Search for global asymmetry of UHECR arrival directions with space-based detectors (TUS, JEM-EUSO)

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***Abstract*. A space detector of ultrahigh-energy (UHE) cosmic-rays (CR) has opportunity to detect particles arrived from all directions in the sky during a year of operation. We simulated the detector operation and showed that it will have the uniform exposition over the whole sky. We studied the prospect of searching of global asymmetry of UHECR arrival directions expected if sources of UHE protons follow the distribution of the visible matter in the Universe. The optimal research strategy, which needs low statistics, was developed for the first space-based detectors TUS and JEM-EUSO.**

***Keywords*: UHECR global asymmetry**

I. Introduction

One of the important signatures of particular UHECR models is the global anisotropy of arrival directions of the highest-energy events. ”Bottom-up” scenarios (models where the origin of UHECR is attributed to the acceleration in astrophysical objects) naturally predict that the distribution of arrival direction follows the distribution of these cosmic accelerators. The steeply falling spectrum of cosmic rays makes it very difficult to obtain a reliable measure of the global anisotropy in any combination of terrestrial experiment. On the other hand, the ”top-down” models with the distribution of sources in the Galactic halo following the dark matter predicts the Galactic center-anticenter asymmetry due to the non-central position of the Sun in the Galaxy.

Today the experiment is not conclusive: the AGASA experiment claims continuation of the spectrum measured before expected GZK energy limit while the results of HiRes and of the Pierre Auger Observatory are in favor of the GZK cut-off. Limits on the gamma-ray fraction in the primary cosmic-ray flux (currently the most restrictive ones arise from the AGASA and Yakutsk muon data at $E > 100$ EeV[1] , from the Yakutsk muon data at $E > 40$ EeV and from the Pierre Auger Observatory data on the shower geometry at $E > 20$ EeV) disfavor the SHDM scenario and even exclude it for particular values of the dark-matter parameters. Current experiments do not report any significant deviations from the global isotropy at the highest energies. This is however not conclusive both due to the low statistics and due to a limited field of view of a terrestrial-based installation. The steeply falling spectrum of cosmic rays makes it very difficult to obtain a reliable measure of the global anisotropy in any combination of terrestrial experiments because possible observations of global anisotropy can be attributed both to a physical effect and to unknown systematic error in the energy determination.

On the other hand, the planned space-based experiments, TUS [2] and JEM-EUSO [3], will provide a unique opportunity to observe full sky with a single detector. While not being free from systematic uncertainties in the energy determination, an experiment of this kind would not introduce strong direction dependent systematic and thus would be able to perform the studies of the global anisotropy at high confidence.
One may expect that in future space-based experiments with their huge exposures, particular sources of UHECR will be determined on event-by-event basis. This is not an easy task, however: limited angular resolution together with large numbers of events would lead to identification problems similar to those of the gamma-ray astronomy but strongly enhanced due to magnetic deflections of the charged cosmic-ray particles, see [10] and [6].

The searches for global patterns in the distribution of UHECR arrival directions will thus be important in any case. A robust method for the study of any global asymmetry in the arrival directions is the harmonic analysis, [1]. It works perfectly if the predicted effect may be clearly seen in the first few harmonics but requires large statistics to reveal/exclude more complicated patterns.

Here, we determine the optimal strategy for the searches of global anisotropies even with the low-resolution experiments and for short operation time. The strategy is to fix two regions of the sky (not necessary covering full 4π) which are expected to provide the strongest contrast in over/under density of events with

[1] 1 EeV $= 10^{18}$ eV

respect to the null hypothesis of the isotropic distribution. The shape and the size of these regions, as well as the energy range of the events, are determined a priory in order to balance the strength of the expected anisotropy (increasing for smaller regions and higher energies) and its statistical significance. The aim of this paper is to simulate optimal regions and energies for TUS detector [**?**] and JEM-EUSO detectors [**?**] suitable to test the scenarios of extragalactic sources. To this end, we performed new and improved (with respect to [5]) simulations of the distribution of arrival directions.

II. Statistical Hypothesis

To test statistical hypothesis of global asymmetry of UHECR arrival directions we assume that the number of sources within GZK sphere is large enough so that the large-scale structure of the Universe traces well their distribution within 100-200 Mpc. Assumption about uniform source distribution is used as null-hypothesis. As alternative we take the assumption that the distribution of the sources follows that of luminous matter (galaxies).

Accordingly to obtain the function of the source (i.e. the number density of galaxies for a given direction and distance) we take the most complete full-sky catalog of galaxies 2MASS XSC [7]. But at "small" distances where 2MASS is insufficient we use another full-sky galaxy catalog, LEDA (details of catalog calibration are given in [5]). To suppress unphysical fluctuations we smoothed the distribution on function of the source at the scale 5° and 10 Mpc. By making use of a numerical propagation code [8] which is based on kinematic equations written in the expanding Universe and accounts for numerous interaction processes, we estimated the fraction of survived hadrons as function of energy and propagation distance so obtain the distribution of the UHECR arrival directions expected by the alternative hypothesis.

For energy > 70 EeV the galaxies distribution size in GZK sphere which radius is some more than 100 Mpc is strongly non-uniform having the structure called SuperGalaxy (SG) it is suitable to present the UHECR arrival direction distribution in SG coordinates: l_{SG} and b_{SG}, see Fig. 1. A color map there demonstrates the difference between event densities, alternative (non-isotropic source model) and null (isotropic). The central vertical belt presents a zone-of-avoidance cut of the LEDA catalog (region with $|b_G| < 15^\circ$, where b_G is galactic longitude). It was taken into account that due to orbit precession of space detectors the detector exposure is uniform in all directions. It is expected that the strongest excess of arrival directions locates along Supergalactic plane, in particular from the Virgo cluster ($l_{SG} = 103^\circ, b_{SG} = -2.8^\circ$) and Perseus-Pisces Supercluster.

III. Statistical Criterion

For statistical analysis we divide the sky into three parts: part 1 corresponds to the strongest expected excess of events over uniform distribution, part 2 corresponds to the strongest deficit and part 3 is the rest of the sky. As a research number we choose $\Delta = n_1 - n_2$ the difference between number of events in region 1 and 2. The 1 and 2 regions were optimized so that numbers Δ for null and alternative hypotheses were strongly different. To be more precise, with fixing type I error $\alpha = 5\%$ (i.e. with confidence level CL $= 95\%$) and type II error β ($1 - \beta$ is the power of test which express the probability of statistical analysis when alternative is correct) we determine the required number of events N to reject null-hypothesis for different choice of region 1 and 2. We have chosen two rectangular (in SG coordinates) regions with minimum N: the first region is in direction to Virgo cluster and for $\beta = 5\%$ has coordinates:

$$85^\circ < l_{SG} < 125^\circ, \quad -30^\circ < b_{SG} < 15^\circ \qquad (1)$$

The second region is in direction to the North pole of SG:

$$0^\circ < l_{SG} < 360^\circ, \quad 35^\circ < b_{SG} < 90^\circ \qquad (2)$$

Calculations have shown that for checking the hypothesis of Global anisotropy with errors of 5% one needs to detect $N = 55$ of events from all the sky. In this case the average difference Δ for null hypothesis will be -9 (3 events from region 1 and 12 events from region 2) and for alternative hypothesis it will be +3 (9 events from the region 1 and 6 events from region 2). For comparison it should be noted that if we measure only events in one region than the results of the same confidency will be achieved for number of event in the first region $N = 76$ and in the second region $N = 100$.

IV. Predictions for space-based experiment

The TUS lower energy threshold is estimated as 70 EeV and arrival direction accuracy is different for different zenith angles θ: for $\theta < 30^\circ$ the direction is estimated only roughly as being vertical in the error cone of 30°; for $30^\circ < \theta < 60^\circ$ the error approaches 10° and for $60^\circ < \theta < 90^\circ$ the error is no more than 5°. For events with $60^\circ < \theta < 90^\circ$ the exposure of TUS detector is about 4500 (in the first operation year for orbit height $R = 500$ km) and 3000 (for the next year, $R = 400$ km) $\mathrm{km}^2\,\mathrm{sr}\,\mathrm{yr}$, and for events with $30^\circ < \theta < 90^\circ$ is about 6750 (4500) $\mathrm{km}^2\,\mathrm{sr}\,\mathrm{yr}$.

To calculate the number of events and time, which need TUS to test the hypothesis we assumed average exposition for the years of operation for both angle ranges (3500 km^2 sr year for $60^\circ - 90^\circ$ and 5200 $\mathrm{km}^2\,\mathrm{sr}\,\mathrm{yr}$ for $30^\circ - 90^\circ$). The expected number of measured events with energy more than 70 EeV

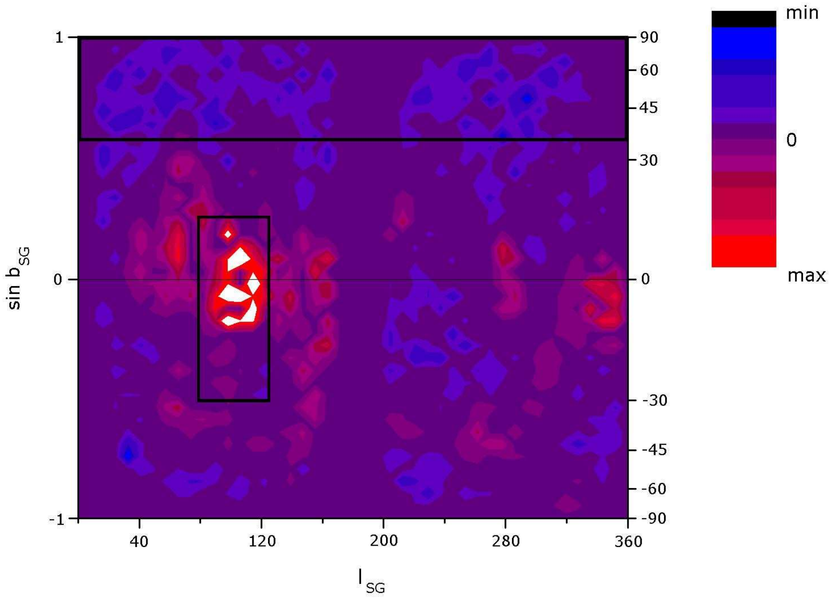

Fig. 1: Difference between event densities for alternative and null hypothesis. l_{SG} and b_{SG} - Supergalactic longitude and latitude, black rectangles correspond to critical region 1 (with the center direct to Virgo cluster) and 2 (polar region).

for TUS experiment, calculated using the absolute energy spectrum from the results of Pierre Auger Observatory [9], is 5 events for $60° - 90°$, and 7 events for $30° - 90°$.
To test the hypothesis with the CL $= 95\%$ and type II error $\beta = 50\%$ TUS needs 3 years of operation for $60° - 90°$ range and 2 years for $30° - 90°$. During this time detector achieve uniform exposition, and can measure sufficient number of events.

The JEM-EUSO detector is expected to have an instantaneous aperture 580000 km^2 sr [11], and duty cycle of about 15%. The exposition of detector $1.1 \cdot 10^4$ km^2 sr yr, that is 40 times more than TUS exposition. The angular resolution of JEM-EUSO is few degrees; the ISS orbit parameters are uniform over the sky.
The number of events for this detector is more than 150 events per year. With such events statistics the test of hypothesis with CL $= 95\%$ and $\beta = 5\%$ could be made during few months, but to achieve the uniform exposition the operation time for this research should be of about a year.

V. Conclusion

In this work, we made quantitative predictions for the global anisotropy of the UHECR arrival directions expected in the ”bottom-up” scenario of the origin of the highest-energy cosmic rays. The predictions will be tested with the limited statistics in the first space-based TUS mission. However, only JEM-EUSO will be able to detect the predicted over/under density pattern of arrival directions of UHECR particles.

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