

The method for measuring of the characteristics of the cosmic ray dipole anisotropy in the PAMELA experiment

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Abstract. The large-scale cosmic ray anisotropy has been studied in the equatorial coordinate system in the PAMELA experiment. The method to obtain dipole anisotropy characteristics as well as some its modernizations is discussed in detail.

1. Introduction

The results of the ground-based measurements for studying of an anisotropy of cosmic rays are well known [1-5]. To observe this phenomenon at an anisotropy intensity level of 10^{-3} there were collected a large number of events \sim tens of millions. Unlike these experiments the satellite PAMELA experiment [6] provides with much lower statistics due to the small size of its aperture and exposure. Finally about 600,000 events were obtained after applying the selection criteria for experimental data of 9 years of observations (Jun. 2006 – Nov. 2014) [7, 8].

All the results of the ground-based experiments agree with each other in the fact that a large-scale anisotropy exists and has a dipole character at the first approximation, while the measurements of the phase and amplitude of this dipole gave inconsistent values. The aim of our study was to measure the phase and amplitude of this dipole using information collected in the PAMELA experiment within the energy range 1 – 20 TeV/n. The results were obtained with the use of the electromagnetic calorimeter [9] and published in [7, 8]. Here the method which has been used in those works is discussed as well as its variation.

2. The general approach

The measurement of the anisotropy of cosmic rays means a construction of a distribution of primary particle arrival directions. In the PAMELA experiment the electromagnetic calorimeter was used to obtain such distribution. The cosmic ray arriving directions were measured as the axis of the showers initiated by the primary particles inside the calorimeter [10].

The anisotropy of cosmic rays was obtained by using of two distributions: the background or reference and the experimental ones. The reference direction distribution of events corresponds to the case when the cosmic ray arrival direction distribution is perfectly isotropic taking into account a real exposure and a registration efficiency of the apparatus. The reference distribution was simulated with a shuffling technique [11]. These distributions were performed in the equatorial coordinate system. In our case only a single coordinate was considered. It was a right ascension which varied from 0 to 360 degrees. All events along a declination coordinate



were summarized. The reference distribution contained the 100 times more events than the real one. The existence of the anisotropy of cosmic rays in the PAMELA data was confirmed by comparing of two distributions: the reference and the experimental ones with the Kolmogorov-Smirnov test.

3. The Kolmogorov-Smirnov test

The first step of the study was to check the fact that basing on the collected statistics we are able to make a conclusion about the difference between the reference and the real distributions. For this reason the Kolmogorov-Smirnov test (see fig. 1) was used [12]. The KolmogorovSmirnov statistics $D_{exp}=0.3889$ while the critical value is $D_c=0.1015$. Therefore, the null hypothesis about similarities of experimental and reference distributions was rejected at level 0.05.

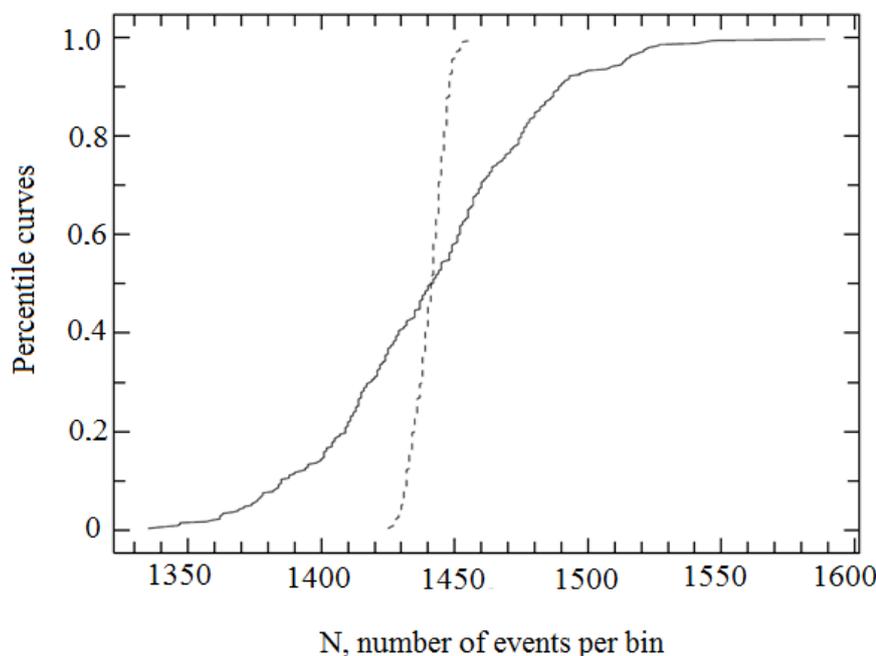


Figure 1. The percentile curves for experimental (solid line) and reference distributions (dashed line).

4. Measuring of the dipole characteristic

Since the existence of the dipole anisotropy based on the ground-based observations is not questioned, so far the task was to obtain its characteristics which are the amplitude and the phase of the dipole. About 600,000 right ascension values represented the arrival directions of the particles in the experimental data while the data in the reference distribution consisted of 100 times more events (as they were simulated their number could be as high as any number).

The basis of the analysis was the experimental fact that the measuring distribution is the dipole one (in the first harmonic). For this reason the size of an integration bin in right ascension equal to 180 degrees was chosen. In our approach this bin is equivalent to an integration radius in the HEALPIX method for the anisotropy study in 3D map [13]. The all events were integrated within this bin. A bin center was being shifted throughout the entire range from 0 to 360 degrees with a five degree step. Than bins were averaged to get 12 mean values. The dipole

dependence was obtained in terms of ratio of intensities ($I_r/I_s - 1$) where I_r is the experimental number of events per bin and I_s the reference one. The number of events in the reference distribution was normalized to the experimental one.

The dipole dependence was approximated by a sine function with the Levenberg-Marquardt algorithm [14]. It is necessary to emphasize a fact that the uncertainties in the figures that has been shown before in the works [7, 8] are not statistical errors and indicate just the average level of the statistics. That is why using of this uncertainties might be questionable. As the obtained numbers of events are correlated to each other the uncertainties do not correspond to the real level of fluctuations. So in the new approach we did not use these uncertainties for the approximation procedure. The scatter of points itself was taking into account. This scatter depends on the statistics level and starts to rise when the statistics goes down.

The amplitude and phase (calculated as a position of the maximum value, differs on $\pi/2$ from a sin phase) were obtained from this new approximation with taking into account factor $k=2/\pi$ (the correction factor between amplitude of the initial dipole and the one obtained with described here method): $A=0.0013\pm 0.0003$, $\phi = 70\pm 10$ degrees.

The demonstrated uncertainties as in the previous works [7, 8] were taken from the approximation. It should be noticed that the results in previous publications and these new ones are in agreement within a level of the uncertainties.

5. The result of a reliability test

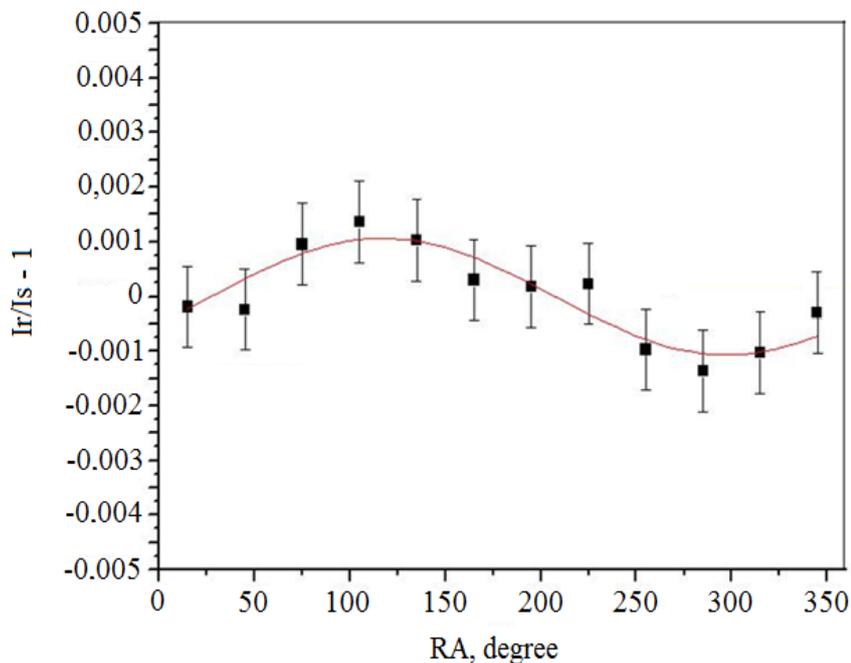


Figure 2. One of the dipoles obtained by using Monte Carlo simulation and the procedure described here.

To check the reliability of the obtained results a numerical simulation test was done. This test included a multiple numerical simulation by the Neuman (rejection) method [15] of events distributed according to a sine function. The simulated dipole dependences had an amplitude value similar to observed one and a phase value equal to 90 degrees. The procedure described above was applied to the simulated dipole distributions to obtain the values similar to the ones

shown in fig. 2. The multiple simulation has given a determination coefficient [16] equal to 0.89 ± 0.07 , while in the actual experimental data its value was 0.88. This coincidence confirmed the reliability of the results obtained at a high probability level (more than 0.9). Furthermore, the level of uncertainties in the approximation for the values of the amplitude and phase in the numerical simulations coincided with the real experimental values.

Acknowledgments

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