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Search for magnetically-induced signatures in the arrival directions of ultra-high energy cosmic rays measured by the Pierre Auger Observatory

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The search for magnetically-induced signatures in ultra-high energy cosmic ray data is a promising path for the identification of their sources. We use data of the Pierre Auger Observatory measured between 2004 and 2018, for two energy thresholds, 20 EeV and 40 EeV, providing unprecedented statistics: the number of cosmic rays included in the analyses for these energy thresholds is above 6500 and 1100, respectively. Two analysis approaches are used. In one, we search for inversely energy-ordered deflection patterns, while in the other we analyze the strength of collimation of energy along the local system of principal axes. We apply the analyses for a targeted search in regions around source candidates of active galactic nuclei and starburst galaxies. In addition, for the energy-ordered patterns an all-sky search has been performed. We also report the performance of the method evaluated using simulated data sets, including deflection in a model of the Galactic magnetic field which includes coherent and turbulent components, and with different composition scenarios.

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1. Introduction

The identification of the sources of ultra-high-energy cosmic rays (UHECRs) remains a challenging task. Being charged particles, they are deflected by the extragalactic and Galactic magnetic fields on their path from their sources to Earth. Despite the considerable experimental efforts [1, 2], the knowledge of these intervening magnetic fields is still poor. Moreover, the composition of UHECRs at the highest energies is also uncertain, given the low statistics and the dependence on the modelling of the hadronic interactions. From measurements of the maximum of the shower development [3], the data indicates that the composition becomes heavier with increasing energy. However, it does not rule out a light nuclei fraction at the highest energies, that may eventually originate in few nearby sources, different from the average ones. In such a case, the identification of several events from the same source can be performed by searching for magnetically-induced signatures in the arrival directions of the measured UHECRs. In this work, we show the results of two different methods that search for such signatures in the data measured by the Pierre Auger Observatory.

2. The Pierre Auger Observatory and the data set

The Pierre Auger Observatory [4], located in Argentina, is with a total area of 3000 km^2 the world's largest observatory for measuring ultra-high energy cosmic rays (UHECRs). The observatory consists of an array of 1660 water-Cherenkov stations arranged in an equilateral triangular grid (the surface detector), and 27 fluorescence telescopes on four sites (the fluorescence detector), which overlook the atmosphere above the surface detector. While the surface detector measures the lateral distribution of the air shower at ground level, the fluorescence detector can reconstruct the longitudinal profile of the air shower.

We select data recorded with the surface detector between 1 January 2004 and 31 August 2018 with zenith angles up to 80°. We choose energy thresholds 20 EeV and 40 EeV, which yield data sets of 6568 and 1119 events, respectively. The events are required to have at least four (five) active stations surrounding the station with the highest signal for the events with zenith angle smaller (larger) than 60°. For the events with zenith angle smaller than 60°, the reconstructed core must be inside an equilateral or isosceles triangle of active stations.

3. Methods

We investigate the arrival directions and energies of the UHECRs with two different methods. In the first one, we search for sets of events with different energies that come from a single point-like source, showing a correlation between their arrival direction and the inverse of their energy (a "multiplet"). The second method uses an observable built from a principal component analysis in a localized region of the sky, measuring the elongation of a pattern with respect to the region of interest (ROI) center. In the following, we will denote this observable as thrust ratio.

3.1 Multiplet search

Deflections of UHECRs in coherent magnetic fields can be approximated as linear if the total deflection angle $|\vec{\Theta}|$ is small. Thus, with the unit vectors of the source direction $\vec{\Theta}_s$ and the arrival direction after deflection $\vec{\Theta}$, we can write the deflection behavior as:

$$\vec{\Theta} \simeq \vec{\Theta}_s + \frac{\vec{D}(\vec{\Theta}_s)}{E}, \tag{3.1}$$

where E is the energy of the CR and $\vec{D}$ is the integral along the line of sight of the perpendicular component of the magnetic field $\vec{B}$ times the charge Ze of the particle $\vec{D}(\vec{\Theta}_s) = Ze\int_0^L \mathrm{d}\vec{l} \times \vec{B}(\vec{l})$. The "deflection power" $D \equiv |\vec{D}|$ will be given in units $1^\circ \times 100$ EeV.

To determine if a set of cosmic rays forms a multiplet, we first use a coordinate system ($\hat{\mathbf{u}}$, $\hat{\mathbf{w}}$), which is tangential on the surface of the celestial sphere. The system is then rotated around the respective radial unit vector with an angle such that the covariance

$$\mathrm{Cov}(w, 1/E) = \frac{1}{N}\sum_{i=1}^{N}(w_i - \langle w\rangle)(1/E_i - \langle 1/E\rangle) \tag{3.2}$$

between the cosmic ray coordinates w_i and their inverse energy $1/E_i$ is zero and the covariance $\mathrm{Cov}(u, 1/E)$ is maximal. The correlation between the coordinate u and $1/E$ is measured through the correlation coefficient

$$C(u, 1/E) = \frac{\mathrm{Cov}(u, 1/E)}{\sqrt{\mathrm{Var}(u)\mathrm{Var}(1/E)}} \tag{3.3}$$

where the variances are given by $\mathrm{Var}(x) = \left\langle (x - \langle x\rangle)^2 \right\rangle$.

To identify possible candidates among background chance alignments we introduce two cuts: on the one hand, the correlation coefficient $C(u, 1/E) > C_{\mathrm{min}}$ must exceed the threshold C_{min}, and on the other hand, the spread in the perpendicular direction $\hat{\mathbf{w}}$ of the multiplet may not exceed a threshold $\max(|w_i - \langle w\rangle|) < W_{\mathrm{max}}$. The two parameters were found to perform best on simulations for values of $C_{\mathrm{min}} = 0.9$ and $W_{\mathrm{max}} = 1.5^\circ$. A more detailed description can be found in [5].

3.2 Thrust ratio

Deviations from a clear correlation between the energy and the deflection angle can arise from larger turbulent field components or a mixed nuclear composition of the cosmic rays, as deflections scale also with the nuclear charges Z_i of the particles. In this case, the thrust ratio T_2/T_3 is expected to still find an elongation of the arising pattern in the arrival directions. The thrust observables T_k are constructed by successively maximizing the values

$$T_k = \max_{\hat{n}_k}\left(\frac{\sum_i |\omega_i^{-1}\,\vec{p}_i \cdot \hat{n}_k|}{\sum_i |\omega_i^{-1}\,\vec{p}_i|}\right) \tag{3.4}$$

with respect to the axes $\hat{n}_k$ starting with $k = 1$. The sum iterates over all cosmic rays in the chosen ROI, $\vec{p}_i = E_i\,\hat{e}_{r_i}$ is the momentum of particle i, and ω_i is the exposure towards this direction. The principal axes $\hat{n}_k$ are perpendicular to each other ($\hat{n}_1 \perp \hat{n}_2 \perp \hat{n}_3$), thus, by construction we obtain for the thrust observables the relation $T_1 > T_2 > T_3$.

While the thrust axis $\hat{n}_1$ points radially to the local barycenter of the energy distribution within the ROI, the axes $\hat{n}_2$ and $\hat{n}_3$ form an orthonormal coordinate system tangential to the local spherical plane. In this system, a signal like structure would be characterized by a strong collimation of arrival directions around the $\hat{n}_2$-axis, and therefore by a high thrust observable T_2. To be less affected by the radial cosmic ray distribution within the ROI, we choose instead the thrust ratio T_2/T_3 as observable. A more detailed description of the procedure can be found in [6].

4. Target selection and benchmark simulation

In this section, we motivate the choice of source candidates for a targeted search and set a benchmark simulation of ultra-high energy cosmic rays originating from these sources and propagating through a model of the Galactic magnetic field.

4.1 Target selection

A recent investigation found a promising hint of UHECR anisotropy in the direction of nearby galaxies, in particular, starburst galaxies (SBG) weighted by their radio flux and to a lesser extent, active galactic nuclei (AGN) weighted by their gamma-ray flux [7]. For the targeted search in this analysis, we test a 'merged' sample of 32 SBGs with distances up to 250 Mpc as described in [7] (section 3.1). We also test active galactic nuclei (AGN) as source candidates. The candidates are taken from the *Third Fermi-LAT Catalog of High-Energy Sources* (3FHL), providing a total number of 33 targets for distances up to 250 Mpc [8].

The expected UHECR flux from a certain source measured on Earth will strongly depend on the propagation distance through the extragalactic space. Therefore, we performed simulations of helium nuclei and preselected the source candidates by a cut on the helium flux contribution of 1% relative to the source with the highest contribution. Table 1 lists the source candidates that survive this cut, and they will be used as targets for the methods defined in section 3:

Nearby AGN from the 3FHL catalog [8]			
Target	gal longitude [°]	gal latitude[°]	distance [Mpc]
Cen A	309.5	19.4	3.7
M87	283.8	74.5	16.5
Fornax A	240.2	-56.7	17.4
Nearby SBG from [7]			
Target	gal longitude [°]	gal latitude [°]	distance [Mpc]
NGC 253	97.4	-88.0	3.6
NGC 4945	305.3	13.3	3.7
Circinus	311.3	-3.8	4.2
M83	314.6	32.0	4.7
NGC 4631	142.8	84.2	7.4
NGC 1808	241.2	-35.9	9.1
NGC 1068	172.1	-51.9	19

Table 1: Target selection of starburst galaxies and active galactic nuclei. For a hypothetical helium acceleration, all sources are expected to still contribute at least 1% the level of the strongest source contribution after suffering from losses during the propagation.

4.2 Benchmark simulation

To evaluate the performance of the above-defined methods, we probe their response on an arrival scenario of UHECRs which originate from the targets defined in table 1 and then propagate through a model of the Galactic magnetic field. We use the regular model of Jansson and Farrar [9] and as a lower and upper limit two different versions of turbulent fields: the first one contains striation plus a Kolmogorov field with a coherence length of 60 pc as proposed in [10]. In the following, we refer to it as GMF-A model. Recent measurements by the Planck satellite indicate that the turbulent strength of GMF-A model is likely to be too large [11]. Therefore, we also probe a weaker version of the Kolmogorov field with the same coherence length but a downscaled magnetic field strength amplitude of factor $1/3$ and no additional striated field. We will refer to this as GMF-B in the following.

For both energy thresholds, 20 EeV and 40 EeV, we test the hypothesis of an outstanding nearby source emitting a certain number of signal cosmic rays N_s with an energy spectrum following a simple power-law spectrum and spectral index of $\gamma = -2$. The arrival directions are obtained by propagating them through either GMF-A or GMF-B magnetic field models. The remaining cosmic ray sky is simulated isotropically following the geometrical exposure and measured energy spectrum at the Pierre Auger Observatory. The source scenarios for the two energy thresholds will only differ in the chemical composition of the accelerated cosmic rays: while in the $E > 40$ EeV scenario the source accelerates helium nuclei up to 200 EeV, in the $E > 20$ EeV scenario also protons are accelerated with proton energies between 20 EeV - 40 EeV and helium energies between 40 EeV - 80 EeV. The flux of arriving helium candidates is assumed to be twice as high as the flux of the proton candidates. Note that with these energy ranges the source features a simple rigidity-dependent acceleration mechanism as expected by a magnetic field based process.

In all simulations, we assumed a total number of 900 events above 40 EeV and 6000 above 20 EeV. [1] We apply an experimental energy uncertainty of 14% and an angular resolution of 1°.

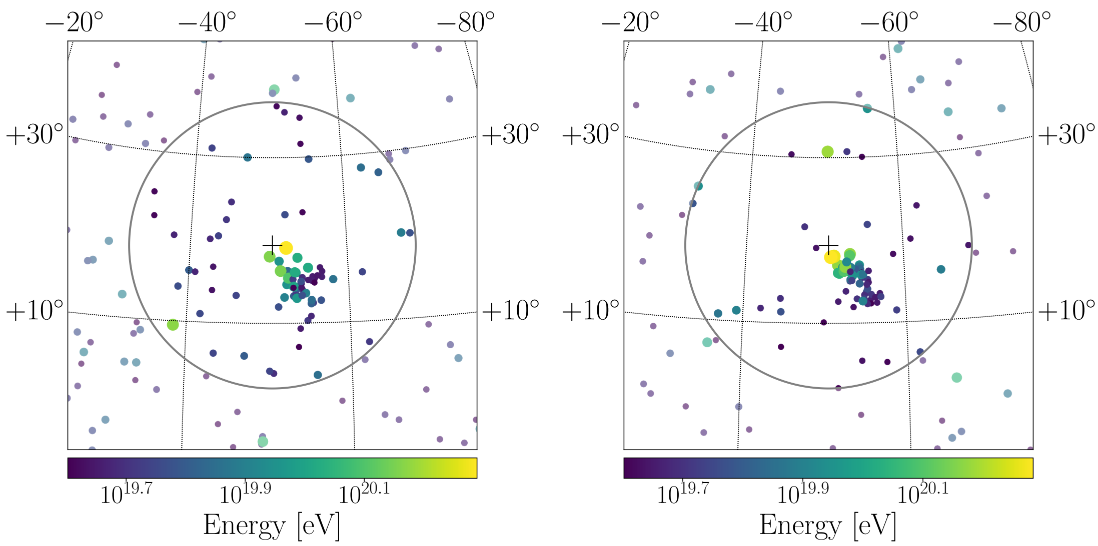

Figure 1: Visualization of arrival directions in Galactic coordinates for the benchmark simulations from target Cen A and energy threshold $E > 40$ EeV for the strong turbulent *GMF-A* Galactic magnetic field model (left) and the weaker version *GMF-B* (right).

[1]These numbers are slightly smaller than the actual event number in data, which however is expected to have a minor impact on the sensitivity.

Example simulations for a number of injected signal cosmic rays of $N_s = 50$ from the Cen A source are visualized for the $E > 40$ EeV energy threshold in figure 1.

5. Expected sensitivity

5.1 Multiplets

We present the performance of the multiplet search on the benchmark simulation with the 40 EeV energy cut as specified in section 4. Figure 2 (left) shows the chance probability that the number of found cosmic rays associated with the multiplet occurs in isotropic simulations for the different targets and the simulation with the GMF-A turbulent magnetic field model. The markers indicate different chosen numbers of injected signal cosmic rays from the respective target. Due to the variety of the arrival patterns that arise from the deflection in the Galactic magnetic field and the non-uniform observatory exposure, the sensitivity depends highly on the evaluated target, e.g. nine injected signal cosmic rays for the sources M87 and NGC1068 and 18 injected cosmic rays for the source NGC 4945 are needed to reach a sensitivity of 3σ. This corresponds to signal fractions of 1% and 2%, respectively. As expected, for the weaker GMF-B model, the analysis performs better for almost all targets as can be seen in the right panel of figure 2.

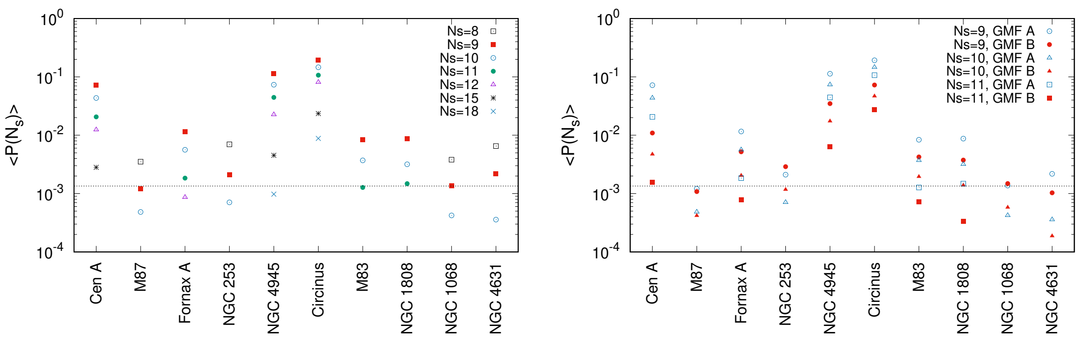

Figure 2: Expected sensitivity for the multiplet search on the benchmark simulation with the energy cut 40 EeV. (Left) Isotropic chance probability for chosen injected signal cosmic rays N_s for the different targets and GMF-A model. (Right) Comparison between GMF-A and GMF-B models.

5.2 Thrust ratio

For the thrust-ratio, the patterns produced by the source candidate have a larger impact on the sensitivity than in the case of the multiplets, as can be seen by the big spread between the lines in figure 3. For the 20 EeV energy cut and GMF-A, most of the targets reach the $3\,\sigma$ confidence level between $N_s \approx 40$ and $N_s \approx 60$ signal cosmic rays, corresponding to small signal fractions between 0.7% and 1.0% as can be seen in the left of figure 3.

In case of the 40 EeV energy cut, a relatively high number of $N_s \approx 30$ to $N_s \approx 60$ injected signal cosmic rays is needed to pass the $3\,\sigma$ confidence level, which correspond to signal fractions between 3% and 6%. This performance is inferior to the multiplet search, which might be explained by the fact that it does not make direct use of the energy information. The weaker turbulent magnetic

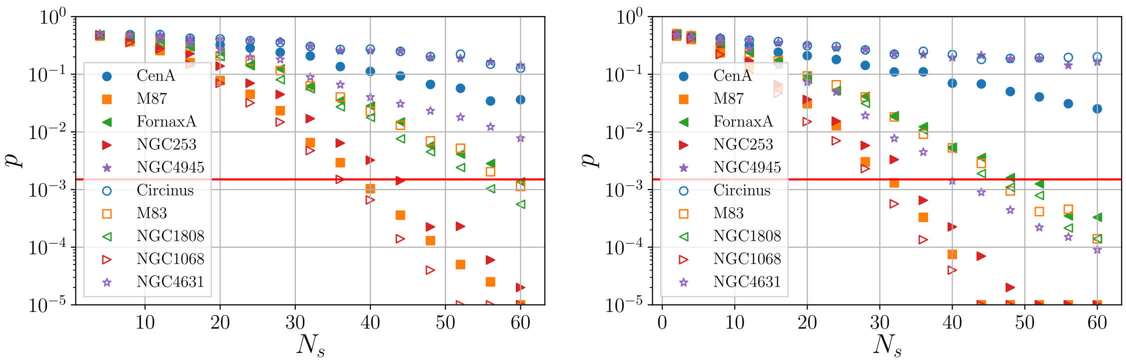

Figure 3: Expected sensitivity for the thrust-ratio observable on the benchmark simulation with the stronger GMF-A turbulent magnetic field model. Shown for the 20 EeV energy cut on the left and the 40 EeV energy cut on the right.

field model GMF-B yields just a minor improvement on the performance: on average, the same sensitivity as in the case of GMF-A is gained when injecting two signal cosmic rays less.

6. Application to data

6.1 Targeted search

In this section, we apply the multiplet and thrust methods to the data of the Pierre Auger Observatory as presented in section 2. All individual chance probabilities that isotropic arrival directions respond at least as strong as found on data are above 1% thus no significant alignment pattern around the chosen targets could be found (cf. table 2).

Isotropic chance probabilities			
Target	Multiplet (40 EeV)	Thrust-ratio (20 EeV)	Thrust-ratio (40 EeV)
Cen A	1.2×10^{-2}	0.75	0.42
M87	0.61	0.44	0.85
Fornax A	0.96	0.21	1.9×10^{-2}
NGC 253	0.54	0.98	0.88
NGC 4945	0.25	2.9×10^{-2}	3.7×10^{-2}
Circinus	0.99	0.82	0.58
M83	0.20	0.14	0.54
NGC 4631	—	0.59	0.85
NGC 1808	0.61	0.63	0.77
NGC 1068	0.75	6.0×10^{-2}	0.29

Table 2: Isotropic chance probabilities for the targeted search with the multiplet and thrust-ratio observables applied on data of the Pierre Auger Observatory.

The most striking candidate for the multiplet search is in the Cen A region above 40 EeV with a chance probability of 1.2% to arise from isotropic arrival scenarios. The fitted deflection power is $D = (9 \pm 2)^\circ \times 100$ EeV. In the case of the thrust-ratio, the sources Fornax A above 40 EeV, NGC 1068 above 20 EeV and NGC 4945 for both energy thresholds are most striking with chance probabilities between 2% and 6%. There is barely any overlap between the cosmic rays within the multiplet of the Cen A region and the region of interests evaluated for the thrust observables.

6.2 Blind search

We also perform the multiplet search on the entire sky for the energy threshold above 40 EeV. The largest multiplet found has a multiplicity of 10. The probability that it appears by chance from an isotropic distribution of events is 11%. The second largest multiplet has a multiplicity of nine events. The chance probability of finding at least two multiplets with multiplicity larger or equal than nine in isotropic simulations is 19%. The respective deflection power values are $D = (8.0 \pm 1.3)^\circ \times 100$ EeV and $D = (12 \pm 2)^\circ \times 100$ EeV.

7. Discussion

We introduced two observables to search for magnetically-induced deflection patterns in the energy and arrival direction distribution of ultra-high energy cosmic rays above 20 EeV and 40 EeV in data recorded by the Pierre Auger Observatory.

Neither in a targeted search around chosen sources of active galactic nuclei and starburst galaxies nor in a blind search could any significant pattern be found. The largest deviations from isotropic distributions were found with a p-value of 2% around the Fornax A region for the thrust search above 40 EeV and with a p-value of 1% around the Cen A region for the multiplet search above 40 EeV. The next-to-leading ones were found with p-values of $3-6\%$ around the NGC 4945 and NGC 1068 for the thrust search above 20 EeV. These probabilities are not penalized for the use of ten different candidates.

Further investigations to apply the multiplet search for energies down to 20 EeV, and the thrust search on the entire sky are planned.

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