Declination dependence of the cosmic-ray flux at extreme energies

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Abstract. We study the large-scale distribution of the arrival directions of the highest energy cosmic rays observed by various experiments. Despite clearly insufficient statistics, we find a deficit of cosmic rays at energies higher than $10^{20}$ eV from a large part of the sky around the celestial North Pole. We speculate on possible explanations of this feature.

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1. Introduction

The physics of the highest-energy cosmic rays continues to attract significant interest of both particle physicists and astrophysicists. Experimental data allow to determine energies and arrival directions of the cosmic particles and may give some hints about their nature. At energies of order $10^{19}$ eV, spectra measured by different experiments are in a good agreement modulo overall normalization. Contrary, two major experiments disagree about the observed flux and shape of the spectrum at highest energies, $E \gtrsim 10^{20}$ eV: the data from the HiRes experiment exhibit the suppression of the flux, the so-called GZK feature [1, 2], while the AGASA experiment does not see the suppression. Arrival directions of the cosmic rays with energies $E \gtrsim 10^{19}$ eV are distributed isotropically over the sky (see, for instance, Ref. [3]) and clustered at small angles [3, 4, 5]. In this note, we focus on the highest energy region, $E \gtrsim 10^{20}$ eV, and demonstrate that the current data exhibit a trend to non-uniform distribution of the arrival directions. Namely, there is a deficit of events from a large region around the celestial North pole.

For the most energetic cosmic rays observed by AGASA, the absence of particles coming from the North has been pointed out in Refs. [3, 6, 7, 8]. However, the distribution of the arrival directions of these AGASA events is consistent with isotropy [9], given the non-uniform exposure. To test the conjecture of anisotropy (and also to improve statistics, still very poor), we include the results from other Northern hemisphere experiments in our analysis. We do observe a non-uniform distribution of events with probability of this anisotropy to occur as a result of a chance fluctuation about one percent; this would correspond to two standard deviations for the Gaussian distribution. If confirmed by better statistics, this observation might mean that at highest energies, a new component appears in the cosmic ray flux. Indeed, it is widely believed now that at $4 \cdot 10^{19}$ eV $\lesssim E \lesssim 10^{20}$ eV, the dominant part of the cosmic rays are protons [10, 11] from active galactic nuclei (in particular, BL Lac type objects suggested recently as the source candidates [12, 13, 14]). Due to the GZK effect, this component cannot explain even the most conservative HiRes flux at $E \gtrsim 10^{20}$ eV (see Refs. [15, 16] for a quantitative analysis). We will see that indeed, the anisotropy becomes significant at energies $E \gtrsim 10^{20}$ eV.

In the rest of the paper, we discuss in detail the datasets used, analyze the declination distribution of the highest-energy events detected by Northern-hemisphere experiments, present the results of the Monte Carlo simulations to estimate the chance probability of the observed anisotropy and study at what energies the anisotropic component becomes significant. We discuss possible ways to explain the effect and demonstrate its irrelevance to the AGASA/HiRes discrepancy. We emphasize that the number of events is too small to make a definite conclusion about the anisotropy and briefly discuss prospects for larger statistics.
2. The cosmic-ray sample

Our basic data set (hereafter, Set I) consists of the cosmic rays with energies higher than $10^{20}$ eV observed by all experiments in the Northern hemisphere. The choice of the $10^{20}$ eV cut is determined by the availability of data from fluorescent detectors at $E > 10^{20}$ eV only. However, it is roughly consistent with the expected energy at which the super-GZK component could start to dominate. Alternatively, we consider a set of cosmic rays with $E > 4 \cdot 10^{19}$ eV observed by Volcano Ranch, Yakutsk and AGASA (Set II; arrival directions of events with $E < 10^{20}$ eV are unpublished for other Northern-hemisphere experiments). The latter set is useful in determination of the "critical" energy at which the new, anisotropically distributed, component becomes important. As it will be demonstrated below, this analysis points to $E \approx 10^{20}$ eV as the critical energy.

When comparing data from different experiments, one should be careful about energy normalization. It is widely believed that at $E \sim 10^{19}$ eV, where the shapes of the spectra measured by different experiments agree quite well, the difference in overall normalization is due to systematic errors in the energy determination. One possibility is to introduce correcting factors for energy values in such a way that the total flux measured at $E = 10^{19}$ eV by different experiments would coincide, within one standard deviation, with the flux measured by a given (no matter which one) reference detector (in our study, we normalize all fluxes to HiRes data because otherwise the HiRes dataset is not complete). The study of the dependence on the choice of the reference detector is completely equivalent to the study of the dependence on the "critical" energy performed in section 4. Quantitatively, this rescaling depends crucially on the assumed spectral index. We checked, however, that the effect discussed in this paper is insensitive to this choice: different normalizations (for spectral indices between two and four) do not change the result – absence of events with high declinations – compared to the case of no rescaling. For completeness, we report here (see Table 2) both the results obtained without energy normalization and with renormalization assuming spectral index three. In the latter case, the corrected energy $E' = \eta E$, where $E$ is the reported energy of an event and $\eta = (J_{\text{ref}}/J)^{1/2}$ (see, for instance, Ref. [8]). Here, $J_{\text{ref}}$ and $J \equiv dN/dE$ are the cosmic ray fluxes measured by the reference detector and the detector under consideration, respectively. The fluxes $J$ at $E \sim 10^{19}$ eV and normalization factors $\eta$ are listed in Table 1 together with the information required to calculate and compare exposures of the experiments and with references.

For the data sample, we took the most recent publicly available data and impose zenith angle cuts of $45^\circ$ for ground array experiments and $60^\circ$ for fluorescent experiments.

Three experiments (Haverah Park, Yakutsk and HiRes II in the monocular mode) have considerable exposure at the ultra-high energies but contributed no events to the Set I (though their exposure was taken into account).

Energies of the Haverah Park events published in the Catalog [25] were reconsidered.
Table 1. Cosmic ray experiments. (1): name; (2): flux measured at $10^{19}$ eV (in units of $10^{-33}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$ eV$^{-1}$) and reference; (3): energy rescaling factor; (4): geographic latitude (in degrees); (5): total exposure (in units of $10^{16}$ m$^{2}$ s sr) (for the cosmic rays with energies above $10^{19}$ eV; for AGASA different exposures for published data above $10^{19}$ eV and $10^{20}$ eV; for Haverah Park, Fly’s Eye and HiRes – at $10^{20}$ eV) and reference.

| Experiment          | $J$     | $\eta$ | $B$ | $A$ |
|---------------------|---------|---------|-----|-----|
| Volcano Ranch       | $3 \pm 1$ [17] | 0.95    | 32  | 0.2 [18] |
| Haverah Park        | 2.2 [18] | 0.90    | 54  | 0.9 [18] |
| Yakutsk             | $4.3 \pm 0.6$ [19] | 0.70    | 62  | 1.8 [19] |
| Fly’s Eye           | $2.5 \pm 0.3$ [20] | 0.89    | 40  | 2.6 [20] |
| AGASA, $>10^{20}$ eV | 0.85    | 36      | 5.3 | 21  |
| AGASA, $<10^{20}$ eV | $2.7 \pm 0.2$ [21] | 0.85    | 36  | 4.0 [3] |
| HiRes I mono        | $1.6 \pm 0.2$ [22] | 1.00    | 40  | 6.5 [22] |
| HiRes II mono       | $1.6 \pm 0.3$ [22] | 1.00    | 40  | 0.7 [23] |
| HiRes stereo        | $2.2 \pm 0.2$ [24] | 0.95    | 40  | 4.6 [24] |

twice, in Refs. [26] and [27]. According to the most recent publication [27], the energy of the highest event is $E \approx 8.3 \cdot 10^{19}$ eV. Revised event-by-event data were not published.

The Yakutsk event with the energy $E \approx 1.2 \cdot 10^{20}$ eV has zenith angle $> 45^\circ$ and thus it is not included in Set I (note that its declination [28] is $\delta \approx 45^\circ$, so its account would only support our conclusions).

Coordinates of the Volcano Ranch events, both of the only shower with $E > 10^{20}$ eV and of showers with lower energies (Set II) were taken from Ref. [25].

For the Set I, we use the most recent AGASA data from the experiment’s web page [9]. From eleven events, eight are left after rescaling from $E$ to $E'$. The lower energy data for the Set II are available for a shorter period of operation, Ref. [3]. This is the reason for smaller exposure used for the lower-energy data, as indicated in Table 1.

For fluorescent detectors, the data are published for the highest energy events only. The single Fly’s Eye event contributing to Set I is described in detail in Ref. [29]. For the HiRes detector in the monocular mode, we take the working period reported in Ref. [22]. The arrival direction of the single event with $E > 10^{20}$ eV registered during that period and passed all cuts is taken from Ref. [30]. For the HiRes stereo experiment, we use the data reported in Refs. [24, 31]‡.

3. Declination-dependent exposure

Different parts of the sky are seen by various experiments with different exposures. In this paper, we use two different approaches: firstly, we model the dependence of the

‡ According to Ref. [30], about 80% of the stereo events are not included in the HiRes I monocular data set because of different trigger requirements and quality cuts, so we consider the exposure of the stereoscopic observations as one of an independent experiment.
exposure on declination theoretically; secondly, we use the actual distribution of the lower-energy events to compare with one of the highest-energy events.

For a theoretical model of exposure of a ground array, we use the geometrical differential exposure. A small plaquette of area $d\sigma$ [sr] on the celestial sphere at the zenith angle $\theta$ is effectively seen by the area $dA = A_0 \cos \theta d\sigma$ of a ground array, where $A_0$ is the maximal aperture. The total exposure for a plaquette $d\sigma$ can be found by integration over the working time of the detector. The explicit formulae which result from this integration for a continuously operating ground array are given in Ref. [32]. The exposure does not depend on the right ascension $\alpha$ in this case. At energies $E \sim 10^{19}$ eV these expressions are in rather good agreement with the observed data (see Fig. 1(b)). To obtain the normalization factor $A_0$, important for any analysis which involves data of different experiments, one has to integrate $dA/d\sigma$ over $d\sigma$ and to compare the resulting total exposure $A$ with the published value listed in Table 1.

For the fluorescent detectors, this simple geometrical estimate does not work. A monocular fluorescent detector accepts, at each particular moment, the cosmic rays uniformly in azimuth and in zenith angle up to about 50$^\circ$, with a relatively sharp drop at larger zenith angles [33]. In stereoscopic mode, acceptance depends also on the azimuthal angle. In all cases, fluorescent detectors work on clear moonless nights only. The information about typical weather and dark sky availability may be encoded in the dependence of acceptance on sidereal time [33]. For the HiRes experiment, we use the zenith angle dependence of acceptance from Refs. [33] (monocular detector with parameters of HiRes) and [24] (stereo HiRes detector), the azimuth angle dependence for the stereo mode from Ref. [24] and the sidereal time dependence from Ref. [33]. Though one could expect different zenith angle dependences of the exposure for different energies, the one we use agrees quite well with the actual distribution of the HiRes I high-energy events [34]. We are not aware about any published estimate of the coordinate-dependent exposure for the Fly’s Eye experiment in the monocular mode and (loosely) use the HiRes exposure for it. We present the results both with and without account of the Fly’s Eye event in Table 2.

4. Declination distribution of the cosmic rays

4.1. Illustration

We are ready to analyze the global distribution of the arrival directions. To illustrate the anisotropy, we divided the observed part of the sky into five bands in declination with equal areas, and integrated the exposure over these bands. These exposures were compared then to the number of observed events, band per band. The results for the Set I of cosmic rays are shown in Figure 1(a). The left (red) bar in each pair corresponds to the exposure per band, normalized to the total number of events in the sample. It represents the number of events expected from isotropy. The right (blue) bar corresponds to the actual number of observed events in the sample. The deficit of
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Figure 1. Expected and observed distributions of declinations of the cosmic rays: (a) from the Set I \((E' > 10^{20} \text{ eV})\); (b) from the Set II \((4 \cdot 10^{19} \text{ eV} < E' < 10^{20} \text{ eV})\).

events in the Northern bin is clearly seen. To estimate this effect quantitatively, we perform Monte Carlo simulations of the arrival directions of cosmic rays.

4.2. Monte-Carlo simulations

Let us determine the exposure function

\[ a(\delta) = N \sum_i \frac{dA_i}{d\delta}, \]

where the sum is taken over all relevant experiments, each one’s total exposure reflected in \(A_0\), and \(N\) is the constant such that \(\max_\delta a(\delta) = 1\). The code generates a value of declination \(\delta\) in such a way that the resulting cosmic rays cover the sky uniformly; then it either accepts (with the probability \(a(\delta)\)) or rejects this event and proceeds to the next one until the total number of accepted events reaches the number of events in the real dataset. In this way, a sufficient number of mock sets is produced. The number of sets with no events in the Northern bin, divided by the total number of sets, determines the probability to observe the anisotropy by chance. The results are presented in Table 2.

To study the stability of our results, we calculated the probabilities to observe the actual number of events in the Northern bin, \(\delta > \delta_0\), for different values of \(\delta_0\) (see Figure 2). The position of the broad minimum determines the size of the Northern “zone of avoidance”.

To understand, at which energy the anisotropically distributed component becomes important, we use the Set II. In Figure 3, based on subsets of the Set II, we present the probability of the actual number of events to fall in the Northern bin as a result of a random fluctuation of the isotropic distribution for different cuts on the lower energy

\[ \text{§ For calculations without energy rescaling, one cannot sum the exposures of different experiments. Instead, we generate the actual number of observed events for each experiment in turn; in this way, we do not account the experiments which observed no events.} \]
of the cosmic rays in the set. The result is consistent with our expectations: at lower energies, we confirm the well-known statement about isotropic distribution; at higher energies, $E > 10^{20}$ eV, protons (from active galactic nuclei) are no longer dominant in the cosmic ray flux because of the GZK effect, and the new component is responsible for the observed events, distributed anisotropically.

Several comments are in order. First, the chance probabilities at $E' > E_c = 10^{20}$ eV presented in Figure 2 (Northern bin corresponds to $\delta_0 \approx 48.6^\circ$) and in Figure 3 are of the same order, but do not coincide exactly. The reason is that the sets of experimental data (Set I and Set II) used in the analysis are different.

Second, because of experimental uncertainties in the determination of the energies and arrival directions of the cosmic rays, it is not well-grounded to consider lowest values
Table 2. Probabilities to obtain the observed distribution of declinations from the isotropic distribution calculated by means of Monte-Carlo simulations of the lack of events in the Northern bin. Numbers in parentheses are calculated without the Fly’s Eye event (see Sec.3).

| Energy rescaling                  | yes  | no  |
|----------------------------------|------|-----|
| $E > 10^{20}$ eV versus          |      |     |
| theoretical exposure             | 1.2%(1.6%) | 0.9%(1.4%) |
| $E > 10^{20}$ eV versus          |      |     |
| $10^{19}$ eV $< E < 10^{20}$ eV  | 1.3% | 1.3% |

of probability $P$ plotted in Figures 2 and 3 as exact numbers: some averaging over the uncertainty intervals in $\delta$ and $E_c$ should be performed to get more reliable numbers. The resulting probabilities will be higher, but still the isotropy is excluded at the level of about $2\sigma$ for Gaussian distribution.

Third, the lowest probability in Figure 3 corresponds to the critical energy $E_c \simeq 0.8 \cdot 10^{20}$ eV. With the available data it is impossible to conclude whether this is the exact energy scale where the anisotropic component of ultra–high-energy cosmic rays becomes dominant. Indeed, apart from experimental uncertainties in energy determination, a systematic error is caused by an arbitrary choice of the reference detector necessary for a joint analysis of the data from different experiments (for instance, normalization to one of the ground arrays instead of HiRes would shift the minimum in Fig. 3 to $\sim 10^{20}$ eV). Our choice of the $10^{20}$ eV cut in Set I and of HiRes as the reference detector was a priori determined by availability of data and hence was not adjusted to obtain better results (in fact, Fig. 3 suggests that the best results could be achieved with another choice). We thus do not introduce statistical penalty associated with this cut but consider our quantitative results only as an estimate.

5. Conclusions

Clearly, the number of events in our sample is insufficient to make a definite conclusion about anisotropy of the arrival directions. However, the current dataset gives a strong hint that the deficit of events with energies higher than $10^{20}$ eV and coming from the region $\delta \gtrsim 50^\circ$ is significant. If confirmed by future experiments, this fact might suggest that a new component emerges in the cosmic ray flux at extreme energies. The physics which could result in the observed distribution of declinations will be discussed elsewhere; we just mention here possible ways of explanation. One possibility is that the Northern region of the sky coincides with the direction to some large-scale cosmic structure which affects propagation of the cosmic rays at very high energies or causes inhomogeneous distribution of their sources (at $10^{20}$ eV this effect is not smeared out by the galactic magnetic field). Another option is that the primaries of the cosmic rays with $E \gtrsim 10^{20}$ eV interact with the geomagnetic field and produce showers in different
ways at high and low latitudes. This may lead to a relative systematic error in the determination of energy between the particles arriving from different directions. One example of this effect was discussed in Ref. [35]: if the primary particle is a photon, then an electromagnetic cascade develops in the geomagnetic field before the particle reaches the top of the atmosphere. The observed superposition of several atmospheric showers mimics a single shower of the same energy as the primary particle but developed higher, so that its energy may be underestimated by a ground array. The current bounds on the chemical composition of UHECRs [36, 37] do not constrain strongly the fraction of photonic primaries at $E \gtrsim 10^{20}$ eV; to conclude that the primaries are protons on the base of the shower profiles and muon counting, one needs much better statistics than available. However, the data give some indications to the hadronic nature of primary particles. Primary protons do not produce pre-atmospheric cascades. Still, the development of proton-induced showers is affected by the geomagnetic field: for instance, the separation of muons and anti-muons is important for modelling [38, 39] and energy estimation [40] of inclined showers. The effects of the geomagnetic field would affect also the distribution of the arrival directions in azimuth, which will be considered elsewhere.

Future experiments with larger statistics will be able to support or disfavour the conjecture of anisotropy discussed here. The effects of the geomagnetic field could be studied with the Southern site of the Pierre Auger observatory. Clearly, to confirm or reject the option of a “favourite direction” occasionally coinciding with the North, large detectors in the Northern hemisphere (such as the second Auger site, the Telescope Array or the EAS-1000 experiment) or full-sky cosmic observatories (EUSO, OWL, TUS) would be required.

We stress that the use of currently unpublished data from Haverah Park, Fly’s Eye and HiRes at $E < 10^{20}$ eV, as well as of the AGASA events with zenith angles larger than $45^\circ$, would immediately enlarge the statistics without awaiting for the future experiments.

Finally, we comment on a recent proposal [8] that the discrepancy between the AGASA and HiRes fluxes at highest energies might be explained by different fields of view. Indeed, the HiRes’ differential exposure peaks in the Northern region while one of AGASA has a maximum at $\delta \approx 36^\circ$, the AGASA detector’s latitude. The “zone of avoidance” in the North affects the results of the flux measurements which usually assume the isotropic distribution of arrival directions. We estimate this effect by a rough assumption that the cosmic rays with $E \gtrsim 10^{20}$ eV are distributed uniformly at $\delta < 50^\circ$ but are absent at $\delta \geq 50^\circ$. With this assumption, a flux measured by HiRes would be about 40% smaller than one averaged over all sky, while a flux measured by AGASA decreases by about 20%. Clearly, this effect cannot eliminate the conflict between the two experiments.
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