PROCEEDINGS OF SCIENCE

TA anisotropy summary

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The Telescope Array has collected 7 years of data. We make use of these data to search for large- and small-scale anisotropy of UHECR. At small angular scales we examine the data for clustering of events and correlations with some classes of putative sources. At large angular scales we present an update of the search for localized excesses by the oversampling method previously performed with the 5-year data set [1], and examine the data for correlations with the LSS of the Universe. We confirm the existence of the "hot spot" of the radius $\sim 20^\circ$ in the direction R.A. $= 148.4^\circ$, Dec. $= 44.5^\circ$ (equatorial coordinates) in the high-energy subset with $E > 57$ EeV. The post-trial significance of the hot spot in the 7-year data set is 3.4σ, the same as in the 5-year data set.

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1. Introduction

Detection of anisotropy of ultra-high energy cosmic rays (UHECR) is the most obvious way towards the identification of their sources. A complication, however, is that UHECR are likely to be charged particles, so they may be deflected on their way to the Earth and thus do not necessarily point back to their production sites. Moreover, the magnitude of the UHECR deflections is rather uncertain; it depends on energy and charge of the UHECR particles, as well as on the value of the extragalactic and Galactic magnetic fields. Depending on whether UHECR are protons or heavier nuclei, on their arrival direction (Galactic center or anti-center) and on the value of the extragalactic magnetic field, the deflections may vary from several degrees to values exceeding 180° even at UHECR energy of 10^{20} eV. The search for anisotropy must, therefore, take into account all these possibilities.

If the deflections in magnetic fields are within several degrees, the sources may manifest themselves as multiplets of events coming from close directions. This would result in a non-zero correlation function at small angles. Such a signal was reported in the AGASA data [2]. It was not, however, confirmed in other experiments. Various classes of sources have been tested for correlations with UHECR. Both negative and positive results [3, 4, 5, 6] were reported. The positive correlations, however, have not been confirmed with the accumulation of data.

If the deflections of UHECR do not exceed a few tens of degrees, one may expect a detectable large-scale anisotropy at large angles that reflects a non-uniform distribution of UHECR sources over the sky. Indeed, the UHECR propagation distance at highest energies drops below ~ 50 Mpc. At these scales the Universe is inhomogeneous. Assuming source distribution traces that of the ordinary matter, one thus expects higher flux from the directions of nearby structure, notably, from clusters of galaxies. These structures produce flux variations at the scale of a few tens of degrees; if the deflections are not much larger than that, these variations would not be washed out and can be observed.

In this paper we examine for anisotropy the Telescope Array (TA) surface detector (SD) data collected in the 7 years of operation. TA is a hybrid UHECR detector located in the Northern hemisphere in Utah, USA ($39^\circ 17' 48''$ N, $112^\circ 54' 31''$ W). It has been fully operational since March 2008. The surface array of TA consists of 507 scintillator detectors covering the area of approximately 700 km^2 (for details see [7]). The atmosphere over the surface array is viewed by 38 fluorescence telescopes arranged in 3 stations [8]. In this analysis we use the SD events as having by far the largest statistics and a simple (geometrical) exposure.

2. Data

Most of this analysis makes use of the special data set prepared for anisotropy studies. It contains SD events until May 2015, which corresponds to first full 7 years of the TA operation. Unlike the event set used in the spectrum reconstruction, the anisotropy data set has the zenith angle cut of 55° and a relaxed border cut. We have found that relaxing the cuts in this way does not lead to a significant loss of the data quality, while considerably increasing the number of events. The anisotropy set contains 2996 events with energies $E > 10$ EeV, 210 events with $E > 40$ EeV, and 83 events with $E > 57$ EeV.

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By comparing the thrown and reconstructed arrival directions of the simulated data sets, the angular resolution of TA events with $E > 10$ EeV was found to be approximately 1.5°. Events with zenith angles between 45° and 55° have even better angular resolution. The energy resolution of the TA surface detector at $E > 10$ EeV is close to 20% [9].

The anisotropy studies rely crucially on the knowledge of the exposure function. The exposure of the TA SD detector was calculated by the Monte-Carlo technique with the full simulation of the detector. It follows from these Monte-Carlo simulations that above 10 EeV the efficiency of the TA SD is 100%, while the exposure is indistinguishable from the geometrical one with the current statistics. In order to save computational time, the geometrical exposure is used in this analysis, unless stated otherwise.

3. Global distribution of the TA events

First, we examine the distributions of the TA events in the right ascension and declination in the two coordinate systems: equatorial and supergalactic (SG), and three energy thresholds of 10 EeV, 40 EeV and 57 EeV. To this end we generate a large (10^5) Monte-Carlo event set corresponding to the uniform UHECR flux modulated with the TA exposure. We then compare the distribution of the right ascensions and declinations of the events in the data and in the MC set by the Kolmogorov-Smirnov (KS) test.

The sets with the energy thresholds of 10 EeV and 40 EeV are found compatible with isotropy. The smallest p-value found in these sets is 0.12, which corresponds to the case of 40 EeV and the distribution in the right ascension.

A moderate deviation from isotropy is observed in the highest-energy set with $E > 57$ EeV. The results of the KS test for this case are summarized in Table 1. The largest deviation occurs in

$E > 57$ EeV

frame	longitude	latitude
equatorial	0.07	0.04
SG	0.01	0.03

Table 1: Results of the comparison of the data set with $E > 57$ EeV with the uniform distribution by the KS test.

the supergalactic longitude where the KS p-value is 0.01.

4. Autocorrelation function

The autocorrelation function is determined by the excess of pairs of events separated by a given angular distance δ as compared to a uniformly distributed set with the same total number of events. In practice, the deviation from isotropy is more conveniently characterized by the δ-dependent p-value $P(\delta)$. The latter is defined as the probability that a simulated uniform event set would have larger or equal number of pairs of events separated by angles $\leq \delta$ than is in the real data set.

Since the value of δ is not fixed, we treat it as a free parameter. Correspondingly, $P(\delta)$ at a given scale is a *pre-trial* significance. The results of the calculation of $P(\delta)$ are presented in Fig. 1 for the energy thresholds of 10 EeV, 40 EeV and 57 EeV. As one can see, there is a moderate

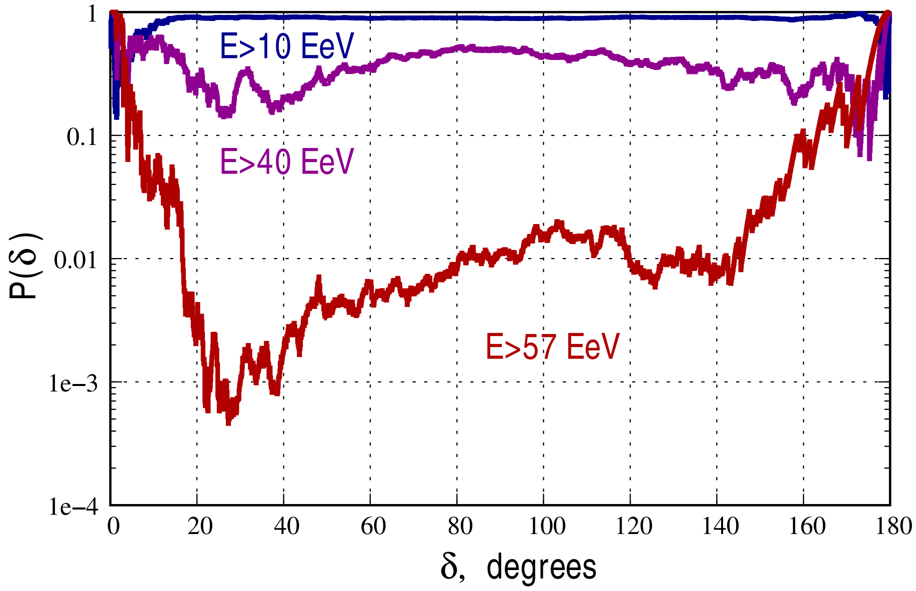

Figure 1: The dependence of the p-value $P(\delta)$ on the pair separation angle δ for the energy thresholds of 10 EeV, 40 EeV and 57 EeV as marked next to the curves. **Figs to be updated.**

deviation from isotropy at angular scales between 20° and 30° in the highest-energy data set.

5. Correlations with AGN and other classes of point sources

In the absence of deflections the UHECR would directly point back to their sources. If the deflections are present but are not too large (not exceeding several degrees) the association between the UHECR events and their sources may still be revealed through a nonzero correlation between the events and the corresponding source catalog. Technically, this can be done as follows. First, the probability p_0 is determined by the Monte-Carlo simulation that, for a given set of sources and a fixed angular separation δ, a single UHECR event falls within the angle δ from any of the sources, assuming the events are distributed uniformly. Then one counts the number n of pairs source – observed UHECR event that are separated by an angular distance less than δ. The p-value that characterizes the correlation at the angular scale δ is then obtained from the cumulative binomial distribution.

When interpreting the results of such a correlation analysis two points should be kept in mind. First, since the magnitude of deflections is not known, it has to be scanned over, in which case the penalty should be calculated and applied in order to get the final significance. This penalty should also take into account scanning in several catalogs if that has been done. Another important point is that positive correlations with a class of objects do not automatically imply that those objects are sources, as it may arise merely because the objects trace the distribution of actual sources in space.

Several candidate sources of UHECR have been examined in the previous TA publication [10] with the negative result. We do not update these analyses here. Instead, we concentrate on the case of the nearby AGNs from the Veron-Cetty & Veron 2006 catalog [11]. We fix the correlation parameters following Ref.[5] as follows: $\delta = 3.1^\circ$, $E > 57$ EeV, the maximum redshift is 0.018 (472 AGNs in total). No penalty factors are thus required. For compatibility with our previous analysis [12], we apply the zenith angle cut of 45° and tight border cuts. With these parameters we find $p_0 = 0.2415$, while the number of correlating events corresponding to the total of $N = 64$ events is $n = 24$. This gives the p-value $p = 0.012$.

6. Hot spot

In the highest energy set with $E > 57$ EeV collected during the first 5 years of the TA operation, a concentration of events has been observed in the circle of radius 20° around the direction R.A. = 147°, Dec. = 43° [1] (equatorial coordinates). The number of observed events in this "hot spot" was found to be 19 out of 72 total, while 4.49 were expected in the case of a uniform background. The post-trial significance of this excess was evaluated to be 3.7×10^{-4} (3.4σ).

With two more years of data 37 more events have been added to the set, so that the total number of events has increased to 109 (for the description of the data set used in the hot spot analysis see [1]). Of these 37 new events 4 have been found within 20° of the hot spot center of Ref. [1], while the expected number from the uniform distribution is 2.31. The probability of such an excess is $\sim 20\%$. The sky map showing TA events (separately first 5 years and last 2 years), as well as the position of the hot spot is presented in Fig. 2.

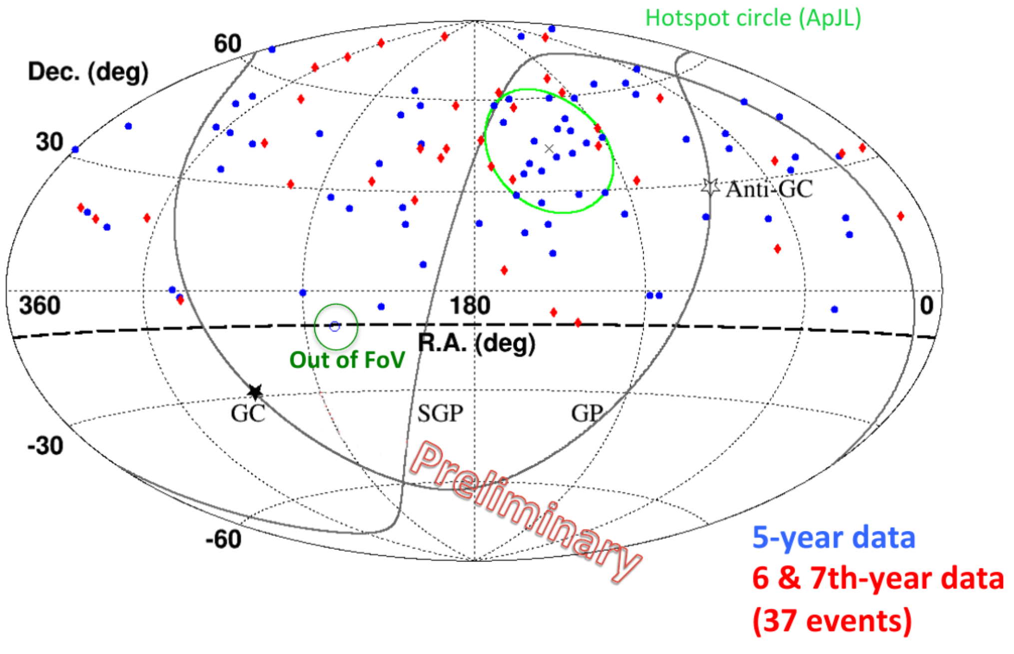

Figure 2: The skymap of 7 years of TA events with $E > 57$ EeV in equatorial coordinates. Blue (red) dots: TA events collected in the first 5 (last 2) years of operation. Green circle: the hot spot region as in Ref. [1].

Next, the complete procedure of Ref. [1] has been repeated for the full data set. The most significant excess was found in the circle of radius 20° centered at the direction R.A. = 148.4°, Dec. $= 44.5^\circ$ (equatorial coordinates). The post-trial Li-Ma significance, calculated in the same way as in Ref. [1], was found to be 3.4σ, the same as in the 5-yr data set.

7. Correlation with the LSS

The persistence of the hot spot in the TA data raises a question of its origin. The large size of the spot as compared to typically assumed magnetic deflections suggests that it might have been produced by a group of sources rather than a single source. One may wonder whether this group corresponds to any known structure on the sky.

Regardless of their nature, the UHECR sources are expected to trace the matter distribution in the nearby Universe. In the limit when the sources are numerous and can be treated statistically, the UHECR flux can be calculated, as a function of energy, with essentially one free parameter, the typical deflection angle θ. The predictions of this quite a generic model may be compared to observations and thus give constraints on the possible values of θ. The analysis of this type has been previously performed using the HiRes [13], the PAO [14, 15] and the TA [12] data. We present here the update of the TA correlation analysis with the LSS using the 6 years of the TA data. The update including 7 years of data will be presented at the conference.

In our analysis, the mass distribution in the Universe was inferred from the 2MASS Galaxy Redshift Catalog (XSCz) that is derived from the 2MASS Extended Source Catalog (XSC). We have assumed that sources follow the matter distribution, and propagated UHECRs from sources to the Earth taking full account of the energy attenuation processes under the assumption that the primary particles are protons. The arrival directions were smeared with the 2d Gaussian function of the angular width θ.

The map of the predicted flux was compared to the sky distribution of the observed UHECR events by the parameter-free flux-sampling test (see Refs. [16, 12] for details). For comparison, we also compared, by the same test, the distribution of the TA events with the isotropic one. At a given value of θ, the result of the test is the p-value that shows how likely it is that the UHECR distribution follows the one expected in a given model (LSS or isotropy). The results of the test, as a function of θ, are shown in Fig. 3 for the energy threshold of 57 EeV. The blue stars and green crosses show the p-values obtained by testing the isotropy and the LSS model, respectively. The red horizontal line marks the confidence level of 95%.

At low energies $E > 10$ EeV (not shown in Fig. 3), we found that the data are compatible with isotropy and not compatible with the structure model unless the smearing angle is larger than $\sim 20^\circ$. This is expected, since even in the case of protons, and taking into account the regular component of the Galactic magnetic field only, the deflections of the UHECR at $E \sim 10$ EeV are expected to be of the order of $20 - 40^\circ$, depending on the direction.

At intermediate energies $E > 40$ EeV (also not shown in Fig. 3), the situation is similar. The TA data are compatible with the isotropic distribution and not compatible with the LSS model unless the deflections exceed $\sim 10^\circ$.

Finally, at the highest energies $E > 57$ EeV, the behavior is different. The data are compatible with the structure model but incompatible with the isotropic distribution at the $\sim 3\sigma$ C.L. (pre-trial), for all but the smallest values of the smearing angle.

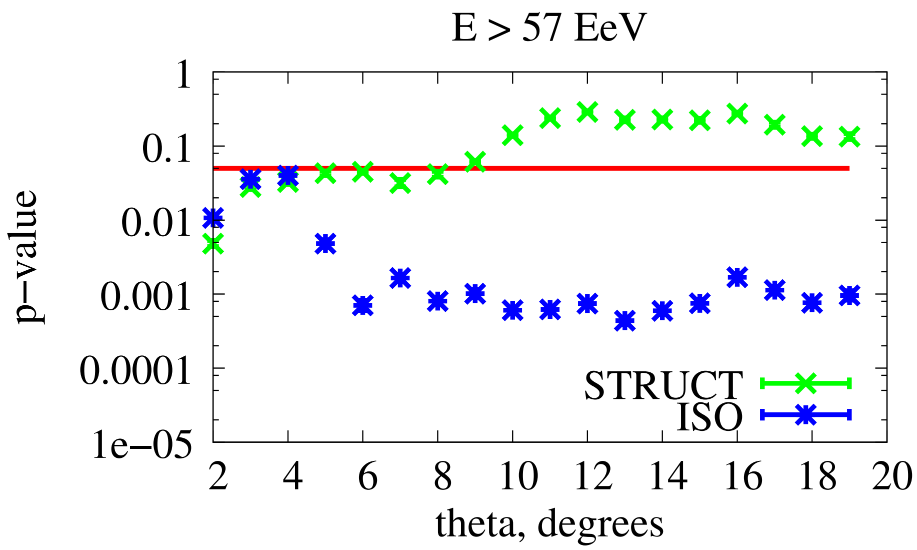

Figure 3: P-values obtained by the flux-sampling test. The blue stars and green crosses correspond to testing the isotropy and the LSS model, respectively. The red horizontal line marks the confidence level of 95%.

8. Summary

In summary, we have examined the TA SD data set collected during 7 years of operation for various possible deviations from isotropy: distributions in the right ascension and declination in equatorial and supergalactic coordinates, clustering, correlations with AGN and correlation with the LSS of the Universe.

The lower-energy event sets with energies $E > 10$ EeV and $E > 40$ EeV show no deviation from isotropy in none of these tests. The highest-energy set with $E > 57$ EeV demonstrates moderate deviations in all the tests, which are manifestations of the "hot spot" in the distribution of the events — a concentration of the events of the radius $\sim 20^\circ$ in the direction R.A. $= 148.4^\circ$, Dec. $= 44.5^\circ$ (equatorial coordinates). The post-trial significance of the hot spot in the 7-year data set is 3.4σ, the same as in the 5-year data set [1]. The last 2 years of data have 4 events in the hot spot region while 2.31 are expected from the uniform distribution.

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