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A comparative study of correlations between arrival directions of ultra-high-energy cosmic rays and positions of their potential astrophysical sources

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Abstract

We consider various classes of persistent extragalactic astrophysical sources which have been suggested in literature as possible emitters of ultra-high-energy cosmic rays (UHECR). We compare the strength of the claimed correlations by a uniform procedure for all classes of sources by making use of the AGASA, Yakutsk and HiRes stereo data. BL Lac type objects correlate with the cosmic rays detected by all three independent experiments and are more probably, compared to other astrophysical sources, related to the UHECR origin. With the account of the Galactic magnetic field (not possible for the HiRes data at the moment), apart of BL Lac type objects, unidentified gamma-ray sources may be correlated with AGASA and Yakutsk cosmic rays.

1. Introduction

Thousands of cosmic rays with energies higher than 10^{19} eV have been detected by various experiments. Still, the origin of these energetic particles remains unknown. Deflections of charged particles by cosmic magnetic fields are relatively small (though significant) at these energies; moreover, presence of a fraction of neutral particles, which propagate rectilinearly, is not excluded. This opens a possibility for direct searches of astrophysical sources of the high-energy cosmic rays by positional correlations.

Several difficulties limit the application of this approach. Firstly, at least a large fraction of air showers with $E \gtrsim 10^{19}$ eV is believed to be caused by protons, whose trajectories are bend by cosmic magnetic fields by several degrees. Lack of knowledge about these fields makes it difficult to account for the deflections while at highest energies, where

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the deflections are believed to be small, low statistics of the cosmic rays prevents one from making definite conclusions.

Secondly, the angular resolution of the cosmic-ray experiments is very poor by the astronomical standards. The most precise ground array, AGASA, has an average error of 1.8° in determination of the arrival directions at the highest observed energies, and 2.5° at $E \sim 10^{19}$ eV [1]. As a result, an impressive number of astrophysical objects fall in the error box of each particular cosmic ray. The situation improved with the availability of the first set of the HiRes stereo data [2] with claimed angular resolution of 0.6°. Still, this resolution is quite poor for direct identification: dozens of optical, radio and X-ray sources are contained in a given circle of 0.6° radius on the Celestial sphere.

With these complications, statistical methods give the only possible clue to search for positional correlations between the cosmic rays and their potential sources. An excess of cosmic rays at small angular distances (in particular, at those compared to the experiment's angular resolution) from objects of a certain class may suggest that this class of objects contains more probably the sources of these cosmic rays than other classes, which do not exhibit such an excess. [1]

Many astrophysical sites have been suggested which can host an accelerator powerful enough to produce particles with $E \sim 10^{19}$ eV and higher. Most of them are extragalactic (which is consistent with the lack of global galactic anisotropy of the arrival directions of high-energy cosmic rays). Various cosmic accelerators may operate by similar mechanisms, so the most efficient way to distinguish between them is based on direct positional correlations. Up to now, the correlations with different classes of objects were studied by different methods, with different data sets, or were not studied at all. This work aims at filling this gap and calculating the chance probabilities of the claimed correlations by a uniform method, which allows to compare the strength of correlations and to figure out more probable sources among those suggested previously.

The rest of the paper is organized as follows. In Section 2, we discuss the logic of the statistical analysis of correlations, describe the methods we use and emphasize several subtle points. Section 3 lists potential astrophysical sources, briefly recalls motivations for these candidates and previous correlation studies. For each class of sources, we give here references for the catalogs we use in the current study. In Section 4, we present the results of the correlation studies for several representative samples of cosmic rays. The conjectures about positional correlations were formulated on the basis of the cosmic rays observed by AGASA, and sometimes by the Yakutsk experiment. We use the samples of cosmic rays with energies $4 \times 10^{19} < E < 10^{20}$ eV observed by AGASA (49 rays) and by AGASA and Yakutsk (59 rays) to treat the suggested sources uniformly and to reformulate the conjectures. We consider independently neutral and proton primaries and in the latter case, we account for proton deflection in the Galactic magnetic field. Then, we test the same conjectures with recently published HiRes stereoscopic data (271 cosmic ray with $E > 10^{19}$ eV), assuming only neutral primaries, since energies of the HiRes events are unpublished. Finally, we look for correlations of suggested sources with the cosmic rays of the highest ($E > 10^{20}$ eV) energies. Section 5 contains conclusions and discussion.

2. The correlation analysis

The general logic of the correlation studies by statistical methods is to test the hypothesis that the distribution of the observed arrival directions of the cosmic rays is *isotropic*, and that there is no excess of the cosmic rays at small angular distances [2] from the sources listed in a given catalog (and *not* to test the hypothesis that the sources from the list emit cosmic rays). To this end, a large number of cosmic-ray events are simulated which

[1] The background of random coincidences is always present, and one cannot claim that one particular object is a source of a given cosmic ray based on these statistical arguments only.

[2] That is, at those of order of the experimental angular resolution.