4. The two panels show the statistical power assuming the confidence levels of 95% and 99% (left and right panel, respectively). Taking the middle value $\theta = 6^\circ$ as a reference (that is, assuming that the typical deflections of protons in the magnetic fields at energy $E = 57$ EeV are of the order of 6°), we see that to have a 90% chance to rule out isotropy at the 95% C.L. one has to accumulate ~ 80 events (roughly twice the current number). To have a 90% chance to rule out isotropy at 99% C.L., one has to accumulate 120 events. According to the upper panel of Fig. 4, with 52 events, one has a $\sim 60\%$ chance to rule out isotropy at the 95% C.L.

5 Conclusions

In conclusion, we have examined the largest available TA data set for correlations with the large-scale structure of the Universe. The UHECR flux expected in the model where sources trace the distribution of galaxies was calculated and compared to the distribution of arrival directions of the UHECR events. No deviations from isotropy have been found at lower energy thresholds of 10 EeV and 40 EeV. These sets are not compatible with the LSS model unless the smearing angle is larger than $\sim 20^\circ$ and $\sim 10^\circ$, respectively, in which case the event sets are compatible with both the LSS model and the isotropic distribution.

In the highest energy set consisting of 52 events with $E > 57$ EeV we found a deviation from isotropy at about $\sim 3\sigma$ C.L. (pre-trial). This deviation shows up in both the distribution of events in the right ascension in equatorial coordinates, and in the flux sampling test. At the same time, the highest-energy set is compatible with the LSS model according to the same test. It is possible, therefore, that the observed deviation from isotropy is due to the inhomogeneous distribution of UHECR sources in the nearby Universe. Note, however, that the significance of the deviation is marginal and more statistics is needed for a definite conclusion.

To estimate the necessary number of events, we have calculated the statistical power of the flux sampling test. According this calculation, several times larger statistics will have to be accumulated before the isotropic distribution and the LSS model can be distinguished with certainty.

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