Magnetic deflections and possible sources of the ultra-high-energy cosmic rays in the AGASA–HiRes–Yakutsk cluster

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Abstract. The cluster of ultra-high-energy cosmic rays observed by the AGASA, HiRes and Yakutsk experiments is studied with respect to possible deflections of particles in regular magnetic fields. Best-fit positions of a potential source of these clustered particles are found, with account of the errors in energy estimation, both in the frameworks of particular models of the Galactic magnetic field and treating the direction and the amount of deflection as free parameters. The study suggests that an unknown regular component of either Galactic or extragalactic magnetic field may dominate over modelled components in the direction of the cluster. Possible sources of the cosmic rays in that direction are considered.

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1. Introduction

Clustering of arrival directions of the cosmic rays with energies exceeding \(4 \cdot 10^{19}\) eV, evidence to which was originally found [1] on the basis of the early AGASA data, was subject to numerous tests and reanalyses both with the updated AGASA event list and with the event sets of other experiments [2, 3, 4]. All statistically significant positive results were obtained by making use of the sets of cosmic rays which included the original list of Ref. [1], the one used to formulate the conjecture — without these 36 events, the cosmic-ray samples were simply depleted statistically at these high energies. Recently, the world data set was supplemented by the events detected by the HiRes experiment in the stereoscopic mode. The arrival directions were determined with unprecedented accuracy and, by themselves, did not exhibit any significant clustering [5]. The attempts to explain this apparent discrepancy between AGASA and HiRes included both the criticism of the previously reported values of the probability of chance clustering [6] and analyses which demonstrated the absence of significant discrepancy at all [7, 8].

A subsequent combined analysis of the HiRes and AGASA data [9] did not find strong autocorrelation. However, it has been found that one event observed by HiRes in the stereo mode falls in the middle of the AGASA triplet. Though the energy of this event, as reported by the HiRes collaboration, is just below the \(4 \cdot 10^{19}\) eV threshold of the AGASA sample, the possible systematic energy shift between the two experiments (see e.g. Ref. [10]) brings it above the threshold. Another HiRes-detected cosmic-ray event from a direction close to the cluster [11] has energy between \(10^{19}\) eV and \(2.8 \cdot 10^{19}\) eV which exact value is unpublished. The latter fact makes it difficult to include the event in the analysis of deflections; together with the lack of published data of other experiments at these energies this forces us to postpone the consideration of this event until more information become available.

Very recently, the Yakutsk collaboration reanalised their data with novel methods and tools, which resulted in improved precision in the determination of both the energies and the arrival directions [12]. Remarkably, this reanalysis revealed another event whose arrival direction is very close to the cluster under discussion. In the present study, we consider five cosmic-ray events: the AGASA triplet, the Yakutsk event and the HiRes event with published energy.

The HiRes-AGASA quadruplet was studied in Ref. [11], where the best-fit position with account of random magnetic deflections was found. It has been demonstrated there that in the frameworks of the model of the Galactic magnetic field by G. Medina Tanco, the best fit for the regular magnetic deflection is zero. As it has been pointed out in Ref. [11], a more detailed analysis should take into account the errors in experimental determination of the particle’s energies and, since the Galactic magnetic field is poorly known (especially in the cluster direction), should treat both the direction and the amount of the regular deflection as free parameters.

In this paper, we perform this kind of analysis of the regular magnetic deflections in the AGASA-HiRes-Yakutsk cluster for various assignments of the electric charges of
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the primary cosmic particles. Apart from a blind model-independent two-parametric fit, several particular models of the Galactic magnetic field are considered. We discuss also the implications of the existence of this tight cluster, present a list of potential astrophysical sources and decline the possibility that all five particles resulted from a single interaction or decay of an extreme-energetic particle which took place in the vicinity of the Earth.

The rest of the paper is organised as follows. In Sec. 2 we list measured coordinates and energies of the five events, estimate the experimental errors and discuss possible systematic shifts in the energy scales between the experiments. We proceed in Sec. 3 with simulations of the best-fit positions in a simplified but unconstrained model where the direction of the shift and the amount of the deflection per unit energy are kept free parameters, however common for all five cosmic-ray events. The fits with regular magnetic shifts are, for some choices of parameters, better than those for neutral particles or for random deflections only. In Sec. 4 we consider various models of the Galactic magnetic field. We vary now the amount of deflection per unit energy, while the directions of deflections (now slightly different for different members of the cluster) are taken from the models. The results of Sections 3, 4 and their implications for the origin of the cosmic-ray particles which form the cluster are discussed in Sec. 5; the conclusions are briefly formulated in Sec. 6.

2. The cosmic-ray events forming the cluster

The region of the sky close to the Beta Ursa Major star attracts the attention of cosmic-ray physicists since the announcement [2] that the third cosmic-ray particle with energy in exceed of $4 \cdot 10^{19}$ eV, observed by the AGASA collaboration, arrived from that direction which hosted already a cosmic-ray doublet [1]. With the addition of the HiRes [9] and Yakutsk [12] events, this becomes the hottest spot for the search of possible astrophysical sources of the ultra-high-energy cosmic rays. Notably, even without the two events from the set used to formulate the clustering conjecture [1], it is still a triplet (and maybe a quadruplet, if a lower-energy HiRes event is included). The significance of this clustering signal will be analysed elsewhere.

The coordinates and energies of the three AGASA events were published in Ref. [2]. The error bars in energy estimations by AGASA are taken to be about 18% (see Ref. [13] for a detailed discussion). For the arrival directions, we use the energy-dependent 68% errors published in Ref. [2]: note that they are more conservative than those used in Ref. [11], obtained from a private communication.

As it has been stated in Ref. [9], the energy determination error in the HiRes stereo dataset does not exceed 20%, and 68% of events are reconstructed within 0.6° (which corresponds to the two-dimensional Gaussian distribution with the standard deviation of 0.4°). We use these values in our simulations.

The error bars for the energy determination of the Yakutsk events are given in Ref. [12] on the event-by-event basis. For the event under consideration, 23% are quoted.
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Table 1. Events forming the cluster. (1), the event code used in this paper; (2), the name of the experiment; (3), the arrival date (dd/mm/yyyy); (4), the energy reported by the experimental collaboration (in units of $10^{19}$ eV); (5), the energy corrected to the AGASA scale (in units of $10^{19}$ eV); (6), the relative error in energy measurement; (7) and (8), the arrival direction in the J2000 equatorial coordinates (in degrees); (9), the accuracy of the arrival direction (in degrees).

| Event | Experiment | Date     | $E$  | $E'$ | $\Delta E/E$ | $\alpha^\circ$ | $\delta^\circ$ | $\sigma^\circ$ |
|-------|------------|----------|------|------|----------------|-----------------|----------------|---------------|
| A1    | AGASA      | 26/01/1995 | 7.76 | 7.76 | 0.18           | 168.5           | 57.6           | 1.0           |
| A2    | AGASA      | 01/08/1992 | 5.5  | 5.5  | 0.18           | 172.25          | 57.1           | 1.7           |
| A3    | AGASA      | 04/04/1998 | 5.35 | 5.35 | 0.18           | 168.25          | 56.0           | 1.9           |
| H     | HiRes      | 29/04/2003 | 3.76 | 4.7  | 0.20           | 169.0           | 55.85          | 0.4           |
| Y     | Yakutsk    | 17/03/1975 | 5.7  | 5.3  | 0.23           | 163.6           | 52.9           | 3.0           |

The arrival direction is determined with the accuracy of $3^\circ$. Note that compared to the originally published data [14], the arrival direction was shifted by about one degree and the energy was increased by a factor of 1.5.

All three experiments have observed a significant number of events with energies studied here; their fields of view are quite similar; and still, the energy spectra measured by them exhibit systematic difference. This may be attributed to possible systematic shifts in energy determination (see, for instance, Ref. [10]), which may be easily estimated from the reported fluxes. To treat the events observed by different experiments on a uniform basis, it is necessary to account for these systematic shifts, so we correct the HiRes and Yakutsk energies by shifting them to the AGASA scale. Of course, the absolute choice of the scale is not important for our study which treats the amount of deflection per unit energy as a free parameter. The shift is 25% up for HiRes and 7% down for Yakutsk.

The details of the five events are summarised in Table 1 for reference. The arrival directions and their errors are plotted in Fig. 1.

3. Best-fit positions of the source in the unconstrained magnetic-field model

Deflections of charged particles in cosmic magnetic fields are very important for studies of anisotropy in the distribution of arrival directions and for searches of possible sources of cosmic rays. However, these studies are limited by poor knowledge of cosmic magnetic fields.

On its way from an extragalactic source to the detector, a charged cosmic-ray particle is affected by the following components of the magnetic fields. Firstly, there are (potentially very strong) magnetic fields in the source – these are clearly not important for the case of distant sources seen as point-like ones. Then, there are intergalactic magnetic fields; current theoretical and observational estimates of their strength vary by orders of magnitude [15, 16]. These fields are random and result in a distortion of a
“cosmic-ray image” of the source. We note that the very existence of tight cosmic-ray clusters, in assumption of a common origin of cluster members from a distant source, favours the low intergalactic magnetic field [16] with deflections not exceeding $0.1^\circ$ for the direction and energies of interest. The dominant deflection is caused by the Galactic magnetic field which, in turn, can be separated into the random and regular components. Though the random component is locally stronger (see, e.g., Ref. [17] for a recent review), the deflection it causes is most probably a subleading effect compared to that caused by the regular component [18].

The cluster of cosmic rays under consideration (without the Yakutsk event) has been recently studied for the deflections caused by random (intergalactic and Galactic) magnetic fields in Ref. [11]. Since the inclusion of the fifth event cannot change the conclusions significantly, we restrict our attention to the regular magnetic fields here.

As we will see in Sec. 4, the latters are poorly known, especially for the high Galactic latitudes where the cluster arrived from. There are many particular models on the market, and the parameter estimates vary widely. That is why we postpone the discussion of specific models to Sec. 4 and perform here a blind model-independent test.

We assume that the deflections of the cosmic-ray particles in the cluster are...
driven by two parameters: the direction and the amount of deflection per unit energy, with values of parameters equal for all five particles. This is a simplification since the comparison with particular GMF models demonstrates (Sec. 4) that the distance between the cluster members is sufficient for these parameters to vary slightly (by a few percent) from one arrival direction to another. However, this parametrization is the only model-independent way to study the regular deflections.

The deflection is inverse proportional to the particle’s energy. As a result, relatively large experimental errors in energy determination affect strongly the amount of deflection and should be taken into account.

We assume that all five particles originate from a single source and do not study the statistical significance of this claim. Under this assumption, the best tool to search for the most probable source position is the chi-square method which we adopt to incorporate the errors in energy determination, not only in the determination of the arrival direction.

Let us denote by $\phi$ the position angle of the direction to which a positively-charged particle is shifted, measured in the equatorial coordinates clockwise from East from $0^\circ$ to $360^\circ$. The amount of the deflection of a $10^{19} \text{ eV}$ proton is denoted by $\epsilon$ degrees; that is the shift of a particle of energy $E$ and charge $q$ is given by

$$
\rho = \frac{q\epsilon}{E_{19}} \tag{1}
$$

(hereafter, $E_{19} = E/(10^{19} \text{ eV})$). To determine the probability for each particular position on the sky to host the source of the cluster with some magnetic deflection, we proceed as follows. We fix the coordinates of the position, $\alpha$ and $\delta$; then we scan over $0^\circ \leq \phi < 360^\circ$ and $0 \leq \epsilon < 50^\circ$ to try different configurations of the magnetic field. For each configuration, the arrival directions of cosmic rays are shifted in the direction $\phi$ by the amount $\rho$ given by Eq. (1) for the energy of a particle $E$ (corrected energy, $E'$, for the HiRes and Yakutsk events). For each cosmic ray, a local coordinate system is introduced which allows one to separate the angular distance between the current point $(\alpha, \delta)$ and the corrected arrival direction into two components — $\Delta_{||}$, measured in the direction of the shift, and the orthogonal $\Delta_{\perp}$ (both along the great circles of the Celestial sphere). The chi square value is then a sum over all cosmic rays,

$$
\chi^2 = \sum_i \chi^2_i,
$$

of the quantity

$$
\chi^2_i = \frac{\Delta_{i||}^2}{\sigma^2_i + \sigma^2_{i\ell} + \sigma^2_{i\perp}} + \frac{\Delta_{i\perp}}{\sigma^2_i},
$$

where $\sigma_i$ is the standard error in the determination of the $i$th arrival direction (given in Table 1) and

$$
\sigma^{\pm}_i = \frac{q\epsilon}{E_{19}} \frac{\Delta E_i}{E_i \pm \Delta E_i}
$$
are determined from the conditions
\[ \rho(E_i \mp \Delta E_i) = \rho(E_i) \pm \sigma_i^{(\pm)}. \]

\( \Delta E_i \) is the error in energy measurement determined from column (6) of Table 1. The choice of \( \sigma^{(+)} \) or \( \sigma^{(-)} \) is determined by the angle \( \psi \) between the direction of the shift and the direction from the shifted position to the current point \( (\alpha, \delta) \): for \( \psi < 90^\circ \), we take the larger error \( \sigma^{(-)} \), for \( 90^\circ \leq \psi \leq 180^\circ \) — the smaller error \( \sigma^{(+)} \). The discontinuity of \( \chi^2 \) at \( \psi = 90^\circ \) does not arise because \( \Delta || = 0 \) there.

For each particular direction \( (\alpha, \delta) \), we minimise the \( \chi^2 \) with respect to \( \epsilon \) and \( \phi \). If the errors were Gaussian, the proper measure of the quality of the fit — the probability of this value of \( \chi^2 \) to be obtained randomly — would be given by a chi-square distribution with 6 degrees of freedom (10 coordinates of the 5 events minus 4 parameters \( \alpha, \delta, \epsilon, \phi \))‡. In practice, the errors are not Gaussian, but this probability \( P \) is still an instructive measure of comparative quality of fits, so we quote it in our results. Better fits correspond to lower \( P \) in these notations.

We considered the sets both with and without the Yakutsk event. The latter fits are slightly better because of the relatively low precision of the Yakutsk measurement, but both cases are consistent with each other. To test the stability of the results, we dropped also one of the AGASA events - the A2, which arrived from a bit apart of the cluster center. The results did not change considerably, though the quality of fits became worse.

In Table 2, we present the best-fit positions of the sources for different charge assignments, motivated, in particular, by the following considerations. The experimental data at the energies of interest converge to the proton-dominated composition of cosmic rays, so the most natural choice of the charge is +1. The presence of the clustered component [19] and correlations of distant BL Lacs with HiRes stereo events at very small angular separations [20] suggest a fraction of neutral particles, hence we allow for zero charges. Finally, one may note that the events, though they have very close energies, may be aligned along some direction (more or less parallel to the Galactic plane in our case), precisely like may happen in two particular models: in the Z-burst model [21], where protons, anti-protons and neutrons are equally possible (to test this conjecture, we assign charges \(-1, 0 \) and \(+1 \) for the corresponding primaries), and in the model [22], where the cosmic-ray flux is dominated by the remnants of photodesintegrated nuclei, so that neutrons, protons and alpha-particles can be detected (hence the allowed charges are 0, +1 and +2). We have thus chosen for this study five most natural charge assignments which are listed in Table 2. Other assignments are less motivated; some of them were considered but resulted in worse fits.

‡ We treat both coordinates as independent random variables with \( \sigma \) properly adjusted. When we assume zero charges, we have two parameters less and hence 8 degrees of freedom. When one is interested in the fit for a given location (e.g. a candidate source), \( \alpha \) and \( \delta \) are fixed, and the number of degrees of freedom increases by two.
Table 2. Best fits for the source positions with different charge assignments. Columns: (1), the reference code of the charge assignment; (2), charge assignment (see Table 1 for the event codes); (3) and (4), the best-fit position in the J2000 equatorial coordinates (in degrees); (5), the best-fit value of $\chi^2$ and the number of degrees of freedom; (6), the probability to obtain this value of $\chi^2$ randomly, assuming the chi-square distribution; (7) and (8), the best-fit parameters of the magnetic deflection (in degrees).

| Fit charges (2) | $\alpha$ | $\delta$ | $\chi^2$/d.o.f. | $P$ | $\epsilon$ | $\phi$ |
|-----------------|---------|---------|-----------------|-----|-----------|-------|
| (1) A1 A2 A3 H Y | (3)     | (4)     | (5)             | (6) | (7)       | (8)   |
| 0 0 0 0 0 0      | 169.0   | 56.1    | 6.44/8          | 0.40| -         | -     |
| P 1 1 1 1 1      | 167.6   | 62.7    | 2.83/6          | 0.17| 35        | 265   |
| Z 0 1 0 0 −1     | 168.8   | 56.0    | 3.30/6          | 0.23| 15        | 144   |
| N1 1 2 1 1 0     | 164.4   | 56.2    | 4.62/6          | 0.41| 13        | 185   |
| N2 1 0 1 1 2     | 171.6   | 58.3    | 2.16/6          | 0.10| 14        | 301   |

The conclusion one may obtain from a look at Table 2 is that the inclusion of the magnetic field makes the fits better compared to the case of neutral particles. Still, the precision is relatively low and the fits are not overwhelmingly good. In particular, for good fits, the 90% probability contours extend for several degrees which makes it difficult to locate the possible source (see Sec. 5 for a discussion and Fig. 2 for the probability contour plots).

4. Particular models of the Galactic magnetic field

The cluster is located at high Galactic latitude, $b \approx 56^\circ$. This implies that the Galactic magnetic field in that direction is (a) weak and (b) poorly known. Indeed, the GMF models are based dominantly on the measurements of the Faraday rotation of pulsars’ emission, and most of the pulsars are located in the Galactic plane, at low latitudes (see e.g. a skymap in Fig. 8 of Ref. [24]). The impact of the field in the Milky Way disk is relatively small for that large $b$ while the experimental information about the halo field is currently far from being sufficient.

Let us summarize briefly contemporary GMF models, following the reviews in Refs. [17–29].

The regular magnetic field in the disk follows the spiral structure of the Milky Way. The models of the disk field currently on the market are characterized by a few continuous parameters determined by the local measurements with relatively good accuracy (see Table 3, we use the values of Ref. [25] consistent with the most recent data) and are classified into a few discrete classes depending on the assumed global structure. The axisymmetric (ASS) models assume similar field directions in different spiral arms, while the bisymmetric (BSS) models assume field reversals between the arms. Though current measurements favour the BSS structure (see e.g. Ref. [17]), Ref. [29] announced their possible incorporation in an ASS type model to be formulated. We consider models of both classes here. In the dipole-type (D) models, the field direction in the Southern
Figure 2. The skymap of the cluster surroundings. The shaded areas are the regions of $1-P > 68\%$ for different charge assignments, indicated in italic (for the $\theta$ and $N1$ fits, the 68% areas are void; the 50% area is presented by the light shading for the $N1$ fit, while the similar area for the $\theta$ fit is located inside the 68% area of the $Z$ fit). The small boxes represent potential sources of the clustered cosmic-ray particles listed in Table 5 (see Column 1 of Table 5 for the source labelling numbers, given in bold face). For the source 2, we plot the contour which includes the source with 99% statistical probability [23] (the dashed part corresponds to extrapolation of the published contour). No potential sources were found outside the plot boundary for the extended area corresponding to the fit $P$. 
Galactic hemisphere is opposite to that in the Northern one, while in the quadrupole-type (Q) models it is the same.

The halo field is much worse known. Among commonly used approximations for the field above and below the Galactic plane are the disk field multiplied by a falling exponent \[ h \] with a scale height \( h \) or by a two-scale piecewise exponent \[ h_1 \text{ and } h_2 \] and glued at the height \( h_0 \). They may represent a part of the global halo field with a toroidal or poloidal structure, strong near the Galactic Center (see Ref. \[ 28 \] for a detailed discussion).

Recent studies of the magnetic deflections of ultra-high-energy cosmic rays made use of the BSS field configuration with both Q and D behaviour and a single vertical exponent \[ 25 \], or with Q behaviour and a two-step vertical exponent \[ 31 \]. Recent simulations \[ 28 \] included also the toroidal and poloidal fields as well as some turbulent components. Here, we use both the ASS and BSS models with both one- and two-step exponents. Q/D distinction is irrelevant for the current study because the cluster is located in the Northern Galactic hemisphere. For the toroidal field, we use the explicit equations of Ref. \[ 28 \] for the maximal value of 1 mkG. We approximate the poloidal field by exact magnetic-dipole field strength normalized to have a local vertical component \( B_z = 0.2 \text{ mkG} \) and cut off at 1 kpc from the Galactic Center.

The procedure we implement for the analysis of particular GMF models is very similar to that described in Sec. \[ 3 \] Now, we fix the direction of the shift according to a specific model (the directions are allowed to be different for different members of the cluster), but allow the amount of the shift (or, in other words, the overall scale of the field strength) to be a free parameter. This approach is justified by the fact that it is difficult to extract the strength of the local regular magnetic field from the measurements, and the experimental uncertainty in this parameter is very large (see Table \[ 3 \] for examples). The chi-square method allows one to determine the best fit for the field strength in each particular model and for a given charge assignment. The results are almost insensitive to the model of the disk field (ASS or BSS, one or two exponents) – the chi-square values differ by a few per cent. Hence, we quote (see Table \[ 4 \]) only the numbers for the most popular BSS model with one exponent, both with and without inclusion of the less known toroidal and poloidal halo fields.

In the frameworks of all GMF models currently published, one cannot achieve a fit for charged particles significantly better than the fit for neutral ones (fit 0), in accordance with the results of Ref. \[ 11 \] for a particular model. On the other hand, we have seen in Sec. \[ 3 \] that some regular deflections can make the fit much better. To illustrate this fact, we plot in Fig. \[ 3 \] the directions and amounts of the shifts, parametrized by \( \epsilon \) and \( \phi \), both for the best fits of Sec. \[ 3 \] and for GMF models considered in this section. We see that our study may suggest that an unknown regular component of either Galactic or extragalactic magnetic field is present. This observation agrees with the conclusions of Refs. \[ 32 \] where a question was addressed, in which direction the cosmic rays are shifted from their potential sources in different parts of the sky. It would be interesting to perform a careful study of the astrophysical data which may reveal the new component
Table 3. Parameters of the regular Galactic magnetic field. The second column gives
the experimental constraints on the parameters, the third one gives the values adopted
in this study. Note that $B_0$ is less than the total local magnetic field strength due to
presence of a random component [17].

| parameter                        | data                  | value used          |
|----------------------------------|-----------------------|---------------------|
| **disk field:**                  |                       |                     |
| spiral structure                 | ASS or BSS            | ASS or BSS          |
| North-South reversal             | D or Q                | irrelevant          |
| local strength of the regular field, $B_0$ | $(1.4 \pm 0.2)$ mkG [17] | free parameter $B_0$ |
| pitch angle, $p$                 | $-8^\circ \pm 1^\circ$ [17] | $-8^\circ$          |
| distance to the nearest field reversal, $d$ | $-0.2 \ldots -0.6$ kpc [25] | $-0.5$ kpc         |

| **field outside the disk:**      |                       |                     |
| fall-off of the disk field       | 1 or 2 exponents      | 1 or 2 exponents    |
| one-exponent height, $h$         | 1.5 kpc [17]          | 1.5 kpc             |
| second, $h_2$                    | 4 kpc [30]            | 4 kpc               |
| gluving, $h_0$                   | 0.5 kpc [30]          | 0.5 kpc             |
| proper halo field                | toroidal, poloidal?   | no or toroidal+poloidal |
| maximal strength of the toroidal field | 1 mkG [28]          | $B_0/1.5$           |
| local vertical component of the field | 0.2 mkG [27]      | 0.2 $\cdot$ $B_0/1.5$ |
| maximal extent of the field, $R_{\text{max}}$ | 20 kpc               |                     |

Table 4. Best fits for the source positions in two models of the Galactic magnetic
field with different charge assignments. Columns: (1), the reference code of the charge
assignment; (2.1) and (3.1), the best-fit values of $\chi^2$ and the number of degrees of
freedom; (2.2) and (3.2), the probability to obtain this value of $\chi^2$ randomly, assuming
the chi-square distribution; (2.3) and (3.3), the best-fit local strength of the regular
magnetic field (in mkG; minus sign indicates the direction opposite to that given by a
model). Columns (2.1)–(2.3) and (3.1)–(3.3) refer to the BSS model with one exponent,
respectively without and with the toroidal and poloidal halo fields.

| Charge assignment | without halo field $\chi^2$/d.o.f. | $P$ | $B_0$ | with halo field $\chi^2$/d.o.f. | $P$ | $B_0$ |
|-------------------|------------------------------------|-----|-------|---------------------------------|-----|-------|
|                   | (2.1)                              | (2.2) | (2.3) |                                | (3.1) | (3.2) | (3.3) |
| 0                 | 6.44/8                             | 0.40 | -     | 6.44/8                          | 0.40 | -     |
| P                 | 5.49/7                             | 0.40 | -0.98 | 6.32/7                          | 0.50 | -0.15 |
| Z                 | 6.05/7                             | 0.47 | -0.38 | 5.11/7                          | 0.35 | -0.53 |
| N1                | 5.01/7                             | 0.34 | -0.60 | 5.45/7                          | 0.39 | -0.23 |
| N2                | 6.44/7                             | 0.51 | 0     | 6.44/7                          | 0.51 | 0     |
Figure 3. Amounts and deflections of the shifts calculated for the best-fit values for various charge assignments (P, Z, N1, N2) and for the models of the Galactic magnetic field with and without inclusion of toroidal and poloidal halo fields. The deflections for the GMF models were calculated for the location of the H event assuming the BSS model with one-exponent fall-off; for other models the results are very close. The length of an arrow is proportional to $\epsilon$; the direction is given by $\phi$ (shift to the North, $\phi = 270^\circ$, corresponds to the upward direction).

independently.

5. Potential sources and discussion

Various potential astrophysical sources of ultra-high-energy cosmic rays have been suggested in literature (see Ref. [33] for a recent review and Ref. [34] for a comparative study of correlations between the cosmic-ray arrival directions and source locations). In this section, we consider all possible sources around the cluster direction which were listed in at least one of the catalogs of Ref. [34]. We note that in this way, we restrict ourselves to persistent extragalactic sources only. There are nine candidates in a large area spanned by the cluster position shifted by magnetic fields with various charge assignments. They are listed in Table 5 and plotted on a skymap, Fig. 2, together with the best-fit positions of the cluster source for different charges.

5.1. Notes on individual sources.

TXS 1055+567. This is an outstanding low-energy peaked BL Lac type object listed as a confirmed “BL” in the Véron catalog [36]. With its visual magnitude of $15^m.8$, strong dominance of the optical over X-ray emission and possible association with a EGRET sub-GeV source, this object satisfies all conditions for a BL Lac to be a potential cosmic-ray source, as discussed in Refs. [25, 40, 11, 12]. There is a recent evidence, based on
Table 5. Candidate sources around the cluster direction. (1), reference number for the skymap; (2), object name; (3), object class (BLL=BL Lac type object, Sy=nearby Seyfert galaxy, coll.=a pair of colliding galaxies, γ-s.= a gamma-ray source, IR=a luminous infrared galaxy); (4), the probability for the class (3) to correlate with the AGASA $E > 4 \cdot 10^{19}$ eV cosmic rays by chance, calculated on the basis of positional correlations without the account of multiple tries [34] with (or, for the fit “0”, without) correction for GMF (lower values correspond to more probable sources of cosmic rays); (5), distance to the object (in Megaparsecs, assuming $H = 70$ km$\cdot$s$^{-1}\cdot$Mpc$^{-1}$); (6) and (7) – object position in the J2000 equatorial coordinates (in degrees); (8), the probability to be randomly associated with a cluster’s source with charge assignment (8) (lower values correspond to better fits); (10), “yes” means that the combination of distance and charge assignment requires new physics or cosmology. See text (and footnote on page 7) for details.

| No. | Name             | Class       | $P_{\text{class}}$ | $d$  | $\alpha$ | $\delta$ | Fit  | $P$  | new phys. |
|-----|------------------|-------------|---------------------|------|----------|----------|------|------|-----------|
| 1   | TXS 1055+567     | BLL         | $4 \cdot 10^{-4}$  | 617  | 164.66   | 56.47    | N1   | 0.21 | yes       |
| 2   | 3EG J1052+5718   | γ-s.        | -                   | -    | (163.2)  | (57.3)  | extended | -       |
| 3   | NGC 3642         | Sy          | 0.62                | 23   | 170.57   | 59.07    | N2   | 0.05 | no        |
|     |                  |             |                     |      |          |          |      |      | P 0.13    |
| 4   | MCG +10-16-111   | Sy          | 0.013               | 120  | 169.85   | 59.35    | N2   | 0.09 | yes       |
|     |                  |             |                     |      |          |          |      |      | P 0.11    |
| 5   | NGC 3488         | coll.       | 0.15                | 43   | 165.35   | 57.68    | P    | 0.23 | no        |
| 6   | NGC 3517         | coll.       | 0.27                | 118  | 166.40   | 56.52    | 0    | 0.54 | yes       |
| 7   | M 108            | IR          | 0.11                | 10   | 167.87   | 55.67    | 0    | 0.35 | no        |
|     |                  |             |                     |      |          |          |      |      | Z 0.45    |
| 8   | NGC 3471         | IR          | 0.47                | 30   | 164.79   | 61.53    | N2   | 0.14 | no        |
| 9   | IC 694           | IR,coll.    | 0.15                | 45   | 172.13   | 58.57    | N2   | 0.04 | no        |

The high-precision HiRes stereo data, that the objects of this particular subclass of BL Lac’s may emit neutral ultra-high-energy particles [20, 42]. This makes its association with the cluster at the charge assignment N1 — with a neutral Yakutsk primary — rather plausible, despite a comparatively low quality of the fit ($\chi^2$/d.o.f. = 4.72/8; the BL Lac position corresponds almost exactly to the highest-probability point).

3EG J1052+5718. This gamma-ray source [23] is probably associated with the same BL Lac TXS 1055+567 [23] (see also Ref. [41]). The source is relatively weak and variable; its gamma-ray location is determined with rather poor accuracy, and the 95% C.L. position contours extend for several degrees. We thus do not quote the probability values for this object, but plot instead the position contours in Fig. 2. The connection of sub-GeV gamma-rays to the emission and propagation of ultra-high-energy cosmic rays has been pointed out several times [41, 43, 44, 45].
NGC 3642 and MCG +10-16-111 are nearby Seyfert galaxies listed, correspondingly, in the catalogs [36] and [37] and satisfying the criteria of Ref. [46] to be possible sources of cosmic rays.

NGC 3488 and NGC 3517 are interacting pairs of galaxies from the Vorontsov-Veliaminov catalog [47]. Colliding galaxies were considered as possible sources of ultra-high-energy cosmic rays in Refs. [2, 48].

NGC 3556 and NGC 3471 are luminous infrared galaxies from the HCN [38] and PDS [39] catalogs, correspondingly. Possible origin of energetic cosmic particles in luminous infrared and starburst galaxies was discussed in Refs. [49].

IC 694 is a colliding pair of galaxies [47] with a starburst region [39]. A possible relation of this object to the AGASA triplet was discussed in Ref. [2]. It enters the list of luminous infrared galaxies with a gamma-ray flux in excess of the expected GLAST sensitivity [50].

A note on NGC 3610 and NGC 3613. These two objects, located not far from the direction of the cluster, entered the list of twelve dead quasar candidates of Ref. [51] selected from the catalog [52] by five parameters. It was their proximity to the AGASA triplet which was responsible to the correlations of these objects with cosmic rays reported in Ref. [51] (two sources and three cosmic rays contributed most of the observed coincidences). However, updated galaxy catalogs [53] quote fainter corrected blue magnitude for these objects, so that they no longer satisfy quite involved criteria of Ref. [51]; that is why we do not include them in the list of possible candidates. We note in passing that the list of objects selected from the catalog [53] by criteria of Refs. [51, 52] no longer exhibits any correlations with energetic cosmic rays [34].

5.2. A simultaneous interaction?

One of possible ways to explain the existence of a tight cluster of charged particles is to suppose that their path through the magnetic fields was short enough. This might be the case if all five particles, or some of them, originated in an interaction of a single particle which took place not far from the Earth. This could be a photodesintegration of a nuclei, or a Z-burst. In that case, the time delays between the arrivals of particles should be approximately proportional to their angular deflections from the direction to the place where the interaction happened. This is hardly possible in our case because the particles arriving later falled between the two which arrived first (see Table 1). This does not exclude, however, the scenario when numerous enough particles were created in a single explosive event like a gamma-ray burst and, being randomly deflected by magnetic fields, continue to reach the Earth for very long time.
6. Conclusions

The existence of a cluster of five cosmic rays with energies exceeding $4 \times 10^{19}$ eV (AGASA scale), observed by three independent experiments, supports the conjecture of clustering of ultra-high-energy cosmic rays and of their astrophysical origin. Three of the events did not enter the original AGASA sample, on the basis of which the conjecture was formulated, thus allowing for the first evidence for a triplet purely independent of the original claim. Our study does not address the statistical significance of clustering but suggests that the five cosmic rays were of common origin.

At high Galactic latitude corresponding to the cluster direction, the Galactic magnetic field is weak and poorly known (the effect of unknown halo fields may dominate over that of fading disk field). The existence of a cluster of charged particles may be considered as an argument towards the weak intergalactic magnetic field scenario [16].

The fits for the possible position of the source of these five cosmic rays are better with the assumption of regular magnetic deflection than without it, suggesting that at least some of the particles were charged. Best-fit source positions are listed in Table 2, but the uncertainties in the positions are large, as shown in Fig. 2.

Within particular published models of the Galactic magnetic field, the fits are not better than without magnetic deflections at all. Better fits appear in a two-parametric analysis and correspond to shifts in other directions. These facts may be interpreted as a signature for unknown regular Galactic or extragalactic magnetic field component in this direction.

Within given experimental accuracy, the fits cannot prefer, nor exclude, any particular astrophysical source. Relative estimates of the quality of fits for different sources may be found in Table 5. Under particular charge assignments, the BL Lac type object TXS 1055+567, the EGRET source 3EG J1052+5718, probably associated with this BL Lac, and the colliding starburst galaxy IC 694 may be related to the clustered cosmic rays, but the evidence is far from being firm. Clearly, better angular resolution (like that of the HiRes stereoscopic experiment) is required for firm identification of the cosmic-ray sources from other clusters. This is a necessary direction of further studies.

One should note that the physical scenarios discussed here are strongly constrained by the propagation of energetic particles in cosmic background radiation. Within the conventional physics and cosmology, the Z-burst model is excluded [34]; the protons of the energies considered here can propagate for about several hundred megaparsecs; the nuclei photodisintegration scenario is relevant for the source distances up to 100 Mpc [22]. As for the neutral particles, photons may propagate for $5 \ldots 10$ Mpc while neutrons of this energy can travel only $\sim 1$ Mpc before decay. Looking at the distance to the sources (Col. 5 of Table 5), one may note that in some cases, the explanation of the association of a given source with the cluster within a scenario indicated in Col. 8 requires new, unconventional physics or cosmology (see Col. 10 of the table).

Future investigations should include also attempts to identify the chemical composition of the clustered primary particles both by statistical methods and on the
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(less precise) case-by-case study of the shower profiles, muon content etc.

Much better knowledge of the Galactic magnetic field, especially at high Galactic latitudes, is required for identification of the sources of charged ultra-high-energy cosmic-ray particles. On the other hand, once these sources are identified, the cosmic-ray arrival directions may trace the magnetic fields with some accuracy.

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