Correlations and Charge Composition of UHECR without Knowledge of Galactic Magnetic Field

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Abstract

We develop a formalism which allows to study correlations of charged UHECR with potential sources without using any Galactic Magnetic Field (GMF) model. The method is free of subjective chose of parameters on which the significance of correlations depends strongly. We show that correlations of the AGASA dataset with BL Lacs (found previously after reconstruction of particle trajectories in a specific GMF) are present intrinsically and can be detected without reference to a particular model of magnetic field.

1. Introduction

Correlations between UHECR and BL Lacs [3] improve noticeably after correction of UHECR arrival directions for deflections in GMF [4]. The GMF model and its parameters were chosen in Ref. [4] following the literature where they were obtained by fitting to the observed Faraday rotation measurements. Because of the uncertainties in the model of magnetic field, it is clearly desirable to have an alternative procedure capable of detecting charged correlations of UHECR without referring to a particular GMF.

Any *chance coincidences* between cosmic rays and potential sources should be distributed over the sky according to the local density of sources and exposure of a cosmic ray experiment. Any significant deviations from this distribution gives independent signature that the correlations are real and should reflect physical effects. There are *a priori* reasons to expect such deviations from "uniformity" for real signal. The extra-galactic magnetic fields are unlikely to be small in all directions. If primary particles are protons, one may expect good correlation with sources in some areas of the sky and no correlations in the other. Poor knowledge of the Galactic magnetic field may have similar effect: the directions of cosmic rays before they enter the Galactic magnetic field may be obtained correctly only in the regions where actual GMF is described well by the model used. Thus, one

pp. 671–674

may expect that correlating rays will not cover the acceptance region uniformly, but will form *spots* where the rate of correlations is high, while in other areas the number of correlating rays will not exceed the random background. Such spots in distribution of correlating rays were indeed found [5]. But are they due to deviations of GMF from a model in certain regions, or the reason is different? The method which is insensitive to the GMF model may give answer to such questions.

Why should such a procedure exist at all? Deflections by GMF form a regular vector field; they are expected to point in close directions in relatively small regions of the sky. On the contrary, if extra-galactic fields dominate the deflections, or if the association between cosmic rays and "sources" is due to a mere coincidence, the vectors of deflections would form a random field. In this talk we develop the statistical test to distinguish between these two situations, and confront it with the AGASA data, Ref. [1].

2. Formulation of the procedure

The procedure which we propose consists in the following steps: (1) Choose reasonably small region on the sky (the domain where the deflections are expected to point roughly in the same direction). (2) Within this domain, identify pairs source – cosmic ray by choosing rays which have nearest source not further than maximum expected deflection angle; this defines a set of directions of deflections corresponding to the data. (3) Perform Kolmogorov-Smirnov (KS) test to compare these directions with the ones obtained for the same domain, the same set of sources, but randomly generated cosmic rays. The test which is reparametrization-invariant on the circle should be used.

Consider this procedure in more detail in the case of AGASA cosmic rays with energy $E > 4 \times 10^{19}$ eV and the set of confirmed BL Lacs with mag < 18 (the same set as in Refs. [4,5]):

(1) First, we have to divide the sky in regions. A natural choice is the regions introduced previously in Ref. [5]. There, the part of the sky overlapping with AGASA acceptance region was divided into 4 equal area domains corresponding to north/south and inner/outer Galaxy. These regions are labelled as follows:

$$
\begin{array}{lll}
\text{I:} & 0^\circ < l < 120^\circ, & b > 0 \\
\text{II:} & 120^\circ < l < 240^\circ, & b > 0 \\
\text{III:} & 120^\circ < l < 240^\circ, & b < 0 \\
\text{IV:} & 0^\circ < l < 120^\circ, & b < 0
\end{array}
$$

For a particular GMF model adopted in Ref. [4], significant correlations between cosmic rays and BL Lacs were found in regions I and III, while no signal was observed in regions II and IV, see [5]. Note that in all existing models the deflections point roughly in the same directions throughout region II or III (outer Galaxy), but field of deflections is complicated in regions I and IV (inner Galaxy).

(2) To proceed, we have to find a set of pairs source – cosmic ray which define the deflections $\delta\mathbf{n}_i \equiv (\mathbf{n}_i^{\rm cr} - \mathbf{n}_i^{\rm src}) / \mid \mathbf{n}_i^{\rm cr} - \mathbf{n}_i^{\rm src} \mid$, where $\mathbf{n}_i^{\rm cr}$ and $\mathbf{n}_i^{\rm src}$ are unit vectors pointing in the direction of i-th cosmic ray and its candidate source, respectively. We identify such pairs as follows. For a typical energy of cosmic ray $\sim 4 \times 10^{19}$ eV and typical magnitude of GMF, the deflections are of order $3 - 8$ degrees. So, we look for candidate sources within 10° of the rays (we have verified that the results change insignificantly when this parameter is increased to 20°). We select the closest source if there are many candidates, and reject the ray if there are none within specified region. Thus obtained deflections $\delta\mathbf{n}_i$ are projected onto a fixed direction $\mathbf{e}_l$ of constant Galactic latitude b. This defines the set of angles, $\alpha_i \equiv \arccos(\delta\mathbf{n}_i \cdot \mathbf{e}_l)$, which are expected to be distributed roughly uniformly from 0 to 2π if cosmic rays and sources are uncorrelated, or if the deflections are due to a random field.

(3) Finally, we perform a KS test to compare this distribution to the one obtained for a large number of randomly generated cosmic rays. Since both distributions are defined on a circle, we use a cyclic version of the KS test [2]. This eliminates the dependence on the fixed direction $\mathbf{e}_l$ the deflections were projected onto.

3. Results

In the region III, we find that deflections are aligned: their directions vary within $60^\circ \lesssim \alpha \lesssim 90^\circ$. Corresponding cumulative distribution is shown in Fig. 1, where solid and dotted curves represent the real data and Monte-Carlo simulation with random cosmic rays, respectively. These two distributions are incompatible at the significance level of $P = 4 \cdot 10^{-5}$.

One should be careful applying correlation analysis to highest energy CR data. Namely, the AGASA dataset is autocorrelated on the scale of 2.5° and this may cause spurious correlation effects. Within present procedure it is meaningless to incorporate UHECR clustering into Monte-Carlo generator (as it was done e.g. in Ref [3]) since the expected distribution will be uniform anyway. But we can eliminate any effects related to clustering by replacing each cluster in the real data (regardless of its multiplicity) by a single cosmic ray located at the cluster center. Real significance can be only higher compared to the one found with clusters being removed. We carried out this procedure of cluster reduction (eliminating three doublets in region III) and found $P_{\rm no\,clusters} = 1.3 \cdot 10^{-4}$ in cyclic KS test.

In regions I and II we also find that the data deviate from uncorrelated distribution, with KS significance $\approx 10^{-2}$ in each region. In region IV we see no signal (note however that this region has the smallest number of AGASA CRs).

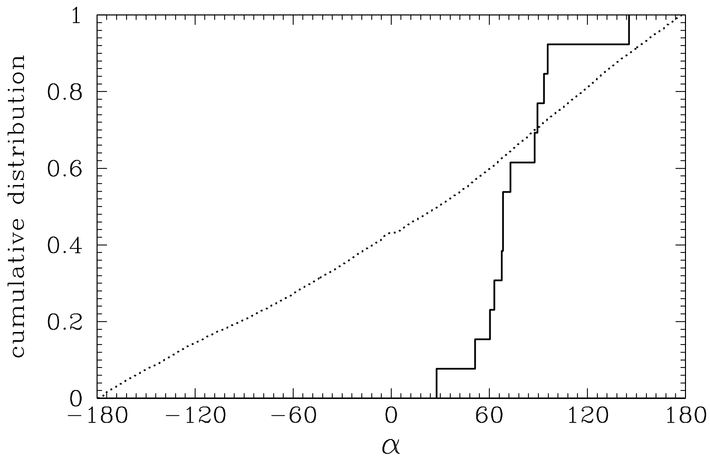

Fig. 1. Cumulative distribution of angles α_i between cosmic ray deflections in region III and direction $\mathbf{e}_l$ of constant Galactic latitude b. Dotted line - Monte-Carlo simulation of uncorrelated rays, solid line - real data.

4. Conclusions

In region III the AGASA data are incompatible with uncorrelated distribution; the significance is $4 \cdot 10^{-5} < P < 10^{-4}$. Overall deflection angle is consistent with expectation derived in GMF models with small vertical component of the magnetic field. In region II the deflections are also expected to be aligned; smaller signal in this region may be due either to a fluctuation, or to the effect of extra-galactic magnetic fields.

5. List of Symbols/Nomenclature

GMF=Galactic Magnetic Field
EGMF= Extra-Galactic Magnetic Field
l=Galactic longitude
b=Galactic latitude
mag=Apparent magnitude
KS=Kolmogorov-Smirnov test

6. References

1. Hayashida N. et al. 1999, Astrophys. J. 522, 225 and astro-ph/0008102
2. Press W. H. et al. 1992, Numerical Recipes, chapter 14 (Cambridge University Press)
3. Tinyakov P. G., Tkachev I. I. 2001, JETP Lett. 74, 445
4. Tinyakov P. G., Tkachev I. I. 2002, Astropart. Phys. 18, 165
5. Tinyakov P. G., Tkachev I. I. 2003, International Workshop on Extremely High Energy Cosmic Rays, Wako, Japan, 5-6 Nov 2002, hep-ph/0212223