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Dipolar anisotropy of cosmic rays above 8 EeV

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We report an anisotropy in the flux of cosmic rays with energies above 8 EeV observed using data recorded at the Pierre Auger Observatory with more than 12 years of operation. We consider events with zenith angles up to 80°, so that 85% of the sky is observed, and for energies in excess of 4 EeV, for which the Observatory is fully efficient. An analysis of the first harmonic in right ascension is performed in the two energy bins 4 EeV $< E <$ 8 EeV and $E \geq$ 8 EeV. The amplitudes obtained are $0.5^{+0.6}_{-0.2}$% and $4.7^{+0.9}_{-0.7}$%, respectively. Events in the lower energy bin follow an arrival distribution consistent with isotropy. In the higher bin a significant anisotropy is found, with the measured amplitude having a p-value of 2.6×10^{-8} under the isotropic null hypothesis. After penalization for the fact that two different energy bins were considered, this anisotropy has a significance of 5.4σ. Combining the first harmonic analysis in right ascension with another one in azimuth, which is sensitive to the dipolar component along the Earth's rotation axis, the signal above 8 EeV is well-described by a dipole with a total amplitude of $6.5^{+1.3}_{-0.9}$%. Its direction points towards Galactic coordinates $(\ell, b) = (233°, -13°)$, which is $\sim$125° from the Galactic Center, suggesting that the anisotropy has an extragalactic origin.

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1. Introduction

The origin and nature of the ultra-high energy cosmic rays is still one of the important open problems in physics and astrophysics. Besides the measurement of the cosmic ray spectrum, whose features may indicate the transitions between different propagation regimes or source populations, and the determination of the identity of the particles to know which kind of nuclei contribute to the fluxes, also the analysis of the arrival direction distribution provides a crucial handle for these studies. In particular, the identification of the cosmic ray sources should help to understand how these particles, which have the highest energies observed in nature, are produced and how they do propagate up to us.

The Pierre Auger Observatory [1] is located in Malargüe, Argentina, at a latitude of $-35.2°$. It is operated as a hybrid system consisting of an array of 1600 water-Cherenkov detectors spanning an area of about 3000 km^2 on a triangular grid with 1.5 km spacing. A smaller denser sub-array covers about 1% of the area, but it is not used in this analysis. It also has four buildings with 27 telescopes overlooking the array to observe the fluorescence light emitted by the nitrogen molecules in the air that were excited by a shower of particles that crossed the atmosphere. The surface detectors sample the lateral profile of the showers at ground level while the fluorescence telescopes measure its longitudinal profile in the atmosphere.

The Auger Observatory has reported studies of the large-scale distribution of arrival directions in right ascension [2, 3] and in both declination and right ascension [4, 5], from the analysis of events with zenith angles smaller than 60°. These analyses provided hints of a change in the phase of the first harmonic in right ascension taking place at few EeV energies. Results including also events with zenith angles between 60° and 80°, and hence increasing the sky coverage from 71% to 85%, showed indications at the 4σ level of a non-vanishing amplitude in the first harmonic in right ascension for events with energies above 8 EeV [6]. In a recent publication [7], an observation of a large-scale anisotropy in the right ascension distribution of cosmic rays above 8 EeV with a significance of 5.4σ has been reported. Here we present details of this measurement, which includes ∼2.6 additional years of data with respect to [6] and also consider a less restrictive trigger selection of events, leading to an increase in exposure of 60%.

2. Data set

In this work we consider the data recorded at the Pierre Auger Observatory from 1st January 2004 to 31st August 2016, excluding periods of instability in the data acquisition process. The collected exposure is about $76,800\,\mathrm{km}^2\,\mathrm{sr\,yr}$. The events are reconstructed by fitting the signals and arrival times associated with the secondary particles of the air showers reaching the water-Cherenkov detectors of the surface array. The events with zenith angles $\theta \leq 60°$, referred to as vertical events, have a different reconstruction and separate calibration from those having $60° < \theta < 80°$, referred to as inclined events. We focus on events with energies in excess of 4 EeV, for which the array is fully efficient for zenith angles $\theta < 80°$. This allows us to get rid of all systematic modulations related to trigger inefficiencies and permits the inclusion of the inclined events which are reliably reconstructed above this energy.

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The estimation of the energy in the vertical sample is based on the shower size at 1000 m from the shower core. The steepness of the energy spectrum of cosmic rays implies that even small variations in this energy estimator as a function of the angular coordinates or of time, can induce significant systematic modulations in the counting rate of events above a given signal. The variations of the atmospheric conditions are one of the sources of these distortions. In particular, the air density affects the lateral profile of the showers while the pressure determines the depth along the longitudinal profile at which the shower is observed at ground. The bias in the modulation of the first harmonic arising from the weather conditions could be up to $\pm1.7\%$ in solar frequency, although it is smaller in sidereal frequency because it is averaged after many years of observation. These effects are taken into account by correcting the energy estimator [8]. Another effect that influences the shower size at 1000 m is the deflection of the shower particles in the geomagnetic field. This breaks the circular symmetry of the shower around its axis and leads to a spurious azimuthal modulation of about $\sim 0.7\%$, that is corrected following [9].

For inclined showers the muonic component is dominant as the electromagnetic one is attenuated because the amount of atmosphere traversed by a shower is higher for larger zenith angles. This leads to a negligible dependence on the atmospheric effects while the effects induced by the geomagnetic field are already taken into account at the reconstruction stage of these events [10].

We consider here the energy bins 4 EeV$< E <$8 EeV and $E \geq 8$ EeV, which are included in preceding anisotropy searches [2–6]. The median energies in these bins are 5.0 EeV and 11.5 EeV.

Previous large-scale anisotropy studies [2,4,6], some of which extended also to lower energies, considered only events passing a strict trigger condition in which the station with the highest signal is surrounded by six detectors in operation at the time of detection. This quality cut is mandatory when working with lower energy events to guarantee a reliable reconstruction of its energy and arrival direction. Nevertheless, in the present study we consider showers with energies above 4 EeV. A fraction of 99.2% of these showers triggered four or more detectors (this fraction is 99.9% above 8 EeV), allowing also the use of events with only five of its closest neighbour detectors working at the time of the event.

To assess the reliability of showers passing the relaxed cuts we re-analysed a set of events fulfilling the tight trigger condition after removing one of its six neighbouring stations. The reconstructed directions differ on average by 0.4° for 4 EeV $< E <$ 8 EeV and 0.3° for $E \geq 8$ EeV, while for the energy reconstruction the differences are on average 0.3% and 0.2%, respectively. The dispersion in the energy assignments obtained with the two reconstructions is about 8% in the lower energy bin and $\sim$5% above 8 EeV. This is well below the statistical uncertainties in the energy determination, which is better than 16% above 4 EeV and 12% above 10 EeV. The systematic uncertainty on the absolute energy scale is 14% [11].

Relaxing the trigger condition increases the total number of events by 18.7%, in agreement with what would be expected from the associated increase in exposure of 18.5%.

3. Analysis method

A standard approach to study the distribution at large angular scales of the arrival directions of cosmic rays is to perform a classical harmonic analysis [12] generalized by introducing weights. The weights take into account possible small modulations in the coverage of the array arising from

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the variations in its operating size as a function of time and for the effects of a net tilt of the array surface [6]. We performed two harmonic analyses over the distributions in right ascension, α, and azimuth, ϕ, which are sensitive to the component of a dipole orthogonal and parallel to the Earth's rotation axis, respectively. An advantage of this combined harmonic analysis is allowing us to join the vertical and inclined samples considered here without introducing a spurious large-scale modulation which could arise from differences in the energy calibration of the two samples.

The two Fourier amplitudes of the harmonic modulation are

$$a^x = \frac{2}{\mathscr{N}} \sum_{i=1}^{N} w_i \cos(x_i) \quad , \quad b^x = \frac{2}{\mathscr{N}} \sum_{i=1}^{N} w_i \sin(x_i), \tag{3.1}$$

with $x = \alpha$ or ϕ. The sums run over the number N of events in the considered energy ranges and α_i (ϕ_i) is the right ascension (azimuth) of the i-th event. The weights are denoted as w_i (see [6] for details). The normalization factor is $\mathscr{N} = \sum_{i=1}^{N} w_i$.

3.1 Harmonic analysis in right ascension

From the coefficients in eq. (3.1) we determine, for $x = \alpha$, the corresponding amplitude and phase of the first harmonic in right ascension as

$$r^\alpha = \sqrt{(a^\alpha)^2 + (b^\alpha)^2} \ , \ \varphi^\alpha = \mathrm{atan}\frac{b^\alpha}{a^\alpha}. \tag{3.2}$$

In Table 1 we list the resulting parameters in the energy intervals considered. The statistical uncertainties for the Rayleigh coefficients are given by $\sqrt{2/\mathscr{N}}$, while the 68% confidence interval of the marginalized probability distribution of the amplitude and phase is quoted. The probability that an amplitude larger than the one observed could arise from fluctuations in an isotropic distribution (p-value) is given by $P(\geq r^\alpha) = \exp\left(-\mathscr{N}(r^\alpha)^2/4\right)$ and is presented in the last column. In the first bin, with $4\,\mathrm{EeV} < E < 8\,\mathrm{EeV}$, the result is compatible with isotropy, and the upper limit on the amplitude is 1.2% at the 95% confidence-level. On the other hand, for events with $E \geq 8\,\mathrm{EeV}$ the amplitude observed is $4.7^{+0.8}_{-0.7}\%$, which has a p-value of 2.6×10^{-8}, equivalent to 5.6σ. The probability is a factor of $\sim$20 smaller than the one corresponding to the 5σ discovery limit and even considering a penalization factor of two for the fact that two independent energy bins were scrutinised the resulting significance is 5.4σ. The phase of the modulation is at $100^\circ \pm 10^\circ$.

E [EeV]	N	a^α	b^α	r^α	$\varphi^\alpha\,[^\circ]$	$P(\geq r^\alpha)$
4 - 8	81 701	0.001 ± 0.005	0.005 ± 0.005	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
≥ 8	32 187	-0.008 ± 0.008	0.046 ± 0.008	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

Table 1: Results of the first harmonic analysis in right ascension.

In Figure 1 we show the distribution of the normalized rate of events with $E \geq 8\,\mathrm{EeV}$ as a function of the right ascension. The function corresponding to the first harmonic is also indicated with a solid line, showing that the distribution is compatible with a dipolar modulation.

It is worth emphasizing that the harmonic analyses performed in the past with reduced data sets [2, 6] led to amplitudes and phases compatible with the ones obtained here: the present larger data set leads to an increased significance.

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Figure 2 shows the flux of cosmic rays with $E \geq 8$ EeV smoothed in angular windows of 45° to better visualize the dipolar pattern.

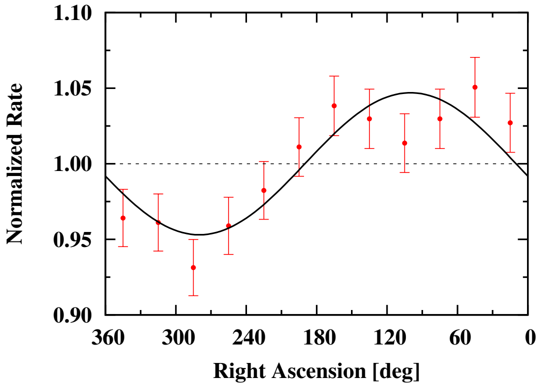

Figure 1: Observed number of events, normalized to the mean, as a function of the right ascension, for $E \geq 8$ EeV. The black line is a sinusoidal function showing the first harmonic from Table 1.

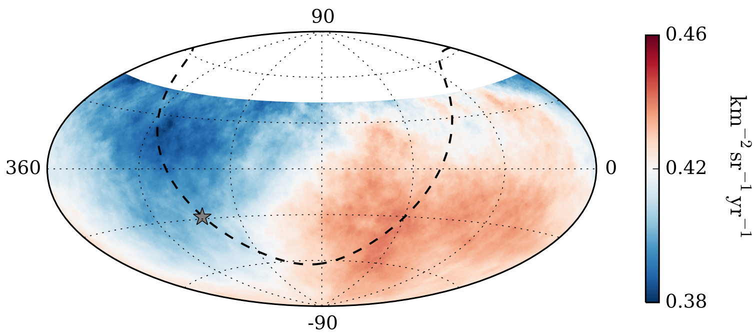

Figure 2: Map of the flux of cosmic rays above 8 EeV in equatorial coordinates and smoothed with a 45° top-hat window. The star represents the direction of the Galactic center and the dashed line shows the Galactic plane.

3.2 Reconstruction of the dipole

The combination of first harmonic analyses in right ascension and azimuth distributions allows the reconstruction of the three components of a dipole. The right ascension distribution, presented in the previous section, is sensitive to a dipolar component along the equatorial plane. In turn, the distribution in the azimuth angle, particularly the b^{ϕ} coefficient, reflects the presence of a North-South dipole. Table 2 summarizes the results of the harmonic analysis in azimuth for the energy bins considered. The departure from isotropy has low statistical significance, with the measured coefficient having a probability of 0.9% (8%) of arising from an isotropic distribution for 4 EeV $< E <$ 8 EeV ($E >$ 8 EeV).

The amplitude of the dipole component in the equatorial plane $d_{\perp}$, that along the rotation axis of the Earth d_z and the right ascension and declination of the dipole's direction (α_d, δ_d), assuming that the dipolar pattern dominates and hence neglecting higher multipoles, can be estimated as

E [EeV]	N	b^{ϕ}	$P(\geq \lvert b^{\phi}\rvert)$
4 - 8	81 701	-0.013 ± 0.005	0.009
≥ 8	32 187	-0.014 ± 0.008	0.08

Table 2: Harmonic analysis in azimuth.

$$\begin{aligned} d_{\perp} &\simeq \frac{r^{\alpha}}{\langle \cos\delta \rangle}, \\ d_z &\simeq \frac{b^{\phi}}{\cos \ell_{obs} \langle \sin\theta \rangle}, \\ \alpha_d &= \varphi^{\alpha}, \\ \delta_d &= \arctan\left(\frac{d_z}{d_{\perp}}\right), \end{aligned} \tag{3.3}$$

where $\langle \cos\delta \rangle = 0.78$ is the average cosine of the declinations of the events, $\langle \sin\theta \rangle = 0.65$ the average sine of the zenith of the events and $\ell_{obs} \simeq -35.2°$ the average latitude of the Observatory.

The resulting parameters are listed in Table 3, from which we see that for energies above 8 EeV the total dipole has an amplitude $d = 6.5^{+1.3}_{-0.9}\%$ and points in the direction $(\alpha_d, \delta_d) = (100°, -24°)$.

E [EeV]	d_z [%]	$d_{\perp}$ [%]	d [%]	$\delta_{\rm d}$[°]	$\alpha_{\rm d}$[°]
4 - 8	-2.4 ± 0.9	$0.6^{+0.7}_{-0.3}$	$2.5^{+1.0}_{-0.7}$	-75^{+17}_{-8}	80 ± 60
≥ 8	-2.6 ± 1.5	$6.0^{+1.1}_{-1.0}$	$6.5^{+1.3}_{-0.9}$	-24^{+12}_{-13}	100 ± 10

Table 3: Dipole components and direction in Equatorial coordinates.

4. Discussion and conclusions

We have presented the results of an analysis of the large angular scale distribution of the arrival directions of cosmic rays detected by the Pierre Auger Observatory with an increased data set. Two energy bins above full efficiency were analysed: from 4 to 8 EeV and above 8 EeV. In the lower energy bin no significant departure from isotropy is observed. For energies above 8 EeV a signal in the first harmonic in right ascension at the 5.4σ level is observed, confirming previous hints reported in [3] with vertical events alone up to end of 2012 and in [6] including also the inclined sample up to end of 2013.

The observed distribution of the arrival directions of cosmic rays above few EeV is indicative of an extragalactic origin. In particular, models proposing Galactic sources up to the highest energies [14, 15] imply an amplitude of the first harmonic in right ascension that goes beyond existing bounds [4] if the cosmic rays are light nuclei, or require a predominantly heavy composition at EeV energies, which is in disagreement with observations [16]. Moreover, the maximum of the flux would be expected to lie close to the direction of the Galactic center, while the direction of the dipole determined above 8 EeV, which in Galactic coordinates is $(\ell, b) = (233°, -13°)$, lies $\sim$125° off the center of the Galaxy.

On the other hand, extragalactic source scenarios for ultra-high energy cosmic rays have been explored. The expected anisotropies have been analysed for the cases of sources that have an inhomogeneous large-scale distribution [17–19] or a few dominant nearby sources from which the nuclei diffuse through intergalactic magnetic fields [18–21]. The predicted amplitudes of these anisotropies depend on the charge of the nuclei and on the distribution of the sources, having typical values of 5-20% at 10 EeV.

If the sources were to follow the distribution of galaxies, which has a significant dipolar component, it is expected that a dipole in the cosmic ray flux would be induced. As an example, considering the 2MRS catalogue [13] the flux-weighted dipole obtained from local infrared galaxies points in the direction $(\ell, b) = (251°, 38°)$, which is $\sim$55° away from the dipole associated with cosmic rays above 8 EeV. Figure 3 shows the map of the flux of cosmic rays above 8 EeV in galactic coordinates, indicating also the direction of the 2MRS dipole. One should also take into account that magnetic fields are ubiquitous in the Galactic medium and affect the propagation of cosmic rays through the Galaxy. We hence indicate with arrows how a dipolar distribution of cosmic rays pointing in the direction of the 2MRS dipole outside the galaxy would be modified when observed at the Earth (tip of the arrows). We adopt a particular model of the Galactic magnetic field, given in [22], and consider $E/Z = 5$ EeV or 2 EeV, which are typical values given the inferred average for the cosmic ray charge number $Z \sim 1.7$ to 5 at 10 EeV. It is interesting that after reasonable assumptions about Galactic magnetic fields and charge composition the deflected directions are in better agreement with the observed one, which is indicated with a star.

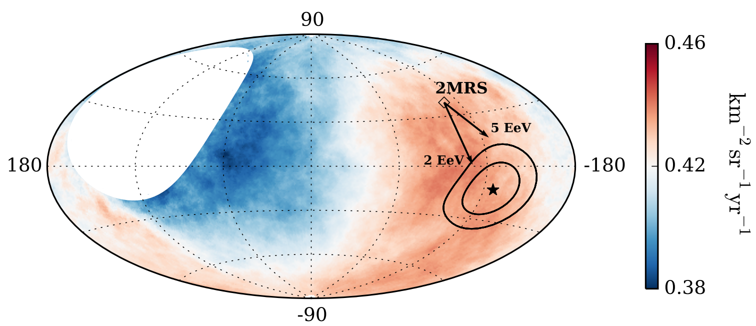

Figure 3: Map of the flux in Galactic coordinates for $E \geq 8$ EeV, smoothed on windows of 45°. The reconstructed dipole direction is indicated with a star, the contours represents the 68% and 95% CL regions. Also indicated is the direction of the dipole in the distribution of galaxies from 2MRS and how a dipole along this direction would be modified by the action of the Galactic magnetic field.

Summarizing, the first measurement with a significance higher than 5σ of an anisotropy in the arrival directions of ultra-high energy cosmic rays has been reported. It corresponds to a large-scale dipolar modulation appearing at energies above 8 EeV, which suggests an extragalactic origin for these particles. Since the magnetic deflections decrease with increasing energy, the location of the dominant sources that contribute to this anisotropy could be eventually identified with further observations at the highest energies.

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