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Studies of clustering in the arrival directions of cosmic rays detected at the Pierre Auger Observatory above 10 EeV

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Abstract: If clustering of the arrival directions of ultra high energy cosmic rays is discovered, this would provide important information about their origin, composition, and the galactic and extragalactic magnetic fields. We present here the analysis of the autocorrelation function of the data from the Pierre Auger Observatory as a function of the angular scale and the energy threshold. We compare our results with the signals found by previous experiments.

Introduction

The identification of the sources of the ultra high energy cosmic rays is one of the main open problems in astrophysics. The study of their arrival directions is likely to provide significant insight into this question. If cosmic rays are charged particles, their trajectories will be bent by the intervening galactic and extragalactic magnetic fields and the arrival directions will not point back to their sources. The intensity and orientation of these fields are not well known, but as the deflections decrease with the inverse of the energy, the effect is smaller at the largest energies. Thus, it is at the highest energies that cosmic rays are most likely to point towards their sources.

On the other hand, the distance from which ultra high energy protons can arrive to the Earth is expected to be limited by the energy loses caused by the photo-pion production processes in the interaction with the cosmic microwave background (GZK effect [1, 2]), and similarly nuclei can undergo photo-disintegration processes. This would strongly attenuate the flux coming from distant sources. Hence, at energies above ~ 60 EeV, cosmic rays are expected to come mostly from nearby sources.

These ideas have motivated an extensive search of clustering signals both at small angular scales, looking for point-like sources, and at intermediate angular scales, looking for the pattern characterizing the distribution of nearby sources. Although the data from a number of experiments have shown a remarkably isotropic distribution of arrival directions, there has been a claim of small scale clustering at energies larger than 40 EeV by the AGASA experiment [3, 4, 5]. The HiRes experiment has found no significant clustering signal at any angular scale up to $5°$ for any energy above 10 EeV [6]. A hint of correlation at scales around $25°$ and energies above 40 EeV, combining data from HiRes stereo, AGASA, Yakutsk and SUGAR experiments has been pointed out in ref. [7].

The data set

We use data recorded by the Surface Detector of the Pierre Auger Observatory between 1 January 2004 and 15 March 2007 with energies above 10 EeV and zenith angle smaller than $60°$. This represents a set of 1672 events, with 62 of them having energies larger than 40 EeV, that pass our reconstruction quality cuts, with 5 active stations surrounding the station with the highest signal and with the reconstructed core position lying inside an active triangle of stations. We only considered events that triggered 6 or more stations, which angular resolution, defined as the angular radius around the true cosmic ray direction that would contain 68% of the reconstructed shower directions, is at these energies 0.9° [8]. The energy is calibrated using the hybrid events simultaneously detected by the fluorescence and the surface detectors.

The fact that the surface detectors array is fully efficient for events with energy larger than 3 EeV implies that the exposure area is determined only by geometric factors leading to a simple analytic dependence on declination. A small modulation in right ascension is also present due to the growth of the array during the data taking period, but this effect is small and can be ignored in this analysis.

Methods

A standard tool for studying anisotropies is the two-point angular correlation function. This counts the number of pairs separated by less than an angle θ among the events with energy larger than an energy threshold E. We show in Figure 1 the result for all the events above 10 EeV. The expected number of pairs is obtained by generating a large number of Monte Carlo simulations with the same number of events with an isotropic distribution modulated by the exposure of the detector, from which the mean number of pairs and the 95% CL band is extracted for each angular scale. The fraction of simulations with a larger number of pairs than the data gives a measure of the probability that an observed excess of pairs arise by chance from an isotropic distribution of events.

The result of the autocorrelation function analysis depends of course on the values of θ and E considered. However, the fact that the deflections expected from galactic and extragalactic magnetic fields and the distribution of the sources are largely unknown makes it difficult to fix these values a priori. The significance of an autocorrelation signal at a given angle

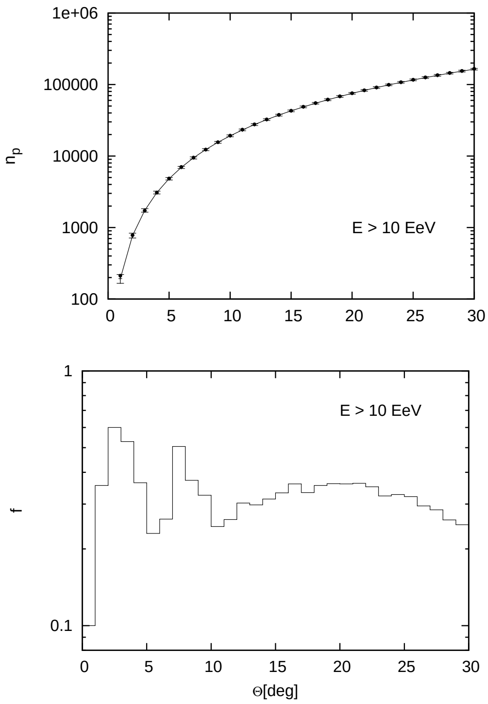

Figure 1: Upper panel: Autocorrelation function above 10 EeV as a function of the angle (dots) and autocorrelation function for an isotropic distribution with 95% confidence level band. Lower panel: Fraction of isotropic simulations with larger number of pairs than the data.

and energy when these values have not been fixed a priori is a delicate issue, that has made the AGASA small scale clustering claim very controversial [9].

We adopt here the method proposed by Finley and Westerhoff [9], in which a scan over the minimum energy and the angle is performed. For each value of E and θ a chance probability is estimated by generating a large number of isotropic Monte Carlo simulations of the same number of events, and computing the fraction of simulations having an equal or larger number of pairs than the data for those values of E and θ. The most relevant clustering signal corresponds to the values of θ and E that have the smaller value of the chance probability, P_{min}. Finally, the probability that such clustering arises by chance from an isotropic

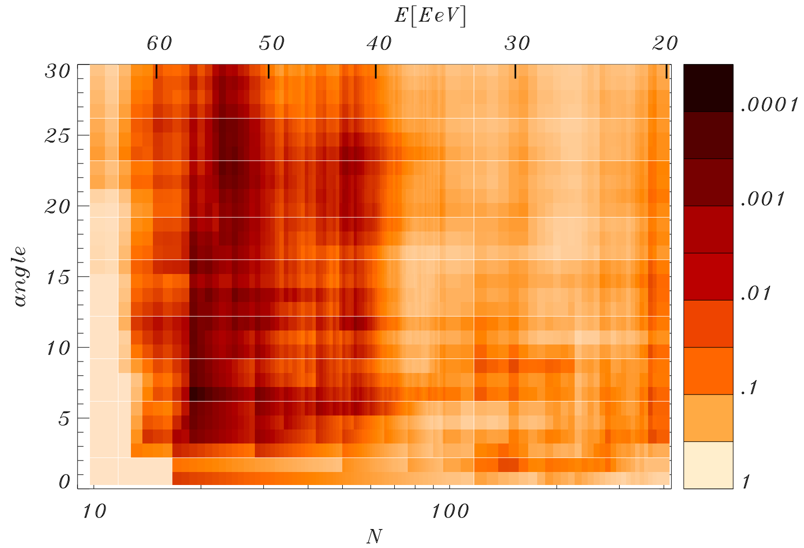

Figure 2: Autocorrelation scan for events with energy above 20 EeV

distribution is estimated by performing a similar scan on a large number of isotropic data sets simulated by the Monte Carlo technique and finding the fraction of the simulations having a smaller P_{min} than the data.

We show in Figure 2 the result of the scan above a minimum energy of 20 EeV and up to a maximum angle of 30°. A broad region with an excess of correlation appears at intermediate angular scales and large energies. The minimum appears at 7° for the 19 highest energy events ($E > 57.5$ EeV), where 8 pairs are observed, while 1 was expected. The fraction of isotropic simulations with larger number of pairs at that angular scale and for that number of events is $P_{min} = 10^{-4}$, obtained by comparing the observed number of pairs with that arising in 10^6 isotropic simulations. An extended scan for the 1672 events with $E > 10$ EeV shows no new minimum.

The chance probability of a $P_{min} < 10^{-4}$ to arise from an isotropic distribution, obtained by performing the same scan to 10^5 simulations, is $P \simeq 2 \times 10^{-2}$.

Previous analyses of other experiments have reported small scale clustering signals at 2.5° in AGASA data [3, 4, 5] and at intermediate scales (around 25°) in a combination of data from different experiments [7], both for energies above 40 EeV.

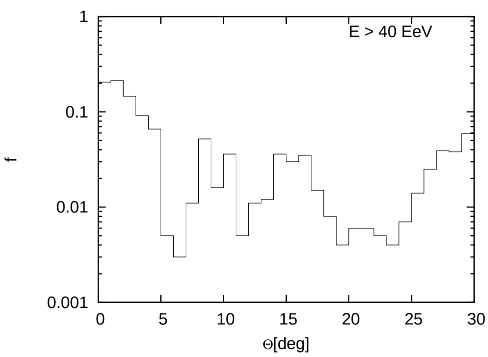

Figure 3: Fraction of simulations with larger number of pairs than the data for the 64 events with $E > 40$ EeV.

We show in Figure 3 the fraction of simulations with more pairs than the data for the events with $E > 40$ EeV (62 events). The small scale clustering in Auger data is compatible with that expected from an isotropic flux with our present statistics. We observe 2 pairs within 2.5°, while 1.5 were expected from an isotropic flux. Due to a possible difference in the energy calibration between Auger and AGASA, the clustering signal reported by AGASA could appear in Auger data at a different (lower) energy scale. We show in Figure 4 the probability for a larger or equal number of pairs within $\theta = 2.5°$ as a function of the number of events (or threshold energy). At this angular scale, no strong excess of clustering appears in the present data set. In the relevant energy range there is a slight excess of pairs, for example for $N = 150$ ($E > 30$ EeV) 14 pairs are observed while 8.5 are expected, with a probability for this to happen by chance in an isotropic distribution of about 5%. This excess is anyhow much smaller than the one reported by AGASA, where 7 pairs were observed while 1.45 were expected (out of 57 events).

Regarding the intermediate angular scales signal, some hint of clustering, though not very significant with the present statistics, is apparent. It is weaker at this energy than at higher energies (above 50 EeV) as discussed above (Figure 2).

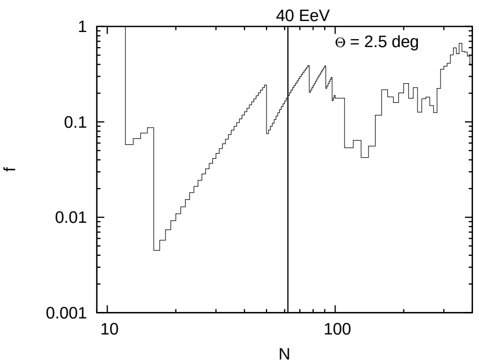

Figure 4: Fraction of simulations with more pairs separated by $\theta < 2.5°$, as a function of the number of events.

Conclusion

We have searched for clustering signals in the Auger data with energies above 10 EeV. In particular we have checked the clustering signal at 2.5° for $E > 40$ EeV reported by AGASA. No strong excess of clustering is present at this angular scale in our data set.

An extensive scan in angle and energy threshold shows some hints of clustering at larger energies ($E > 50$ EeV) and intermediate angular scales, that could be a signal of the large scale distribution of nearby sources. However, taking into account the scan performed, the probability that this kind of signals appear by chance from an isotropic flux is $P = 2\%$. Thus it is only marginally significant with our present statistics. Auger future data will be used to check if this correlation is real.

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