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Medium scale clustering of ultrahigh energy cosmic ray arrival directions

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Abstract: The two-point autocorrelation function of ultrahigh energy cosmic ray (UHECR) arrival directions has a broad maximum around 25 degrees, combining the data with energies above 4×10^{19} eV (in the HiRes energy scale) of the HiRes stereo, AGASA, Yakutsk and SUGAR experiments [1]. This signal is not or only marginally present analyzing events of a single experiment, but becomes significant when data from several experiments are added. Both the energy dependence of the signal and its angular scale might be interpreted as first signatures of the large-scale structure of UHECR sources and of intervening magnetic fields.

Introduction

The sources of ultrahigh energy cosmic rays (UHECR) are despite of more than 40 years of research still unknown. Main obstacle for doing charged particle astronomy are deflections of the primaries in the Galactic and extragalactic magnetic fields. While the magnitude and the structure of extragalactic magnetic fields are to a large extent unknown, already deflections in the Galactic magnetic field alone are large enough to prevent UHECR astronomy if the primaries are heavy nuclei [2, 3]. Assuming optimistically that the primaries are protons, typical deflections in the Galactic magnetic field are around five degrees in most part of the sky at $E = 4\times10^{19}$ eV [3]. Therefore, it might be possible to perform charged particle astronomy, if moreover deflections in extragalactic magnetic fields are sufficiently small.

This scenario can be divided in two quite different sub-cases: In the first one, a small number of bright point sources results in small-scale clusters of arrival directions around or near the true source positions. Accumulating enough events, the identification of sources will become possible using e.g. correlation studies. In the second sub-case, a large number of weak sources tracing the large scale structure together with relatively large magnetic fields in clusters prevents the observation of two or more UHECRs from the same source with the present statistics. However, the measured UHECR distribution is anisotropic and over-/underdense regions exist that reflect the angular size of up-to 15–20 degrees of typical structures in the galaxy distribution. Obviously, Nature might have chosen a mixture of these two extreme possibilities: The vast majority of UHECR sources might produce only singlet events, while a subclass of sources with extreme luminosity might be detectable as point sources via small-scale clustering studies. Furthermore, point sources might be easier to identify at the highest energies, if the number density of sources decreases with the maximal energy $E_{\max}$ to which they can accelerate as argued in Ref. [4].

In Ref. [1], we studied the arrival direction distributions of the UHECRs, putting emphasis in contrast to most earlier studies on intermediate angular scales. Since these two-dimensional distributions average three-dimensional structures (with typical scale L) over the mean free path l of UHECRs, no anisotropies reflecting the large-scale structure of sources are expected for $l \gg L$. To obtain an optimal compromise between the number of events used, the mean free path l of UHECRs and deflections in magnetic fields, it is important to use a consistent energy scale when combining different experiments, which we discuss in the following section.

UHECR data sets and their energy scale

We used data of the AGASA [5], Yakutsk [6], SUGAR [7] and HiRes [8, 9] experiments. From the Volcano Ranch, Haverah Park, Flye's Eye experiments no detailed information is available about their events. Therefore, we could use only the events with $E > 10^{20}$ eV for which the arrival directions are given in Ref. [10]: four events from Haverah Park, and one both from Volcano Ranch and Flye's Eye. More details of each data set and the exposure of each experiment were discussed in [1].

The absolute energy scale of each experiment has a rather large uncertainty. To reproduce correctly spectral features like the dip, the energies E given by the experiments have to be shifted to new energies E'. First, we assumed that the normalization of the HiRes stereo spectrum is consistent with the one of HiRes in monocular mode, following Ref. [11]. In Ref. [12], we had found that rescaling the SUGAR energies calculated with the Hillas prescription by 15% downwards, $E' = E_{\rm Hillas}/1.15$, makes their data consistent with the ones from AGASA. In contrast to Ref. [12], we fixed the energy scale by the HiRes mono data. Therefore, we shifted the AGASA data by 30% downwards, and the SUGAR data by 50% downwards. According to Ref. [6], the Yakutsk energy scale is systematically 15-20% above the AGASA energy scale. Thus, in order to match the Yakutsk data to the HiRes energy scale we rescaled all energies of UHECR events of Ref. [6] by 50% downwards.

In Fig. 1, we show a skymap in equatorial coordinates of the arrival directions of the UHECR used in the analysis below. An inspection by eye indicates an overdense region around and south the AGASA triplet as well as several underdense regions or voids.

Autocorrelation analysis

We used as our statistical estimator for possible deviations from an isotropic distribution of arrival directions the angular two-point auto-correlation function w. We define w as function of the angular scale δ as

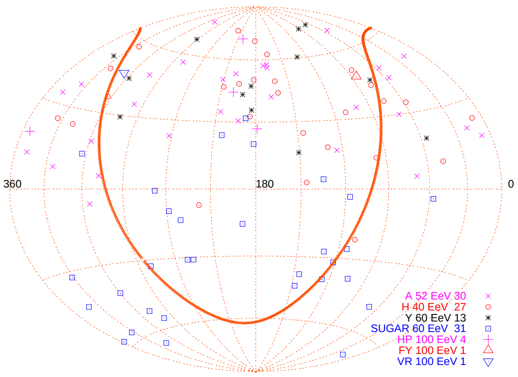

Figure 1: Skymap of the UHECR arrival directions of events with rescaled energy $E' > 4\times10^{19}$ eV in equatorial coordinates; magenta crosses–30 Agasa (A) events with $E > 5.2 \times 10^{19}$ eV, red circles–27 HiRes (H) events with $E > 4 \times 10^{19}$ eV, black stars–13 Yakutsk (Y) events with $E > 6\times10^{19}$ eV, blue boxes–31 Sugar (S) events with $E > 6 \times 10^{19}$ eV, magenta crosses–4 Haverah Park (HP) events with $E > 10^{20}$ eV, red triangle–one Flye's Eye (FY) event with $E > 10^{20}$ eV, blue triangle–Volcano Ranch (VR) event with $E > 10^{20}$ eV.

$$w(\delta) = \sum_{i=1}^{N} \sum_{j=1}^{i-1} \Theta(\delta - \delta_{ij}) \,, \qquad (1)$$

where Θ is the step function, N the number of CRs considered and $\delta_{ij} = \text{acos}\,(\cos\rho_i \cos\rho_j + \sin\rho_i \sin\rho_j \cos(\phi_i - \phi_j))$ is the angular distance between the two cosmic rays i and j with coordinates (ϕ, ρ) on the sphere. Having performed a large sample of Monte Carlo simulations, we call the (formal) chance probability $P(\delta)$ to observe a larger value of the autocorrelation function $w(\delta)$ the fraction of simulations with $w > w^*$, where w^* is the observed value. We would like to warn the reader at this point that we have not fixed a priori our search and cut criteria. Thus the obtained probabilities are only indicative. But they can be used in particular to compare for different data sets the

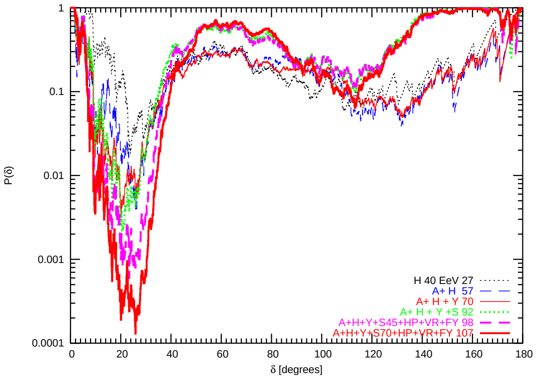

Figure 2: Probability $P(\delta)$ to observe a larger value of the autocorrelation function as function of the angular scale δ for different combinations of experimental data; label of experiments as in Fig. 1.

relative likelihood to observe the signal as chance fluctuation.

In Fig. 2, we show the chance probability $P(\delta)$ as function of the angular scale δ for different combinations of experimental data. The chance probability $P(\delta)$ shows already a 2σ minimum around 20–30 degrees using only the 27 events of the HiRes experiments with $E' \geq 4 \times 10^{19}$ eV. Adding more data, the signal around $\delta = 25^\circ$ becomes stronger, increasing from $\sim 2\sigma$ for 27 events to $\sim 3.5\sigma$ for 107 events. It is comforting that the position of the minimum of $P(\delta)$ is quite stable adding more data and every additional experimental dataset contributes to the signal. Moreover, autocorrelations at scales smaller than 25° become more significant increasing the dataset.

To understand better how the search at arbitrary angular scales influences the significance of our signal we have calculated the penalty factor[1] for the scan of $P(\delta)$ over δ. The penalty factor increases for increasing resolution $\Delta\delta$ of the angular scale δ, but reaches an asymptotic value for $\Delta\delta \to 0$. The numerical value of the penalty factor found by us in the limit $\Delta\delta \to 0$ varies between 6 for the HiRes data set alone and 30 for the combination of all data. Since the energy cut we use is determined by the one chosen in Ref. [9], no additional penalty factor for the energy has to be included. We conclude therefore that the true probability to observe a larger autocorrelation signal by chance is $P \approx 3 \times 10^{-3}$ for the complete data set.

Discussion

Our results, if confirmed by future independent data sets, have several important consequences.

Firstly, anisotropies on intermediate angular scales constrain the chemical composition of UHECRs. Iron nuclei propagate in the Galactic magnetic field in a quasi-diffusive regime at $E = 4 \times 10^{19}$ eV and all correlations would be smeared out on scales as small as observed by us. Therefore, models with a dominating extragalactic iron component at the highest energies are disfavored by anisotropies on intermediate angular scales.

Secondly, the probability that small-scale clusters are indeed from point sources will be reduced if the clusters are in regions with an higher UHECR flux. For example, the AGASA triplet is located in an over-dense spot (cf. map in Fig. 1) and the probability to see a cluster in this region by chance is increased. In contrast, the observation of clusters in the ”voids” of Fig. 1 would be less likely by chance than in the case of an UHECR flux without medium scale anisotropies.

However, the most important consequence of our findings is the prediction that astronomy with UHECRs is possible at the highest energies. The minimal energy required seems to be around $E' = 4 \times 10^{19}$ eV, because at lower energies UHECR arrive more and more isotropically [1]. This trend is expected, because at lower energies both deflections in magnetic fields and the average distance l from which UHECRs can arrive increase. Since the two-dimensional skymap corresponds to averaging all three-dimensional structures (with typical scale L) over the distance l, no anisotropies are expected for $l \gg L$. Thus, if the signal found in this analysis will be confirmed it has to be related to the local large-scale structure.

Reference [13] confirmed that the results described above are at the $2\,\sigma$ level consistent with the expectation that UHECR sources follow the observed

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[1] For a discussion of the use of penalty factors see e.g Ref. [18].

large-scale structure. A more than linear bias would improve the agreement. The same authors found however no significant cross-correlation between UHECRs and the distribution of galaxies—a result that may be explained either by deflections in magnetic fields or the small statistics. Finally, we note that Ref. [14] found that around 400 events are needed to reject the hypothesis that the UHECR sources trace the galaxy distribution. We consider it as an fluctuation that the HiRes data set alone (as well as the SUGAR data set with zenith angle $\theta \leq 70°$) shows already a 2σ signal with 27 events. To check this signal, an independent data set of order $O(100)$ events with $E' > 4 \times 10^{19}$ eV is required.

Summary

We have found that the two-point autocorrelation function of UHECR arrival directions has a broad maximum around 25 degrees. Combining all publicly available data with energy $E' > 4 \times 10^{19}$ eV, the chance probability that a stronger autocorrelation is obtained from an isotropic distribution is around $P \approx 3 \times 10^{-3}$ after taking penalty factor for search at all angles $\delta \in [0 : 180°]$. We have checked that the autocorrelation signal disappears lowering the energy threshold, indicating that it is not caused solely by an incorrect combination of the exposure of different experiments. The autocorrelation signal found by us around $\delta = 25°$ should be tested with future, independent data sets from HiRes, the Pierre Auger Observatory [15] and the Telescope Array [16]. If confirmed, it constrains the UHECR primary type together with the magnitude of extragalactic magnetic fields and opens the door to astronomical studies with UHECRs.

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