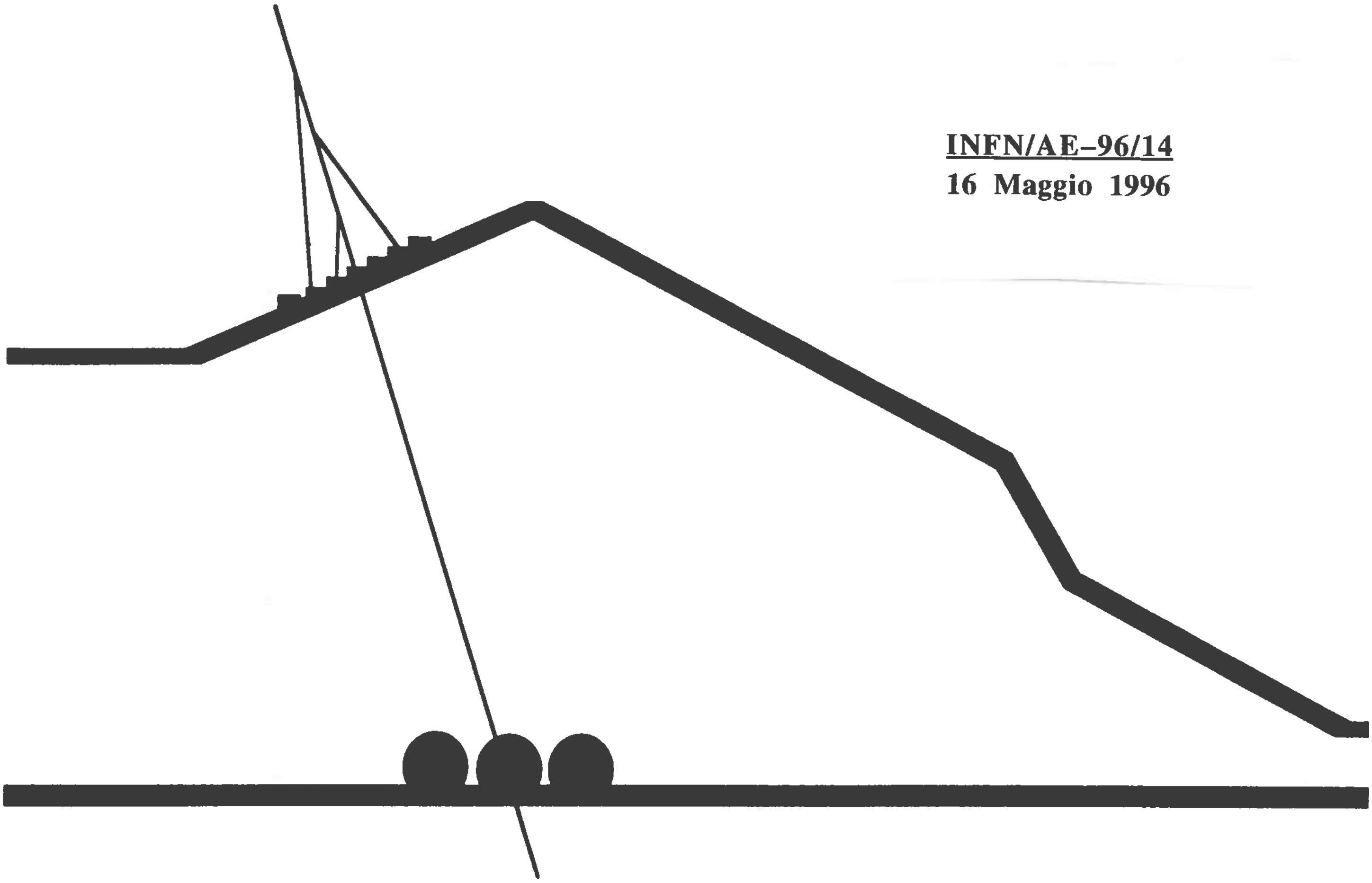

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A measurement of the solar and sidereal cosmic ray anisotropy at $E_0 \sim 10^{14}$ eV

EAS-TOP COLLABORATION

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Abstract

The results of the measurement of the cosmic ray solar and sidereal anisotropies at primary energy $E_0 \approx 10^{14}$ eV performed by the EAS-TOP Extensive Air Shower array (Campo Imperatore, National Gran Sasso Laboratories, 2005 m a.s.l., 42.5 deg. lat. North) are presented. The measurement includes four years of data taking (1990,'92,'93,'94) for a total of 1.3 10^9 events, and is performed at two different mean primary energies: $\overline{E_0^v} \approx 1.5\ 10^{14}$ and $\overline{E_0^i} \approx 2.5\ 10^{14}$ eV. The two results are compatible (within 2 s.d.) and can therefore be combined. The obtained amplitude and phase of the first harmonic in sidereal time are (in the equatorial plane):

$A_{sid,\delta=0^0}(\overline{E_0} \approx 2.10^{14}\ \mathrm{eV}) = (3.73 \pm 0.57)\ 10^{-4}$, and

$\varphi_{sid} = 1.82 \pm 0.49$ h lst,

with significance 6.5 s.d..

The amplitude of the anisotropy exhibits the expected cosδ dependence.

A first harmonic in solar time compatible with the expected Compton-Getting effect due to the motion of revolution of the Earth around the Sun is observed with significance 7.3 s.d. The corrisponding measured amplitude and phase (also in the equatorial plane) are:

$A_{sol,\delta=0^0} = (4.06 \pm 0.55)\ 10^{-4}$, and $\varphi_{sol} = 4.92 \pm 0.53$ h,

the expected values being $4.7 \cdot 10^{-4}$ and 6.0 h.

Different checks of stability of the detectors and consistency of the data are presented.

Subject heading: cosmic rays

1 Introduction.

The amplitude and phase of the sidereal anisotropy, together with the energy spectrum and the chemical composition, are the observables that characterize the primary cosmic radiation. Their measurements, and the data on their variations over a wide range of primary energies are expected to provide significant information on the cosmic ray origin and propagation.

The existing data on the sidereal anisotropy of cosmic rays cover with good consistency the energy range between $\sim 10^{12}$ and $\sim 5.10^{13}$ eV (Fenton et al. 1976; Gombosi et al. 1975; Alexeenko et al. 1981; Andreyev et al. 1987; Nagashima et al. 1989; Bergamasco et al. 1990; Aglietta et al. 1993a, including preliminary data of this experiment). Over such energy range the amplitude and phase of the first harmonic are rather constant at the level: $A_{sid} = (5. - 10.)\ 10^{-4}$, and $\varphi_{sid} = (23 - 2.6)$ h lst. Measurements are performed: at the lower energies through the detection of muons underground, and at $E_0 > 10^{13}$ eV through the detection of the electromagnetic component of the Extensive Air Showers (EAS) produced by the cosmic ray interactions in the atmosphere. At higher primary energies ($E_0 > 10^{14}$ eV) the anisotropy could provide an indication of the origin of the steepening of the spectrum observed at $E_0 \approx 2 \cdot 10^{15}$ eV, and prove its proposed connection with the cosmic ray propagation in the Galaxy. In fact at such energies larger amplitudes have been reported (see e.g. the reviews of Kiraly et al. 1979 and Linsley 1983 and the more recent data of Alexeenko et al. 1993), but the statistical uncertainties are still large.

Besides the statistical problems, due to the smallness of the effect, and the necessity of long term observations, the detectors' operation play an important role, and the data have to be submitted to severe checks of stability and consistency.

In this paper we report the results of the study of the cosmic ray anisotropy performed by means of the EAS-TOP array (Aglietta et al. 1993b) between 1990 and 1994; the total number of collected events is $1.3\ 10^9$ (preliminary results have been presented in Aglietta et al. 1993a, 1995). As a first step, we concentrate our analysis of the experimental data on the first harmonic component.

We discuss the instrumental stability and the consistency of the results, proved by:

- the absence of significant anisotropies in antisidereal time;

- the observation of the anisotropy in solar time due to the Compton-Getting effect (Compton & Getting 1935), connected to the motion of the Earth around the Sun;

- the correct rotation of the monthly vector of the anisotropy, as resulting from the combination of the sidereal and solar anisotropies;

- the time shift of the anisotropy observed in angular sectors: vertical (i.e. $\theta < 20^0$), and inclined $\theta > 20^0$ in different directions: North, South, East, West. This analysis allows to separate real anisotropies (that have to be seen at different times in the East and West directions) from instrumental effects (that are expected to be dominated by the temperature and therefore are correlated in solar time).

The latter analysis, by exploiting the absorption of Extensive Air Showers in the atmosphere, further provides the possibility of performing the study at two different mean primary energies: $\overline{E_0^v} \approx 1.5\ 10^{14}$ eV and $\overline{E_0^i} \approx 2.5\ 10^{14}$ eV.

2 The data and the analysis.

EAS-TOP (Aglietta et al. 1986) is an Extensive Air Shower array located above the underground Gran Sasso Laboratories, at the altitude of 2005 m a.s.l., 42.5 deg. lat. North. It includes detectors of the different EAS components: electromagnetic, muon, hadron, atmospheric Cerenkov light. For the present analysis we are interested in the electromagnetic detector data. This is made of 35 modules of scintillator detectors, 10 m^2 each, 4 cm thick, distributed over an area of $\approx 10^5\ m^2$ (Aglietta et al. 1993b). The triggering condition is provided by the fourfold coincidence of any four neighbouring modules, discriminated at 0.3 of the energy loss level of a minimum ionizing particle, i.e. ≈ 3 MeV. The trigger rate is $f \approx 25$ Hz. The EAS arrival directions, corresponding to the arrival directions of the primary particle, are measured through the time of flight technique with accuracy $\sigma_\psi = 2.5^0$. Every 20 minutes the numbers of counts inside a cone with opening angle $\theta = 20^0$ around the zenith, and in 512 sectors (of $\Delta\varphi = 5.6^0$ in azimuth and $\Delta\theta = 5^0$ in zenith angle, for $20^0 < \theta < 60^0$) are stored, together with the atmospheric pressure and the air temperature.

In order to perform independent analysis, the barometric coefficient is measured separately for each sector. The dependence of the barometric coefficient on the zenith angle has been verified to follow the $sec\theta$ law (deviating only above 60^0): $\beta = dn/dx \approx -0.77 sec\theta$ %mb^{-1} (Aglietta et al. 1995). All data are therefore corrected for the atmospheric pressure, with the regression coefficient obtained at the appropriate zenith angle for each individual run, i.e. about two weeks of data taking. Events are grouped in five classes: vertical ($\theta < 20^0$), inclined ($20^0 < \theta < 60^0$): E ($45^0 < \varphi < 135^0$), S ($135^0 < \varphi < 225^0$), W ($225^0 < \varphi < 315^0$), N ($315^0 < \varphi < 45^0$). The average primary energies corresponding to the two average ("vertical" and "inclined") zenith angles of observation: $\overline{\theta^v}(0^0 < \theta < 20^0)=12.7^0$ and $\overline{\theta^i}(20^0 < \theta < 60^0)=32^0$ are respectively[1] : $\overline{E_0^v} \approx 1.5\ 10^{14}$ eV and $\overline{E_0^i} \approx 2.5\ 10^{14}$ eV (1).

3 The Results.

3.1 The solar time analysis

The results of the analysis of the first harmonic in solar time, for the four years data, are shown in tab.1 separately for the different regions of zenith and azimuth angles. A significant first harmonic is seen in all data sets. These data have to be compared with the expected amplitude and phase of the Compton-Getting (CG) effect due to the motion of the Earth around the Sun that, at our latitude, are: $A_{sol} = 3.4 \cdot 10^{-4}$, $\varphi_{sol} = 6.0$ h.

It is interesting to compare the phases of the harmonics measured for $20^0 < \theta < 60^0$ in the East and West directions: the genuine CG effect is expected to be seen about 2.5 h before 6 h in the East direction, and 2.5 h after 6 h in the West direction. A shift is indeed observed, of about ±1.5 h (with errors ± 0.8 h) around phase 4.6 h, at which the effect is seen in the vertical ($\theta < 20^0$) sample.

By combining through a maximum likelyhood procedure the measurements in the five sectors, assuming the $\cos\delta$ (δ= mean declination of the showers of the sector) dependence of the effect, we obtain for the amplitude and phase of the first harmonic (at the equatorial plane):

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[1] The electromagnetic EAS array is sensitive to the total number of particles (dominated by e^+ and e^-) at the observation level (Ne); the conversion factor from Ne to primary energy E_0, for primary protons and vertical incidence, at the EAS-TOP observation level, is $E_0(eV)=1.2\ 10^{10} Ne^{0.87}$. This, together with the absorption length of EAS in the atmosphere (λ=222 gr/cm^2) (Aglietta et al. 1993c, EAS-TOP Coll. 1995) provides the average primary energy as a function of zenith angle.

	$A \times 10^{+4}$	φ (h)	A/σ
$\theta < 20^0$	1.96 ± 0.61	4.67 ± 1.19	3.2
$20^0 < \theta < 60^0$			
N	3.88 ± 0.97	4.24 ± 0.96	4.0
S	3.56 ± 1.02	5.64 ± 1.09	3.5
E	4.44 ± 0.99	3.68 ± 0.85	4.5
W	4.62 ± 1.00	6.12 ± 0.82	4.6

Table 1: *Results of the analysis of the first harmonic in solar time.*

$A_{sol,\delta=0^0} = (4.06 \pm 0.55) \cdot 10^{-4}$, and $\varphi_{sol} = 4.92 \pm 0.5$ h,
the expected values being $4.7 \cdot 10^{-4}$ and 6.0 h.

The significance of the signal is 7.3 s.d., and a χ^2 test of compatibility between the measured and the expected vectors gives $\chi^2 = 2.3$/d.f..

Such value of χ^2, together with the ≈ 2 s.d. differences in the E-W shifts in time with respect to the expected ones, indicate the presence of uncorrected systematic effects, however bounded to less than two s.d. (see also the antisidereal-time analysis).

3.2 The sidereal time analysis

For the *vertical* sample ($\theta < 20^0$) the counting rate vs. the local sidereal time in 20' time intervals is shown in fig. 1, from which the first harmonic (significance 5.9 s.d.) over the fluctuations in the individual channels is clearly seen.

The results of the first harmonic analysis in sidereal time for all angular samples are shown in tab. 2.

Among *inclined* showers, most significant (> 4 *s.d.*) is the amplitude of the signal at the South, while no signal is seen at the North. In fact the expected dependence of the amplitude of the anisotropy, if of vectorial character, on the declination of observation (δ) is $A \propto \cos\delta$.

The effects in the East and West directions have lower significances but, as for the case of the solar time analysis, are shifted between each other of 3 ± 2.3 hours.

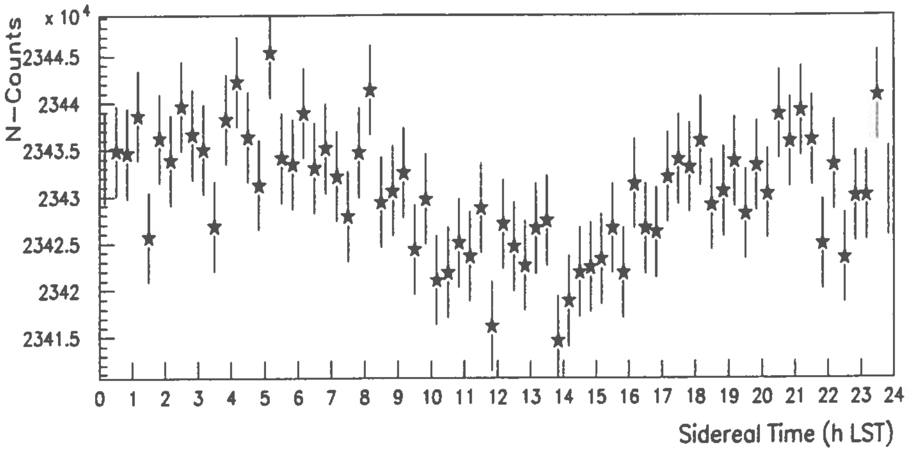

Figure 1: *Vertical events counting rate (in 20' bins) vs. the local sidereal time.*

The dependence of the amplitude on the declination, showing the cosδ dependence, is shown in fig. 2.

Through a maximum likelyhood fit of the inclined data, that takes into account such cosδ dependence of the amplitude, we obtain the best fit of the first harmonic of the sidereal anisotropy (at the equatorial plane):

$A_{sid,\delta=0^0} = (3.22 \pm 0.67) \cdot 10^{-4}$, $\varphi_{sid} = 0.95 \pm 0.68$ h lst.

In the bin corresponding to the declination of the vertical data this gives:

$A_{sid} = (2.36 \pm 0.49) \cdot 10^{-4}$, i.e. about 1.5 s.d. lower than the vertical measurement (shown in first lane of tab. 2).

The two measurements are obtained at two slightly different primary energies: $\overline{E_0^v} \approx 1.5\ 10^{14}$ eV and $\overline{E_0^i} \approx 2.5\ 10^{14}$ eV (see (1)).

Their difference ($\approx$ 2 s.d. including the phase difference) is not significant, and we can combine all measurements together to obtain a global information at primary energy $\overline{E_0} \approx 2.10^{14}$ eV:

$A_{sid,\delta=0^0}$ ($\overline{E_0} \approx 2.10^{14}$ eV) $= (3.73 \pm 0.57) \cdot 10^{-4}$, and

$\varphi_{sid} = 1.82 \pm 0.49$ h lst,

	$A \times 10^{+4}$	φ (h lst)	A/σ
$\theta < 20^0$	3.60 ± 0.61	2.77 ± 0.65	5.9
$20^0 < \theta < 60^0$			
N	0.63 ± 0.97	12.48 ± 5.95	0.64
S	4.37 ± 1.02	0.60 ± 0.89	4.3
E	3.06 ± 0.99	23.52 ± 1.24	3.1
W	1.90 ± 1.00	2.58 ± 2.00	1.9

Table 2: *Results of the analysis of the first harmonic in sidereal time*

with significance 6.5 s.d..

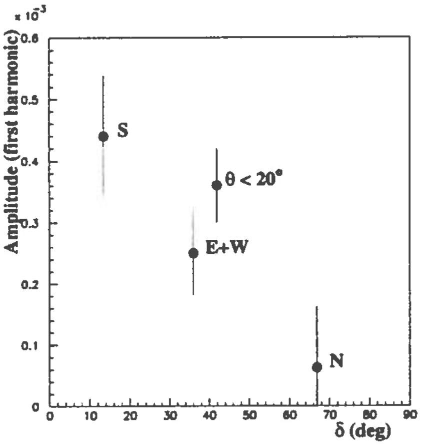

Figure 2: *Amplitude of the first harmonic in sidereal time vs. the mean declination of observation in the different sectors (the East and West data, refering to the same declination, are averaged).*

3.3 The anti-sidereal time analysis

As a usual test of absence of solar effects in the sidereal measurements, the data are analyzed in anti-sidereal time. The results of such first harmonic analysis are shown in tab.3. We verify that no significant first harmonic is observed at a level exceeding 2.2 s.d., i.e. a much lower level than for the solar and sidereal amplitudes. In principle the sidereal

	$A \times 10^{+4}$	φ (h ast)	A/σ
$\theta < 20^0$	1.34 ± 0.61	5.19 ± 1.74	2.2
$20^0 < \theta < 60^0$			
N	2.03 ± 0.97	8.59 ± 1.83	2.1
S	1.91 ± 1.02	9.43 ± 2.03	1.8
E	1.26 ± 0.99	7.13 ± 3.01	1.3
W	1.56 ± 1.00	7.36 ± 2.44	1.6

Table 3: *Results of the analysis of the first harmonic in anti-sidereal time*

amplitude and phase could be corrected for such effect (Farley & Storey 1954), but due to its smallness and the uncertainty on its origin, we will not apply such correction.

3.4 Rotation of the solar vector

Due to the combination of the solar and sidereal anisotropies, the solar vector is expected to rotate clockwise during the year. This is a significant check, that also guaranties the reliability of the data. The monthly solar vectors of the first harmonic, averaged over the four years of measurement, are shown in fig. 3 (a), together with the mean expected vectors (b) obtained from the measured solar and sidereal amplitudes.

To check the expected rotation, a χ^2 is calculated:

$$\chi^2 = \sum_{i=1}^{12} \frac{|\overline{A_i}^{meas} - \overline{A_i}^{exp}|^2}{(1.5\ |\overline{\sigma}_{\overline{A_i}}|)^2} \tag{1}$$

(where $\overline{A_i}^{meas} - \overline{A_i}^{exp}$ is the vector difference between the measured and expected monthly solar vectors, and $\overline{\sigma}_{\overline{A_i}}$ is the error of the monthly measured vector, also shown in fig. 3a; the factor 1.5 accounts for ≈ 70 % probability in the bidimensional analysis). The obtained value of χ^2/d.f. is 1.25. In fig. 4 the distribution of the χ^2/d.f. obtained for further 10^5 random combinations of the monthly measured and calculated vectors is shown: the value obtained for the real data, besides being compatible with the expectations, represents the minimum of such distribution, thus showing that the rotation of the vector is correct.

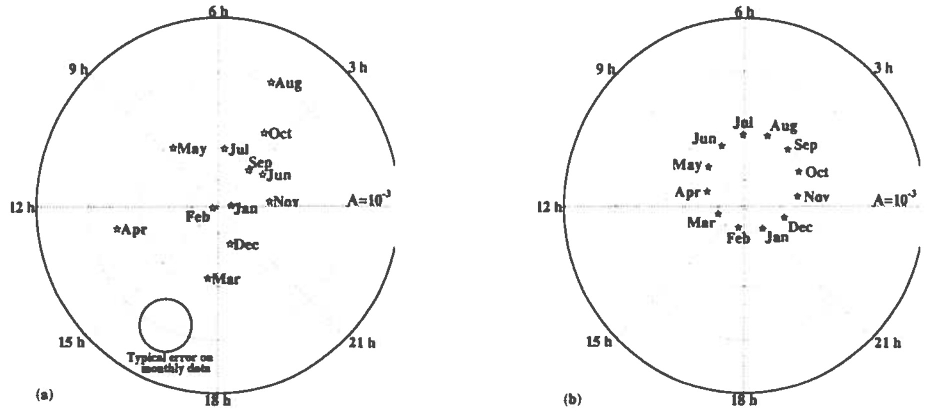

Figure 3: *Measured monthly solar vector of the anisotropy (a). The expected one (b) is calculated by combining for each month the annual sidereal and solar measured vectors.*

4 Conclusions.

The present measurement of the cosmic ray anisotropy obtained by means of the EAS-TOP array (2005 m a.s.l., 42.5 deg. lat. North) at $E_0 \approx 10^{14}$, including four years of data taking, and a total of 1.3 10^9 EAS events gives the following results:

- for vertical events, i.e. mean primary energy $\overline{E_0^v} \approx 1.5\ 10^{14}$ eV, the amplitude and phase of the first sidereal harmonic are:

  A_{sid} ($\overline{E_0} \approx 1.5\ 10^{14}$ eV) = $(3.60 \pm 0.61)\ 10^{-4}$, and

  $\varphi_{sid} = 2.77 \pm 0.65$ h lst,

  with significance 5.9 s.d..

  The amplitude converted to the equatorial plane with the cosδ law gives:

  $A_{sid,\delta=0^0}$ ($\overline{E_0} \approx 1.5\ 10^{14}$ eV) = $(4.83 \pm 0.82)\ 10^{-4}$.

- for events with zenith angle $\theta > 20^0$, i.e. $\overline{E_0^i} \approx 2.5\ 10^{14}$ eV, by using the measured cosδ dependence of the amplitude, we obtain (at the equatorial plane):

  $A_{sid,\delta=0^0}$ ($\overline{E_0} \approx 2.5\ 10^{14}$ eV) = $(3.22 \pm 0.67) \cdot 10^{-4}$ and

  $\varphi_{sid} = 0.95 \pm 0.68$ h lst,

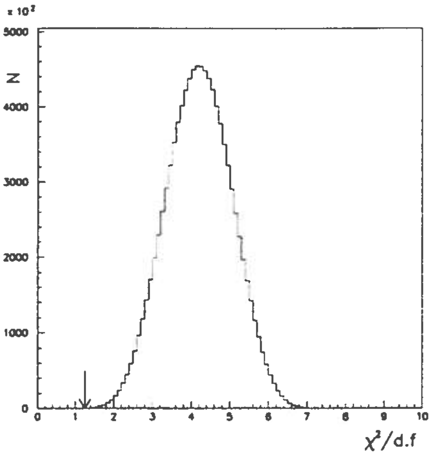

Figure 4: *Distribution of the* χ^2 *obtained for* 10^5 *random combinations of the measured and calculated monthly solar vectors. The arrow indicates the value corresponding to the real data, showing its correspondance with the minimum value of* χ^2.

with significance 4.8 s.d..

- these two data are compatible within ≈ 2 s.d., and together with the results of the quoted lower energy experiments, show that the first harmonic of the cosmic ray anisotropy is nearly constant in amplitude and phase from $E_0 \approx 10^{12}$ eV to $E_0 \approx 10^{14}$ eV, and exclude an increase of the c.r. anisotropy around 10^{14} eV.

- by using the vertical and inclined data together, as belonging to the same sample, we obtain at average primary energy $\overline{E_0} \approx 2.10^{14}$ eV, at the equatorial plane:

  $A_{sid,\delta=0^0}(\overline{E_0} \approx 2.10^{14}\ \mathrm{eV}) = (3.73 \pm 0.57) \cdot 10^{-4}$,

  $\varphi_{sid} = 1.82 \pm 0.49$ h lst,

  with significance 6.5 s.d..

- a signal compatible with the Compton-Getting effect due to the motion of revolution of the Earth is seen. The measured amplitude and phase of the first harmonic in solar time are (at the equatorial plane):

$A_{sol,\delta=0^0} = (4.06 \pm 0.55)\cdot 10^{-4}$, and $\varphi_{sol} = 4.92 \pm 0.5$ h, with significance 7.3 s.d.; the expected values, due to the Compton-Getting effect, being $4.7 \cdot 10^{-4}$ and 6.0 h.

The consistency of the data is proved by:
i) the absence of significant anisotropies in antisidereal time;
ii) the consistency of the phases of the solar and sidereal anisotropies observed in the East and West directions;
iii) the correct rotation of the solar vector during the year, as expected from the combination of the measured solar and sidereal anisotropies;
iv) the observation of the expected solar anisotropy due to the motion of revolution of the Earth around the Sun.

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