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Evolution of the cosmic ray anisotropy above 10^{14} eV

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Abstract. The study of the evolution of the amplitude and phase of the cosmic ray anisotropy into the energy region $10^{14} - 10^{16}$ eV can provide a significant tool for the understanding of the "knee" of the primary spectrum. We extend here the EAS-TOP measurement performed at $E_0 \approx 10^{14}$ eV, to higher energies by using the full data set (8 years). Results derived at about 10^{14} and $4 \cdot 10^{14}$ eV are compared and discussed. Hints of increasing amplitude and change of phase above 10^{14} eV are reported.

1. Introduction

The "knee" observed at $E_0 \approx 3 \cdot 10^{15}$ eV represents a remarkable feature of the energy spectrum of cosmic rays and its characterization is therefore a main tool for the understanding of the galactic radiation. Composition studies have shown that it is related to the steepening of the lightest primaries (protons, helium, CNO) spectra [1, 2].

Such effect can be due, on the one side, to energy limits of the acceleration process at the source, namely diffusive shock acceleration in supernova remnants, generally considered to be the sources of galactic cosmic rays (see e.g. [3]). On the other side, this feature has been possibly explained in terms of a change in the cosmic ray propagation properties inside the Galaxy [4, 5]. Galactic propagation is described through diffusion models whose parameters have been obtained through composition studies (mainly from the ratio of secondary to primary nuclei) at energies well below 1 TeV (see e.g. [6, 7]). The diffusion coefficient, D, is found to increase with magnetic rigidity ($D \propto R^{0.6}$, or $D \propto R^{0.3}$ for models including reacceleration). However, no confirmation, and no information has till now been obtained at higher energies, where the main observable is represented by the large scale anisotropy in the cosmic rays arrival directions, that is known to be strictly related to the diffusion coefficient (see e.g. [8]). The study of the evolution of the anisotropy in the "knee" energy region can therefore provide a

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significant test of the diffusion models, and a valuable insight for the discrimination between the two possible explanations of the spectral steepening.

At $E_0 \approx 10^{14}$ eV the EAS-TOP results [9] demonstrated that the main features of the anisotropy (i.e. of cosmic ray propagation) are similar to the ones measured at lower energies ($10^{11} \div 10^{14}$ eV), both with respect to amplitude ($(3 \div 6) \cdot 10^{-4}$) and phase ($(0 \div 4)$ h LST). At higher energies the limited statistics does not allow to draw any firm conclusion (see [10], for an extended bibliography). We present here the EAS-TOP measurement based on the full data-set and we extend the analysis to about $4 \cdot 10^{14}$ eV.

2. The experiment and the analysis

The EAS-TOP Extensive Air Shower array was located at Campo Imperatore (2005 m a.s.l., lat. 42° 27′ N, long. 13° 34′ E, INFN Gran Sasso National Laboratory). The electromagnetic detector [12] consisted of 35 modules of scintillator counters, 10 m^2 each, distributed over an area of about 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 event 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. To select different primary energies, a cut is applied to the events based on the number of triggered modules. Events with at least 4 (12) triggered modules correspond to an average primary energy of 1.1×10^{14} eV (3.7×10^{14} eV), evaluated for primary protons and QGSJET01 hadron interaction model in CORSIKA [13].

For the analysis of the anisotropy, we adopt a method based on the counting rate differences between East-ward and West-ward directions, that allows to remove counting rate variations of atmospheric origin. The events used in the analysis are the ones with azimuth angle ϕ inside $\pm 45°$ around the East and West directions, and zenith angle $\theta < 40°$. The number of collected events in the East+West sectors is 1.5×10^9 (1.7×10^8) at 1.1×10^{14} eV (3.7×10^{14} eV). The difference between 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), is related to the first derivative of the intensity $I(t)$ as: $\frac{dI}{dt} \simeq D(t) = \frac{C_E(t) - C_W(t)}{\delta t}$ where δt is the average hour angle between the vertical and each of the two sectors (1.7 h in our case). The harmonic analysis is performed on the differences $D(t)$; the amplitudes and phases of the variation of $I(t)$ are obtained through the integration of the corresponding terms of the Fourier series [14].

3. Results

The harmonic analysis has been performed in solar, sidereal and anti-sidereal time. For the two different primary energies, the reconstructed amplitudes and phases of the first and second harmonics are shown in table 1, together with their Rayleigh imitation probabilities (P).

E_0[eV]	A^I_{sol} 10^4	ϕ^I_{sol}[h]	P^I_{sol}(%)	A^I_{sid} 10^4	ϕ^I_{sid}[h]	P^I_{sid}(%)	A^I_{asid} 10^4	ϕ^I_{asid}[h]	P^I_{asid}(%)
$1.1 \cdot 10^{14}$	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
$3.7 \cdot 10^{14}$	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
	A^{II}_{sol} 10^4	ϕ^{II}_{sol}[h]	P^{II}_{sol}(%)	A^{II}_{sid} 10^4	ϕ^{II}_{sid}[h]	P^{II}_{sid}(%)	A^{II}_{asid} 10^4	ϕ^{II}_{asid}[h]	P^{II}_{asid}(%)
$1.1 \cdot 10^{14}$	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
$3.7 \cdot 10^{14}$	1.7 ± 2.5	-	79.4	1.5 ± 2.5	-	83.5	1.2 ± 2.5	-	89.1

Table 1. *Results of the analysis of the first (amplitude A^I, phase ϕ^I, and Rayleigh imitation probability P^I) and second harmonic (A^{II}, ϕ^{II}, P^{II}) in solar, sidereal and anti-sidereal time. Phases are not defined when amplitudes are smaller than their uncertainties.*

– Concerning the **first harmonic**:

(a) At $1.1 \cdot 10^{14}$ **eV**, from the analysis in solar time, the obtained amplitude and phase ($A^I_{sol} = (2.8 \pm 0.8) \cdot 10^{-4}$, $\phi^I_{sol} = (6.0 \pm 1.1)$ h, $P^I_{sol} = 0.2\%$) are in excellent agreement with the expected ones from the Compton-Getting effect [15] due to the revolution of the Earth around the Sun: at our latitude $A_{sol,CG}$=$3.0 \cdot 10^{-4}$, $\phi_{sol,CG}$=6.0 h. With respect to the sidereal time analysis, the measured amplitude and phase ($A^{I}_{sid} = (2.6 \pm 0.8) \cdot 10^{-4}$, $\phi^{I}_{sid} = (0.4 \pm 1.2)$ h LST), with imitation probability $P^{I}_{sid} = 0.5\%$, confirm the previous EAS-TOP result [9].

(b) At $3.7 \cdot 10^{14}$ **eV** the amplitude and phase of the first harmonic in solar time are still consistent with those expected for the Compton-Getting effect, although, due to the reduced statistics, the chance imitation probability is rather high. Concerning the analysis in sidereal time, we obtain $A^{I}_{sid} = (6.4 \pm 2.5) \cdot 10^{-4}$, $\phi^{I}_{sid} = (13.6 \pm 1.5)$ h LST, with an imitation probability of about 3.8%. This indicates therefore a change of phase (from 0.4 to 13.6 h) and an increase of amplitude (by a factor 2.5) with respect to the first harmonic measured at $1.1 \cdot 10^{14}$ eV.

– Concerning the **second harmonic** most significant ($P^{II}_{sid} = 1.6\%$) is the amplitude observed in sidereal time in the lower energy class of events (comparable with the first harmonic one: $A^{II}_{sid} = (2.3 \pm 0.8) \cdot 10^{-4}$, $\phi^{II}_{sid} = (6.3 \pm 0.7)$ h LST) (see also [11]).

Both at $1.1 \cdot 10^{14}$ eV and $3.7 \cdot 10^{14}$ eV, no significant amplitude is observed in anti-sidereal time, showing that no additional correction is required due to residual seasonal effects.

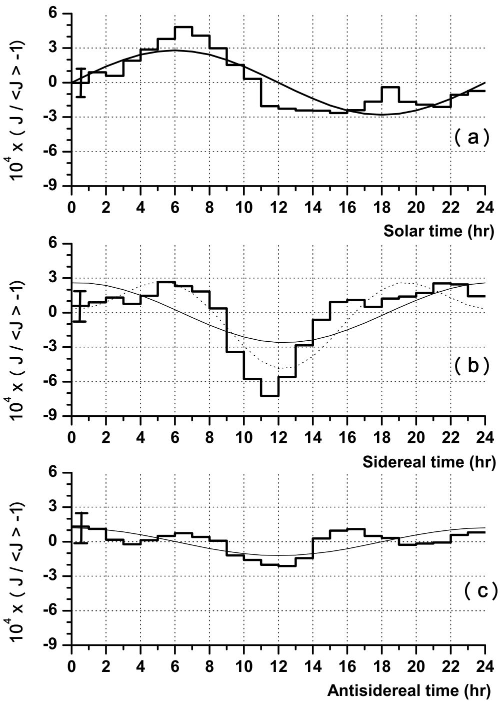

Figure 1. *Thick black lines: counting rate curves in solar (a), sidereal (b) and anti-sidereal (c) time at* $1.1 \cdot 10^{14}$ *TeV. Results from the first harmonic analysis are also shown (light lines); for the sidereal time curve, the combination of I and II harmonics is superimposed as a dotted line.*

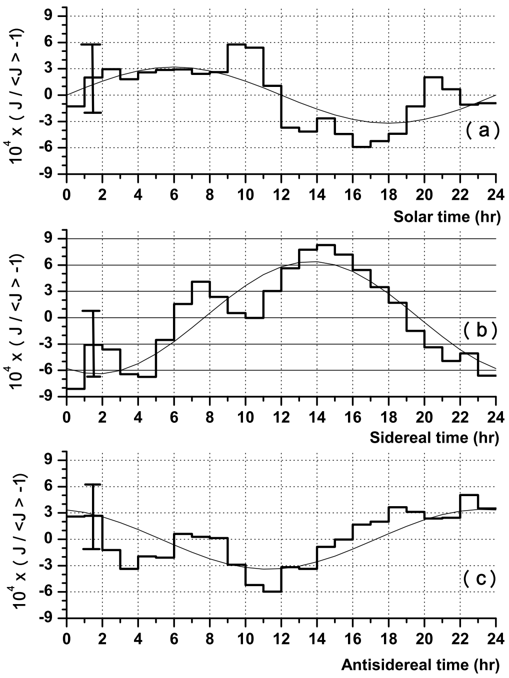

Figure 2. *Thick black lines: counting rate curves in solar (a), sidereal (b) and anti-sidereal (c) time at* $3.7 \cdot 10^{14}$ *TeV. The curves resulting from the first harmonic analysis are also shown (light black lines). The statistical uncertainty for each bin is given in the first one.*

Besides the harmonic analysis, it is interesting to visualize the variations of the cosmic ray intensity versus time, $I(t)$, as reconstructed by integration of the East-West differences, $D(t)$. They are shown in figs. 1 and 2, for the classes of events at $1.1 \cdot 10^{14}$ eV and $3.7 \cdot 10^{14}$ eV, respectively (a,b,c for solar, sidereal, and anti-sidereal time scales). As already shown by the harmonic analysis, at both energies the curves in solar time are dominated by the Compton-Getting effect due to the motion of the Earth, and no modulation is visible in the anti-sidereal time scale. A main difference is observed in the sidereal time curves: while the shape of the curve at $1.1 \cdot 10^{14}$ eV is in remarkable agreement with the EAS and muon measurements reported at and below 100 TeV, the curve related to the highest energy class of events is characterized by a broad excess around 13-16 h LST.

4. Conclusions

High stability data obtained from long time observations (8 years) from the EAS-TOP array confirm the amplitude and phase of the cosmic ray anisotropy already reported at 10^{14} eV: $A^I_{sid} = (2.6 \pm 0.8) \cdot 10^{-4}$, $\phi^I_{sid} = (0.4 \pm 1.2)$ h LST, with Rayleigh imitation probability $P^I_{sid} = 0.5\%$. The result is supported by the observation of the Compton-Getting effect due to the revolution of the Earth around the Sun, and by the absence of anti-sidereal effects. It confirms the homogeneity of the anisotropy data over the energy range 10^{11}-10^{14} eV.

At higher energies (around $4 \cdot 10^{14}$ eV) the observed anisotropy shows a larger amplitude, $A^I_{sid} = (6.4 \pm 2.5) \cdot 10^{-4}$, and a different phase, $\phi^I_{sid} = (13.6 \pm 1.5)$ h LST, with an imitation probability of 3.8%. The statistical significance is still limited, but the measurement has the highest sensitivity with respect to previous experiments at these energies, and it is not in contradiction with any of them.

The dependence of the anisotropy amplitude over primary energy ($A \propto E_0^{\delta}$) deduced from the present two measurements can be represented by a value of $\delta = 0.74 \pm 0.41$. Therefore, at least in the energy range $(1-4) \cdot 10^{14}$ eV, such dependence is compatible with that of the diffusion coefficient as derived by composition measurements at lower energies.

On another side, the sharp increase of the anisotropy above 10^{14} eV may be indicative of a sharp evolution of the propagation properties, and therefore of the diffusion coefficient just approaching the steepening of the primary spectrum. This opens the problems of obtaining an improved theoretical and experimental description of the whole evolution of the diffusion processes vs primary energy, and understanding how such evolution could affect the energy spectra at the "knee". From the experimental point of view, the extension of the anisotropy measurements with high sensitivity to and above 10^{15} eV will be of crucial significance.

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