# Observation of the temporal variation of the sidereal anisotropy by Tibet III array

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***Abstract.*** **We have analyzed the large scale sidereal anisotropy of multi-TeV Galactic cosmic rays by Tibet Air Shower Array, with the data taken from Nov. 1999 to Nov. 2005. To study the temporal variation of the anisotropy, the data set is divided into 6 samples, each in a time scale of one year.It is shown that the sidereal anisotropy with the magnitude about 0.1% is fairly stable from year to year over the entire observation period. This indicates that the anisotropy of TeV galactic cosmic rays is insensitive to solar activities.**

***Keywords*: temporal variation, sidereal anisotropy, multi-TeV**

## I. Introduction

Galactic cosmic rays(GCRs) are high energy nuclei (most protons) which are accelerated in our galaxy and continuously arriving at Earth after traveling through the heliosphere. The intensity of GCRs is nearly isotropic because of the influence of magnetic fields in the Galaxy. However, numerous observations show that there is a slightly anisotropy on the isotropic background. The anisotropy of GCRs is due to a combination of several effects. First, it may result from the uneven distribution of cosmic ray sources such as SNRs[1] and the process of cosmic ray propagation in the Galaxy[2]. The directional anisotropy of GCR intensity is expected to carry important information about the origin and the propagation mechanism of the GCRs. Anisotropy can also be induced through both large scale and local magnetic field configurations, possibly including effects of the heliosphere. It is a useful tool in probing the local interstellar space surrounding the heliosphere and the magnetic structure of the heliosphere[3]. In addition, an expected anisotropy is caused by the relative motion between the observer and the cosmic ray plasma, known as the Compton-Getting(CG) effect[4]. It predicts that due to the motion of the solar system around the galactic center through the rest frame of the cosmic-ray plasma, a dipole term should arise with the maximum being in the direction of motion. By analyzing the events recorded by the Tibet III Air Shower experiment, Amenomori et al. [7] showed that GCRs corotate with the local GMF environment through the null result of the Galactic CG effect. Another CG modulation due to the earth's revolution around the sun has been successfully detected by several experiments in multi-TeV energy[5], [6].

The flux of cosmic rays with energy per nucleon in the range of $10^{11} \sim 10^{14}$ eV is known to have a sidereal anisotropy of the order $O(10^{-4})$. Because the gyro radius of cosmic rays in this energy region in a GMF of about 3 $\mu$G is about several AU - 0.03 pc, which is much smaller than the size of Galaxy, the large scale sidereal anisotropy of cosmic rays in this energy region gives us an important piece of the information about the magnetic structure of the heliosphere and the local interstellar space surrounding the heliosphere.

From the analysis of numerous experiments, it can be seen that both amplitude and phase of the best-fit first harmonic vary with energy[10]. But in the multi-TeV region, both the amplitude and the phase of the first harmonic vector of the daily variation are remarkably independent of primary energy[11] . Utilizing the advantage of the large field of view and high count rates as well as good angular resolution of the incident direction, EAS arrays play an important role in the multi-TeV region's GCR anisotropy study. The Tibet III Air Shower experiment is currently the world's highest precision measurement of GCR intensity in this energy region.

In this paper, we analyze the temporal variation of sidereal anisotropy of multi-TeV GCR intensity with data of Tibet III array from Nov. 1999 to Nov. 2005.

## II. Tibet Air Shower Array Experiment

The Tibet Air Shower Array experiment has been successfully operating at Yangbajing (90.522 E, 30.102 N; 4300 m above the sea level) in Tibet, China since 1990. The array was gradually upgraded by increasing the number of the counters. The Tibet III array[8], was completed in the later fall of 1999. This array consists of 533 scintillation counters of 0.5 $m^2$ each placed on a 7.5 m square grid with an enclosed area of 22,050 $m^2$ and each viewed by a fast-timing (FT) photomultiplier tube. A 0.5 cm thick lead plate is placed on the top of each counter in order to increase the array sensitivity by converting $\gamma$ rays into electron-positron pairs. The shower size $\sum \rho_{\rm FT}$ is regarded as an estimator of energy, where the size of $\sum \rho_{\rm FT}$ is defined as the sum of the particles per $m^2$ for each fast-timing(FT) detector. To study the energy dependence of anisotropy, $\sum \rho_{\rm FT}$ variable is used to divide the data into three sub-sets: [10,27), [27,47) and [47,178), each corresponds to an modal energy of 4, 6.2 and 12 TeV as in [6], [11].

In the present analysis, GCR events are selected based on following criteria: (1) the air shower core position is located in the array; (2) the zenith angle of arrival direction is less than $45°$; (3) any fourfold coincidence in the FT counters recording more than 0.8 particles in charge; In total, about $3.5 \times 10^{10}$ events are used in the present analysis.

## III. Analysis and Result

Sitting on an almost horizontal plane, the Tibet III Air Shower Array has almost azimuth-independent efficiency in receiving the cosmic ray shower events for any given zenith angle. Therefore, the equi-zenith angle method is used in the analysis. In brief, simultaneously collected air shower events in the same zenith angle belt can be used to construct the "off-source windows" and to estimate the background for a candidate point source located in the same zenith angle belt. This method can eliminate various detecting effects caused by instrumental and environmental variations, such as changes in pressure and temperature which are hard to be controlled and intend to introduce systematic errors in measurement.

With the large statistics, we can conduct a 2D measurement to reveal detailed structural information of the large-scale GCR variation beyond the simple time profiles. The idea of this method is that for each short time step(e.g. 8 minuites in the present analysis), for all directions, if we scale down (or up) the number of observed events by dividing them by their relative CR intensity, then statistically, those scaled observed numbers of events in a zenith angle belt should be equal anywhere. A $\chi^2$ can be built accordingly, and the relative intensity of cosmic rays $I$ and its error $\Delta I$ in each direction can be solved by minimizing the $\chi^2$ function(see Refs. [12] for details).

Using Lomb-Scargle Fourier transformation method with data recorded by Tibet III array, [13] showed that besides the well known solar diurnal, sidereal diurnal and sidereal semi-diurnal modulations at a level of $10^{-3}$, no other periodicity was found to have large enough significance from 1 hour to 2 years in energy range from 3.0 TeV to 12.0 TeV. The sidereal daily variation can be described by the first and second harmonics and solar daily variation can be described by the first harmonic alone. Based on this, in the present analysis, we assume that at any moment $t$, the relative intensity of cosmic rays at any given direction $(\theta, \phi)$ in the horizontal coordinate, is modulated as a product of $I(\alpha_{sid}, \delta_{sid})$ and $I(\alpha_{sol}, \delta_{sol})$. Here $I$ denotes the cosmic-ray intensity, $(\alpha_{sid}, \delta_{sid})$ and $(\alpha_{sol}, \delta_{sol})$ is the position corresponding to the celestial coordinate in the local sidereal time scale and the local solar time scale respectively of the same point $(t, \theta, \phi)$ in horizontal coordinate. So substituting $I$ by $I(\alpha_{sid}, \delta_{sid}) \times I(\alpha_{sol}, \delta_{sol})$ in the $\chi^2$ function, we can obtain $I(\alpha_{sid}, \delta_{sid})$ and $I(\alpha_{sol}, \delta_{sol})$ simultaneously after minumizing the $\chi^2$ function. This method can effectively avoid the mutual interference of solar diurnal variation and sidereal modulation of cosmic rays intensity caused by nonuniform observational data taking of detectors.

The data were acquired by the Tibet III Air Shower Array for 1318.9 live days from Nov. 1999 to Nov. 2005. To examine the temporal variation of the large scale sidereal anisotropy, the data set was divided into six subsets, corresponding to six running periods of the Tibet III Air Shower Array, as summarized in Table I.

TABLE I
DEFINITION OF SIX PHASES OF TIBET III FROM NOV. 1999 TO NOV. 2005

| Phase | Start time | End time | Live time |
|---|---|---|---|
| 1 | Nov.18 1999 | Jun.29 2000 | 173.1 |
| 2 | Oct.28 2000 | Oct.11 2001 | 283.7 |
| 3 | Dec. 5 2001 | Sep.19 2002 | 201.8 |
| 4 | Nov.18 2002 | Nov.18 2003 | 259.1 |
| 5 | Dec.14 2003 | Oct.10 2004 | 123.6 |
| 6 | Oct.19 2004 | Nov.15 2005 | 277.6 |

As described above, for any direction in the horizontal coordinate at any moment in the observation period, a $\chi^2$ function can be constructed. By minimizing the total $\chi^2$ accumlated over entire observation period, we can get the cosmic ray intensity variation in the frame of local sidereal time and local solar time simultaneously averaged over this period. Fig. 1 shows the intensity map of GCRs with modal energy of 4 TeV in local sidereal time frame averaged over all six phases of Tibet III Air Shower Array and one-dimensional projection averaged over the entire declination belt($-14.89°$ to $75.11°$). The result is consistent with former observation results of Tibet III experiment with different methods[11], [7], [3]. The amplitude of the sidereal anisotropy is about 0.1%, and the maximum around 6 hr in local sidereal time. The maximum phase shifts to earlier hours as the viewing declination moves southward in two-dimensional inten-

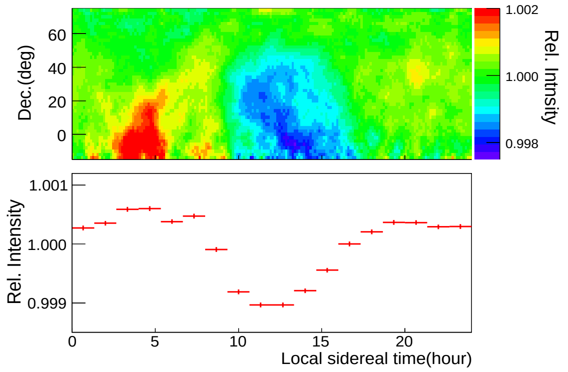


Fig. 1. Top: sidereal diurnal variation of cosmic rays intensity with modal energy at 4 TeV averaged over all six phases of Tibet III Air Shower Array from Nov. 1999 to Nov. 2005. Bottom: the 1D projection of 2D maps averaged over all declinations in local sidereal time, the statistic error of each point was obtained by solving $\chi^2$ function as is mentioned in context.

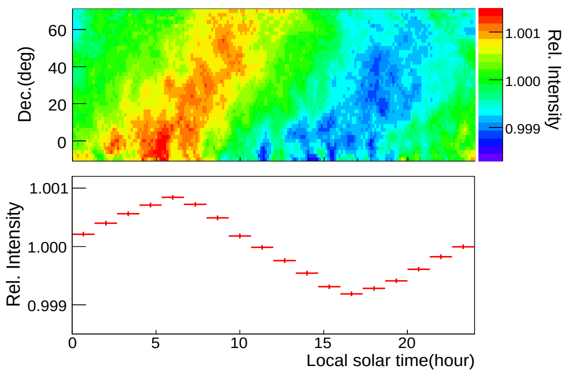


Fig. 2. Top: cosmic rays intensity variation in local solar time with modal energy at 4 TeV averaged over all six phases of Tibet III Air Shower Array from Nov. 1999 to Nov. 2005. Bottom: the 1D projection of 2D maps averaged over all declinations in local solar time, the statistic error of each point was obtained as in Fig. 1.

sity map. The excess around the Cygnus region direction can also be seen in the map. Meanwhile, the cosmic ray intensity distribution in local solar time frame obtained simultaneously is showed in Fig. 2. The anisotropy is much consistent with the former result from [14], with an extra modulation superimposed on expected CG effect.

Using data samples recorded during each seperated phase of Tibet III array, the intensity variations of GCRs averaged over each phase were obtained. The one-dimensional intensity variaitons of cosmic rays with modal energy at 4 TeV in local sidereal time frame of different phases are showed in Fig. 3. The solid red markers in each plot denote the relative intensities of GCR in local sidereal time frame over corresponding observation period, while the dashed blue markers with smooth curve in each plot represent the relative intensities in sidereal time averaged over all six phases of Tibet III array, the same as the bottom plot in Fig. 1. From the comparison of cosmic rays sidereal anisotropy in different phases from Nov. 1999 to Nov. 2005, it can

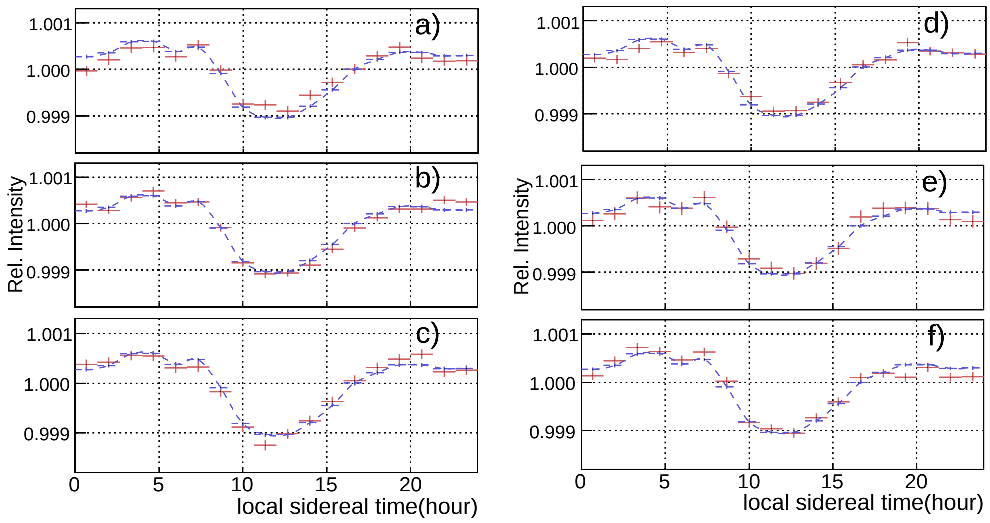


Fig. 3. Cosmic rays intensity variation in local sidereal time frame for cosmic rays with modal energy at 4 TeV. Plots in (a), (b), (c), (d) and (e), (f) corresponding to Phase 1, 2, 3, 4 and 5, 6 of Tibet III Air Shower Array respectively. The points with solid red lines in each plot show the intensity variation over each phase respectively, while the points with dashed blue lines represent the intensity averaged over all six phases of Tibet III array, which is same as in Fig. 1.

be seen that the cosmic rays intensity variation in local sidereal time is fairly stable year by year.

As described above, the relative intensity variations of 4 TeV GCRs in local solar time frame were obtained simultaneously by minimizing the $\chi^2$ function. Through the analysis of temporal variation year by year of solar diurnal anisotropy for the same cosmic ray events covering all six phases, a similar result is obtained. The amplitudes and phases of each seperated phase have no significant changes. This differs more or less with the long-term variation of the sub-TeV cosmic rays solar diurnal anisotropy measured by deep underground muon detector observation[15].

Similar to the result of 4 TeV data sample, the stable temporal variations were found both in local sidereal time and local solar time frame by analyzing 6.2 TeV and 12 TeV data samples(not shown here). The sidereal anisotropy has no significant energy dependence in this energy region. The intensity variations in local solar time at 6.2 TeV and 12 TeV are fairly consistent with the Compton-Getting anisotropy due to the terrestrial orbital motion around the sun. These results are in fairly good agreement with former results[11], [6]

## IV. Conclusions

With the observation that there are no other periodicity besides the well known solar diurnal[13], sidereal diurnal and sidereal semi-diurnal modulations from 1 hour to 2 years, we can get the intensity map in local sidereal time and in local solar time simultanously. Using about $3.5\times10^{10}$ events recorded by Tibet III Air Shower Array from Nov. 1999 to Nov. 2005, the temporal variation of large scale sidereal anisotropy has been obtained. At the modal energy of multi-TeV, the sidereal anisotropy is fairly stable year by year covering all 6 phases of Tibet III array. The feature in this energy region provides the constraints on explanations of the sidereal anisotropy origin, which has no convincing and wide consistent explanations until now.

## V. Acknowledgements

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