The comparison of correlation properties of ultra-high energy cosmic rays events with Luminous Infrared Galaxies.

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***Abstract*. We present the correlation properties for Auger and AGASA UHECR events with luminous infrared galaxies. This type of sources emit in infrared light more than 10^{11} of the luminosity of Sun. Such sources are expected as UHECR candidates. The two-dimensional Kolmogorov-Smirnoff correlation test was used. A lot of series of tests at different cuts were carried out to find the best correlation of those two samples. Those cut-offs select the events by energy and sources by distance and luminosity. We take into account the luminosity of the sources and experiment exposure as weight factors.**

***Keywords*: correlation, cosmic rays, LIRG**

I. Introduction

One of the main problems in astrophysics is identification of the sources of the ultra high energy cosmic rays (UHECR). We search for anisotropies in arrival directions of particles to find this. There are several correlation tests used in research works. In this paper one of them was used - Two-Dimensional Kolmogorov-Smirnow (2DKS) test. As possible sources we take into account Luminous Infrared Galaxies [1] which are systems with total infrared emission brighter than 10^{11} L_{Sun}. To do this test, we use data form two cosmic ray observatories which are located on the opposite sides of the hemisphere - Auger and AGASA. A correlation agreement between those observatories was found, for sources closer than 75 Mpc.

II. Luminous Infrared Galaxies

Potential type of sources of UHECRs are Luminous Infrared Galaxies. LIRGs are astrophysical objects which show intensive and violent star formation processes initiated by collisions and gravitational interactions between galaxies. In these objects particles are accelerated in wind's large scale conditions in multiple supernova explosions and in strong turbulent magnetic field. The LIRGs span the full range of nuclear spectral types (AGN, starbursts) and interaction stages (major mergers, minor mergers, isolated galaxies). Luminous infrared galaxy mergers are dynamically evolving galaxies that exhibit complex structure and harbor both obscured and unobscured starbursts and AGNs. The most powerful galaxies detected in the IRAS (Infrared Astronomical Satellite) survey revealed that virtually all show evidence of a strong interaction or double nuclei. In our work, we use PCSz catalogue [2]. We get a sample of sources with $L_{FIR} > 10^{11} L_{SUN}$ (LIRG) and we limit distance to objects from Local Universe (redshift closer than 0.03). The cuts select the sample of 204 sources which was used to correlation tests with arrival directions of the detected particles.

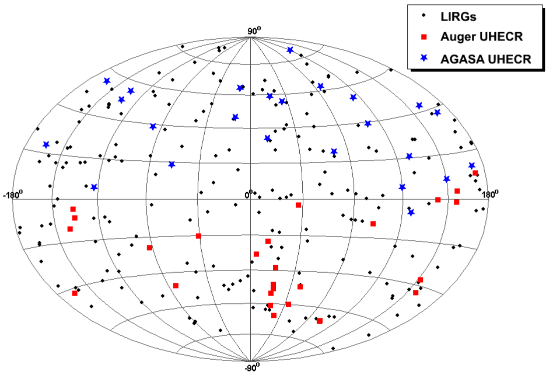


Fig. 1. The map of source (LIRGs) positions and arrival directions of UHECRs detected by Auger and AGASA experiments described in Equatorial Coordinate System and Aitoff projection.

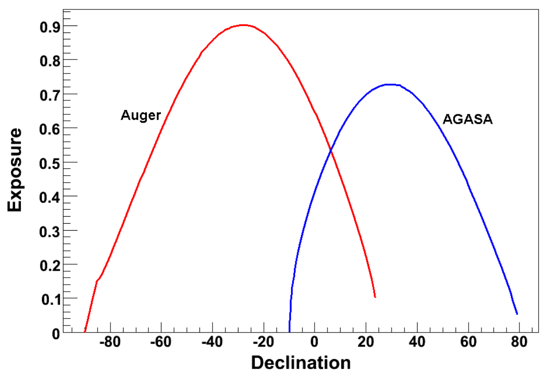
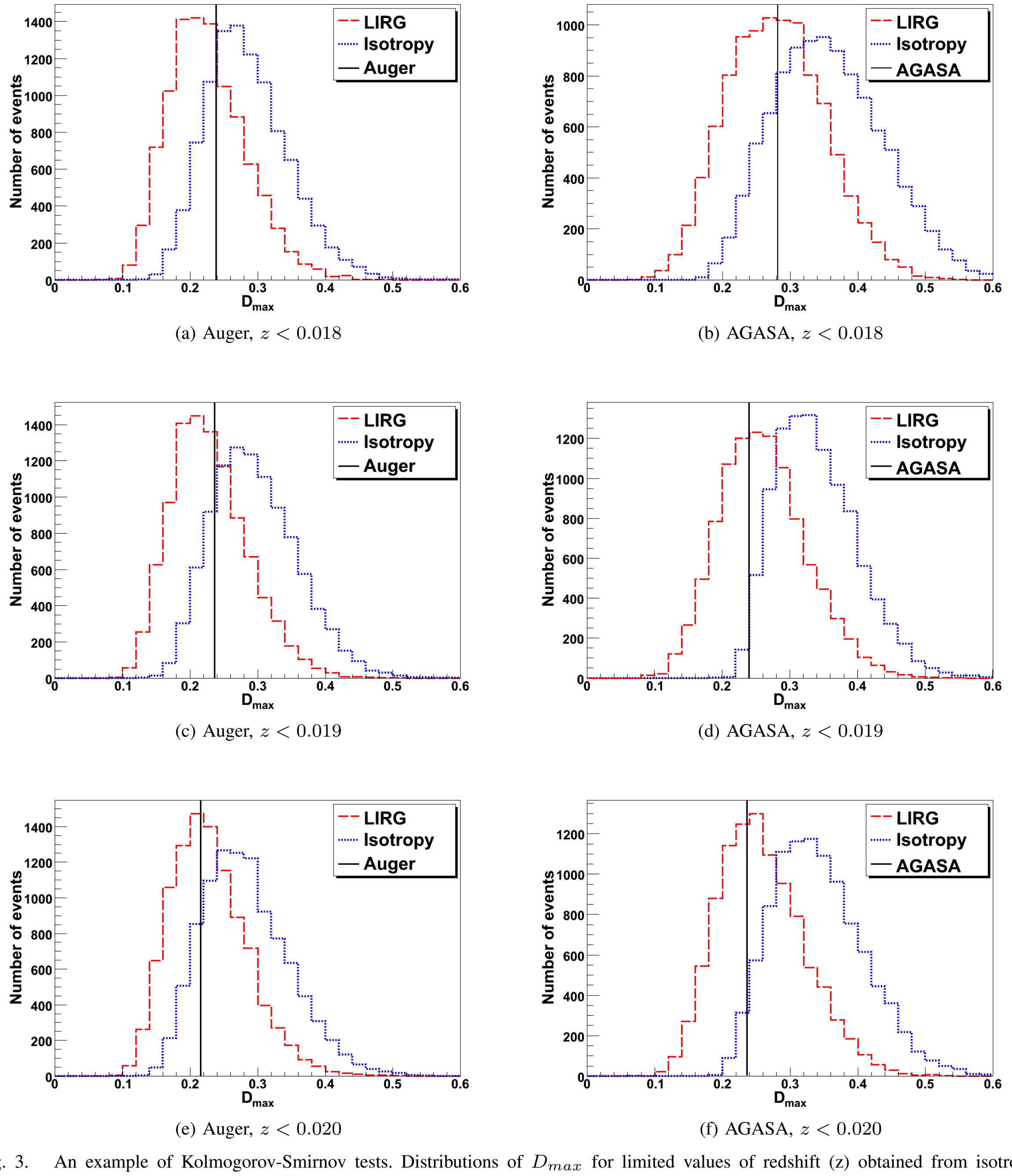


Fig. 2. Relative exposures of Auger and AGASA experiments, which are located in different hemispheres.

III. The Data Set

We take into account data from Auger and AGASA Experiments to study properties of correlations of Luminous Infrared Galaxies and Ultra High Energy Cosmic Rays. Exposition for each of observatories cover different hemispheres (see Fig. 2). Thanks to this situation



(a) Auger, $z < 0.018$ (b) AGASA, $z < 0.018$

(c) Auger, $z < 0.019$ (d) AGASA, $z < 0.019$

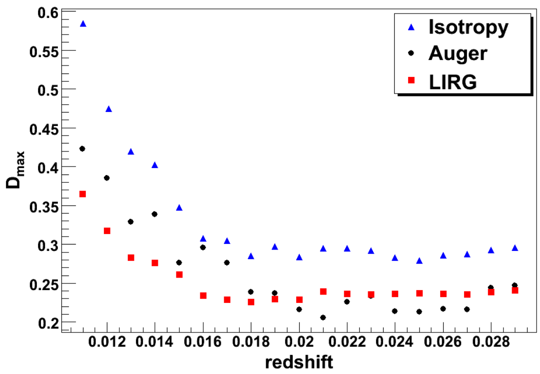
(e) Auger, $z < 0.020$ (f) AGASA, $z < 0.020$

Fig. 3. An example of Kolmogorov-Smirnov tests. Distributions of D_{max} for limited values of redshift (z) obtained from isotropy and catalogue simulations, vertical lines are D_{max} values of Auger or AGASA tests obtained from real data.

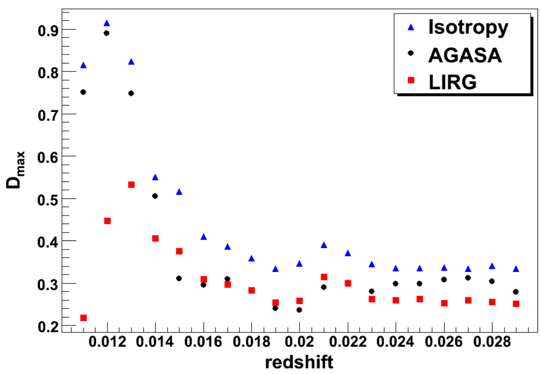
it is possible to compare correlation properties on both hemispheres. We use 27 events recorded by the Pierre Auger Observatory, with energies above 56 EeV [3], and for AGASA Experiment we selected 24 events with energies above 56 EeV [4]. These cuts could ensure that trajectories of the arriving particles were not distorted by galactic magnetic fields and their directions could show coordinates of cosmic ray sources.

IV. Correlation Test

We use generalization of Two Dimensional Kolmogorov-Smirnov test described by Fasano & Franceschini [5], a variant of an earlier idea of Peacock [6]. In one dimension $1DKS$ test is the general test of goodnes of fit besides the Pearson χ^2. It is a form of minimum distance estimation used as a nonparametric test of equality of one-dimensional probability distributions used to compare a sample with a reference probability distribution, or to compare two samples. In two-dimensional $2DKS$ case each point (the source coordinates and cosmic rays directions - n points) is described by two equatorial coordinates x_i and y_i. In each of n data points we divide our data into quadrants and calculate the maximum difference between reference probability fraction of both data



(a) Auger



(b) AGASA

Fig. 4. Results of 2DKS tests as a function of source redshifts.

samples. The 2DKS statistic D is taken to be the maximum difference of the corresponding integrated probabilities. The probability fraction $(F^I_{j,source}(x,y))$ is increased by $1/n$ each time a data point appears in quadrant I.

$$D^{2Dim}_j = max(D^I_j, D^{II}_j, D^{III}_j, D^{IV}_j) \quad (1)$$

where,

$$D^I_j = \sup_{allx,ally} (F^I_{j,source}(x,y) - F^I_{j,CR}(x,y)) \quad (2)$$

The 2DKS test checks whether the particle directions are distributed in the sky in the same ratios as the sources from the catalogue. We may obtain this by checking if there is any quadrant in which the fraction of both samples is significantly different.

V. Results

In our work we used tests with additional normalized weights. The first type of weight was taken as a exposure of each observatories. This exposure takes into account the geographical position of observatory (Auger - $\phi = -35.2^o$, AGASA - $\phi = 35^o47^{'}$), and maximal zenith angle of view (Auger - $\Theta_{max} = 60^o$, AGASA - $\Theta_{max} = 45^o$). The exposure measures the time integrated effective collecting area. For detector in continuous operation it is uniform in right ascension/(hour angle), being only a function of the declination. If the detector is fully efficient for particles arriving with zenith angle $\Theta < \Theta_{max}$, the exposure has only a $cos(\Theta)$ modulation due to the change in the effective detection area. The exposure towards a direction (δ, α) is proportional to the integral of $cos(\Theta(t))$ for all the time when $\Theta(t) < \Theta_{max}$ and is given by equation (3):

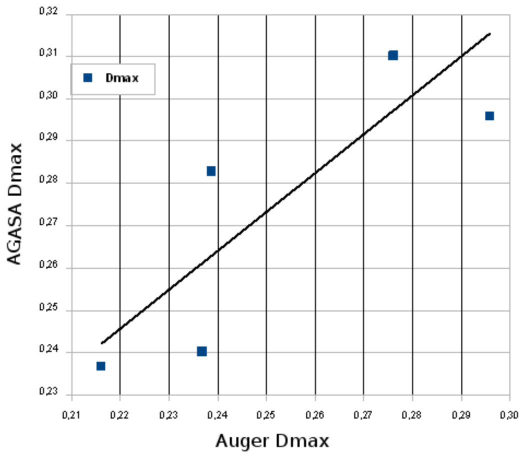


Fig. 5. Correlation's agreement of Auger and AGASA Experiments. There are values of D_{max} for both observatories on the axis.

$$\epsilon(\delta) = cos(\delta)[\alpha_{max} sin(\phi) sin(\delta) + cos(\delta) cos(\phi) sin(\alpha_{max})] \quad (3)$$

where:

$$\eta = \frac{cos(\Theta_{max}) - sin(\phi) sin(\delta)}{cos(\phi) cos(\delta)}, \quad (4)$$

$$\alpha_{max} = \begin{cases} 0 & \text{if } \eta > 1; \\ \pi & \text{if } \eta < -1; \\ arccos(\eta) & \text{elsewhere.} \end{cases}$$

The first two cases (0 and π) correspond to the situation when a source with a given declination does not cross the level $90 - \Theta_{max}$ from bottom (0) and top (π) respectively.

As a second weight, we use reference light flux of Luminous Infrared Galaxy, which contains information about its luminosity and distance. The data was taken from LIRGs catalogue. In tests we take into account redshift (z) of sources. We divide our data into bins with different maximum value of z (z_{max}). For each of these bins the corresponding tests were prepared. Several tests of this kind, were presented as an example in Fig. 3, which show comparison between Auger and AGASA samples for limited redshift: $z < 0.018, z < 0.019$ and $z < 0.20$. In all tests both types of weights were used. The two histograms on each figures show distributions of statistic value D_{max} obtained as results of 2DKS test for one realization randomly selected out of 27 events for Auger - left panel (or 24 events for AGASA - right panel), from two different distributions of cosmic rays sources - full isotropy (dotted line) and followed LIRGs distributions from a catalogue (dashed line). The randomly selected 27 or 24 events pass correlation 2DKS test in the same way as real events. The statistic D_{max} was calculated for each two thousands realizations. The vertical line indicates the value of D_{max} for events recordered by Auger or AGASA experiment. The rows in figure 3 show graphs for cuts selected by LIRGs redshift. The D_{max} from experimental data from both observatories indicates rather to cosmic rays source distribution as LIRGs catalogue. The correlation is even stronger for AGASA data (panels b,d,f in Fig. 3), for Auger events only for LIRGs within the radius $z < 0.02$ (panel e Fig. 3) correlation is evident. The correlations depend on the collection radius of cosmic ray sources. For explanation of this dependence series of tests with cut for maximal radius (z_{max}) to source were provided. The correlations test 2DKS was repeated for the LIRGs within the maximum radius z_{max}, where z_{max} was changing from value 0.01 to 0.029 with the step of 0.001. Figure 4 shows the results where triangles are average values of D_{max} for the simulated events from isotropic distribution, squares are average values of D_{max} for the simulated events from LIRG catalogue and circles are D_{max} values for real cosmic ray events - panel (a) Auger, panel (b) AGASA experiment. It is evident that in range of z_{max} (0.015-0.023) for AGASA and z_{max} (0.018-0.026) for Auger, D_{max} are closer to LIRGs catalogue than to the isotropy distribution. Figure 5 shows the correlation between Auger and AGASA D_{max} values for range radius z_{max} (0.015-0.020) where the best correlation for real data was obtained. The correlation is noticeable but D_{max} for AGASA are greater than Auger D_{max}.

VI. Conclusion

The correlation between direction of UHECR ($E > 56EeV$) Auger and AGASA events with luminous infrared galaxies LIRG have been evaluated using two dimensional Kolmogorov-Smirnov test. The D_{max} statistic indicates a positive correlation of directions of UHECR with positions of LIRG (Fig. 3 and 4). Evaluated dependence of D_{max} as a function of redshift (Fig. 4) indicates a wide range of z_{max} where the above-mentioned conclusion is valid. The relation between D_{max} from the data and simulations is almost identical for AGASA and Auger with the exception of $z_{max} \sim$ 0.02 ($\sim$ 80 Mpc) where D_{max} reaches a minimum value but Auger simulated events have not minimum in this point in contrary to AGASA case. It can be some indication that, at this distance, the distribution of cosmic ray sources or/and LIRGs on south and north sphere are not the same.

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