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Search for Large Scale Anisotropies with the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory studies the nature and the origin of Ultra High Energy Cosmic Rays ($> 3 \cdot 10^{18}$ eV). Completed at the end of 2008, it has been continuously operating for more than six years. Using data collected from 1 January 2004 until 31 March 2009, we search for large scale anisotropies with two complementary analyses in different energy windows. No significant anisotropies are observed, resulting in bounds on the first harmonic amplitude at the 1% level at EeV energies.

1. Introduction

The large scale anisotropy, and in particular its dependence on primary energy, represents one of the main tools for studying the origin and the propagation of cosmic rays, especially in the energy region around 10^{18} eV, where the transition from a galactic to an extragalactic origin is expected to take place. This transition should in fact induce a significant change in the large scale angular distribution of cosmic rays, giving important information on their nature and on the magnetic fields that modify their trajectories.

The shape and the amplitude of the anisotropy are predicted to be dissimilar among different theoretical models; a measure of the anisotropy or the eventual bounds on it are thus relevant to constrain different models for the CRs origin.

2. Data Analysis and results

The statistics accumulated so far by the Pierre Auger Observatory (2000) allows us to perform large scale analyses with a sensitivity that is already at the percent level. For this analysis we used data recorded from 1 January 2004 to 31 March 2009, removing the periods of unstable data acquisition ($\sim$ 3% of the whole data set).

Searching for %-level large-scale patterns requires control of the sky exposure of the detector and of various acceptance effects, such as detector instabilities and weather modulations. The main effects are expected to appear at the solar frequency but may also be non-negligible at other frequencies. In particular, spurious variation can be generated by the combination of diurnal and yearly modulations of the acceptance, with similar amplitudes at both the sidereal and the anti-sidereal frequencies (2000).

The main tool to analyze the frequency pattern is the Fourier transform of the arrival times of the events. The analysis of the frequency patterns and of their modulation can be performed with a resolution of the order of the inverse of the experimental exposure time.

The variations due to the non-uniform detector on-times can be taken into account using a generalised Rayleigh analysis (2000).

This method corrects for the effects of a non-uniform acceptance in right ascension by weighting each event with a factor ω_i inversely proportional to the relative exposure of the region of the sky observed at the arrival time of the event (α_{di} is the right ascension of the zenith of the detector at the time the event i is detected) (2000). Computing the coefficients:

$$A = \frac{2}{\Omega} \sum_i \omega_i(\alpha_{di}) \cos\alpha_i \quad (1)$$

$$B = \frac{2}{\Omega} \sum_i \omega_i(\alpha_{di}) \sin\alpha_i \quad (2)$$

where $\Omega = \sum_i \omega_i(\alpha_{di})$, the Rayleigh amplitude and phase are obtained through:

$$r = \sqrt{A^2 + B^2} \quad \text{and} \quad \phi = \text{atan}\frac{B}{A} \quad (3)$$

Since the deviations from a uniform exposure are small, the probability that an amplitude larger or equal to r arises from an isotropic distribution may be estimated with the standard expression $P = \exp(-k_0)$, where $k_0 = r^2N/4$ with N total number of events. Atmospheric effects, such as changes in the air density and pressure, are taken into account in the energy estimation of each event (2000). The results presented here with this method are valid above $\sim$ 1 EeV; below this energy, in fact, the weather effects also start to affect the trigger efficiency in a significant way.

After applying such corrections all the spurious modulations are removed. For instance, in the energy interval $1 - 2$ EeV a first harmonic in solar time of 3.33% (corresponding to a chance probability $P \sim 10^{-20}$) is reduced to 0.88% ($P \sim 2\%$) after all the corrections. The corresponding first harmonics in sidereal and anti-sidereal time are of the same order, being respectively 0.90% and 0.71%, with a probability to result from a fluctuation of an isotropic distribution of $\sim 2\%$ and $\sim 8\%$.

An alternative method, which is largely independent of possible systematic effects, is the differential East-West method (2000), which exploits the differences in the number of counts between the eastward and the westward arrival directions at a given time. In this way, since the instantaneous eastward and westward acceptances are equal and the two sectors are equally affected by the instabilities of the apparatus, direction-independent phenomena, such as atmospheric and acceptance effects, can be removed without applying any correction. The difference in the number of counts $E(t) - W(t)$ is related to the physical CR intensity $I(t)$ by $\mathrm{d}I/\mathrm{d}t = (E(t) - W(t))/\delta t$. The first harmonic analysis of $I(t)$, whose amplitude and phase are (r_I,ϕ_I), can be derived from the first harmonic analysis of $E(t) - W(t)$, of amplitude and phase (r_D,ϕ_D):

$$r_I = \frac{1}{\sin\delta t}\frac{n_{int}}{N} r_D \quad \text{and} \quad \phi_I = \phi_D + \frac{\pi}{2} \quad (4)$$

where N is the total number of events, n_{int} is the number of intervals of sidereal time used to compute the first harmonic amplitude of $E(t) - W(t)$ and δt is the average hour angle between the vertical and the events from sector E (or W). The probability that an amplitude equal or larger than r arises from an isotropic distribution is $P = \exp(-r^2N\sin^2\delta t/4)$.

Since this method is largely independent of spurious time variations, the analysis can be performed also on the whole data set (median energy $\sim 6 \cdot 10^{17}$ eV), even below the energy threshold for full efficiency. For the complete data set the amplitudes in solar and anti-sidereal time are respectively 0.29% ($P \sim 55\%$) and 0.24% ($P \sim 66\%$), showing that any spurious modulation has been removed (the amplitude in solar time with the standard Rayleigh analysis, without corrections, is 3.98%). The corresponding amplitude in sidereal time is $r = 0.48\%$, the probability for it to result from a fluctuation of an isotropic distribution is $\sim 20\%$ (see the first line of Tab.1).

The results of the E-W and the Rayleigh analyses on all the events above increasing energy thresholds and in energy bins of 0.1 Log(E) are shown respectively in Fig.1 and 2. No significant modulation in sidereal time is detected throughout the scan. The two methods are complementary: while the Rayleigh analysis can only be reliably used above 1 EeV, the East-West analysis can be safely applied even below 1 EeV but it is affected by larger statistical uncertainties.

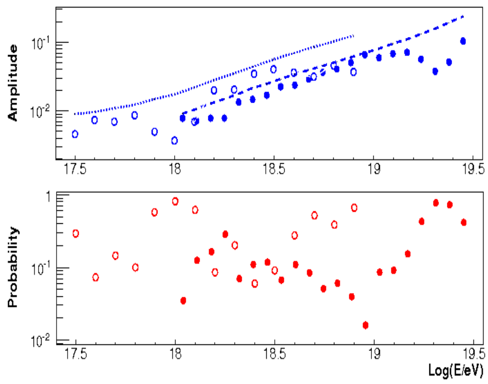

Fig. 1. Rayleigh amplitude (top) and probability for the amplitude to result from fluctuations of an isotropic background (bottom) as a function of increasing energy thresholds, obtained with both the generalised Rayleigh analysis, after correcting for non-constant acceptance and weather effects, (*filled circles*) and the East-West method (*empty circles*). The *dotted lines* indicate the 99% c.l. upper bound on the amplitudes that could result from fluctuations of an isotropic distribution.

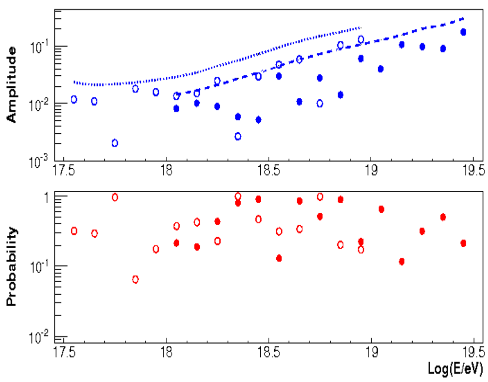

Fig. 2. The same as Fig.1 but here it is displayed for energy bins (instead of energy thresholds).

To overcome the lack of statistics, we matched some of the energy intervals of Fig.2 and repeated a first harmonic analysis using the two approaches. The results are collected in Tab.1. No significant departure from isotropy is observed with both methods. Having proved that both analyses account for the systematic effects, upper limits at 99% c.l. can be derived using only the statistical uncertainties. Such upper bounds, reported in the last column of Tab.1, have been calculated according to the distribution drawn from a population characterised by an anisotropy of unknown amplitude (2000).

3. Discussion

Information about the galactic/extragalactic transition can be obtained by studying large scale anisotropies as a function of energy. The upper limits obtained in this study are shown in Fig.3, together with some predictions for the anisotropies arising from both galactic and extra-galactic models.

If the transition occurs at the ankle energy (2000), cosmic rays at 10^{18} eV are predominantly galactic and their escape from the Galaxy by diffusion and drift motions could induce a modulation at the % level at EeV energies. The exact value strongly depends on specific models. We show in Fig. 3 the models discussed by Candia et al. (2000), which predict the anisotropy amplitudes up to EeV energies arising from the diffusion in the Galaxy. These predictions depend on the assumed galactic magnetic field model as well as on the sources distribution. The bounds obtained here already exclude the predictions from the particular model with an antisymmetric halo magnetic field (A) and are starting to become sensitive to the predictions of the model with a symmetric field (S).

According to another scenario, the transition could take place at lower energies, i.e. around the so-called "second knee", at $\sim 5 \cdot 10^{17}$ eV (2000). EeV cosmic rays would then be dominantly of extra-galactic origin and their large scale distribution could be influenced by the relative motion of the observer with respect to the frame of the sources. For instance, if the frame in which the CR distribution is isotropic coincides with the CMB rest frame, the resulting anisotropy due to the Compton-Getting effect (*C-G Xgal* in Fig. 3) would be about 0.6% with a phase $\alpha \simeq 168°$ (2000). This amplitude is very close to the upper limits set in this analysis (the statistics required to become sensitive to such amplitude at 99% c.l. is $\sim$ 3 times the present statistics).

Table 1. Results of the two analyses in different energy ranges. The statistical uncertainties are characterised by the quantities $s_R = \sqrt{2/N}$ and $s_{EW} = \sqrt{2/N}/\sin\delta t$. Rayleigh probabilities and 99%c.l. upper limits are also given. Since all the measured amplitudes are compatible with background, the phases are not significant and are not reported here.

	Rayleigh analysis			**E-W method**			**upper limits**
Energy range [EeV]	r [%]	s_R [%]	P [%]	r [%]	s_{EW} [%]	P [%]	$r_{99\%}$ [%]
all energies				0.48	0.27	19.5	1.05
0.2 - 0.5				0.25	0.43	84.2	1.19
0.5 - 1				1.08	0.44	4.8	2.03
1 - 2	0.90	0.32	1.8	0.77	0.65	49.9	1.59
2 - 4	0.79	0.64	45.8	1.65	1.33	46.3	2.12
4 - 8	0.71	1.33	86.6	5.05	2.73	18.0	3.66
>8	5.36	2.05	3.3	2.76	4.08	79.5	9.79

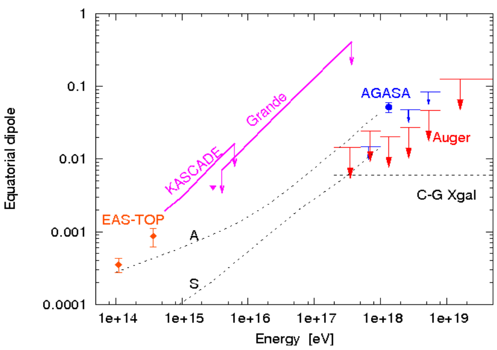

Fig. 3. Upper limits on the anisotropy amplitude as a function of energy. Also shown are the predictions from two different galactic magnetic field models with different symmetries (*A* and *S*) and the expectations from the Compton-Getting effect for an extra-galactic component isotropic in the CMB rest frame (*C-G Xgal*).

In the same figure we also show previous results from EAS-TOP, KASCADE, KASCADE-Grande and AGASA (to take into account the particular sky coverage of each experiment, we consider the components of the dipole in the equatorial plane). The results presented here do not confirm the ∼ 4% anisotropy reported by AGASA in the 1 − 2 EeV energy bin (2000).

4. Conclusions

We have searched for large scale patterns in the arrival directions of events recorded at the Pierre Auger Observatory using two complementary analyses and we obtained 99% c.l. upper limits at the percent level at EeV energies. All models predicting anisotropy amplitudes greater than ∼ 2% below 4 EeV can be excluded by our results. Further statistics will be obtained in the coming years using data from the Pierre Auger Observatory, thus improving our sensitivity.

Finally we do not confirm the 4% modulation detected by AGASA at 4 s.d. between 1 and 2 EeV.

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