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

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OUTLINE

Large scale anisotropies

- Essential tool for understanding CR origin and propagation
- At $10^{14} - 10^{15}$ eV can provide insight on the origin of the "knee" of the spectrum (source effect or propagation result)

From the experimental point of view (EAS arrays)

- Main problems are both statistical and systematical:
  - large number of events are required,
  - collected by long duration experiments
  - over large areas.
- Detector stability is a crucial issue, and 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.

LARGE SCALE ANISOTROPIES and EAS-TOP PAST RESULTS

AT 100 TeV

- Data correction for atmospheric effects
- Harmonic analysis on corrected data
- Observation of significant anisotropy (10 "σ" level) in sidereal time ($A_{sid} = (3.4 \pm 0.3)\ 10^{-4}$, $\phi_{sid} = (3.3 \pm 0.4)$ h LST)
- Observation of expected Compton Getting effect (due to Earth revolution around Sun) in solar time and absence of anti-sidereal signal insured the reliability of the observation

The EAS-TOP result extended the anisotropy measurement up to 100 TeV, showing the constancy (in amplitude and phase) with respect to lower energy ones (amplitude ($(3 \div 6)\ 10^{-4}$) and phase ($(0 \div 4)$ h LST) between 10^{11} and 10^{14} eV

LARGE SCALE ANISOTROPIES and EAS-TOP PAST RESULTS

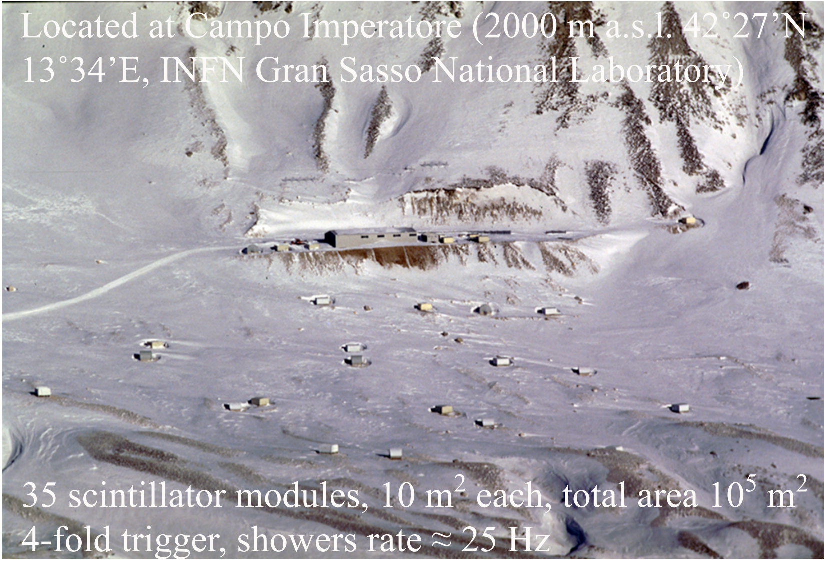
AT HIGHER ENERGIES, i.e., ABOVE 400 TeV

- Same analysis technique as for 100 TeV (i.e., correction for pressure effects on EAS)
- Observation of increasing amplitudes in sidereal harmonic analysis, but with a limited significance level
- Upper limits given

Present analysis

- We use the full EAS-TOP data set (i.e., eight full years of data)
- We apply cuts to select two primary energies (100 and 400 TeV)
- We adopt a differential method (EW), based on the counting rate differences between East-ward and West-ward directions, to remove spurious counting rate variations (no need for atmospheric corrections)

THE EAS-TOP ARRAY



THE DATASET

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

- 1431 full days between January 1992 and December 1999
- Counting rates every 20 min
- ϕ inside $\pm 45°$ around the East and West directions
- $\theta < 40°$
- Two primary energies: cuts in number of triggered modules (E_0 evaluated for primary protons and QGSJET hadron interaction model in CORSIKA)

THE EAST-WEST METHOD

$$\frac{dI}{dt} \simeq \frac{C_E(t) - C_W(t)}{\delta t}$$

$C_{E,W}(t)$=n. of counts from the East,West sectors in Δt=20 min

I=total intensity

δt=1.7 h = average hour angle between the vertical and each of the two sectors

The integrated 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 $t_{N_{int}} = N_{int} \cdot \Delta t$.

- Harmonic analysis performed on the differences $D(i) = C_E(i) - C_W(i)$
- Differential amplitude and phase are transformed into the integral ones: $r_I = \frac{r_D}{\delta t}$ and $\phi_I = \phi_D + \frac{\pi}{2}$
- Uncertainties on r_I and ϕ_I: $\sigma_{r_I} = \frac{1}{\delta t}\sqrt{\frac{2}{N_{EW}}}$ and $\sigma_{\phi_I} = \frac{\sigma_{r_I}}{r_I}$
- Rayleigh imitation probability: $P = exp\left(-\frac{r_I^2}{2\sigma_{r_I}^2}\right)$

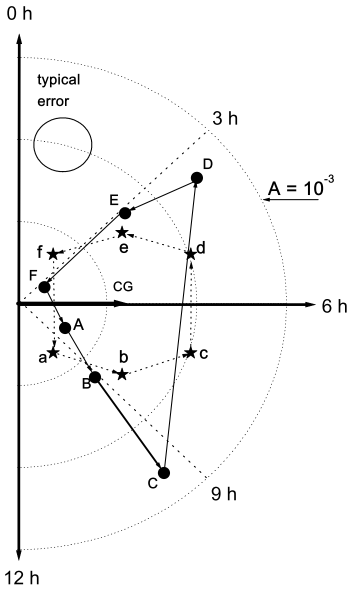
100 TeV

$A_{sol}\ 10^4$	ϕ_{sol}[h]	$P(\%)$	$A_{sid}\ 10^4$	ϕ_{sid}[h]	$P(\%)$	$A_{asid}\ 10^4$	ϕ_{asid}[h]	$P(\%)$
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

- **Solar time analysis**: amplitude and phase in excellent agreement with expected Compton-Getting effect at our latitude, $A_{sol,CG} = 3.0\ 10^{-4}$, $\phi_{sol,CG} = 6.0$ h.
- **Sidereal time analysis**: amplitude and phase (chance probability 0.5%) consistent with our previous results
- **Anti-sidereal time analysis**: no significant amplitude.

From the astronomical point of view

Higher counting rate when looking inside the Galaxy and a lack of events from directions corresponding to northern galactic latitudes.



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Bi-monthly solar vectors of the I harmonic (black dots), and expected ones (black stars) from the measured solar and sidereal amplitudes.

- Expected anti-clockwise rotation of the solar vector clearly visible
- Instantaneous observed anisotropy = combination of solar and sidereal vectors
- Expected and measured rotations fully compatible within the statistical uncertainties

400 TeV

A_{sol} 10^4	ϕ_{sol}[h]	$P(\%)$	A_{sid} 10^4	ϕ_{sid}[h]	$P(\%)$	A_{asid} 10^4	ϕ_{asid}[h]	$P(\%)$
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

- **Solar time analysis**: significance of the first harmonic rather marginal, but amplitude and phase still consistent with the Compton-Getting effect.
- **Sidereal time analysis**: indication of change of phase (from 0.4 to 13.6 h) and increase in amplitude by a factor 2.5 (limited significance, chance probability 3.8%)
- **Anti-sidereal time**: no significant amplitude

From the astronomical point of view

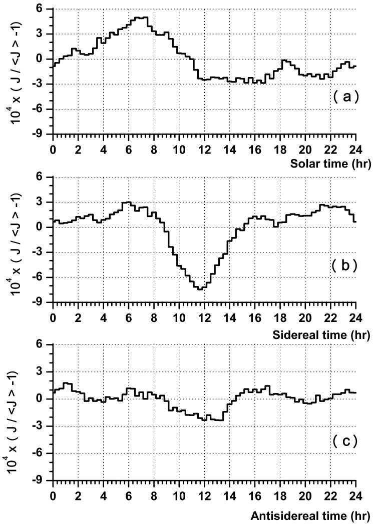
The change of phase would correspond to an excess of events towards northern galactic latitudes, inside the local galactic arm.

Second harmonic analysis

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

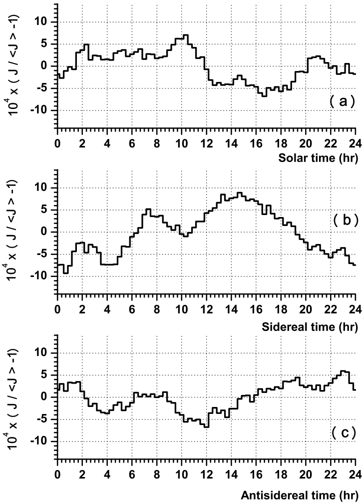
- Significant amplitude in sidereal time at 100 TeV (comparable with the first harmonic one: $A^{II} = (2.3 \pm 0.8)\ 10^{-4}$, $\phi^{II} = (6.3 \pm 0.7)$ h LST, $P = 1.6\%$)
- No other effects observed

WAVE SHAPES AT 100 TeV



- **Solar wave**: Compton-Getting effect clearly seen
- **Sidereal wave**: shape in remarkable agreement with previous measurements (EAS and underground muon detectors)
- **Anti-sidereal wave**: no significant structure.

WAVE SHAPES at 400 TeV



- **Solar wave**: Compton-Getting effect still marginally visible
- **Sidereal wave**: rather different from the one at 100 TeV: a signal is rising with max around 13-16 h LST, and increased amplitude
- **Anti-sidereal wave**: no significant structure

Summary

- A new measurement of the CR anisotropy by EAS-TOP:
  - full data-set (8 years of data)
  - cuts in energy at 100 and 400 TeV
  - East-West analysis method
    - Includes systematical uncertainties into statistical ones
    - Loss of significance but not affected by systematics
- From the analysis of the first harmonic at 100 TeV:
  - in solar time: CG effect observed
  - in sidereal time: consistency with previous measurements
  - in anti-sidereal time: no significant effect
- From the analysis of the first harmonic at 400 TeV:
  - in solar time: CG effect marginally observed
  - in sidereal time: indication of change of phase (from 0.4 ± 1.2 to 13.6 ± 1.5) and increase in amplitude (from $2.6 \pm 0.8\ 10^{-4}$ to $6.4 \pm 2.5\ 10^{-4}$
  - in anti-sidereal time: no significant effect