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EAS-TOP: the cosmic ray anisotropy in the energy region $E_0 = 10^{14} \div 10^{15}$ eV

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Abstract: The amplitude and phase of the cosmic ray anisotropy are well established experimentally between 10^{11} eV and 10^{14} eV. The study of the evolution of the anisotropy over primary energy in the range $10^{14} - 10^{15}$ eV can provide a significant tool for the understanding of the knee in the primary spectrum. In this paper we extend the EAS-TOP result, obtained at $E_0 \approx 10^{14}$ eV, to higher energies by using the full data set (8 years of data taking), and exploiting an analysis method, the "East-West" one, which is independent from detector and atmosphere effects. Results derived at $4\ 10^{14}$ eV from the harmonic analysis of the data in solar, sidereal and anti-sidereal time are presented and discussed.

Introduction

The study of large scale anisotropies in the arrival directions of high energy cosmic rays, and of their evolution with primary energy, represents a main tool for understanding their origin and propagation. In particular, anisotropy studies in the energy region $E_0 = 10^{14} \div 10^{15}$ eV can provide a crucial insight on the origin of the "knee" in the cosmic ray spectrum (i.e., source effect versus propagation result). From the experimental point of view, the main problems are both statistical and systematical: large number of events are required, collected by long duration experiments over large areas. The detector stability is thus a crucial issue, as well as the atmospheric effects (e.g., variations of pressure and temperature). Data have to be corrected for, and, for high sensitivities, they could induce systematical effects difficult to evaluate.

Results from EAS-TOP were previously reported at $E_0 \approx 10^{14}$ eV [1]: the systematics was proven to be negligible through different tests performed on the data and through the observation of the Compton-Getting effect expected in solar time, due to the revolution of the Earth around the Sun [2]. It was shown that up to such energy the main features of the anisotropy (i.e., of the cosmic rays propagation) were similar to the ones measured in the lower energy range ($10^{11} \div 10^{14}$ eV), both with respect to amplitude ($(3 \div 6)\ 10^{-4}$) and to phase ((0 $\div$ 4) h LST) [3, 4, 5, 6, 7, 8, 9, 10, 11].

At higher energies some indications of increasing amplitude and change of phase have been reported, but the data consist mainly of upper limits [12], or marginally significant observations [13, 14, 15].

To study the possibility of extending the measurement to higher energies, we use the full EAS-TOP data set (i.e., eight full years of data) and we apply an additional cut to select a higher primary energy range (i.e., $4\,10^{14}$ eV). In this paper we present this analysis performed through a differential method (EW), based on the counting rate differences between East-ward and West-ward directions: it allows to remove counting rate variations not related to the primary beam[1], including systematic uncertainties into statistical ones (with a consequent formal loss of significance).

The experiment and the analysis

The EAS-TOP Extensive Air Shower array was located at Campo Imperatore (2005 m a.s.l., lat. $42^\circ\ 27'$ N, long. $13^\circ\ 34'$ E, INFN Gran Sasso National Laboratory). The electromagnetic detector (used for the present analysis) [16] consisted of 35 modules of scintillator counters, 10 m^2 each, distributed over an area of $\approx 10^5$ m^2. The trigger was provided by the coincidence of any four neighbouring modules (threshold $n_p \approx 0.3$ m.i.p./module), the rate being $f \approx 25$ Hz. The data under discussion have been collected between January 1992 and December 1999 for a total of 1431 full days of operation.

Class	$N_{modules}$	E_0 [TeV]	N_{EW}
I	≥ 4	100	$1.5\ 10^9$
II	≥ 12	400	$1.7\ 10^8$

Table 1: *Characteristics of the two classes of events used in the analysis: number of triggered modules, primary energy and number of collected events in the East+West sectors.*

To perform the measurement at different primary energies, a cut was applied to the events based on the number of triggered modules (see table 1); the corresponding energies were evaluated for primary protons and QGSJET hadron interaction model in CORSIKA. For each class, the counting rates every 20 minutes, in nine intervals in zenith angle θ and four different sectors of azimuthal angle ϕ (North, South, East, West) were stored. The events used in the EW analysis (see table 1) are the ones with ϕ inside $\pm 45^\circ$ around the East and West directions, respectively, and $\theta < 40^\circ$.

The number of counts measured from the East sector, $C_E(t)$, and from the West one, $C_W(t)$, at time t in a fixed interval $\Delta t = 20$ min, are related to the first derivative of $I(t)$ (total intensity) as: $\frac{dI}{dt} \simeq \frac{C_E(t)-C_W(t)}{\delta t}$, where δt is the average hour angle between the vertical and each of the two sectors (it is 1.7 h in our case).
By integrating we get the wave shape:

$$I(t_{N_{int}}) = \frac{\Delta t}{N_{int}} \sum_{i=1}^{N_{int}} i \frac{C_E(i) - C_W(i)}{\delta t} + \langle I \rangle$$

where $N_{int} = 72$ intervals of solar / sidereal / anti-sidereal time and $t_{N_{int}} = N_{int} \cdot \Delta t$.
To have a correct evaluation of the uncertainties, the first harmonic analysis is performed on the differences $D(i) = C_E(i) - C_W(i)$ and then the differential amplitude and phase are transformed into the integral ones: $r_I = \frac{r_D}{\delta t}$ and $\phi_I = \phi_D + \frac{\pi}{2}$. The uncertainties on r_I and ϕ_I are: $\sigma_{r_I} = \frac{1}{\delta t}\sqrt{\frac{2}{N_{EW}}}$ and $\sigma_{\phi_I} = \frac{\sigma_{r_I}}{r_I}$.
For the two different primary energies, the amplitudes and phases of the first harmonics are given in table 2, together with the corresponding Rayleigh imitation probabilities: $P = exp\left(-\frac{r_I^2}{2\sigma_{r_I}^2}\right)$.

Results

The harmonic analysis

At 100 TeV, concerning the analysis in solar time, the amplitude and phase ($A_{sol} = (2.8 \pm 0.8)\ 10^{-4}$, $\phi_{sol} = (6.0 \pm 1.1)$ h) are in excellent agreement with the expected ones from the Compton-Getting effect due to the revolution of the Earth around the Sun at our latitude, $A_{sol,CG} = 3.4\ 10^{-4}$, $\phi_{sol,CG} = 6.0$ h.
With respect to the sidereal time analysis, the measured amplitude and phase (with a chance probability of 0.5%) are consistent with our previous results [1, 15], that is, they confirm that the "lower energy" anisotropy observed above 10^{11} eV extends with rather constant amplitude and phase up to $E_0 \approx 10^{14}$ eV. We stress here that, even if the significance obtained by using the EW method is reduced with respect to our previous works, it is proved that the result is not affected by additional systematics uncertainties.

1. In mountain laboratories, the overall counting rate can be affected, in winter time, by snow accumulating near or above the detectors.

E_0[TeV]	$A_{sol}\ 10^4$	ϕ_{sol}[h]	P(%)	$A_{sid}\ 10^4$	ϕ_{sid}[h]	P(%)	$A_{asid}\ 10^4$	ϕ_{asid}[h]	P(%)
100	2.8 ± 0.8	6.0 ± 1.1	0.2	2.6 ± 0.8	0.4 ± 1.2	0.5	1.2 ± 0.8	23.9 ± 2.8	32.5
400	3.2 ± 2.5	6.0 ± 3.4	44.1	6.4 ± 2.5	13.6 ± 1.5	3.8	3.4 ± 2.5	22.3 ± 3.2	39.7

Table 2: *Results of the analysis of the first harmonic (i.e., amplitude, phase, and Rayleigh imitation probability) in solar (columns 2-4), sidereal (columns 5-7), and anti-sidereal time (columns 8-10).*

E_0[TeV]	$A_{sol}\ 10^4$	ϕ_{sol}[h]	P(%)	$A_{sid}\ 10^4$	ϕ_{sid}[h]	P(%)	$A_{asid}\ 10^4$	ϕ_{asid}[h]	P(%)
100	1.4 ± 0.8	7.0 ± 1.2	21.6	2.3 ± 0.8	6.3 ± 0.7	1.6	0.6 ± 0.8	-	75.5
400	1.7 ± 2.5	-	79.4	1.5 ± 2.5	-	83.5	1.2 ± 2.5	-	89.1

Table 3: *Results of the analysis of the second harmonic (i.e., amplitude, phase, and Rayleigh imitation probability) in solar (columns 2-4), sidereal (columns 5-7), and anti-sidereal time (columns 8-10). Phases are not defined when amplitudes are less than their uncertainties.*

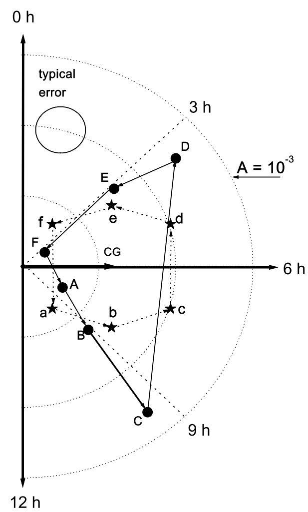

Figure 1: *Bi-monthly solar vector at 100 TeV. Capital and small letters refer respectively to the experimental and theoretical points (A,a = January + February; B,b = March + April; C,c = May + June; D,d = July + August; E,e = September + October; F,f = November + December). The statistical uncertainty of all vectors is shown as a circle.*

The bi-monthly solar vectors of the first harmonic are shown in figure 1 (black dots), together with the expected vectors (black stars) obtained from the measured solar and sidereal amplitudes. The expected anti-clockwise rotation of the solar vector is clearly visible, showing that, at any time, their composition is observed, and that the expected and measured rotations are fully compatible within the statistical uncertainties.

At 400 TeV, due to reduced statistics, the significance of the measured first solar harmonic is rather marginal, but it has to be noted that the amplitude and phase are still consistent with the expected ones for the solar Compton-Getting effect. At this energy, with statistics reduced by about a factor 10 with respect to the lower energy bin, the measured harmonic in sidereal time has an associated imitation probability around 4%. Within such a limited significance, the result indicates a change of phase (from 0.4 to 13.6 h) and an increase in amplitude (by a factor 2.5), as suggested by former experiments [13, 14, 15].

From the astronomical point of view, the measurement at 100 TeV indicates a higher counting rate from the galactic plane and a lack of events from directions corresponding to northern galactic latitudes. The change of phase at 400 TeV would correspond to an excess of events from the the north galactic Pole, inside the local galactic arm.

In table 3 the results of the second harmonic analysis are reported. Most significant is the amplitude in the lower energy class of event (comparable with the first harmonic one: $A^{II} = (2.3 \pm 0.8)\ 10^{-4}$, $\phi^{II} = (6.3 \pm 0.7)$ h LST). Such an effect was reported, at lower energies, by the Baksan group [6].

Both at 100 TeV and 400 TeV, no significant amplitude is observed in anti-sidereal time.

The wave shapes

For the 100 TeV class of data, the counting rate versus local solar, sidereal, and anti-sidereal time is shown in figures 2a,b,c, respectively. From the shape of the solar curve, the Compton-Getting effect is clearly seen, while no significant structure affects the anti-sidereal curve. The shape of the sidereal wave is in remarkable agreement with previously measured shapes, both by EAS arrays and underground muon detectors (see, e.g., the previous EAS-TOP result [1] in which a full data correction was performed).

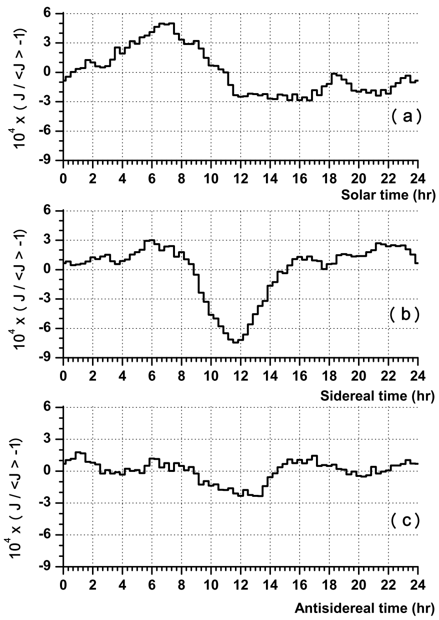

Figure 2: *The solar (a), sidereal (b) and anti-sidereal (c) waves at 100 TeV (the uncertainty for each bin, including fluctuations of the average counting rate, is about 2.9 in this scale).*

Figures 3a,b,c show the counting rate versus solar, sidereal and anti-sidereal time, respectively, for the 400 TeV class of events. A marginal solar Compton-Getting effect is still visible. The shape of the light curve in sidereal time is rather different with respect to the one obtained at 100 TeV: a signal is rising with maximum around 13-16 h LST, resulting in an increased amplitude, the chance imitation probability being 3.8%.

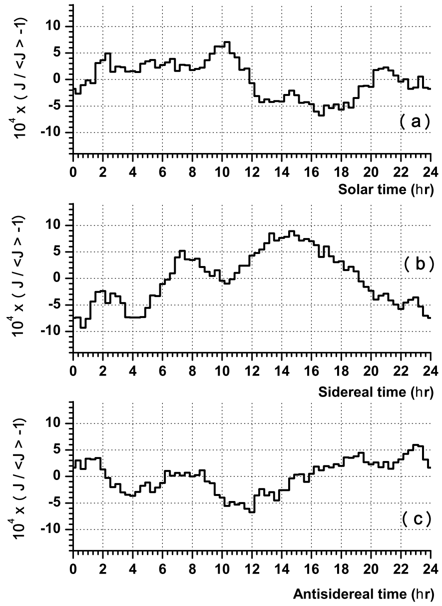

Figure 3: *The solar (a), sidereal (b) and anti-sidereal (c) waves at 400 TeV (the uncertainty for each bin, including the fluctuations of the average counting rate, is about 10.0 in this scale).*

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