

Point source search with the Telescope Array

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Abstract. A search for point sources of the ultra-high energy cosmic rays in the Telescope Array first-year data will be presented. Correlations of UHECR arrival directions with positions of astrophysical objects, reported previously by other experiments, will be tested. These include tests of BL Lac and AGN hypotheses.

Keywords: Correlations, AGN, TA

I. INTRODUCTION

Identification of sources of the ultra-high energy cosmic rays (UHECR) is a one of the key problems in astroparticle physics. Despite obvious importance, no compelling evidence for any of the possible candidates has been found so far. Standard astronomical methods are not applicable for cosmic rays. Unlike photons, arrival directions of cosmic ray primaries do not exactly point back to their sources because of poor angular resolution and deflections in Galactic and extragalactic magnetic fields. At the highest energies deflections become small, but the flux also decreases, so that the standard method of finding local excesses of flux and identifying these excesses with astrophysical objects cannot be used. In this situation the problem of identification can be approached by an alternative technique based on statistical analysis, that is on correlations between given set of arrival directions and a catalog of astronomical objects.

The statistical nature of the analysis limits possible search strategies. At the initial stage, trials are unavoidable in search for correlation signal. These include choice of the objects, choice of the particular catalog, cut adjustments within the catalog. In the calculation of statistical significance of the correlation, these trials have to be compensated by appropriate penalty factors. Statistically significant identifications may be selected in this way. However, use of the penalty factors makes it difficult to formulate, in a quantitative manner, a hypothesis for a subsequent blind statistical test. Such a test becomes possible if the correlation signal reappears, in the new independent cosmic ray data, for a set of parameters fixed at the previous exploratory stage.

During the last ten years, several classes of astrophysical objects were tested for positional correlations with arrival directions of UHECRs. For two classes of astrophysical objects correlations reappeared in the way which allows to formulate a quantitative hypothesis.

These are: i) the correlation signal for the bright BL Lacs in the HiRes data [1], [2] ii) the correlation signal for nearby Active Galactic Nuclei (AGN) in the Auger data [3]. In this talk we restrict ourselves to testing these hypotheses only.

After we describe the Telescope Array observatory in Sect. II, we specify the hypotheses to be tested in Sec. IV and formulate the testing procedure in Sec. III.

II. TELESCOPE ARRAY

The Telescope Array project is a collaboration between Universities and Institutes in Japan, Taiwan, China, Russia, Korea, and the United States. The observatory is located in the high desert in Millard County, Utah, USA and uses a combination of ground array and air-fluorescence techniques. The 507 ground array double layer scintillators fill the area between three fluorescence sites. The inter-detector distance is 1.2 kilometers. The three fluorescence sites are set about thirty kilometers apart from one another, forming an equilateral triangle. The ground array is tuned for observations of cosmic rays with energies above 10 EeV.

Telescope Array has started full operation in spring 2008. In this talk we will report results of point source search in the data collected by ground array during the period April-November 2008.

A. Angular and energy resolutions

For the correlation studies it is crucial to use events with good energy *and* angular resolution. We determine the energy and angular resolution by applying the full reconstruction procedure to the Monte-Carlo events from the database of extensive air showers and comparing the reconstructed energy and arrival direction to their actual values. The Monte-Carlo showers were generated [4] with the use of CORSIKA [5]. For $E > 10$ EeV and cut on zenith angle $ZA < 45^\circ$ our energy resolution is $\approx 20\%$ and does not depend on energy. The angular resolution is better than 2 degrees for these energies and zenith angles. The angular resolution improves with energy.

As a cross-check, we determine angular resolution using a subset of hybrid events. The result is in agreement with the estimate obtained in Monte-Carlo analysis.

III. THE METHOD

Our analysis is based on the calculation of the angular correlation function as in [6], [2], [3]. 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.

IV. THE HYPOTHESES TO BE TESTED

A. BL Lacs

BL Lacs are radiogalaxies with jets pointing in our direction. They are confirmed sources of the highest energy γ -rays observed to date. The correlations of UHECR with BL Lacs were first reported [6] using the cut adjustment procedure in the AGASA and Yakutsk cosmic ray data sets and using most recent (at the time) Veron 2001 catalog of active galactic nuclei. This catalog is kept for the correlation studies with BL Lacs since then. The signal was observed at the angular resolution scale of AGASA. The correlations with bright confirmed BL Lacs re-appeared in the HiRes stereo data [2], [1] with the energy cut $E > 10$ EeV, and again at the angular resolution scale, which for HiRes stereo is 0.6 degrees. This case did not involve cut adjustments and allowed to formulate [7] the quantitative hypothesis for a tests with the future data.

The setup for testing BL Lac hypothesis is fixed as follows:

- Subset of astrophysical objects consists of confirmed BL Lacs with magnitude $m < 18$ from Veron 2001 catalog.
- Cosmic rays are selected with the cut on energy $E > 10$ EeV.
- Correlation signal should be read out at the angular resolution scale.

It should be noted that the angular resolution of the TA ground array is poor as compared to the resolution of HiRes in the stereo mode, and therefore very large statistics is required to confirm or reject the hypothesis. This is apparent in Fig. 1 which shows the expected number

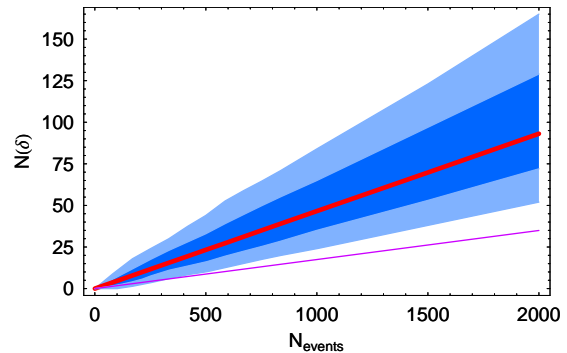


Fig. 1. Number of events expected to correlate with BL Lacs in the TA data-samples if tried hypothesis is true. Thick red line shows mean data counts as a function of the total number of events above 10 EeV. Blue bands correspond to 1 and 2 σ fluctuations, thin violet line shows expected background (Monte-Carlo counts). Angular resolution of 1.5° is assumed.

of correlating events and corresponding background as a function of the total number of events in the sample.

Confirmation of the correlation signal with BL Lacs would likely imply electrically neutral primaries and a new physics. Therefore, extreme caution is required here.

B. AGN

The existence of the Greisen-Zatsepin-Kuzmin cutoff [8] in the spectrum of UHECR [9] points to the extragalactic origin of the primary cosmic ray particles. In this case most of the cosmic rays with energies above the cut-off energy $E \simeq 10^{20}$ eV should come from nearby sources located at the distance $D < 100$ Mpc. Recently the Pierre Auger Collaboration reported a correlation [3] between the arrival directions of highest energy cosmic rays and positions of nearby AGN.

The correlation was found by scanning over the angular separation, and by adjusting cuts on minimum event energy and the maximum AGN redshift. The best signal was found at the angle of 3.1° for the cosmic-ray set consisting of 15 events with reconstructed energies $E > 56$ EeV and for the set of 472 AGN obtained by imposing the cut on the redshift, $z \leq 0.018$, in the Veron 2006 catalog [10]. The correlation re-appeared with the new data set consisting of 13 events, with the parameters fixed from the first data set. The probability that the correlation has occurred by chance is 1.7×10^{-3} as derived from the independent set. This allows to formulate the quantitative hypothesis for a tests with the future data, see Fig. 2.

The correlation signal [3] was found at rather small angles and with a large number of different AGN contributing to it. Therefore, it was naturally interpreted as caused by proton primaries with the large number of associated sources distributed within local Large Scale Structure (LSS). However, the data presented in [3] are not really consistent with such an AGN hypothesis [11]; also, correlations with AGN are absent in the HiRes stereo data [12] (but present in the Yakutsk data [13]).

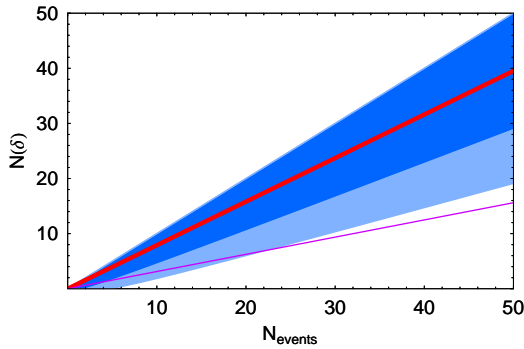


Fig. 2. Number of events expected to correlate with AGN within $\delta = 3.1^\circ$ in TA data-samples if tried hypothesis is true. Meaning of thick red line, blue bands and thin violet line is the same as in Fig. 1, but with $E_{\min} = 56$ EeV.

Moreover, a different interpretation of the Auger correlation signal, with just a few sources unrelated to LSS (or even a single source such as Cen A), and with heavier nuclei making substantial fraction of the flux, is possible [11]. Thus, the situation remains controversial.

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

- Active galaxies from AGN, QSO and BL Lac sections of Veron 2006 catalog (as in Ref. [3]) 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 $E > 56$ EeV.
- Correlation signal should be read out at the 3.1° angular separation.

Correlation signal with AGN (or to this end with the LSS) is rather expected within the framework of standard physics. One may even note that it is “guaranteed” if primaries are protons and extra-galactic magnetic fields are small, but this only emphasizes the importance of efforts for its confirmation.

V. THE PRESENTATION

In the talk we will present results of the corresponding correlation study. The Telescope Array first-year data set will be tried against catalogs of bright confirmed BL Lac and nearby AGN. The hypotheses outlined above will be tested.

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