Blind searches for localized cosmic ray excesses in the field of view of the Pierre Auger Observatory

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Abstract: We present the results of a blind search for overdensities with respect to isotropic expectations in the cosmic ray flux detected by the Pierre Auger Observatory. We analyze maps of significances in different energy ranges and for various angular scales. We have also searched for correlations of cosmic ray arrival directions with some promising candidate sources: the directions close to the Galactic Plane and the Galactic Center itself, in the perspective of a galactic origin of cosmic rays, and the Super-Galactic Plane and Centaurus A, in the perspective of an extra-galactic origin.

Keywords: Pierre Auger Observatory, ultra-high energy cosmic rays, cosmic rays, extensive air showers, anisotropy, Galactic Center, Galactic Plane, Super-Galactic Plane, Cen A

1 Introduction

One of the main goals of ultra-high energy cosmic ray experiments is to search for sources, both at small and large angular scales. We can expect to find localized excesses at small angular scales at energies above 10 EeV (where 1 EeV is \(10^{18}\) eV) because the bending of the trajectories of charged particles in the magnetic fields becomes smaller. It is also interesting to search for excesses at large angular scales, that could result either from the spreading of point-like sources by magnetic fields, or by the contribution of clustered sources. The transition from a galactic to an extra-galactic origin could correspond to the observed ankle feature in the cosmic ray energy spectrum around 4 EeV and the escape of the galactic cosmic rays could be manifest through their sky distribution below this energy.

The Pierre Auger Collaboration reported several results on searches for anisotropy, at small and large angular scales, at energies in the EeV range and above, up to the highest energies. The first blind search has been reported in \([1]\) with a result compatible with an isotropic distribution of the cosmic rays. The results of the search for point-like EeV neutron sources at the level of the angular resolution (smaller than 1.4\(°\)) have been presented in \([2]\), where upper limits on the neutron flux have been set. A similar search but with stacked targets is presented in this conference in \([3]\). In the same energy range, the Galactic Center has been specifically studied in \([4]\) and we reported no deviation from isotropic expectations. Still at small angular scales but at ultra-high energies, we did not find any significant signal using self-clustering studies \([5]\). At very large angular scales and all energies, we set limits on the dipolar and quadrupolar amplitudes \([6,7]\) which are updated in this conference \([8,9]\). Hints of correlation at the highest energies with nearby extragalactic matter and in particular with the direction towards Centaurus A were reported in \([10,11,12]\).

The current paper aims at covering energies above 1 EeV and intermediate angular scales. We report in particular the distributions of significances using top-hat windows of radius 5\(°\) and 15\(°\) over the full field of view in the same 4 energy ranges used in \([6]\) (1-2 EeV, 2-4 EeV, 4-8 EeV and \(\geq 8\) EeV) to search for anisotropies at large angular scales. We also search, in these energy ranges, in the direction of the following specific targets: the Galactic Plane (GP), the Galactic center, the Super-Galactic Plane (SGP) and Centaurus A (CenA).

The data set used in this study covers the period 1 January 2004 to 31 December 2012 and is 24 times larger than that of \([1]\).

2 The data set

The Pierre Auger Observatory is located in Malargüe, Argentina (35.2\(°\)S, 69.5\(°\)W) at an altitude of 1400 m asl. We are using two complementary techniques to observe extensive air showers initiated by cosmic rays: a surface detector (SD) \([13]\) and a fluorescence detector (FD) \([14]\). The SD is composed of 1660 water Cherenkov detectors arranged as an array on a triangular grid with 1.5 km spacing. The SD is fully efficient at \(E \geq 3\) EeV. The FD observes the atmosphere above the SD during dark cloudless nights with 27 telescopes spread over 5 buildings. The fluorescence light emitted by the excited atmospheric nitrogen after the passage of the charged particles of the shower is detected by these telescopes, and permits a calorimetric measurement of the energy of the primary cosmic ray through the observation of the longitudinal profile of the shower. The computation of the exposure of the SD takes into account the growth of the array during construction, from 154 to 1660 water Cherenkov detectors, as well as stations dead times during operation (90% duty cycle). We include events such that the six nearest neighbours of the water Cherenkov detector with the highest signal are fully functional. This defines an active hexagon. These fiducial cuts guarantee good event reconstruction \([15]\). The total exposure for events that satisfy these cuts and have a zenith angle less than 60\(°\) is 31395 km\(^2\) yr sr. There are 750181 showers above 1 EeV within that zenith angle range. The distribution of these events with the energy is given in Table\([1]\) The energy of a given shower is determined using first the constant intensity cut method, which provides the shower size at an axis...
distance of 1000 m that would have been expected if the zenith angle had been 38°, and second, using the calibration curve of the hybrid events independently detected and reconstructed by both SD and FD [16] [17]. The final energy resolution has a statistical uncertainty of 15% and the absolute energy scale has a systematic uncertainty of 14% [18]. Several issues can affect the shower size estimate and have to be corrected for. The influence of the atmospheric conditions has been fully characterized in [19], where we describe the correction to apply to the shower size according to its zenith angle given the measured values of air temperature and pressure at the time of the detection. The geomagnetic field bends the charged secondary particles and broadens their spatial distribution in the direction of the Lorentz force. This effect modifies the lateral distribution function of the particles at the ground level and consequently, the value of the estimated shower size. The correction to apply to the shower size is described in [20]. The data set used in this paper contains all these corrections.

### 3 Directional exposure estimate and events map

The directional exposure provides an estimate of the expected fraction of events within a target solid angle as a function of its direction in the sky, under the assumption of an underlying isotropic distribution of the cosmic rays. We compute the directional exposure from the global acceptance $a_T$ that depends on the shower arrival direction and the time of the detection, using the general formula:

$$W(\alpha, \delta) = \int^{t_{\text{max}}}_{t_{\text{min}}} a_T(t, \theta, \alpha, \delta, \omega, \phi) \, dt, \quad (1)$$

as done in [21], where $\alpha, \delta$ are the usual equatorial coordinates, $t$ is the UTC time and $t_{\text{min}}, t_{\text{max}}$ define the time period considered. In general, $a_T$ explicitly depends on time through, for instance, the time varying size of the SD array. In the case of the Pierre Auger Observatory, this dependence is accounted for through the number of active hexagons as a function of time, denoted by $a_{\text{Hex}}(t)$. Concerning the dependence on arrival direction, the acceptance per unit solid angle simply depends on the geometrical factor $\cos \theta$ when the detector is fully efficient, but at low energies ($E < 3$ EeV) and especially at high zenith angles, for which the particles are particularly attenuated by the large atmospheric depth they have crossed, the efficiency becomes less than unity and is zenith dependent.

The total acceptance $a_T$ should therefore take into account this zenith angle modulation $a_\theta$ through a fit of the zenith angle distribution as done in the semi-analytic (SA) method described in [21], where we argued that the zenith angle distribution is poorly sensitive to an actual cosmic-ray sky anisotropy. We have extended the SA method to account for an azimuthal modulation observed in the event counting rate at relatively low energy and large zenith angles. This modulation is due to the hexagonal shape of the SD grid, which introduces an azimuthal dependence on the trigger rate for inclined showers at energies below full efficiency. This can induce relative differences up to 7% in the directional exposure. We take this effect into account in the total acceptance, which is written as:

$$a_T(t, \theta, \phi) = a_{\text{Hex}}(t) a_\theta(\theta) a_\phi(\phi, \theta, \phi),$$

that can be seen as the product of the probability density functions. The specific acceptance $a_\phi(\theta, \phi) = 1 + \beta(\theta) \cos(6\phi)$ is shown in Fig. 1 for the energy range 1-2 EeV and for zenith angles $54^\circ \leq \theta \leq 60^\circ$. It has an amplitude $\beta = -0.068 \pm 0.004$ in this case. The amplitude of the modulation is relevant for energies below 3 EeV and for relatively inclined showers only. Its dependence with zenith angle can be parametrized as $\beta(\theta) = \gamma \times (\theta/\theta_0) \times \exp((\theta - \theta_0)/w)$ with $\theta_0 = 60^\circ$. The fit for the parameters $\gamma$ and $w$ in the energy range 1-2 EeV is $\gamma = -(9 \pm 3)/\%$ and $w = 4.2^\circ \pm 1.4^\circ$.

At this level, we have all needed quantities to compute the directional exposure by the numerical integration of Eq. (1). The directional exposure must be computed for each considered energy range and is normalized to the corresponding total number of events. In this analysis, we correct for the azimuthal modulation $a_\phi(\theta, \phi)$ below 3 EeV. For $a_\phi$ we use a fit of the zenith angle distribution in the data, even above 3 EeV where full acceptance implies $a_\theta = \sin \theta \cos \theta$, to account for potential residual departures from the geometric distribution due to energy assignment systematics. The explicit time dependence reflects the actual varying size of the SD array $a_{\text{Hex}}(t)$, averaged every five minutes over the 9 years covered by the data set. Note that the directional exposure obtained with this method is very similar to the one provided by the shuffling method [22]. As an example, Fig. 2 presents the integrated directional exposure in galactic coordinates for the energy range 1-2 EeV over circular windows with angular radius of 5°.

For every direction $\alpha, \delta$ at a given angular scale $\alpha a$, the significance of the difference between the number of observed events $n^{\text{obs}}(\alpha, \delta)$ and the number of expected events from the directional exposure $n^{\text{dir}}(\alpha, \delta)$ is computed using the unbiased Li & Ma estimator [23], where the Li & Ma

<table>
<thead>
<tr>
<th>Energy [EeV]</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>557829</td>
</tr>
<tr>
<td>2-4</td>
<td>148790</td>
</tr>
<tr>
<td>4-8</td>
<td>31270</td>
</tr>
<tr>
<td>$\geq$ 8</td>
<td>12292</td>
</tr>
</tbody>
</table>

Table 1: Energy distribution of the events used in the considered dataset.
Figure 2: Integrated number of events with energy in the range 1-2 EeV expected in windows of radius 5° for an isotropic distribution of arrival directions. The map is in galactic coordinates. The solid line is the border of the field of view for arrival directions with zenith angle $\theta \leq 60^\circ$.

The $\alpha_LM$ parameter is taken to be $\alpha_LM = \frac{n^{\omega}_{\text{iso}}(\alpha, \delta)}{N_{\text{tot}} - n^{\omega}_{\text{iso}}(\alpha, \delta)}$, $N_{\text{tot}}$ being the total number of events in the considered data set. We compute $n^{\omega}_{\text{obs}}(\alpha, \delta)$ (resp. $n^{\omega}_{\text{iso}}(\alpha, \delta)$) by integration of the events map (resp. directional exposure) over all directions located at an angular distance smaller than $\omega$ degrees from the direction centered on $(\alpha, \delta)$. We use the HEALPix [24] pixellisation with a pixel width much smaller than 1° ($n_{\text{side}} = 512$). From the full-sky significance map we compute the distribution of significances, and compare it with isotropic expectations. For that purpose we simulate 1000 isotropic Monte Carlo datasets, and determine the 68%, 95% and 99.7% dispersion in their distribution of significances.

4 Results

We perform the search for localized excesses in the energy ranges 1-2 EeV, 2-4 EeV, 4-8 EeV, $\geq 8$ EeV at two angular scales: 5° and 15°. The distributions of the Li & Ma significances at an angular scale of 5° are shown in Fig. 3. The largest observed significances are compatible with isotropic expectations. The same result holds at an angular scale of 15° and will be reported in a forthcoming paper. We searched for excesses in circular regions centered at the directions toward the Galactic center and CenA by comparing the relative differences $(n_{\text{obs}} - n_{\text{iso}})/n_{\text{iso}}$ between the data and the isotropic expectations using 20000 simulated isotropic data sets. As illustration, the results as a function of the angular radius of the target window centered at the location of CenA for cosmics rays with energies between 4 and 8 EeV (resp. $E \geq 8$ EeV) are shown in Fig. 4 (resp. Fig. 5). The results for the location of the Galactic center and cosmic rays with energy in the range 1-2 EeV (resp. 2-4 EeV) are presented in Fig. 6 (resp. Fig. 7).

We have also searched for an excess of arrival directions inside the band within 10° below and above the Galactic and Super-Galactic planes. Table 2 lists the number of events observed with galactic latitudes $-10^\circ < b < 10^\circ$ for cosmic rays in the energy ranges 1-2 EeV and 2-4 EeV, and its ratio with the isotropic expectation, and similarly for arrival directions with Super-Galactic latitudes $-10^\circ < b_{SG} < 10^\circ$ and energies above 8 EeV.

Figure 3: Distribution of Li & Ma significances of the difference between the number of arrival directions observed and the isotropic expectation over windows of radius 5° across the exposed sky. The respective energy range is quoted in each plot. The bands correspond to the 68%, 95% and 99.7% dispersion expected for an isotropic flux. The largest observed significances are compatible with isotropic expectations.

Figure 4: Relative difference between the cumulative number of events observed and the isotropic expectation as a function of the angular distance to CenA. The energy range is 4-8 EeV.

Figure 5: Same as Fig. 4 for $E \geq 8$ EeV.
Figure 6: Relative difference between the cumulative number of events observed and the isotropic expectation as a function of the angular distance to the Galactic center. The energy range is 1-2 EeV.

Figure 7: Same as Fig. 6 for the energy range 2-4 EeV.

Table 2: Results of the search for excesses around the Galactic and Super-Galactic planes. A band within latitudes $10^\circ$ above and below the planes is considered. The number of events observed inside the band is compared to the isotropic expectation. The ratio $n_{\text{obs}}/n_{\text{iso}}$ is indicated with the 68% dispersion expected for an isotropic flux.

<table>
<thead>
<tr>
<th>Target</th>
<th>$E$ [EeV]</th>
<th>$n_{\text{obs}}$</th>
<th>$n_{\text{iso}}$</th>
<th>$n_{\text{obs}}/n_{\text{iso}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP</td>
<td>1-2</td>
<td>95834</td>
<td>95890.4</td>
<td>0.999 ± 0.003</td>
</tr>
<tr>
<td>GP</td>
<td>2-4</td>
<td>25153</td>
<td>25491</td>
<td>0.986 ± 0.006</td>
</tr>
<tr>
<td>SGP</td>
<td>$\geq$ 8</td>
<td>2156</td>
<td>2135.5</td>
<td>1.01 ± 0.03</td>
</tr>
</tbody>
</table>

5 Conclusion

In this study, we searched for regions of excess flux with respect to isotropic expectations at energies above 1 EeV over the exposed sky at the Pierre Auger Observatory. Data between 2004 and 2012 have been analyzed, considering in particular the same four energy ranges already used for the large scale anisotropy analysis in [6, 7]: 1-2 EeV, 2-4 EeV, 4-8 EeV and $E \geq 8$ EeV. Here we searched for anisotropies at intermediate angular scales. We analyzed the distribution of significances for the difference between the number of arrival directions in circular windows of angular radius of 5° and 15° and the isotropic expectation over the full exposed sky. The largest observed significances are compatible with isotropic expectations.

We studied, for the same energy ranges, the distribution of arrival directions with latitudes within 10° of the Galactic and Super-Galactic planes. We analyzed the distribution of arrival directions as a function of the angular distance to the Galactic Center and to the location of the radio-galaxy Centaurus A. We did not find any significant departure from isotropic expectations for these targets in the energy ranges explored.

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