Analysis of the Pierre Auger Observatory data at the highest energies with three-point autocorrelation function.

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Abstract

In this paper we use three-point autocorrelation function to analyse the Pierre Auger Observatory Surface Detector data recorded from January 1, 2004 up to May 31, 2008. Contrary to two-point correlation function which has broad minimum at wide range of angles 5-25 degrees, three-point correlation function has sharp minimum at angles 18-24 degrees. We show that this minimum as well as most of signal in two-point correlation function completely dominated by large 20-degree region around Cen A. Outside of this region sky is consistent with isotropic.¹

1 The Auger data sets used in this analysis. Update on correlations with AGN’s.

In this analysis we use the Pierre Auger Observatory (AUGER) Surface Detector data recorded from January 1, 2004 up to May 31, 2008 in Herald

¹Study of correlation of AUGER data with Cen A region and suggestion for prescription is presented in accompanying GAP-Note 2008-092 [1].
Table 1: Events with $E > 57$ EeV and $\theta < 60^\circ$ (Herald v6 reconstruction, T5 ICRC-2005 trigger) which arrived in the period August 31, 2007 - May 31, 2008. The first column indicates the event ID, the $2^{nd}$ and $3^{rd}$ columns are the Galactic coordinates $l$ and $b$ in deg., the $4^{th}$ is the zenith angle in deg., the $5^{th}$ is the energy in EeV, the $6^{th}$ is the number of tanks used in the reconstruction, the $7^{th}$ is T5 trigger (see text), the $8^{th}$ column is the opening angle between the event and the closest of the 472 preselected AGNs. The star in the last column indicates those events that do not correlate with an AGN within the parameters of refs. [3, 4].

v6 reconstruction [6] with ICRC-2005 trigger for energies $E > 57$ EeV. 27 events recorded up to August 31, 2007 was published by Pierre Auger Collaboration in ref. [4]. From September 1 2007 to May 31, 2008 10 new events with $E > 57$ EeV arrived. Those events are presented in the Table 1.

Regarding the quality trigger condition, in addition to the official “strict” T5 i.e. a full active hexagon of tanks around the hottest station ($T5 = 3$ in Table 1), we have also considered the ICRC-2005 T5 trigger, five active stations around the hottest station and the reconstructed core within a cell triangle of active stations ($T5 = 2$ in Table 1). We keep $T5 = 1$ notation for a “relaxed” T5 trigger of 5 active tanks allowing the core to be outside an active cell, as in previous gap-notes [5], but we will not use this non-official trigger in present work.

As seen from last column of Table 1, only one out of 10 new events correlate with positions of 472 AGN’s from Veron catalog [7] within 3.2 degrees. This is completely consistent with background.
Indeed, in Fig. 1 we present probability of correlation by chance between arrival directions of cosmic rays with $E > 57$ EeV in AUGER data and sky positions of 472 AGN’s within given angle. Angle 3.2 degrees, energy scale $E > 57$ EeV and correlating AGN’s was preselected as discussed in papers [2, 3, 4]. Vertical magenta line show angle of $\delta = 3.2$ degrees. Blue dotted line correspond to 27 events with $E > 57$ EeV published in the ref.[4] (without penalty for running prescription) have minimum about $P = 2 \times 10^{-4}$. Green dashed line with new 10 events from Table 1 completely consistent with background. Finally, red solid line corresponds to all 37 events and has minimum $P = 10^{-2}$. Even if this is not completely consistent with background one can really see that formal signal for correlations with predefined 472 AGN’s is not as strong as before. Besides additional dataset with relaxed trigger also show correlations [5], while HiRes data does not [8].
Can correlation observed in ref. [3, 4] be real correlation with AGN’s? Yes, however it should be a fluctuation up of the signal, taking into account new data. Can it be that there is no correlations with 472 AGN’s? Yes, but we need in more data to tell this definitely. Does it mean that AUGER see isotropic sky? Not at all. It would mean that given test “correlations with 472 AGN’s” presented in refs. [3, 4] does not work.

In order to discuss anisotropy in most conservative way we have to come back to data itself and exclude all uncertainties connected with choice of catalog and it’s incompleteness. Below we will discuss two-point autocorrelation function in the Section 2. We suggest new method with 3-point autocorrelation function in the Section 3 and discuss which part of sky saturate autocorrelations in the Section 4. In the Section 5 we summarize our results.

2 Two-point autocorrelation function

![Figure 2: Sky positions of the 27 AUGER events with E > 57 EeV published in the ref. [4] shown with blue stars. Red stars show sky positions of ten new events presented in Table 1. The red line show the Galactic plane.](image)
First, let us take a look on the sky map of UHECR arrival directions in AUGER for same data which was used to correlation analysis in previous section. In Fig. 2 we show sky map in equatorial coordinates. Positions of the 27 AUGER events with \( E > 57 \text{ EeV} \) published in the ref. [4] are shown with blue stars. Positions of new 10 events from Table 1 are indicated with red stars. Finally, red line show location of the Galactic plane. In Equatorial coordinates AUGER exposure sensitive only to declination (DEC). In Right Ascension (RA) events should come uniformly. AUGER position is \( \text{DEC} = -35.2^\circ \). In Fig.4 one can see that at \( E > 57 \text{ EeV} \) events come almost uniformly north from \( \text{DEC} = -35.2^\circ \), while there is a big cluster on the south. Some new events also located in the same cluster. We come to this point later in the Section 4.

Now let us study possible anisotropy in the data with the standard way by two-point correlation function. An autocorrelation signal at medium scales \( \delta \sim 25^\circ \) already was presented in the analysis of combined data of experiments before Auger [9]. A similar signal was found in the Auger data from January 1, 2004 to December 31, 2006 [10]. Results for data up to March 15, 2007 were presented at the ICRC-2007 conference [11]. In those data the autocorrelation function had two minima’s of the order of \( 10^{-4} \) at angles \( 7^\circ \) and \( 23^\circ \) with a broad minimum \( \sim 10^{-3} \) in the range \( (7^\circ, 23^\circ) \) for \( E > 50 \text{ EeV} \).

Finally, in ref.[12] same data as used for AGN correlations was analyzed. It was shown that raw probability for this data is \( P_{\text{raw}} = 1.5 \times 10^{-4} \) at \( E > 57 \text{ EeV} \) and \( \delta = 11^\circ \).

In order to calculate raw probability we count within given angle and above given energy all pairs of events with angular separation less then this angle. Then we compare total number of pairs in data with one in Monte Carlo simulations of isotropic sky, taking into account AUGER exposure. The number of cases in which MC counting equal or more then one in data related to total number of MC simulations give raw probability that signal seen in data is by chance.

For calculation of penalty factor one need to create many artificial data sets and repeat above procedure for all of them, every time looking for \( P_{\text{raw}} \). Number of cases in which \( P_{\text{raw}}(MC) < P_{\text{raw}}(\text{data}) \) related to total number of datasets would give real chance probability \( P_{\text{chance}} \). Penalty \( p \) is the ratio \( p = P_{\text{chance}}/P_{\text{raw}}(\text{data}) \).

The penalty for scanning in angle and energy in ref.[12] was about \( p = 100 \) making chance probability of this signal on the level \( P_{\text{chance}} = 1.6 \times 10^{-2} \).
Figure 3: Probability that signal in two-point autocorrelation function is fluctuation of background as function of angle for $E > 57$ EeV. Blue dotted line correspond to 27 events with $E > 57$ EeV published in ref.[4]. Red solid line is for 37 events including 10 new events from Table 1.

In the Fig. 3 we show raw probability that signal in two-point autocorrelation function is fluctuation of background as function of angle for $E > 57$ EeV. Blue dotted line reproduce result of ref. [12] for raw probability at $\delta = 11^\circ$ equal to $P_{\text{raw}} = 1.5 \times 10^{-4}$. With red solid line we show same function for data including 10 new events. This probability has similar minimum at $\delta = 11^\circ$ with $P_{\text{raw}} = 4 \times 10^{-5}$. With similar penalty factor $p \sim 100$ this gives $P_{\text{chance}} = 0.4\%$. Note that beside local minimum at $\delta = 11^\circ$ this probability at Fig. 3 have broad minimum at angles up to $\delta = 25^\circ$.

Accumulation of signal with time for two-point correlation function shown in the Fig. 4. We show probability that signal in the two point autocorrelation function is fluctuation of background for 14 events before May 2006 with magenta dashed-dotted line and 21 events before March 2007 with green dashed line. Lines for 27 events before August 31, 2007 and 37 events before May 31, 2008 are same as in Fig. 3. From Fig. 4 one can see that one need at least $N \sim 20$ events to start see anisotropy in two-point autocorrelation.

This makes any blind test time-consuming. Another important point is
that probability has broad minimum in wide range of angles 4-25 degrees, while local minimum can be located at difference scales, depending on dataset (7 degrees for 21 events and 11 degrees for 27 events).

We conclude that analysis of AUGER data with two point correlation function show existence of anisotropy with chance probability $P_{\text{chance}} = 0.4\%$. We can try to find nature of this anisotropy performing other tests. In particular, a recent analysis made with the 2-point Rayleigh test gives a raw probability at the $10^{-5}$ level [13] (however, another analysis with the same method show $10^{-4}$ in this case [14]). This test is sensitive to “filamentary-like” structures which are definitely presented in sky, see Fig. 2. This next section we present another analysis, which contrary sensitive to clusters of events, which are also present in the sky map in the Fig. 2.
Figure 5: Probability that signal in three-point autocorrelation function is fluctuation of background as function of angle. Magenta dashed-dotted line is for 14 events before May 2006 with $E > 57$ EeV. Green dashed line is for 21 events before March 2007. Blue dotted line correspond to 27 events up to August 31, 2007 published in ref.[4]. Red solid line is for 37 events including 10 new events from Table 1.

3 Three-point autocorrelation function

Three-point autocorrelation function can be defined in the analogy with two-point function. For given angle we have to count all triplets of events which are separated on the angular scale less then this angle. In practice we calculate 3 angular distances between any three events and find maximum one. Then remaining procedure is similar to one for the two-point correlation function discussed in the previous section.

In the Fig. 5 we present raw probability for three-point autocorrelation function as function of angle for same data sets as for Fig. 4 in case of two-point autocorrelation function with $E > 57$ EeV. Magenta dashed-dotted line is for 14 events before May 2006. Green dashed line is for 21 events before March 2007. Blue dotted line correspond to 27 events up to August 31, 2007 published in ref.[4]. Red solid line is for 37 events including 10 new
events from Table 1.

For 37 events raw probability has minimum at 18 degrees with value $P_{raw} = 1.3 \times 10^{-5}$. We can not calculate penalty factor for three-point correlation function directly because this is time-consuming operation, which requires months of calculation on modern PC and probably can be done only with supercomputers or big clusters. Here we assume that penalty for the three point autocorrelation function have to be similar to the case of two-point one, i.e. $p \sim 100$, because we scan exactly on the same parameter space energy-angle $(E, \delta)$ same data. Thus we estimate that $P_{\text{chance}} = 1.2 \times 10^{-3}$ for three-point correlation function.

One can see an important difference between Fig. 4 and Fig. 5. Contrary to two-point correlation function three-point one has sharp minimum at 18-24 degree scale in all data sets. Taking into account that three-point correlation function sensitive to clusters of events and seeing such big cluster in the Fig. 2 we can assume that three-point correlation function dominated by this single cluster. We will check this assumption in the next section.

4 Saturation of the autocorrelation function

Analysis of three-point autocorrelation function in previous section suggested that most of signal in it dominated by large cluster of events which situated around Centaurus A. In this section we will check this possibility. In order to do this we cut this region of sky both from data and from MC simulations and calculate again three-point autocorrelation function.

Result is presented in the Fig. 6 with blue line. It is seen from this figure that ALL signal in the three-point autocorrelation function come from this cluster of events. We also check this idea for two-point autocorrelation function and see similar result presented with green line in the Fig. 6, except for 2-sigma signal at small scales $\delta < 10^\circ$.

Thus both signals in the two-point and three-point autocorrelation functions come from the same cluster of events!

5 Summary

In this paper we analyze anisotropy in the AUGER data for period January 1, 2004 up to May 31, 2008.
Since publication of 27 events with $E > 57$ EeV up to August 31, 2007 we had 10 new events for the same T5 ICRC-05 trigger in the Herald reconstruction. There is no correlation signal seen with 472 AGN’s for new 10 events. Combined data does not allow to conclude in either side if correlations within prescribed parameters was by chance or not.

Contrary to correlations with AGN’s, autocorrelation signal calculated with two-point autocorrelation function increased, see Fig. 3. It decreased from $P_{\text{chance}} \sim 1.7\%$ in the case of 27 events [12] to $P_{\text{chance}} \sim 0.4\%$ in the case of 37 events presented here.

We also analyzed same data with the three-point autocorrelation function, see Fig. 5. Raw probability for it has minimum at 18 degrees with value $P_{\text{raw}} = 1.3 \times 10^{-5}$, which give estimate for chance probability $P_{\text{chance}} \sim 0.15\%$.

Finally, the most important result of this study is the fact that both two-
point and three-point autocorrelation functions are saturated by the same large cluster of events located in 20-degree region around Centaurus A. Discussion of possible interpretations of this result together with analysis of correlations of AUGER data with Cen A region are presented in the accompanying GAP-Note [1].

References


[14] D. Harari, S. Mollerach and E. Roulet *Some studies regarding the 2 point Rayleigh estimator*, GAP-Note-2008-035