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Large scale anisotropy studies with the Pierre Auger Observatory

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Abstract. The Pierre Auger Observatory in Argentina measures air showers initiated by cosmic rays at EeV energy scales ($1\,\mathrm{EeV} = 10^{18}\,\mathrm{eV}$). An important goal of the collaboration is to study the distribution of arrival directions of the primary particles and quantify potential anisotropies therein. Using data collected by the surface detector (SD) array of the Pierre Auger Observatory since 1 January 2004, we study large scale anisotropies in different energy windows.

Modulations of the event rate within the period of a sidereal day are studied by means of a periodicity analysis accounting for local effects which may induce an artificial anisotropy. We present results for the event rate modulation in right ascension and derive upper limits for the equatorial component of a dipole amplitude (Auger Coll., 2011; Bonino, 2009).

1 Introduction

Large scale anisotropy studies intend to quantify potential anisotropies at large angular scales. In the context of the Pierre Auger Observatory the observable under investigation is the distribution of the arrival directions of ultra high energy cosmic rays (UHECRs).

The results of large scale anisotropy studies are expected to provide hints with respect to the origin and nature of UHECRs as well as to the (extra-) galactic magnetic fields they propagate through. The energy dependence of measures of anisotropy can provide information connected to features in the energy spectrum: A possible explanation of the ankle in the energy spectrum as a signature of the transition from galactic to extragalactic UHECRs could result in a dipolar pattern in the event rate distribution measured on Earth (Linsley, 1963). Theoretical expectations for the amplitude of such a dipolar anisotropy can be derived from predictions by galactic magnetic field models with different geometries (Candia, 2003). Another possible interpretation of the ankle is the distortion of an extragalactic spectrum dominated by protons which suffer energy losses due to $e^{\pm}$-production with photons of the Cosmic Microwave Background (CMB) (Hillas, 1967). The latter scenario could result in a dipolar pattern due to the movement of the Earth within the CMB rest frame as described by the Compton-Getting effect with an amplitude of the order of $\sim 0.6\%$ (Schwarz, 2004).

Time-dependent changes of local conditions of the detector and the atmosphere could partly be propagated to the event rate distribution and thus introduce artificial anisotropies. Section 2 will cover the discussion of the local effects of a varying detector area and of changing weather conditions. The standard method in (large scale) anisotropy studies is the multipole expansion of the event rate distribution on the sky. In this study, however, we will focus exclusively on dipolar (first order multipole) patterns on the sphere that reduce to a sine-like modulation when projecting them to right ascension (the longitude in equatorial coordinates). In Sect. 3 we present the standard Rayleigh method and how to account for the local effects discussed. Furthermore, we describe the East/West method as an alternative procedure that is independent of these effects. The results will be presented and discussed in Sect. 4.

2 Local effects

Given the position of the observatory and the local arrival direction of an air shower, the time of the measurement is directly linked to the right ascension of the arrival direction of the primary UHECR. Therefore, a modulation of any detector property in time may induce a modulation of the measured event rate in right ascension. In the following section

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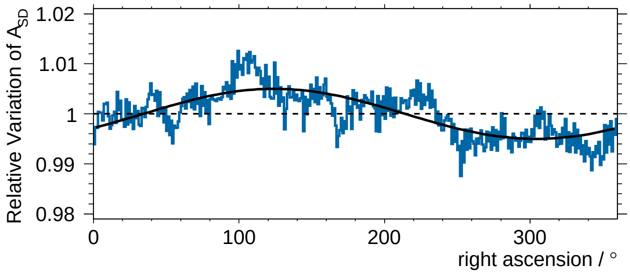

Fig. 1. Relative variation of the area of the SD. A sine fit has been performed to visualize and estimate the effect on the amplitude measurement with first harmonic modulation studies. The amplitude read from the normalized y-axis amounts to ~ 0.5

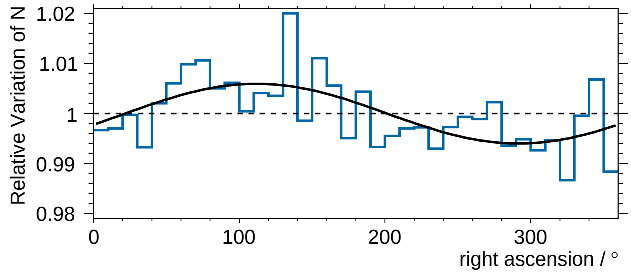

Fig. 2. Relative variation of the event rate in right ascension due to the weather effect. We plot the quotient of the event rate of the data set subject to an energy cut ($1 < \mathrm{E} / \mathrm{EeV} < 2$) with and without applying the energy correction. The sine fit performed to guide the eye and estimate the effect on first harmonic modulation studies yields an amplitude of $\sim 0.6\%$. This amplitude estimate ranges from 0.2% to 1.5% at all relevant energies.

we will discuss the effects of the varying exposure of the SD and of varying atmospheric conditions.

Effect of a varying exposure

The exposure of the SD of the Pierre Auger Observatory is described in (Sommers, 2001). The growth of the detector in the construction phase from 2004 to 2008 and station downtimes due to outages of some batteries during nights lead to a modulation of the area of the SD and, consequently, of the expected event rate over time. The instantaneous size of the SD area is monitored and recorded every second. The time information can be linked to the right ascension coordinate now using the zenith of the observatory as the mean direction in the field of view.

Eventually, a directional dependence of the accumulated area of the SD can be derived: Different directions in the right ascension coordinate are observed by different sizes of the detector. This relation is plotted in Fig. 1, it shows that a first harmonic modulation with an amplitude of $\sim 0.5\%$ is introduced into the SD area depending on right ascension. This is equivalent to a modulation of the detection probability. Thus, accounting for the varying exposure of the SD (see Sect. 3) removes an artificial anisotropy corresponding to an amplitude of $\sim 0.5\%$ in the first harmonic modulation.

Effect of varying weather conditions

Besides the area of the SD, also the atmosphere must be considered as a part of the detector. Changes of the atmospheric conditions affect the longitudinal development of an air shower. Therefore, the particle content at ground level relevant for the SD energy measurement depends on the conditions of the atmosphere at the time of the measurement.

This leads to a time dependent variation of the energy measurement and, consequently, to a directional dependence of the energy in right ascension. When energy cuts are applied to a set of events, the steeply falling energy spectrum causes a non-negligible fraction of this directional dependence to be propagated to the event rate.

In (Auger Coll., 2009) it is shown that the signal $S(1000)$ measured with the SD at 1 km from the shower core impact position correlates with actual local values of pressure P and air density ρ. Using the average values $P_0 = 862$ hPa and $\rho_0 = 1.06$ kg m^{-3} at the location of the observatory as a reference, the signal $S^0(1000)$ that would have been measured at these reference values is:

$$S^0(1000) = [1 - \alpha_P(\theta)(P - P_0) \\ - \alpha_\rho(\theta)(\rho_d - \rho_0) \\ - \beta_\rho(\theta)(\rho - \rho_0)]\, S(1000), \quad (1)$$

where ρ_d is the daily average air density at the time of the measurement of the air shower and θ is the zenith angle. The correlation coefficients α_P, α_ρ and β_ρ have been reported in (Auger Coll., 2009). The energy is obtained from $S(1000)$ via calibration with the energy measurement by the fluorescence detector of the Pierre Auger Observatory (Di Giulio, 2009).

Given the parametrization in Eq. (1), the amplitude of the modulation of the event rate in right ascension can be estimated. As an example, in Fig. 2 we plot the event rate ratio of two scenarios when cutting $1 < \mathrm{E} / \mathrm{EeV} < 2$: For the first scenario, we apply the energy correction beforehand while for the second scenario the energies remain untouched. We find a modulation of $\sim 0.6\%$ amplitude in the ratio of the event rates of the two scenarios over right ascension, ranging from 0.2% to 1.5% at all relevant energies. Thus, correcting the energy for atmospheric effects on an event by event basis removes an artificial anisotropy corresponding to a first harmonic modulation amplitude at the 1% level.

Furthermore, we remark that weather conditions also affect the trigger rate below 3 EeV where the SD does not have full acceptance. The effect is negligible ($< 0.03\%$) down to 1 EeV but for lower energies it becomes difficult to handle. Therefore, any method sensitive to local effects cannot be safely used below 1 EeV.

3 Analysis methods

There are two general points to be considered when going from a full sky investigation of a dipolar pattern to a sine pattern in the right ascension: First, since the directional information of the declination (δ, the latitude) component is ignored, the number of parameters describing a dipolar anisotropy is smaller in the one-dimensional case. On the one hand, that improves the situation in terms of increased statistics per degree of freedom. On the other hand, only dipolar patterns with a direction not too close to one of the poles of the equatorial coordinate system will be accessible. Second, time-independent local effects on the event rate distribution do not affect the study in right ascension. The following section will be dedicated to the standard Rayleigh method and the alternative differential East/West method.

The Rayleigh method to study (first) harmonic modulations (Linsley, 1975) is directly obtained from discrete Fourier analysis. Interpreting the right ascension as the polar angle in the x,y-plane (left of Fig. 3), arrival directions can be distributed on the unit circle. The average values in the x- and y-direction are computed as $X = \frac{2}{N}\sum_{i=1}^{N}\cos\alpha_i$, $Y = \frac{2}{N}\sum_{i=1}^{N}\sin\alpha_i$.
To account for the effect of a varying exposure as described in Sect. 2, these expressions must be generalized. Normalized weights ω_i need to be introduced (similarly to what is described in (Mollerach, 2005)) containing the inverse of a measure of the detector area:

$$X = \frac{2}{\Omega}\sum_{i=1}^{N}\omega_i(\alpha_{di})\cos\alpha_i, \quad Y = \frac{2}{\Omega}\sum_{i=1}^{N}\omega_i(\alpha_{di})\sin\alpha_i, \tag{2}$$

with $\Omega = \sum_{i=1}^{N}\omega_i(\alpha_{di})$ (note that α_{di} is the right ascension corresponding to the zenith at the time of the observation of event i). The amplitude r, its uncertainty σ and the phase ϕ are computed as

$$r = \sqrt{X^2+Y^2}, \ \tan\phi = \frac{Y}{X}, \ \sigma = \sqrt{\frac{2}{N}}, \ \sigma_\phi = \frac{1}{r}\sqrt{\frac{2}{N}}. \tag{3}$$

All measured energies are corrected for atmorpheric effects according to Eq. 1 before subdividing the event set into energy bins and using the Rayleigh method. But, as argued before, at energies lower than 1 EeV trigger effects are difficult to keep under control down to the 1% level. To become insensitive to any local effect and be applicable to the energy range down to 0.2 EeV, the East/West method will be introduced taking advantage of a fundamental symmetry of the setup.

The differential East/West method makes use of the symmetry of all detector properties including atmospheric conditions for the measurement of air showers arriving from eastward and westward directions at a given point in time. The method relates the difference of the number of events observed from East (N_E) and West (N_W) sectors of the sky to

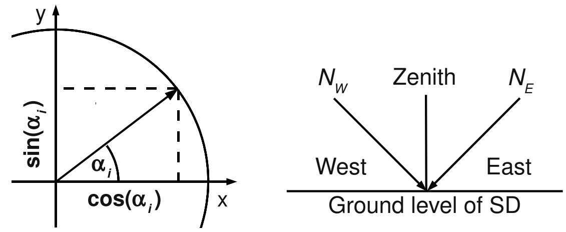

Fig. 3. Left: Visualization of the Rayleigh method; the right ascension can be distributed on the unit circle. Mean values of x and y component yield amplitude and phase (see text for details). Right: Basic principle of the differential East/West method; the difference of the number of events observed from East N_E and West N_W at a given point in time is a measure of anisotropy.

the amplitude r and phase ϕ of a first harmonic modulation (right of Fig. 3):

$$N_E(\tau) - N_W(\tau) \propto r\sin(\tau-\phi), \tag{4}$$

where τ is the local sidereal time; note that τ is directly connected to the right ascension α by $\alpha = \tau - HA$ with HA being the hour angle of the direction of view. The details of this approach are described in (Aglietta, 2009; Auger Coll., 2011).

4 Results and Discussion

The high quality SD data set taken from January 2004 until December 2009 is subdivided into six energy intervals. For the four intervals above 1 EeV the Rayleigh method is applied while the East/West method is used in the lower energy intervals.

To derive information with respect to the statistical significance of a given measurement of the amplitude, the following considerations apply: Isotropic event rate distributions in the right ascension coordinate produce non-zero amplitudes r. These amplitudes follow a Rayleigh distribution and the amplitude expected on average from isotropy is its expectation value[1], $\langle r_{\rm iso}\rangle = \sigma\sqrt{\frac{\pi}{2}} = \sqrt{\frac{\pi}{N}}$. The probability $P(>r)$ that an isotropic event sample produces an amplitude larger than a given value r, can be read from the Rayleigh cumulative distribution function $c_{\rm iso}(r<) = 1 - e^{-r^2/2\sigma^2}$. Upper limits on amplitudes at 99% C.L. can be derived according to the distribution drawn from a population characterized by an anisotropy of unknown amplitude s and phase as was shown by J. Linsley (in his 3$^{\rm rd}$ alternative) (Linsley, 1975):

$$\sqrt{\frac{2}{\pi}}\frac{1}{I_0(r^2/4\sigma^2)}\int_0^{ul}\frac{ds}{\sigma}I_0\left(\frac{rs}{\sigma^2}\right)e^{\left(-\frac{s^2+r^2/2}{2\sigma^2}\right)} = C.L. \tag{5}$$

[1]Note that the formulae in this paragraph apply to the Rayleigh method and must be slightly modified in case of the East/West method (Auger Coll., 2011).

Table 1. Results of first harmonic analysis in different energy intervals using the East/West method below 1 EeV and the Rayleigh method above 1 EeV. E = energy interval, N = number of events observed within this interval, r_{obs} and ϕ_{obs} the amplitude and phase obtained, $\langle r_{\text{iso}}\rangle$ = mean expectation from isotropy, $P(r > r_{\text{obs}})$ = probability that isotropy produces an amplitude larger than r_{obs}, s_{ul} = 99% C.L. upper limit derived from these results and $d_\perp$ = equatorial component of a dipole producing s_{ul}.

		East/West method		Rayleigh method			
E	[EeV]	$0.2-0.5$	$0.5-1$	$1-2$	$2-4$	$4-8$	>8
N		553639	488587	199926	50605	12097	5486
r_{obs}	[%]	0.4	1.2	0.5	0.8	1.8	4.1
$\langle r_{\text{iso}}\rangle$	[%]	0.5	0.5	0.4	0.8	1.6	2.4
$P(r > r_{\text{obs}})$	[%]	67	2	22	47	35	9
s_{ul}	[%]	1.0	1.3	1.1	1.8	4.3	7.7
$d_\perp$	[%]	1.3	1.7	1.4	2.3	5.5	9.9
ϕ_{obs}	[°]	262 ± 64	281 ± 20	15 ± 33	39 ± 46	82 ± 39	117 ± 27

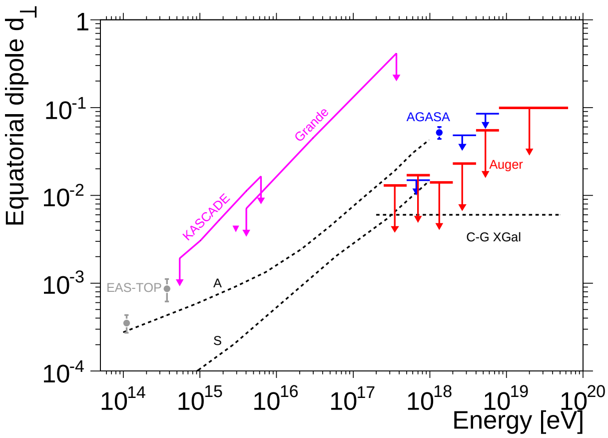

Fig. 4. Upper limits and measurements of the equatorial dipole amplitude $d_\perp$: Auger (red, bold), AGASA (blue, thin), KASCADE / KASCADE Grande (magenta), EAS-TOP (gray). Dashed lines give theoretical expectations for dipolar anisotropies due to galactic magnetic field models with different geometries (A, S) (Candia, 2003) and due to the Compton-Getting effect (C-G XGal).

The results of the periodicity analyses in each energy interval are shown in Table 1. All amplitudes r_{obs} measured are compatible with the expectation from isotropy $\langle r_{\text{iso}}\rangle$ given the current statistics (N). The probability $P(r > r_{\text{obs}})$ that isotropy produces larger amplitudes than the ones measured ranges from 2% to 67%. Thus, upper limits s_{ul} on the amplitudes are derived at the 99% C.L..

From these upper limits s_{ul} on the amplitudes of a one-dimensional modulation of the event rate in right ascension we compute the upper limits on the equatorial component of a dipolar modulation $d_\perp = r/\langle\cos\delta\rangle$. These values are compared to the results obtained by other experiments in Fig. 4. Furthermore, the predictions by galactic magnetic field models and the Compton-Getting effect mentioned in Sect. 1 are plotted.

Conclusions

We have presented the results of periodicity analyses of the event rate measured with the surface detector of the Pierre Auger Observatory in right ascension. We have set 99% C.L. upper limits on the amplitudes of first harmonic modulations in the longitude coordinate and in the equatorial component of a dipole.

Our limits already largely exclude galactic magnetic field models of symmetry type A as well as any other model predicting amplitudes larger than $\sim 2\%$ below 2 EeV. The upper limits obtained with this analysis do not confirm the measurements by AGASA on the northern hemisphere in the energy range between 1 EeV and 2 EeV (Hayashida, 1999). In Hillas (1984) a review is given on former anisotropy findings by Haverah Park, Yakutsk, Chacaltaya and others. Beyond 10^{19} eV anisotropic behaviour is reported as a result of the analysis of the phase ϕ of first harmonic modulations. This interesting topic is covered for the complete energy range of the SD in Auger Coll. (2011).

During the following years we will accumulate more events and get access to predictions by magnetic field models of symmetry type S. Given ~ 3 times larger statistics our analysis will become sensitive at the 99% C.L. to an amplitude of 0.6% predicted by the Compton-Getting effect.

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