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Analysis of the modulation in the first harmonic of the right ascension distribution of cosmic rays detected at the Pierre Auger Observatory

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Abstract: We present an update of the results of searches for first harmonic modulations in the right ascension distribution of cosmic rays detected with the surface detector of the Pierre Auger Observatory over a range of energies. The upper limits obtained provide the most stringent bounds at present above 2.5×10^{17} eV. The infill surface detector array which is now operating at the Pierre Auger Observatory will allow us to extend this search for large scale anisotropies to lower energy thresholds.

Keywords: Ultra-high energy cosmic rays, large scale anisotropies, Pierre Auger Observatory.

1 Introduction

The large scale distribution of arrival directions of cosmic rays represents one of the main tools for understanding their origin, in particular in the EeV energy range - where 1 EeV $\equiv 10^{18}$ eV. Using the large statistics provided by the surface detector (SD) array of the Pierre Auger Observatory, upper limits below 2% at 99% $C.L.$ have been recently reported [1] for EeV energies on the dipole component in the equatorial plane. Such upper limits are sensible, because cosmic rays of galactic origin, while escaping from the galaxy in this energy range, might generate a dipolar large-scale anisotropy with an amplitude at the % level as seen from the Earth [2, 3]. Even for isotropic extragalactic cosmic rays, a large scale anisotropy may be left due to the motion of our galaxy with respect to the frame of extragalactic isotropy. This anisotropy would be dipolar in a similar way to the *Compton- Getting effect* [4] in the absence of the galactic magnetic field, but this field could transform it into a complicated pattern as seen from the Earth, described by higher order multipoles [5].

Continued scrutiny of the large scale distribution of arrival directions of cosmic rays as a function of the energy is thus important to constrain different models for the cosmic rays origin. To do so, we present an update of the results of searches for anisotropies by applying first harmonic analyses to events recorded by the SD array data from 1 January 2004 to 31 December 2010, with the same criteria for event selection as in [1].

2 First harmonic analyses

2.1 Analysis methods

A dipolar modulation of *experimental origin* in the distribution of arrival times of the events with a period equal to one solar day may induce a spurious anisotropy in the right ascension distribution. Such spurious variations can be accounted for thanks to the monitoring of the number of unitary cells $n_{\rm cell}(t)$ recorded every second by the trigger system of the Observatory, reflecting the array growth as well as the dead periods of each surface detector. Here, accordingly to the fiducial cut applied to select events [6], a unitary cell is defined as an active detector surrounded by six neighbouring active detectors. For any periodicity T, the total number of unitary cells $N_{\rm cell}(t)$ as a function of time t within a period and summed over all periods, and its associated relative variations are obtained from :

$$N_{\rm cell}(t) = \sum_j n_{\rm cell}(t+jT), \quad \Delta N_{\rm cell}(t) = \frac{N_{\rm cell}(t)}{\langle N_{\rm cell}(t)\rangle}. \tag{1}$$

with $\langle N_{\rm cell}(t)\rangle = 1/T \int_0^T dt N_{\rm cell}(t)$. Hence, to perform a first harmonic analysis accounting for the slighlty non-uniform exposure in different parts of the sky, we weight each event with right ascension α_i by the inverse of the integrated number of unitary cells for computing the Fourier coefficients a and b as :

$$a = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} \frac{\cos(\alpha_i)}{\Delta N_{\rm cell}(\alpha_i^0)}, \; b = \frac{2}{\mathcal{N}} \sum_{i=1}^{N} \frac{\sin(\alpha_i)}{\Delta N_{\rm cell}(\alpha_i^0)}, \tag{2}$$

where $\mathcal{N}=\sum_{i=1}^{N}[\Delta N_{\mathrm{cell}}(\alpha_i^0)]^{-1}$ and α_i^0 is the local sidereal time expressed here in radians and chosen so that it is always equal to the right ascension of the zenith at the center of the array. The amplitude r and phase φ are then given by $r=\sqrt{a^2+b^2}$ and $\varphi=\arctan(b/a)$, and follow respectively a Rayleigh and uniform distributions in the case of an underlying isotropy.

Changes in the air density and pressure have been shown to affect the development of extensive air showers and consequently to induce a temporal variation of the observed shower size at a fixed energy [7]. Such an effect is important to control, because any seasonal variation of the modulation of the daily counting rate induces sidebands at both the sidereal and the anti-sidereal frequencies, which may lead to misleading measures of anisotropy in case the amplitude of the sidebands significantly stands out from the background noise [8]. To eliminate these variations, the conversion of the shower size into energy is performed by relating the observed shower size to the one that would have been measured at reference atmospheric conditions. Above 1 EeV, this procedure is sufficient to control the size of the sideband amplitude to well below $\simeq 10^{-3}$ [1].

Below 1 EeV, as weather effects affect the detection efficiency to a larger extent, spurious variations of the counting rate are amplified. Hence, we adopt the differential *East-West method* [9]. Since the instantaneous exposure for Eastward and Westward events is the same, the difference between the event counting rate measured from the East sector, $I_E(\alpha^0)$, and the West sector, $I_W(\alpha^0)$, allows us to remove at first order the direction independent effects of experimental origin without applying any correction, though at the cost of a reduced sensitivity. This counting difference is directly related to the right ascension modulation r by [9] :

$$I_E(\alpha^0)-I_W(\alpha^0)=-\frac{N}{2\pi}\frac{2\,\langle\sin(\theta)\rangle}{\pi\,\langle\cos(\delta)\rangle}r\sin(\alpha^0-\varphi). \quad (3)$$

where δ is the declination and θ the zenith angle of the detected events. The amplitude r and phase φ can thus be calculated from the arrival times of N events using the standard first harmonic analysis slightly modified to account for the subtraction of the Western sector to the Eastern one. The Fourier coefficients a_{EW} and b_{EW} are thus defined by :

$$a_{EW}=\frac{2}{N}\sum_{i=1}^{N}\cos(\alpha_i^0+\zeta_i),$$
$$b_{EW}=\frac{2}{N}\sum_{i=1}^{N}\sin(\alpha_i^0+\zeta_i), \quad (4)$$

where ζ_i equals 0 if the event is coming from the East or π if coming from the West (so as to effectively subtract the events from the West direction). This allows us to recover the right ascension amplitude r and the phase φ_{EW} from $r=\frac{\pi\langle\cos(\delta)\rangle}{2\langle\sin(\theta)\rangle}\sqrt{a_{EW}^2+b_{EW}^2}$ and $\varphi_{EW}=\arctan(b_{EW}/a_{EW})$. Note however that φ_{EW}, being the phase corresponding to the maximum in the differential of the East and West fluxes, is related to φ through $\varphi=\varphi_{EW}+\pi/2$.

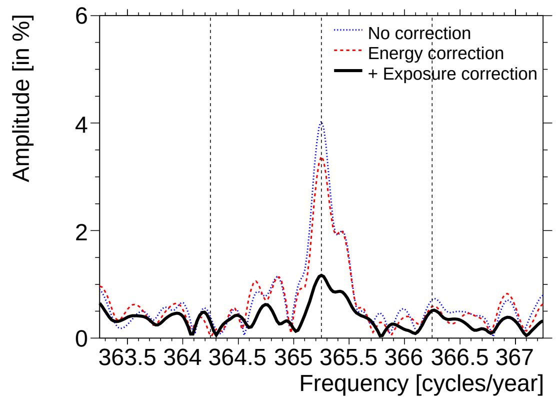

Figure 1: Amplitude of the Fourier modes as a function of the frequency above 1 EeV (see text).

2.2 Analysis of solar frequency above 1 EeV

Over a 7-years period, spurious modulations are partially compensated in sidereal time. Though, since the amplitude of an eventual sideband effect is *proportional* to the solar amplitude, it is interesting to look at the impact of the corrections at and around the solar frequency by performing the Fourier transform of the modified time distribution [10] :

$$\tilde{\alpha}_i^0=\frac{2\pi}{T_{sid}}t_i+\alpha_i-\alpha_i^0. \quad (5)$$

The amplitude of the Fourier modes when considering all events above 1 EeV are shown in Fig. 1 as a function of frequencies close to the solar one (dashed line at 365.25 cycles/year). The thin dotted curve is obtained without accounting for the variations of the exposure and without accounting for the weather effects. There is a net solar amplitude of $\sim 4\%$, highly significant. The impact of the correction of the energies is evidenced by the dashed curve within the resolved solar peak (reduction of $\simeq 20\%$ of the spurious modulations). In addition, when accounting also for the exposure variation at each frequency, the solar peak is then reduced at a level close to the statistical noise, as evidenced by the thick curve. This provides support that the variations in the exposure and weather effects are under control.

2.3 Analysis of the sidereal frequency

The amplitude r at the sidereal frequency as a function of the energy is shown in Fig. 2. The size of the energy intervals was chosen to be $\Delta\log_{10}(E)=0.3$ below 8 EeV, so that it was larger than the energy resolution (about 15% [11]) even at low energies. Above 8 EeV, to guarantee the

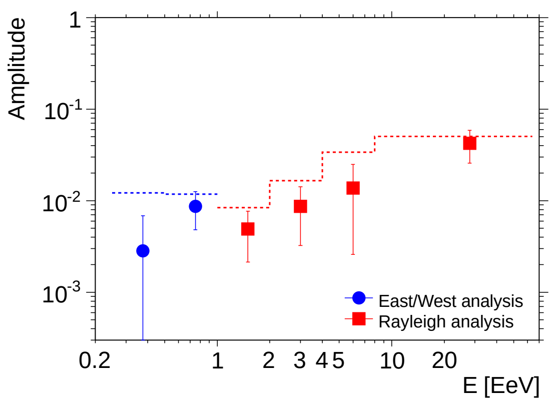

Figure 2: Amplitude of the first harmonic as a function of energy. The dashed line indicates the 99% $C.L.$ upper bound on the amplitudes that could result from fluctuations of an isotropic distribution.

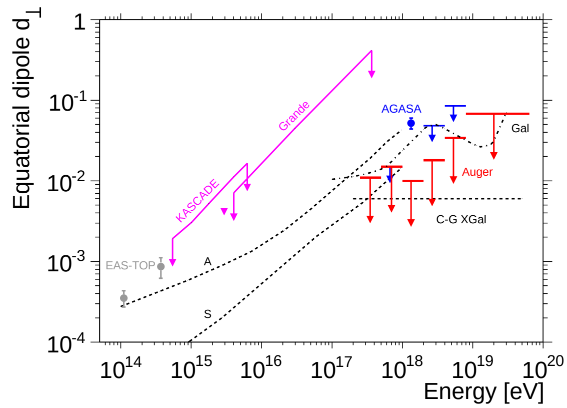

Figure 4: Upper limits on the anisotropy : equatorial dipole component $d_\perp$ as a function of energy from this analysis. Results from EAS-TOP, AGASA, KASCADE and KASCADE-Grande experiments are also displayed, in addition to several predictions (see text).

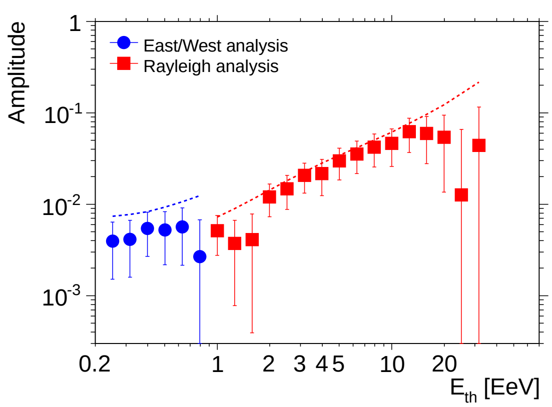

Figure 3: Same as Fig. 2, but as a function of energy thresholds.

determination of the amplitude measurement within an uncertainty $\sigma \simeq 2\%$, all events ($\simeq 5,000$) where gathered in a single energy interval. The dashed line indicates the 99% $C.L.$ upper bound on the amplitudes that could result from fluctuations of an isotropic distribution. There is no evidence of any significant signal in any energy range. The probability with which the 6 observed amplitudes could have arisen from an underlying isotropic distribution can be made by combining the amplitudes in all bins. It is found to be 45%.

Results of the analysis performed in terms of energy thresholds (strongly correlated bins) are shown in Fig. 3. They provide no further evidence in favor of a significant amplitude.

3 Upper limits

From the analyses reported in the previous Section, upper limits on amplitudes at 99% $C.L.$ can be derived according to the distribution drawn from a population characterised by an anisotropy of unknown amplitude and phase as derived by Linsley [12]. The Rayleigh amplitude measured by an observatory depends on its latitude and on the range of zenith angles considered. The measured amplitude can be related to a real equatorial dipole component $d_\perp$ by $d_\perp \simeq r/\langle\cos\delta\rangle$, where δ is the declination of the detected events, allowing a direct comparison of results from different experiments and from model predictions [1]. The upper limits on $d_\perp$ are shown in Fig. 4, together with previous results from EAS-TOP [13], KASCADE [14], KASCADE-Grande [15] and AGASA [16], and with some predictions for the anisotropies arising from models of both galactic and extragalactic cosmic ray origin. In models A and S (A and S standing for 2 different galactic magnetic field symmetries) [3], the anisotropy is caused by drift motions due to the regular component of the galactic magnetic field, while in model Gal [17], the anisotropy is caused by purely diffusive motions due to the turbulent component of the field. Some of these amplitudes are challenged by our current sensitivity. For extragalactic cosmic rays considered in model C-$G\,Xgal$ [18], the motion of our galaxy with respect to the CMB (supposed to be the frame of extragalactic isotropy) induces the small dipolar anisotropy (neglecting the effect of the galactic magnetic field).

4 Phase of first harmonic analyses

The phase of the first harmonic is shown in Fig. 5 as a function of the energy. While the measurements of the amplitudes do not provide any evidence for anisotropy, it does

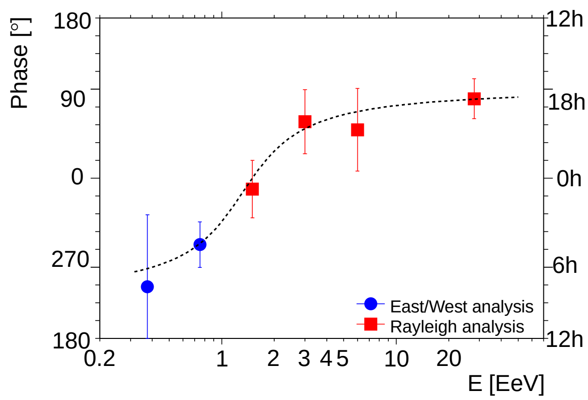

Figure 5: Phase of the first harmonic as a function of energy. The dashed line, resulting from an empirical fit, is used in the likelihood ratio test (see text).

not escape our notice that these measurements suggest a smooth transition between a common phase of $\simeq 270°$ below 1 EeV and another phase (right ascension $\simeq 100°$) above 5 EeV. This is potentially interesting, because with a real underlying anisotropy, a consistency of the phase measurements in ordered energy intervals is indeed expected with lower statistics than that required for the amplitudes to significantly stand out of the background noise [19]. To quantify whether or not a parent random distribution of arrival directions reproduces the phase measurements in adjacent energy intervals better than an alternative dipolar parent distribution, we introduced a likelihood ratio test in our previous report [1]. When applied to data points of Fig. 5, this test leads to a probability of $\sim 10^{-3}$ to accept the random distribution compared to the alternative one. Since we did not perform an *a priori* search for such a smooth transition in the phase measurements, no confidence level can be derived from this result. With an independent data set of comparable size, we will be able to confirm whether this effect is real or not.

It is important to note that an apparent constancy of phase, even though the significances of the amplitudes are relatively small, has been pointed out previously in surveys of measurements made in the range $10^{14} < E < 10^{17}$ eV [20]. A clear tendency for maxima to occur around 20 hours l.s.t. was stressed, not far from our own measurements in the energy range $2.5 \times 10^{17} < E < 10^{18}$ eV. Greisen *et al.* pointed out that most of these experiments were conducted at northern latitudes, and therefore regarded the reality of such sidereal waves as not yet established due to possible atmospheric effects leading to spurious waves. It is important that the Auger measurements are made with events coming largely from the southern hemisphere. In future analyses, we will benefit from the lower energy threshold now available at the Pierre Auger Observatory thanks to the infill array [21], allowing a better overlap with the energy ranges presented in Ref. [20]. Preliminary analyses of this data with the East-West method show also an apparent constancy of the phase.

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