

COSMIC RAYS

Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8×10^{18} eV

The Pierre Auger Collaboration*†

Cosmic rays are atomic nuclei arriving from outer space that reach the highest energies observed in nature. Clues to their origin come from studying the distribution of their arrival directions. Using 3×10^4 cosmic rays with energies above 8×10^{18} electron volts, recorded with the Pierre Auger Observatory from a total exposure of $76,800 \text{ km}^2 \text{ sr year}$, we determined the existence of anisotropy in arrival directions. The anisotropy, detected at more than a 5.2σ level of significance, can be described by a dipole with an amplitude of $6.5_{-0.9}^{+1.3}$ percent toward right ascension $\alpha_d = 100 \pm 10$ degrees and declination $\delta_d = -24_{-13}^{+12}$ degrees. That direction indicates an extragalactic origin for these ultrahigh-energy particles.

Particles with energies ranging from below 10^9 eV up to beyond 10^{20} eV, known as cosmic rays, constantly hit Earth's atmosphere. The flux of these particles steeply decreases as their energy increases; for energies above 10 EeV ($1 \text{ EeV} \equiv 10^{18} \text{ eV}$), the flux is about one particle per km^2 per year. The existence of cosmic rays with such ultrahigh energies has been known for more than 50 years (1, 2), but the sites and mechanisms of their production remain a mystery. Information about their origin can be obtained from the study of the energy spectrum and the mass composition of cosmic rays. However, the most direct evidence of the location of the progenitors is expected to come from studies of the distribution of their arrival directions. Indications of possible hot spots in arrival directions for cosmic rays with energies above 50 EeV have been reported by the Pierre Auger and Telescope Array Collaborations (3, 4), but the statistical significance of these results is low. We report the observation, significant at a level of more than 5.2σ , of a large-scale anisotropy in arrival directions of cosmic rays above 8 EeV .

Above 10^{14} eV, cosmic rays entering the atmosphere create cascades of particles (called extensive air-showers) that are sufficiently large to reach the ground. At 10 EeV , an extensive air-shower (hereafter shower) contains $\sim 10^{10}$ particles spread over an area of $\sim 20 \text{ km}^2$ in a thin disc moving close to the speed of light. The showers contain an electromagnetic component (electrons, positrons, and photons) and a muonic component that can be sampled using arrays of particle detectors. Charged particles in the shower also excite nitrogen molecules in the air, producing fluorescence light that can be observed with telescopes during clear nights.

The Pierre Auger Observatory, located near the city of Malargüe, Argentina, at latitude 35.2°S , is designed to detect showers produced by primary

cosmic rays above 0.1 EeV . It is a hybrid system, a combination of an array of particle detectors and a set of telescopes used to detect the fluorescence light. Our analysis is based on data gathered from 1600 water-Cherenkov detectors deployed over an area of 3000 km^2 on a hexagonal grid with 1500-m spacing. Each detector contains 12 metric tons of ultrapure water in a cylindrical container, 1.2 m deep and 10 m^2 in area, viewed by three 9-inch photomultipliers. A full description of the observatory, together with details of the methods used to reconstruct the arrival directions and energies of events, has been published (5).

It is difficult to locate the sources of cosmic rays, as they are charged particles and thus interact with the magnetic fields in our Galaxy and the intergalactic medium that lies between the sources and Earth. They undergo angular deflections with amplitude proportional to their atomic number Z , to the integral along the trajectory of the magnetic field (orthogonal to the direction of propagation), and to the inverse of their energy E . At $E \approx 10 \text{ EeV}$, the best estimates for the mass of the particles (6) lead to a mean value for Z between 1.7 and 5. The exact number derived is dependent on extrapolations of hadronic physics, which are poorly understood because they lie well beyond the observations made at the Large Hadron Collider. Magnetic fields are not well constrained by data, but if we adopt recent models of the galactic magnetic field (7, 8), typical values of the deflections of particles crossing the galaxy are a few tens of degrees for $E/Z = 10 \text{ EeV}$, depending on the direction considered (9). Extragalactic magnetic fields may also be relevant for cosmic rays propagating through intergalactic space (10). However, even if particles from individual sources are strongly deflected, it remains possible that anisotropies in the distribution of their arrival directions will be detectable on large angular scales, provided the sources have a nonuniform spatial distribution or, in the case of a single dominant source, if the cosmic-ray propagation is diffusive (11–14).

Searches for large-scale anisotropies are conventionally made by looking for nonuniformities in the distribution of events in right ascension (15, 16) because, for arrays of detectors that operate with close to 100% efficiency, the total exposure as a function of this angle is almost constant. The nonuniformity of the detected cosmic-ray flux in declination (fig. S1) imprints a characteristic nonuniformity in the distribution of azimuth angles in the local coordinate system of the array. From this distribution it becomes possible to obtain information on the three components of a dipolar model.

Event observations, selection, and calibration

We analyzed data recorded at the Pierre Auger Observatory between 1 January 2004 and 31 August 2016, from a total exposure of about $76,800 \text{ km}^2 \text{ sr year}$. The 1.2-m depth of the water-Cherenkov detectors enabled us to record events at a useful rate out to large values of the zenith angle, θ . We selected events with $\theta < 80^\circ$ enabling the declination range $-90^\circ < \delta < 45^\circ$ to be explored, thus covering 85% of the sky. We adopted 4 EeV as the threshold for selection; above that energy, showers falling anywhere on the array are detected with 100% efficiency (17). The arrival directions of cosmic rays were determined from the relative arrival times of the shower front at each of the triggered detectors; the angular resolution was better than 1° at the energies considered here (5).

Two methods of reconstruction have been used for showers with zenith angles above and below 60° (17, 18). These have to account for the effects of the geomagnetic field (17, 19) and, in the case of showers with $\theta < 60^\circ$, also for atmospheric effects (20) because systematic modulations to the rates could otherwise be induced (see supplementary materials). The energy estimators for both data sets were calibrated using events detected simultaneously by the water-Cherenkov detectors and the fluorescence telescopes, with a quasi-calorimetric determination of the energy coming from the fluorescence measurements. The statistical uncertainty in the energy determination is $<16\%$ above 4 EeV and $<12\%$ above 10 EeV , whereas the systematic uncertainty on the absolute energy scale, common to both data sets, is 14% (21). Evidence that the analyses of the events with $\theta < 60^\circ$ and of those with $60^\circ < \theta < 80^\circ$ are consistent with each other comes from the energy spectra determined for the two angular bands. The spectra agree within the statistical uncertainties over the energy range of interest (22).

We consider events in two energy ranges, $4 \text{ EeV} < E < 8 \text{ EeV}$ and $E \geq 8 \text{ EeV}$, as adopted in previous analyses [e.g., (23–25)]. The bin limits follow those chosen previously in (26, 27). The median energies for these bins are 5.0 EeV and 11.5 EeV , respectively. In earlier work (23–25), the event selection required that the station with the highest signal be surrounded by six operational detectors—a demanding condition. The number of triggered stations is greater than four for 99.2% of all events above 4 EeV and for 99.9% of events above 8 EeV ,

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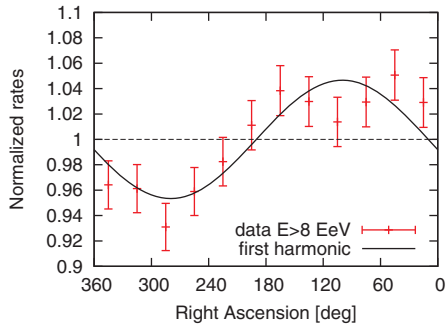


Fig. 1. Normalized rate of events as a function of right ascension. Normalized rate for 32,187 events with $E \geq 8$ EeV, as a function of right ascension (integrated in declination). Error bars are 1σ uncertainties. The solid line shows the first-harmonic modulation from Table 1, which displays good agreement with the data ($\chi^2/n = 10.5/10$); the dashed line shows a constant function.

making it possible to use events with only five active detectors around the one with the largest signal. With this more relaxed condition, the effective exposure is increased by 18.5%, and the total number of events increases correspondingly from 95,917 to 113,888. The reconstruction accuracy for the additional events is sufficient for our analysis (see supplementary materials and fig. S4).

Rayleigh analysis in right ascension

A standard approach for studying the large-scale anisotropies in the arrival directions of cosmic rays is to perform a harmonic analysis in right ascension, α . The first-harmonic Fourier components are given by

$$\begin{aligned} a_\alpha &= \frac{2}{N} \sum_{i=1}^N w_i \cos \alpha_i \\ b_\alpha &= \frac{2}{N} \sum_{i=1}^N w_i \sin \alpha_i \end{aligned} \quad (1)$$

The sums run over all N detected events, each with right ascension α_i with the normalization factor $\mathcal{N} = \sum_{i=1}^N w_i$. The weights, w_i , are introduced to account for small nonuniformities in the exposure of the array in right ascension and for the effects of a tilt of the array toward the southeast (see supplementary materials). The average tilt between the vertical and the normal to the plane on which the detectors are deployed is 0.2° , so that the effective area of the array is slightly larger for showers arriving from the downhill direction. This introduces a harmonic dependence in azimuth of amplitude $0.3\% \times \tan \theta$ to the exposure. The effective aperture of the array is determined every minute. Because the exposure has been accumulated over more than 12 years, the total aperture is modulated by less than $\sim 0.6\%$ as the zenith of the observatory moves in right ascension. Events are weighted by the inverse

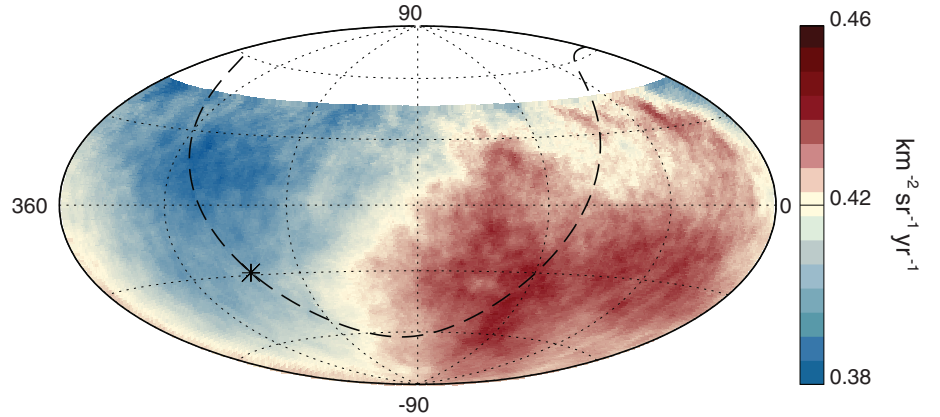


Fig. 2. Map showing the fluxes of particles in equatorial coordinates. Sky map in equatorial coordinates, using a Hammer projection, showing the cosmic-ray flux above 8 EeV smoothed with a 45° top-hat function. The galactic center is marked with an asterisk; the galactic plane is shown by a dashed line.

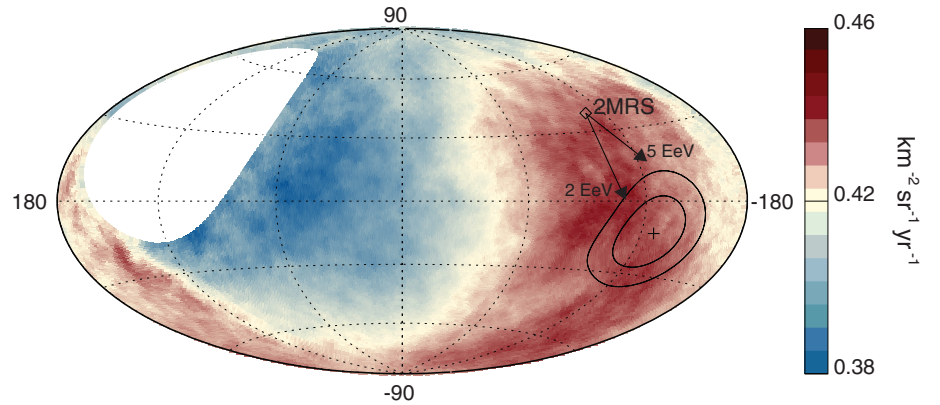


Fig. 3. Map showing the fluxes of particles in galactic coordinates. Sky map in galactic coordinates showing the cosmic-ray flux for $E \geq 8$ EeV smoothed with a 45° top-hat function. The galactic center is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected for a particular model of the galactic magnetic field (8) on particles with $E/Z = 5$ or 2 EeV.

of the relative exposure to correct these effects (fig. S2).

The amplitude r_α and phase φ_α of the first harmonic of the modulation are obtained from

$$\begin{aligned} r_\alpha &= \sqrt{a_\alpha^2 + b_\alpha^2} \\ \tan \varphi_\alpha &= \frac{b_\alpha}{a_\alpha} \end{aligned} \quad (2)$$

Table 1 shows the harmonic amplitudes and phases for both energy ranges. The statistical uncertainties in the Fourier amplitudes are $\sqrt{2/\mathcal{N}}$; the uncertainties in the amplitude and phase correspond to the 68% confidence level of the marginalized probability distribution functions. The rightmost column shows the probabilities that amplitudes

larger than those observed could arise by chance from fluctuations in an isotropic distribution. These probabilities are calculated as $P(r_\alpha) = \exp(-\mathcal{N}r_\alpha^2/4)$ (28). For the lower-energy bin (4 EeV $< E < 8$ EeV), the result is consistent with isotropy, with a bound on the harmonic amplitude of $< 1.2\%$ at the 95% confidence level. For the events with $E \geq 8$ EeV, the amplitude of the first harmonic is $4.7_{-0.7}^{+0.8}\%$, which has a probability of arising by chance of 2.6×10^{-8} , equivalent to a two-sided Gaussian significance of 5.6σ . The evolution of the significance of this signal with time is shown in fig. S3; the dipole became more significant as the exposure increased. Allowing for a penalization factor of 2 to account for the fact that two energy bins were explored, the significance is reduced to 5.4σ . Further penalization for the four additional lower-energy bins examined in (23) has a similarly mild impact on the significance, which falls to 5.2σ . The maximum of the

Table 1. First harmonic in right ascension. Data are from the Rayleigh analysis of the first harmonic in right ascension for the two energy bins.

Energy (EeV)	Number of events	Fourier coefficient a_α	Fourier coefficient b_α	Amplitude r_α	Phase φ_α (°)	Probability $P(\geq r_\alpha)$
4 to 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 2. Three-dimensional dipole reconstruction. Directions of dipole components are shown in equatorial coordinates.

Energy (EeV)	Dipole component d_z	Dipole component d_\perp	Dipole amplitude d	Dipole declination δ_d (°)	Dipole right ascension α_d (°)
4 to 8	-0.024 ± 0.009	$0.006^{+0.007}_{-0.003}$	$0.025^{+0.010}_{-0.007}$	-75^{+17}_{-8}	80 ± 60
≥ 8	-0.026 ± 0.015	$0.060^{+0.011}_{-0.010}$	$0.065^{+0.013}_{-0.009}$	-24^{+12}_{-13}	100 ± 10

modulation is at right ascension of $100^\circ \pm 10^\circ$. The maximum of the modulation for the $4 \text{ EeV} < E < 8 \text{ EeV}$ bin, at $80^\circ \pm 60^\circ$, is compatible with the one determined in the higher-energy bin, although it has high uncertainty and the amplitude is not statistically significant. Table S1 shows that results obtained under the stricter trigger condition and for the additional events gained after relaxing the trigger are entirely consistent with each other.

Figure 1 shows the distribution of the normalized rate of events above 8 EeV as a function of right ascension. The sinusoidal function corresponds to the first harmonic; the distribution is compatible with a dipolar modulation: $\chi^2/n = 10.5/10$ for the first-harmonic curve and $\chi^2/n = 45/12$ for a constant function (where n is the number of degrees of freedom, equal to the number of points in the plot minus the number of parameters of the fit).

The distribution of events in equatorial coordinates, smoothed with a 45° radius top-hat function to better display the large-scale features, is shown in Fig. 2.

Reconstruction of the three-dimensional dipole

In the presence of a three-dimensional dipole, the Rayleigh analysis in right ascension is sensitive only to its component orthogonal to the rotation axis of Earth, d_\perp . A dipole component in the direction of the rotation axis of Earth, d_z , induces no modulation of the flux in right ascension, but does so in the azimuthal distribution of the directions of arrival at the array. A non-vanishing value of d_z leads to a sinusoidal modulation in azimuth with a maximum toward the northern or the southern direction.

To recover the three-dimensional dipole, we combine the first-harmonic analysis in right ascension with a similar one in the azimuthal angle φ , measured counterclockwise from the east. The relevant component, b_φ , is given by an expression analogous to that in Eq. 1, but in terms

of the azimuth of the arrival direction of the shower rather than in terms of the right ascension. The results are $b_\varphi = -0.013 \pm 0.005$ in the $4 \text{ EeV} < E < 8 \text{ EeV}$ bin and $b_\varphi = -0.014 \pm 0.008$ in the $E \geq 8 \text{ EeV}$ bin. The probabilities that larger or equal absolute values for b_φ arise from an isotropic distribution are 0.8% and 8%, respectively.

Under the assumption that the dominant cosmic-ray anisotropy is dipolar, based on previous studies that found that the effects of higher-order multipoles are not significant in this energy range (25, 29, 30), the dipole components and its direction in equatorial coordinates (α_d , δ_d) can be estimated from

$$\begin{aligned} d_\perp &\approx \frac{r_\alpha}{\langle \cos \delta \rangle} \\ d_z &\approx \frac{b_\varphi}{\cos \ell_{\text{obs}} \langle \sin \theta \rangle} \\ \alpha_d &= \varphi_\alpha \\ \tan \delta_d &= \frac{d_z}{d_\perp} \end{aligned} \quad (3)$$

(25), where $\langle \cos \delta \rangle$ is the mean cosine of the declinations of the events, $\langle \sin \theta \rangle$ is the mean sine of the zenith angles of the events, and $\ell_{\text{obs}} \approx -35.2^\circ$ is the average latitude of the observatory. For our data set, we find $\langle \cos \delta \rangle = 0.78$ and $\langle \sin \theta \rangle = 0.65$.

The parameters describing the direction of the three-dimensional dipole are summarized in Table 2. For $4 \text{ EeV} < E < 8 \text{ EeV}$, the dipole amplitude is $d = 2.5^{+1.0}_{-0.7}\%$, pointing close to the celestial south pole, at $(\alpha_d, \delta_d) = (80^\circ, -75^\circ)$, although the amplitude is not statistically significant. For energies above 8 EeV, the total dipole amplitude is $d = 6.5^{+1.3}_{-0.9}\%$, pointing toward

$(\alpha_d, \delta_d) = (100^\circ, -24^\circ)$. In galactic coordinates, the direction of this dipole is $(\ell, b) = (233^\circ, -13^\circ)$. This dipolar pattern is clearly seen in the flux map in Fig. 2. To establish whether the departures from a perfect dipole are merely statistical fluctuations or indicate the presence of additional structures at smaller angular scales would require at least twice as many events.

Implications for the origin of high-energy cosmic rays

The anisotropy we have found should be seen in the context of related results at lower energies. Above a few PeV, the steepening of the cosmic-ray energy spectrum has been interpreted as being due to efficient escape of particles from the galaxy and/or because of the inability of the sources to accelerate cosmic rays beyond a maximum value of E/Z . The origin of the particles remains unknown. Although supernova remnants are often discussed as sources, evidence has been reported for a source in the galactic center capable of accelerating particles to PeV energies (31). Diffusive escape from the galaxy is expected to lead to a dipolar component with a maximum near the galactic center direction (32). This is compatible with results obtained in the 10^{15} to 10^{18} eV range (15, 16, 23, 24, 33), which provide values for the phase in right ascension close to that of the galactic center, $\alpha_{\text{GC}} = 266^\circ$.

Models proposing a galactic origin up to the highest observed energies (34, 35) are in increasing tension with observations. If the galactic sources postulated to accelerate cosmic rays above EeV energies, such as short gamma-ray bursts or hypernovae, were distributed in the disk of the galaxy, a dipolar component of anisotropy is predicted with an amplitude that exceeds existing bounds at EeV energies (24, 33). In this sense, the constraint obtained here on the dipole amplitude (Table 2) for $4 \text{ EeV} < E < 8 \text{ EeV}$ further disfavors a predominantly galactic origin. This tension could be alleviated if cosmic rays at a few EeV were dominated by heavy nuclei such as iron, but this would be in disagreement with the lighter composition inferred observationally at these energies (6). The maximum of the flux might be expected to lie close to the galactic center region, whereas the direction of the three-dimensional dipole determined above 8 EeV lies $\sim 125^\circ$ from the galactic center. This suggests that the anisotropy observed above 8 EeV is better explained in terms of an extragalactic origin. Above 40 EeV, where the propagation should become less diffusive, there are no indications of anisotropies associated with either the galactic center or the galactic plane (36).

There have been many efforts to interpret the properties of ultrahigh-energy cosmic rays in terms of extragalactic sources. Because of Liouville's theorem, the distribution of cosmic rays must be anisotropic outside of the galaxy for an anisotropy to be observed at Earth. An anisotropy cannot arise through deflections of an originally isotropic flux by a magnetic field. One prediction of anisotropy comes from the Compton-Getting

effect (37), which results from the proper motion of Earth in the rest frame of cosmic-ray sources, but the amplitude is expected to be only 0.6% (38), well below what has been observed. Other studies have predicted larger anisotropies. These assume that ultrahigh-energy cosmic rays originate from an inhomogeneous distribution of sources (13, 14, 39), or that they arise from a dominant source and then diffuse through intergalactic magnetic fields (11–14). The resulting dipole amplitudes are predicted to grow with energy, reaching 5 to 20% at 10 EeV. These amplitudes depend on the cosmic-ray composition as well as the details of the source distribution. On average, the predictions are smaller for larger source densities or for more isotropically distributed sources. If the sources were distributed like galaxies, the distribution of which has a significant dipolar component (40), a dipolar cosmic-ray anisotropy would be expected in a direction similar to that of the dipole associated with the galaxies. This effect would be due to the excess of cosmic-ray sources in this direction and is different from the Compton-Getting effect due to the motion of Earth with respect to the rest frame of cosmic rays. For the infrared-detected galaxies in the 2MRS catalog (40), the flux-weighted dipole points in galactic coordinates in the direction $(\ell, b) = (251^\circ, 38^\circ)$. In this coordinate system, the dipole we detect for cosmic rays above 8 EeV is in the direction $(233^\circ, -13^\circ)$, about 55° away from that of the 2MRS dipole.

For an extragalactic origin, the galactic magnetic fields modify the direction of the dipole observed at Earth relative to its direction outside the galaxy. For illustration, Fig. 3 shows a map of the flux above 8 EeV in which the direction of the cosmic-ray dipole is shown along with the direction toward the 2MRS dipole. The arrows in the plot indicate how a dipolar distribution of cosmic rays, in the same direction as the 2MRS dipole outside the galaxy, would be affected by the galactic magnetic field (8). The tips of the arrows indicate the direction of the dipole of the flux arriving at Earth, assuming common values of $E/Z = 5$ EeV or 2 EeV. Given the inferred average values for $Z \sim 1.7$ to 5 at 10 EeV, these represent typical values of E/Z for the cosmic rays contributing to the observed dipole. The agreement between the directions of the dipoles is improved by adopting these assumptions about the charge composition and the deflections in the galactic magnetic field. For these directions, the deflections within the galaxy will also lead to a lowering of the amplitude of the dipole to about 90% and 70% of the original value, for $E/Z = 5$ EeV and 2 EeV, respectively. The lower amplitude in the 4 EeV $< E < 8$ EeV bin might also be the result of stronger magnetic deflections at lower energies.

Our findings constitute the observation of an anisotropy in the arrival direction of cosmic rays with energies above 8 EeV. The anisotropy can be well represented by a dipole with an amplitude of $6.5^{+1.3}_{-0.9}\%$ in the direction of right ascension $\alpha_d = 100^\circ \pm 10^\circ$ and declination $\delta_d = -24^{+12}_{-13}^\circ$. By comparing our results with phenom-

ological predictions, we find that the magnitude and direction of the anisotropy support the hypothesis of an extragalactic origin for the highest-energy cosmic rays, rather than sources within the galaxy.

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ACKNOWLEDGMENTS

The successful installation, commissioning, and operation of the Pierre Auger Observatory would not have been possible without the strong commitment from the technical and administrative staff in Malargüe, and the financial support from a number of funding agencies in the participating countries. Full facility and funding acknowledgments are provided in the supplementary materials. The catalogs of observed cosmic-ray events with $4 < E < 8$ EeV and $E \geq 8$ EeV, along with the data plotted in Figs. 1 and 2, are available at www.auger.org/data/science2017.tar.gz.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/357/6357/1266/suppl/DC1

Materials and Methods

Supplementary Text

Figs. S1 to S4

Table S1

12 April 2017; accepted 10 August 2017

10.1126/science.aan4338

Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8×10^{18} eV

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Science **357** (6357), 1266-1270.
DOI: 10.1126/science.aan4338

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High-energy particles are extragalactic

Cosmic rays are high-energy particles arriving from space; some have energies far beyond those that human-made particle accelerators can achieve. The sources of higher-energy cosmic rays remain under debate, although we know that lower-energy cosmic rays come from the solar wind. The Pierre Auger Collaboration reports the observation of thousands of cosmic rays with ultrahigh energies of several exa-electron volts (about a Joule per particle), arriving in a slightly dipolar distribution (see the Perspective by Gallagher and Halzen). The direction of the rays indicates that the particles originated in other galaxies and not from nearby sources within our own Milky Way Galaxy.

Science, this issue p. 1266; see also p. 1240

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