Sidereal anisotropy of cosmic rays at 10-100 TeV energy range

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Abstract. Results of four year cosmic ray anisotropy measurement, done with Baksan Carpet-2 array at the energy region 10–100 TeV, as a function of energy are presented. Data analysis was performed with “East minus West” method with subsequent Farley-Storey correction on anti-sidereal wave. The amplitude and phase of anisotropy for three integral energy ranges $E > 17$ TeV, $E > 62$ TeV and $E > 100$ TeV are reported.

1. Introduction

This work is an extension of that reported at 30th RCRC [17]. Experimental results on anisotropy of primary cosmic ray flux give us important information for further theoretical study of the origin and propagation processes in cosmic ray physics. Together with numerical characteristics of anisotropy - amplitude and phase, the energy dependence of those characteristic gives additional information for better understanding of the above mentioned processes. Energy range of primary cosmic rays under anisotropy investigation is extremely wide – from ~ 100 GeV up to $10^{15}$ TeV and higher. At 1 - 10 TeV range the measurements were carried out with detectors of Cerenkov emission of Air Showers (AS) or underground muon telescopes (Nagoya, Baksan Underground Scintillation Telescope; MACRO and others). Then, at 100-10000 TeV range, the EAS-TOP and CASCADE results are well known. And finally for $10^{17}$ eV and above anisotropy is studied with giant AS installations such as Yakutsk, AGASA and Auger. One can find review of anisotropy results and bibliography in [14, 15, 16].

At seventieth-eightieth some results of cosmic ray anisotropy study in Northern and Southern hemispheres with a Small Air Shower (SAS) arrays ($E \sim 10$ TeV) were published [3, 4, 5, 6, 7, 8, 9]. Amplitude and phase of anisotropy were derived from Fourier analysis of counting rate along the Right Ascension coordinate, without record of SAS arrival direction. The main results were: 1) Compton-Getting effect [1] due to revolution of the Earth around the Sun in accordance with theoretical prediction was observed, 2) Siderial anisotropy with amplitude ~ 0.056% and faze ~ 1 hour RA was measured with high statistical accuracy. When there are numerous results for $E < 10$ TeV and some for $E > 100$ TeV, the 10-100 TeV range is up to now slightly studied. Lack of experimental results at this energy range gives no possibility to arrive at clear conclusion about energy dependence of amplitude and phase of anisotropy. At 2007, after some modernization of Baksan AS installation, we resumed the measurement of anisotropy of SAS in the range 10-100 TeV with registration of arrival directions in celestial coordinates. In this paper we report the result of four year registration, 2007-2011yy.
2. Experimental set-up and energy response

Central part of Baksan SAS array - “Carpet” - consists of 400 liquid scintillation detectors, arranged in horizontal continuous square geometry, – figure 1. Dimension of the detector is 70x70x30 cm$^3$. There are four outside huts (OH) on square’s diagonals at distance 30m from the center of Carpet. Each hut contains 18 (3x6) detectors. The Carpet is divided into 25 square modules, each module = 16 detectors. For the purpose of this experiment information from four corner modules (CM) and four OH have been used.

![Figure 1. Layout of Baksan Air Shower experimental setup](image)

Twenty nine (25 modules + 4 OH) anode pulses (each pulse is a sum of anode pulses of individual detectors of the module or hut) are discriminated in order to be used by the multiple logic unit designed to produce the SAS triggers. Individual (each of 29) logic pulse is generated if corresponding summed anode amplitude exceeds 0.5 relativistic particle. Arrival direction of SAS is calculated using the relative times from eight TDC channels corresponding to four CM plus four OH. In data acquisition we used three sorts of triggers: a) 4-fold coincidence of four corner modules 4CM, b) 4-fold coincidence of four outside huts 4OH, c) 8-fold coincidence 4CM+4OH. Counting rate of coincidences: f(4CM)=1.3Hz, f(4OH)=1.0Hz, f(4CM+4OH)=0.8Hz. Angular resolution is: for 4CM = 10 deg, for 4OH = 3.5 deg, for 4CM+4OH = 3.3 deg. Four year data set has been processed, only full days were included in analysis. Useful time after “noise” cuts and elimination of “short” days = 60% for OH and 51% for CM. Such low live time efficiency is due both to maintenance jobs on installation and to malfunction of electronic units.

Energy response for three sorts of trigger was calculated by Monte Carlo simulations, made on the basis of CORSIKA codes (ver. 6.501, HDPM and Gheisha models). Vertical proton flux with differential spectrum $\gamma = -2.7$, uniformly distributed over the circle area with $r = 60m$, was used in simulation. The roof above the Carpet with thickness 34 g/cm$^2$ was taken into account. Calculated median energies are: E(4CM) = 17 TeV, E(4OH) = 62 TeV, E(4CM+4OH) = 100 TeV.

3. Procedures of data processing and results

To begin with, we show in table 1, as an example for trigger 4CM(17 TeV), what the initial, - before any corrections, - solar, sidereal and antisidereal waves look like. First harmonic amplitudes of solar and sidereal waves are practically an order of magnitude higher than usual “standard” ones. The main

| 1st harmonic wave | Solar | sidereal | anti-sidereal |
|-------------------|-------|----------|---------------|
| 17 TeV amplitude, % | 0.34  | 0.14     | 0.08          |
| phase, hour       | 11.9  | 4.8      | 18.2          |
factor among others resulting in that is an atmosphere pressure, which e.g. in solar Local time has a maximum near midnight and hence producing in anti-correlation mode the solar wave with maximum near the noontime. And apparatus instabilities are also the reason of arising of the spurious waves. So, to get pure true waves one needs to correct in some or other way the initial waves.

The most often in the past, a clear and simple traditional procedure of meteorological correction was used which worked out well enough in the absence of apparatus instabilities. Now and here we shall do no more than briefly mention the main results of our experience on anisotropy’s data processing. Three years ago we have published [17] results of anisotropy measurement on the same installation “Carpet” with the same as now experimental set-up. Loc. cit. the traditional correction procedure was compared with “East-West” method [18] in favour of using the method, as leading to more reliable results. But it is worthwhile to mark now that even the “East-West” method is not capable to countervail the possible seasonal amplitude modulation of the wave in solar time. One of the others, an obvious reason of such modulation is seasonally varying atmosphere temperature resulting finally in daily variation of effective cut-off in primary energy – similar to Compton-Getting effect. Hence, as a result of such modulation the spurious siderial and anti-siderial (solar-side harmonics) do inevitably appear. As early as in 1954 Farley and Storey [2] had pointed out this effect, and then in 1977 Nagashima et al [6] further developed the appropriate correction to exclude spurious part of siderial wave using anti-siderial vector.

Well, results reported in this paper were obtained after “East-West” procedure, followed by Farley-Storey correction. We show in table 2 vector characteristics of observed anisotropy of cosmic ray flux in 10-100 TeV range. Solar waves are in total agreement with expected ones due to Compton-Getting effect.

Table 2. Characteristics of resulting 1st harmonics of anisotropy waves.

| 1st harmonic | Solar     | siderial | anti-siderial |
|--------------|-----------|----------|---------------|
| 17 TeV       | amplitude, % | 0.044 ±0.012 | 0.050 ± 0.012 | 0.015 ± 0.012 |
| phase, hour  | 4.7 ± 1.0 | 0.5 ± 0.9 RA | -             |
| 62 TeV       | amplitude, % | 0.030 ± 0.014 | 0.041 ± 0.014 | 0.021 ± 0.014 |
| phase, hour  | 6.8 ± 1.2 | 23.8 ± 1.3 RA | -             |
| 100 TeV      | amplitude, % | 0.038 ± 0.016 | 0.037 ± 0.016 | 0.018 ± 0.016 |
| phase, hour  | 5.3 ± 1.5 | 22.4±1.5 RA | -             |

In figure 2 we show black circles, connected with dot line, representing our siderial result for three energy thresholds. The results of earlier measurements from different groups are also presented. Black circle for 100 Tev is slightly shifted to right for visual convenience. An unbiased observer can say that amplitude of siderial anisotropy is constant through that energy range within the statistical errors and is also in agreement with earlier measurements. But nevertheless there is a slight hint also now in our data, as it has been four years ago [17], on decreasing of anisotropy amplitude with energy through 10-100 TeV range. This hint being taking together with results An-ET03-ET07 puts forward the combined problem and questions on evolution of anisotropy in the energy range 10 TeV-some hundreds TeV [16, 17]. Ibidem a short review of situation was also has been made. Unfortunately, due to very low live-time efficiency of data accumulation during 2007-2011 we didn’t get the desired statistical accuracy which had been hoped for.
Unfortunately, due to very low live-time efficiency of data accumulation during 2007-2011 we didn’t get the desired statistical accuracy which had been hoped for. Regretfully, data acquisition process on anisotropy programme at the “Carpet” has been disrupted and stopped at early 2011 due to some well-known and long-lived organizing problems of Organisation. Ten years earlier the EAS-TOP was also dismounted due to some financial and “green” problems. May be future generation of installations and/or investigators will give answers and/or put a stop to those interesting and intriguing “combined evolution” questions and problems.

4. Discussion

And now below we shall try to explain with a few sentences why we treat the problem of cosmic ray anisotropy evolution being interesting and intriguing. The explanation is also aimed to justify and clarify the first Introduction’s phrases, - being taken stand-alone as set the teeth on edge,-about importance of anisotropy information in study of the processes of the origin and propagation of cosmic rays. There are four experimental anisotropy evidences - facts or hints, which, if to combine them together, lead up us hypothetically to galactic-extragalactic cosmic ray bifurcation, namely: 1) at energy $\leq 100$ TeV a phase of first siderial anisotropy harmonic ($\sim 0$ h Right Ascension) corresponds to direction parallel to Galactic plane, and at the same time the existence of significant second harmonic is a natural sequence of a twice-in-day crossing the vertical with Galactic plane[8], 2) at energy $>> 100$ TeV a drastic change of the phase of the first anisotropy harmonic from 0 hour RA to 13 hour RA [10, 16] that corresponds to direction to north Galactic Pole, 3) at energy $>> 100$ TeV there is an absence of the second siderial anisotropy harmonic[16], 4) possible decreasing with energy of the amplitude of first anisotropy harmonic in the 10-100 TeV range[17, this paper]. One can say that the 4th point (should happen to be a fact) may be explained with increasing input of high energy flux having the opposite phase in RA frame and as a result decreasing initial amplitude with increasing energy. The 3rd point is due to neglect input of galactic CR flux which has the second harmonic. The 2nd point is due to preponderance of CR flux perpendicular to galactic plane. The 1st point is due to preponderance of galactic CR flux. It seems worthwhile to note once more that above mentioned features of high energy anisotropy arise not so far in energy from famous unbending spectrum knee.

![Figure 2](image-url)
Obviously, all above presented speculations need to be checked, confirmed or rejected, by high statistical accuracy ad hoc experiments and, may be, by skill of professionals dealing with supernova explosions, properties of interstellar space and diffusion coefficients.

Conclusions
1. Amplitude of first harmonic of siderial anisotropy is constant within the statistical accuracy of the data at the 10-100 Tev energy range. There is some hint on amplitude decreasing with energy. But our statistics are not rich enough to give definite conclusion on evolution of anisotropy.
2. Further experimental verification is need to be done to check the possible evolution of anisotropy at the energy range 10 Tev -- some hundreds TeV for subsequent employment in the Cosmic Ray origin and propagation theory.

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