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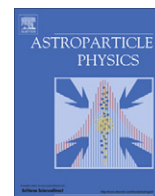
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ABSTRACT

We present the results of an analysis of data recorded at the Pierre Auger Observatory in which we search for groups of directionally-aligned events (or 'multiplets') which exhibit a correlation between arrival direction and the inverse of the energy. These signatures are expected from sets of events coming from the same source after having been deflected by intervening coherent magnetic fields. The observation of several

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events from the same source would open the possibility to accurately reconstruct the position of the source and also measure the integral of the component of the magnetic field orthogonal to the trajectory of the cosmic rays. We describe the largest multiplets found and compute the probability that they appeared by chance from an isotropic distribution. We find no statistically significant evidence for the presence of multiplets arising from magnetic deflections in the present data.

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1. Introduction

The origin of ultra-high energy cosmic rays is a long-standing open question, and the identification of their sources is one of the primary motivations for the research conducted at the Pierre Auger Observatory. If the density of cosmic rays sources is not too large, it is expected that there could be indications of the presence of multiplets, i.e. sets of events with different energy that come from a single point-like source. Due to the magnetic fields that cosmic rays traverse on their paths from their sources to the Earth, they will be deflected and this deflection is proportional to the inverse of their energy if the deflections are small. Therefore, to identify sets of cosmic rays that come from a single source, a search for events that show a correlation between their arrival direction and the inverse of their energy has been performed using the data recorded at the Pierre Auger Observatory. The observation of cosmic ray multiplets could allow for the accurate location of the direction of the source and could also provide a new means to probe the galactic magnetic field, as it should be possible to infer the value of the integral of the component of the magnetic field orthogonal to the trajectory of the cosmic rays. Note that to observe a correlated multiplet the source should be steady, in the sense that its lifetime is larger than the difference in the time delays due to the propagation in the intervening magnetic fields for the energies considered. Moreover, magnetic fields should also be steady in the same sense so that cosmic rays traverse approximately the same fields.

This study relies on the acceleration at the source of a proton component (or intermediate mass nuclei being accelerated and photo-disintegrated during extragalactic propagation with the deflections due to extragalactic magnetic fields being small compared to those in the Galaxy). Due to the magnitude of the known magnetic fields involved, heavy nuclei at these energies would appear spread over a very large region of the sky, probing regions with different amplitudes and directions of the magnetic field, and hence losing their alignment and correlation with the inverse of energy.

The galactic magnetic field is poorly constrained by the available data, even though there has been considerable effort to improve this knowledge using different observational techniques, see, e.g. [1–3]. This field is usually described as the superposition of a large-scale regular component and a turbulent one. The regular component has a few μG strength and is coherent on scales of a few kpc with a structure related to the spiral arms of the galactic disk, and eventually also a more extended halo component (see, e.g. [4]). The deflection of cosmic rays with energy E and charge Z by the regular component of the magnetic field B after traversing a distance L is given by

$$\delta \simeq 16^\circ \frac{20 \text{ EeV}}{E/Z} \left| \int_0^L \frac{d\vec{l}}{3 \text{ kpc}} \times \frac{\vec{B}}{2 \mu\text{G}} \right|, \quad (1)$$

where $1 \text{ EeV} \equiv 10^{18} \text{ eV}$. This is the predominant deflection because, although the turbulent component has a root mean square amplitude of $B_{\text{rms}} \simeq (1 - 2)B_{\text{reg}}$, it has a much smaller coherence length (typically $L_c \simeq 50\text{--}100 \text{ pc}$) [5,6], leading to a smaller deflection, with a typical root mean square value

$$\delta_{\text{rms}} \simeq 1.5^\circ \frac{20 \text{ EeV}}{E/Z} \frac{B_{\text{rms}}}{3 \mu\text{G}} \sqrt{\frac{L}{1 \text{ kpc}}} \sqrt{\frac{L_c}{50 \text{ pc}}} \quad (2)$$

After traveling a distance L through the turbulent field, the trajectories of cosmic rays would be displaced a distance $\sim \delta_{\text{rms}}L$ with respect to the one they would have had if only the regular field were present. If this displacement is smaller than the coherence length L_c , this means that all the particles with that energy have experienced nearly the same values of the turbulent field along their trajectories. Thus, the effect is that the arrival direction of cosmic rays will coherently wiggle with an amplitude $\delta_{\text{rms}}(E)$ around the direction determined by the deflection due to the regular magnetic field as a function of the energy. Conversely, when $\delta_{\text{rms}}(E)L > L_c$, particles of the same energy that have probed uncorrelated values of the turbulent field are able to reach the observer from the source and several images appear, scattered by $\delta_{\text{rms}}(E)$ around the image that would be produced by the regular field alone. Which of the two regimes actually takes place depends on the energy considered and on the distance traveled in the turbulent field. For instance, for $L \simeq 2 \text{ kpc}$ and energy about 20 EeV , the second situation applies, while at much higher energies the first one holds.

Extragalactic magnetic fields could also deflect the trajectories of cosmic rays, but their strength is yet unknown and the relevance of their effect is a matter of debate, see, e.g. [7–9].

2. The Pierre Auger Observatory and the data set

The Pierre Auger Observatory, located in Malargüe, Argentina (35.2°S , 69.5°W) at 1400 m a.s.l. [10], was designed to measure ultra-high energy cosmic rays (energy $E > 10^{18}$) with unprecedented statistics. It consists of a surface array of 1660 water-Cherenkov stations. The surface array is arranged in an equilateral triangular grid with 1500 m spacing, covering an area of approximately 3000 km^2 [11]. The array is overlooked by 27 fluorescence telescopes located on hills at four sites on its periphery [12]. The surface and air fluorescence detectors are designed to perform complementary measurements of air showers created by cosmic rays. The surface array is used to observe the lateral distribution of the air shower particles at ground level, while the fluorescence telescopes are used to record the longitudinal development of the shower as it moves through the atmosphere.

In this work we analyze events with zenith angles smaller than 60° recorded by the surface detector from 1st January 2004 to 31st December 2010. The events are required to have at least five active stations surrounding the station with the highest signal, and the reconstructed core must be inside an active equilateral triangle of stations [13]. The corresponding exposure is $25,806 \text{ km}^2 \text{ sr yr}$. The angular resolution, defined as the 68th percentile of the distribution of opening angles between the true and reconstructed directions of simulated events, is better than 0.9° for events that trigger at least six surface stations ($E > 10 \text{ EeV}$) [14]. The energy resolution is about 15% and the absolute energy scale, given by the fluorescence calibration, has a systematic uncertainty of 22% [15].

3. Method adopted for the multiplets search

In the limit of large energy, and hence small deflections, it is a good approximation to consider the following simplified relation between the cosmic ray observed arrival directions, described by the unit vector $\vec{\theta}$, and the actual source direction $\vec{\theta}_s$

$$\vec{\theta} = \vec{\theta}_s + \frac{Ze}{E} \int_0^L d\vec{l} \times \vec{B} \simeq \vec{\theta}_s + \frac{\vec{D}(\vec{\theta}_s)}{E}, \quad (3)$$

where Ze is the electric charge of the cosmic ray and $D \equiv |\vec{D}(\vec{\theta}_s)|$ will be called the deflection power and will be given in units of 1° 100 EeV, which is $\approx 1.9 e \mu\text{G kpc}$.

In the case of proton sources, departures from the linear approximation are relevant for energies below 20 EeV for typical galactic magnetic field models [16], as the deflections of the trajectories are large and the integral of the magnetic field component orthogonal to the path cannot be approximated as a constant for a fixed source direction. This fact motivates the restriction of the present analysis to events with energies above 20 EeV.

In order to identify sets of events coming from the same source, the main requirement will be that they appear aligned in the sky and have a high value of the correlation coefficient between the arrival direction and the inverse of the energy.

To compute the correlation coefficient for a given subset of N nearby event directions, we first identify the axis along which the correlation is maximal. For this we initially use an arbitrary coordinate system (x, y) in the tangent plane to the celestial sphere (centered in the average direction to the events) and compute the covariance

$$\text{Cov}(x, 1/E) = \frac{1}{N} \sum_{i=1}^N (x_i - \langle x \rangle)(1/E_i - \langle 1/E \rangle) \quad (4)$$

and similarly for $\text{Cov}(y, 1/E)$. We then rotate the coordinates to a system (u, w) in which $\text{Cov}(w, 1/E) = 0$, and hence $\text{Cov}(u, 1/E)$ is maximal. This corresponds to a rotation angle between the u and x axes given by

$$\alpha = \arctan \left(\frac{\text{Cov}(y, 1/E)}{\text{Cov}(x, 1/E)} \right). \quad (5)$$

The correlation between u and $1/E$ is measured through the correlation coefficient

$$C(u, 1/E) = \frac{\text{Cov}(u, 1/E)}{\sqrt{\text{Var}(u)\text{Var}(1/E)}}, \quad (6)$$

where the variances are given by $\text{Var}(x) = \langle (x - \langle x \rangle)^2 \rangle$. We demonstrate this procedure in Fig. 1. In the left panel we show the selection of coordinates u and w for a set of events of a simulated source superimposed on a background of isotropically distributed events. In the right panel the correlation between u and $1/E$ for the same source events is plotted.

A given set of events will be identified as a correlated multiplet when $C(u, 1/E) > C_{\min}$ and, when the spread in the transverse direction w is small, $W = \max(|w_i - \langle w \rangle|) < W_{\max}$ (corresponding to a total width of $\sim 2W_{\max}$ in the perpendicular direction). The values for C_{\min} and W_{\max} were chosen as a compromise between maximizing the signal from a true source and minimizing the background arising from chance alignments. In order to determine the optimal values of these quantities, we performed numerical simulations of sets of events from randomly-located extragalactic sources. In these simulations, protons were propagated through a bisymmetric magnetic field with even symmetry (BSS-S) [17,18] (the local value of the field used was $2 \mu\text{G}$) and the effect of the turbulent magnetic field was included by simply adding a random deflection with root mean square amplitude $\delta_{\text{rms}} = 1.5^\circ$ ($20 \text{ EeV}/E$). Although

the latter is a rough approximation, and a dependence on the arrival directions should be expected, it is good enough for the purpose of fixing C_{\min} and W_{\max} . We considered one hundred extragalactic sources located at random isotropic directions and simulated sets of N events coming from each source ($N = 14, 13, 12$). The energy of the events followed an E^{-2} spectrum at the source and we added random gaussian uncertainties in the angular directions and energies to account for the experimental resolution. Magnetic lensing effects [18] were taken into account in the simulation through the magnification or demagnification of the energy spectrum of each source. As an example we show in Fig. 2(a) the resulting distribution of W for multiplets of 14 events. The significance of a given multiplet can be quantified by computing the fraction of isotropically distributed simulations, with the same total number of events as in the data and with the same energy spectrum, in which a multiplet with the same or larger multiplicity and passing the same cuts appears by chance. At high energies the UHECR angular distribution may not be isotropic, reflecting structure in the distribution of sources within the GZK horizon. However, our data set is dominated by lower energy events for which isotropy is an excellent approximation. We show in Fig. 3(a) the chance probability for multiplets of different multiplicity as a function of W_{\max} . We note that when reducing W_{\max} , some of the events of the multiplets will be missed and their multiplicity will be reduced. However, the significance of a smaller multiplet passing a tighter bound on W_{\max} can be larger than the significance of the complete multiplet with a looser W_{\max} cut. It turns out that the largest mean significance for the simulated sources (i.e. the average of the significances of the resulting multiplets after imposing the cuts) appears when a cut $W_{\max} \simeq 1.5^\circ$ is applied. The angular scale of 1.5° provides in fact a reasonable cut which accounts for the angular resolution and the mean value of the turbulent field deflections. We note that in the case of 14-plets, in 50% of the simulations all the events pass this cut and the multiplet will be reconstructed as a 14-plet, while in 38% of the cases one event is lost and in 11% of the cases two events are lost.

A similar analysis can be performed to fix the cut on the correlation coefficient C_{\min} . The distribution of $C(u, 1/E)$ for the simulated 14-plets is shown in Fig. 2(b) and the chance probability for multiplets of different multiplicity as a function of C_{\min} is illustrated in Fig. 3(b). The largest mean significance is attained now for values of C_{\min} in the range from 0.85 to 0.9, depending on the multiplicity considered. We will then fix in the following $W_{\max} = 1.5^\circ$ and $C_{\min} = 0.9$. Considering simulations with 14 events and for a cut $C_{\min} = 0.9$, we find that in 57% of the cases all events pass the cuts, in 12% of the simulations one event is lost and in 11% of them two events are lost. We note that the choice of the optimal cuts depends slightly on the galactic magnetic field model considered in the simulations and on the modeling of the turbulent field deflections.

We will hence search for correlated multiplets of events with energies above 20 EeV (so that the linear correlation of the deflection with $1/E$ is still expected to be valid for proton sources) which extend up to 20° in the sky (see Eq. (1)). We also require that the multiplet contains at least one event with energy above 45 EeV. We note that the energy of the most energetic event of a set of 10 events with $E > 20 \text{ EeV}$ from a source with spectral index $s = 2.5$ is larger than 45 EeV with a probability of 97% (for a spectral index $s = 3$ this probability is $\sim 90\%$ and for $s = 2$ it is $\sim 99.7\%$). Hence, requiring one high energy event above 45 EeV is not restrictive, and it simplifies the strategy to start the search for multiplets, which proceeds by looking at all possible sets of events contained in windows of 20° around those high energy events. Since we are ultimately interested in multiplicities larger than 8 (see Fig. 3 in which it is apparent that for the present statistics above 20 EeV correlated sets of smaller multiplicity are very likely to appear by

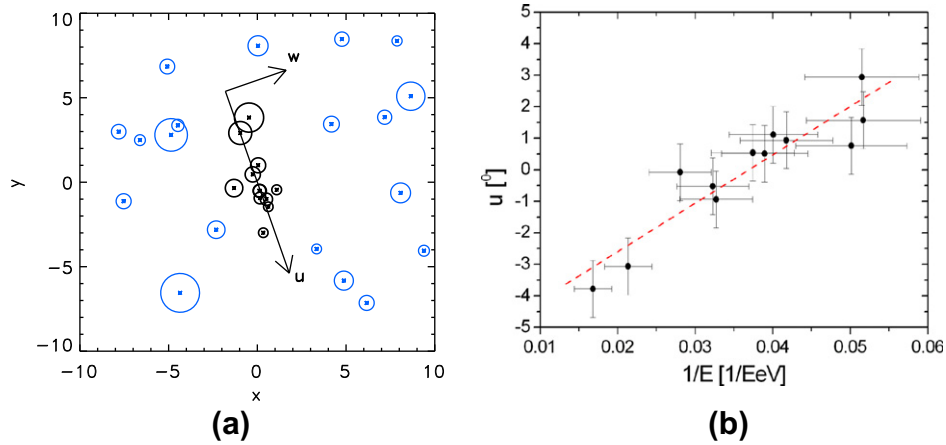


Fig. 1. Selection of coordinates u and w for a set of events of a simulated source (black thick asterisks) superimposed on a background of isotropically-distributed events (blue asterisks) (a). The size of the circles is proportional to the energy of the events. Correlation between u and $1/E$ for the same source events (b). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

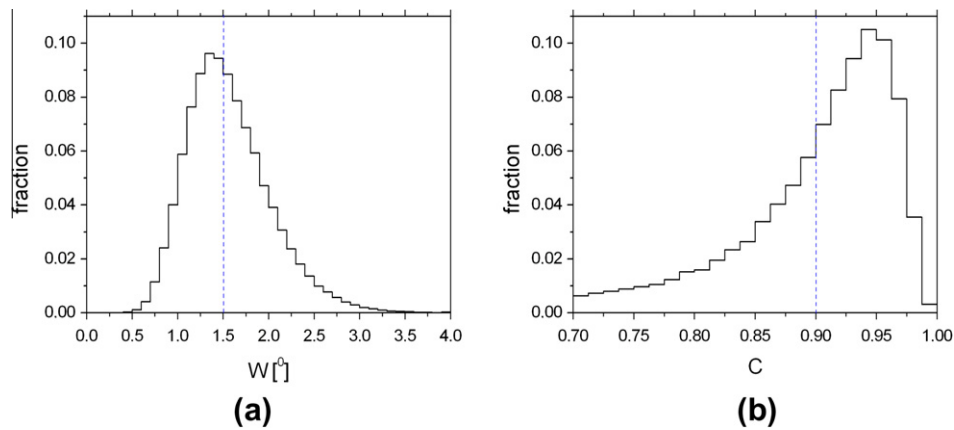


Fig. 2. Distribution of the maximum angular distance W , (a) and the correlation coefficient $C(u, 1/E)$ between the angular position u and $1/E$, (b) for 14-plets from the 100 simulated sources. The vertical dashed lines indicate the cuts on W and C optimized for multiplicity and significance (see text).

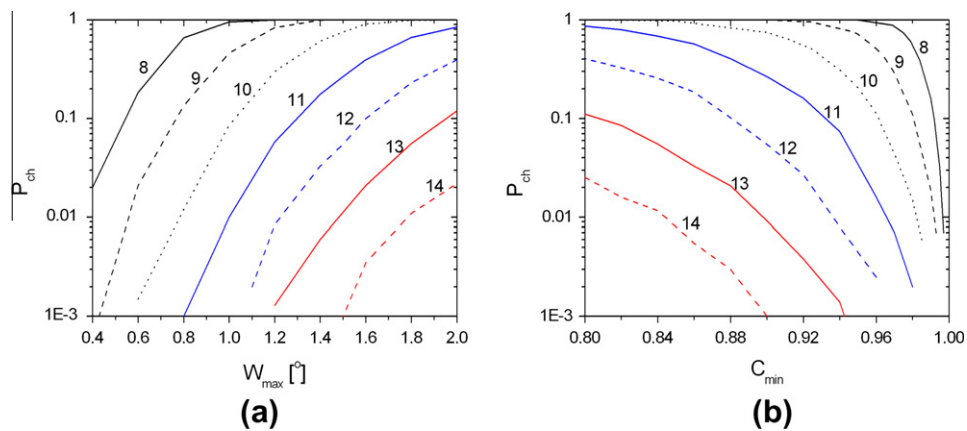


Fig. 3. Chance probability P_{ch} for finding in isotropic simulations one large multiplet of a given multiplicity as a function of W_{max} (adopting $C_{min} = 0.9$) (a) and as a function of C_{min} (adopting $W_{max} = 1.5^\circ$) (b) (see text).

chance in isotropic simulations), it is possible to make this search more efficient by first identifying the high energy end of the candidate multiplets. We hence consider for every event above 45 EeV the quadruplets that it forms with the events within a circle of 15° having energies above 25 EeV and with a correlation coefficient $C(u, 1/E) \geq 0.8$. The precise values of these cuts are not crucial as

long as they allow one to safely include the larger multiplets of interest. For each of these candidates we then extend the search including all the events above 20 EeV with an angular distance to the highest energy one smaller than 20° and at a distance smaller than $3W_{max}$ from the quadruplet axis. This allows us to find the correlated multiplets satisfying the cuts in W_{max} and C_{min} in a very

efficient way, as it is desirable to be able to perform a large number of simulations.

The multiplets search procedure has been designed for sources having a light composition. For sources having instead a heavy composition above 20 EeV, multiplets will be much more difficult to identify since they would typically spread through a larger region in the sky and also the linearity of their directional distribution will be lost.

Once a correlated multiplet is identified, from the linear fit to the relation

$$u = u_s + \frac{D}{E}, \quad (7)$$

the position of the source $(u_s, 0)$ (in the u - w coordinate system) and the deflection power D can be obtained.

A true correlated multiplet arising from magnetic field deflections of events from a single source can also include by chance some events from the background that appear aligned and correlated in energy with the events from the source. We have estimated the fraction of events that is expected to be due to chance background alignments by simulating an isotropic background distribution of events with the energy of the observed events above 20 EeV and superimposing multiplets of 12 events from simulated sources. We found that 29% of the reconstructed multiplets do not pick additional background events, while 46% just pick one additional background event and 25% pick two or more. Thus, the fraction of events added from the background is typically very small.

4. Results

We applied the method discussed in Section 3 to 1509 events above 20 EeV recorded at the Pierre Auger Observatory from 1st January 2004 to 31st December 2010. We implemented a search for all possible multiplets which extend up to 20° in the sky and contain at least one event with energy above 45 EeV, and that have a half-width smaller than $W_{\max} = 1.5^\circ$ and a correlation coefficient larger than $C_{\min} = 0.9$. The largest multiplet found in this data set is one 12-plet and there are also two independent decuplets. They are displayed in Fig. 4. Their deflection power, position of the potential source location and correlation coefficient are listed in Table 1. Decuplet II in Table 1 consists of three dependent sets of ten events (a–c) that are formed by the combination of a set of twelve events. These three decuplets are not independent of each other since they have most events in common. The uncertainties in the reconstruction of the position of the potential sources have been

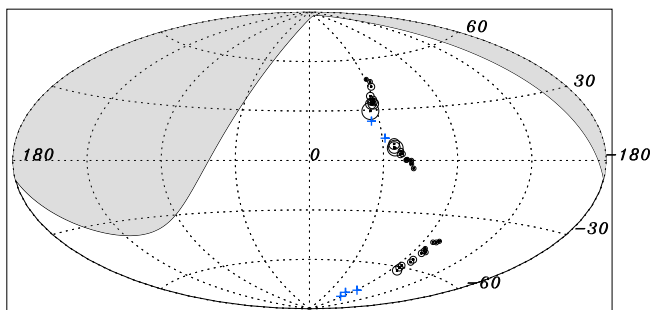


Fig. 4. Observed multiplets with 10 or more events in galactic coordinates. The size of the circles is proportional to the energy of the event. Plus signs indicate the positions of the potential sources for each multiplet. One decuplet is in fact three dependent decuplets that are formed by the combination of twelve events and the three corresponding reconstructions of the potential sources are shown. The solid line represents the border of the field of view of the Southern Observatory for zenith angles smaller than 60° and the grey shaded area is the region outside the field of view.

Table 1

Deflection power, D ; reconstructed position of the potential source in galactic coordinates, (l, b) ; uncertainty in the reconstructed position of the potential source along the direction of deflection, Δu_s , and orthogonal to it, Δw_s ; and linear correlation coefficient, C , for the largest correlated multiplets found. The data correspond to events with energy above 20 EeV from 1st January 2004 to 31st December 2010.

Multiplet	D [$^\circ$ 100 EeV]	(l, b) [$^\circ$]	Δu_s [$^\circ$]	Δw_s [$^\circ$]	C
12-plet	4.3 ± 0.7	$(-46.7, 13.2)$	2.4	0.9	0.903
10-plet I	5.1 ± 0.9	$(-39.9, 23.4)$	2.7	0.9	0.901
10-plet IIa	8.2 ± 1.3	$(-85.6, -80.4)$	4.3	1.9	0.920
10-plet IIb	7.6 ± 1.2	$(-79.6, -77.9)$	4.0	1.6	0.919
10-plet IIc	6.5 ± 1.1	$(-91.5, -75.7)$	3.9	1.6	0.908

calculated propagating the uncertainties in energy and arrival direction to an uncertainty in the rotation angle (Eq. (5)) and in the linear fit performed to the deflection vs. $1/E$ (Eq. (7)).

The probability that the observed number (or more) of correlated multiplets appears by chance can be computed by applying a similar analysis to simulations of randomly distributed events weighted by the geometric exposure of the experiment [19] and with the energies of the observed events. The fraction of simulations with at least one multiplet with 12 or more events is 6%, and the fraction having at least three multiplets with 10 or more events is 20%. Therefore, there is no statistically significant evidence for the presence of multiplets from actual sources in the data. We note that with the present statistics, an individual multiplet passing the required selection cuts should have at least 14 correlated events in order that its chance probability be 10^{-3} .

Measurements by the Pierre Auger Observatory [20] of the depth of shower maximum and its fluctuations indicate a trend towards heavy nuclei with increasing energy. This interpretation of the shower depths is not certain, however. It relies on shower simulations that use hadronic interaction models to extrapolate particle interaction properties two orders of magnitude in centre-of-mass energy beyond the regime where they have been tested experimentally. Magnetic alignment and correlation with the inverse of the energy as searched here are not expected for heavy nuclei. Assuming there are sources which accelerate an appreciable proton component, the non-observation of significant multiplets could be the consequence of having a large density of sources. Given the present statistics, the maximum source density which would allow to observe a multiplet containing 12 events above 20 EeV from the nearest source to the Earth can be roughly estimated by considering that this source should produce a fraction $12/1509 \approx 1/125$ of the total flux observed in the field of view of the Auger Observatory in this energy range. Assuming that the sources have equal intrinsic luminosity and are uniformly distributed and that cosmic rays in this energy range can arrive from distances up to about 1 Gpc, the above mentioned constraints imply that the nearest source should be within ~ 10 Mpc. Thus, the mean local density of sources should not be larger than a few 10^{-4} Mpc^{-3} . The fact that we have not seen a larger multiplet is an indication that the density of sources is probably larger. This very rough estimation is subject to large fluctuations but it is indicative that densities within the current lower limits may lead to the kind of signals searched for here. We note, however, that this bound would be relaxed if contributions of heavy cosmic ray primaries become significant, or if very strong turbulent magnetic fields were present.

5. Conclusions

A search for ultra-high energy cosmic ray multiplets was performed in the data gathered between 1st January 2004 and 31st December 2010 by the Pierre Auger Observatory with energy

above 20 EeV. The largest multiplet found was one 12-plet. The probability that it appears by chance from an isotropic distribution of events is 6%. Thus, there is no significant evidence for the existence of correlated multiplets in the present data set. Future data will be analyzed to check if some of the observed multiplets grow significantly or if some new large multiplets appear.

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