Updated study on multi-TeV cosmic-ray modulation with the Tibet Ⅲ air shower array using the east-west method *

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Abstract: We study the sidereal and solar time modulation of multi-TeV cosmic rays using the east-west method with Tibet Ⅲ air shower array data taken from November 1999 to December 2008. The statistics are twice the amount used in our previous paper. In this analysis, the amplitude of the observed sidereal time modulation is about 0.1%, and the modulation shows an excess from about 4 to 7 hours and a deficit around 12 hours in local sidereal time. The sidereal time modulation has a weak dependence on the primary energy of the cosmic rays. However, the solar time modulation shows a large energy dependence. We find that the solar time modulation is fairly consistent with the prediction of the Compton-Getting effect for high-energy samples (6.2 TeV and 12.0 TeV), but exceeds the prediction for the low-energy sample (4.0 TeV). Such a discrepancy may be due to the solar modulation or the characteristics of the experimental device in the near threshold energy.

Key words: cosmic-ray anisotropy, Compton-Getting effect, east-west method

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1 Introduction

Owing to the deflection of the interstellar magnetic field, galactic cosmic rays (GCRs) lose their original direction and become almost isotropic in solar systems. However, tiny cosmic ray (CR) anisotropy is still observed at a wide energy range [1–6]. The anisotropy may result from the uneven distribution of nearby CR sources such as supernova remnants (SNRs) [7], or be due to the local magnetic field structure which governs the propagation of CRs in the local environment. The anisotropy can also be a pure kinetic effect called the Compton-Getting effect arising from the relative motion between the observer and the CR plasma [8].

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The transportation of GCRs is generally described by Parker's equation, which includes the following processes: diffusion, convection, gradient and curvature drift [9, 10]. The propagation parameters in the equation are related to the interstellar magnetic field. Therefore, the measurement of CR anisotropy can provide information on the galactic magnetic field (GMF) [11, 12]. The sidereal time anisotropy in the multi-TeV energy region has been measured by several experiments using either underground MUON detectors or ground-based air shower arrays [3, 13, 14]. The amplitude of sidereal time modulation is about 0.1% and the projection along the right ascension direction can be fitted by only a few low-order harmonics. For northern hemisphere measurements, CR intensity reaches its maximum at about 6 hours and minimum at about 12 hours in local sidereal time. With two-dimensional measurements, it is now understood that the maximum happens in the direction of the tail of the heliosphere, and the minimum is pointing to the galactic northern pole. The excess is called tail-in and the deficit is called loss-cone.

In Compton-Getting's original work, they studied CR anisotropy as a result of the relative motion of a solar system with respect to the GCR plasma. This is a Doppler effect, just like if you rode a bicycle you would experience wind against you. With a very high precision measurement on the two-dimensional CR anisotropy, the AS gamma experiment found no such anisotropy at a cosmic ray energy of 300 TeV, and demonstrated that GCRs co-rotate with the solar environment around the galactic center [3]. While the CR plasma remains still in the solar system, the observer on Earth is expecting to see the Compton-Getting effect [8] due to the revolution of the Earth about the Sun. The intensity modulation is described as the following formula "Eq. (1)" [15]:

$$\frac{\Delta I}{\langle I\rangle}=(\gamma+2)\frac{v}{c}\cos\theta, \tag{1}$$

where $\langle I\rangle$ denotes the average CR intensity, ΔI is the CR intensity variation, γ is the power law index of the CR energy spectrum, v/c is the ratio of the detector's velocity to the speed of light, and θ is the angle between the arrival direction of the CRs and the direction of the motion of the detector. From "Eq. (1)", the enhancement of the CRs is at 6 hours and the deficit is at 18 hours in local solar time. The amplitude of the CG effect is calculated to be as small as $\approx\pm0.05\%$ or less, depending on the geographic latitude of the experimental site.

In previous published papers [16, 17], we presented, respectively, the solar and sidereal time modulation using the east-west method with Tibet III array data from 1999 to 2003. In this work, we update the results with larger Tibet III array data from November 1999 to December 2008 using the east-west method, and we compare the new results with the previous ones.

2 The Tibet air shower array experiment

The Tibet air shower array experiment has been successfully operated at Yangbajing (90.522° E, 30.102° N; 4300 m above sea level) in Tibet, China, since 1990 [18]. The experiment was gradually enlarged and upgraded to the current scale (Tibet III array) by increasing the number of detectors from the Tibet I and Tibet II arrays. The Tibet III array started collecting data in the late fall of 1999 [19]. The array is composed of 497 fast timing (FT) detectors and 36 density (D) detectors covering a surface area of 22050 m^2. Each FT detector is equipped with a plastic scintillator plate and a 2 inch photomultiplier tube that has a cross-sectional area of 0.5 m^2 and is deployed on a lattice with 7.5 m spacing. A 0.5 cm thick lead plate is placed on top of each counter in order to increase the detector array sensitivity by converting γ rays into electron-positron pairs. A CR event trigger signal is issued when any fourfold coincidence occurs in the FT counters recording more than 0.6 particles, resulting in a trigger rate of about 680 Hz at a few-TeV threshold energy. The shower size $\sum\rho_{\rm FT}$ is regarded as an estimator for the primary particle energy, where the size of $\sum\rho_{\rm FT}$ is defined as the sum of particles per m^2 for each FT detector. During 2002 and 2003, the inside area of the Tibet III array was further enlarged to 36900 m^2 by installing an additional 256 detectors. This full Tibet III array has been operating successfully since 2003. The angular resolution of the Tibet III is about 0.9° in the energy region above 3 TeV, as estimated from full Monte Carlo (MC) simulations and verified by the Moon shadow measurements from observational data.

In this work, CR events are selected with the following criteria. (1) Any four-fold coincidence that occurs in the FT counters with each recording more than 0.8 particles in charge; (2) if the zenith angle of incident direction is less than 45°; and (3) if the air shower core is located in the array. In total, about 53 billion CR events are used in our analysis. The data samples are further divided into three groups according to their characterized primary energy of 4.0 TeV, 6.2 TeV and 12.0 TeV.

3 Analysis

The daily and yearly event rates vary by $\pm2\%$ and $\pm5\%$, which arises mainly from the meteorological effect. To eliminate this effect when studying the daily CR variation with very small amplitude ($\approx\pm0.1\%$), we adopt the following east-west method [16].

The selected events are recorded in either of two histograms in a bin size of one hour, according to the events' arrival time. One histogram is reserved for events from the east and another for events from the west, according to the geographical longitude of the incident direction of the shower events. Then we subtract these two histograms and normalize this difference by their averaged histograms to form the relative intensity difference, and we further divide this relative difference by the hour angle separation averaged over the east and west events to get the differential relative intensity "$D(t)$" .

From the above description, the east-west method can cancel out the meteorological effect and possible instrumental bias, which may produce common variations for both east and west incident events.

We can reconstruct the CR relative intensity "$R(t)$" by integrating "$D(t)$" over the solar time variable. In our analysis, the solar time differential relative intensity "$D(t)$" is fitted by "Eq. (2)":

$$D(t)=A_D\cos\frac{2\pi}{24}(t+\phi_D), \tag{2}$$

where t is the solar time, and A_D and ϕ_D are the amplitude and phase of "$D(t)$". Sidereal or other periodic variations can be obtained by the above east-west method using the respective time scales.

The Tibet III array event number statistics are not uniform because of the maintenance and calibration carried out each year. The spurious variation in both solar and sidereal variation can be produced from the non-uniform event statistics. A live time correction method is used to make the events uniform. The whole year CR events are divided into 12 histograms in monthly bins, equally. Each histogram is multiplied by the correction factor, which can be obtained from the events' distribution. To estimate the systematic error, we can analyze the modulation in anti-sidereal (364 cycles per year) and extended-sidereal (367 cycles per year) timescales.

4 Results and discussion

Figure 1 shows the sidereal time modulation. The sidereal anisotropy amplitude is about 0.1% in three samples (4.0 TeV, 6.2 TeV and 12.0 TeV). An excess around 4 to 7 hours corresponding to tail-in and a deficit around 13 hours corresponding to loss-cone are clearly shown in the map. Meanwhile, the results show that the sidereal time modulation has a weak dependence on the primary energy of the CRs. The results agree well with the previous work [3, 17]. This agreement shows that the sidereal anisotropy variation is very stable.

Figure 2 shows the solar time modulation with the cosinusoidal curves fitting to the data. The χ^2-fitting results of differential relative intensity "$D(t)$" and relative intensity "$R(t)$" are, respectively, presented in Table 1 and Table 2. From the results, solar modulation amplitude A_{R} is about 0.04% and phase A_θ is about 6 hours at higher energy (12.0 TeV and 6.2 TeV). So the results are consistent with the expected CG effect. But the A_{R} ($(8.39\pm0.42)\times10^{-4}$) at lower energy (4.0 TeV) is greater than the expected CG effect.

Figure 3 shows the differential relative intensity in the anti-sidereal and extended-sidereal time frames, which are both statistically insignificant. The left insignificant anti-sidereal variation ensures that the influence of sidereal variation over solar variation is negligible. On the other hand, the insignificant extended-sidereal variation ensures that the influence of solar variation over the sidereal variation is negligible.

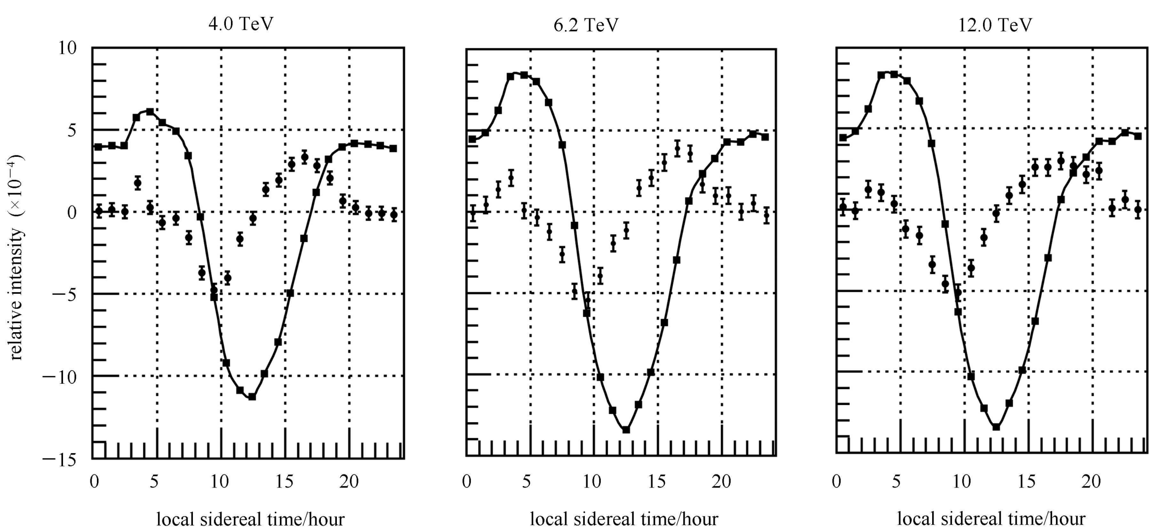

Fig. 1. Sidereal time modulation in three samples (4.0 TeV, 6.2 TeV and 12.0 TeV). The dot shows the observed differential relative intensity "$D(t)$" result, and the solid line shows the relative intensity "$R(t)$".

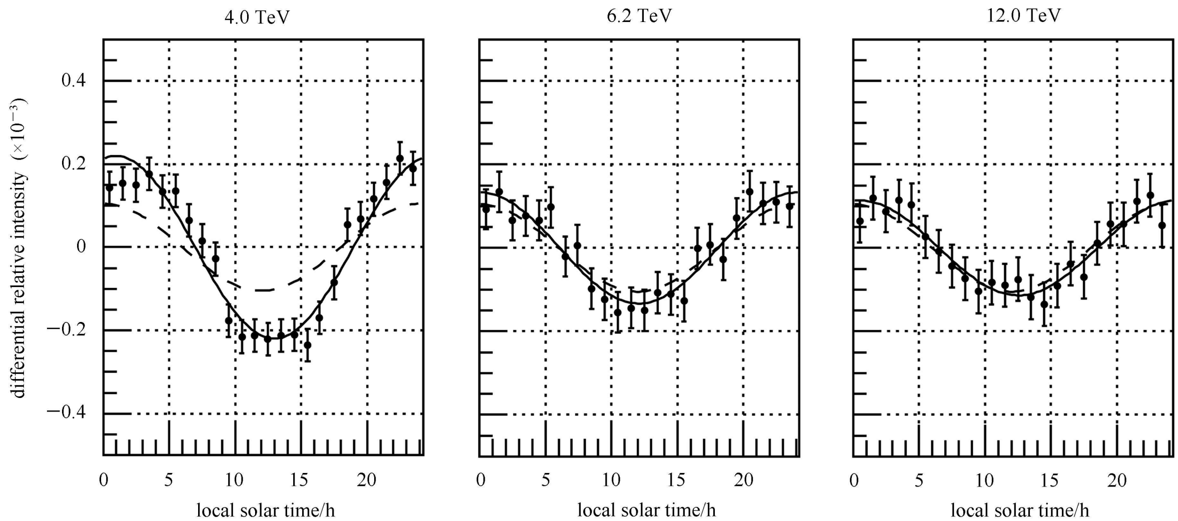

Fig. 2. Solar time modulation in three samples (4.0 TeV, 6.2 TeV and 12.0 TeV). The dot shows the observed differential relative intensity "$D(t)$" result, the solid line shows the fitting results by the cosinusoidal curve, and the broken line shows the expected differential relative intensity "$D(t)$".

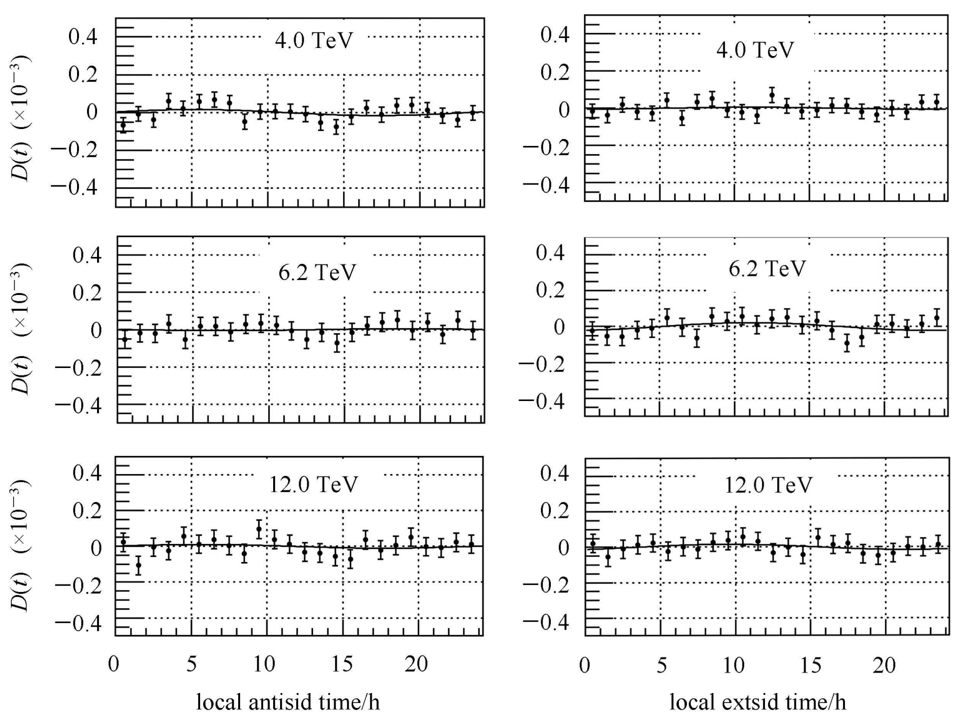

Fig. 3. Differential relative intensity "$D(t)$" in the local anti-sidereal time (left) and extended-sidereal time (right) for three different representative energies: (up) 4.0 TeV, (middle) 6.2 Tev, (bottom) 12.0 TeV.

Table 1. Amplitude A_D and phase ϕ_D of CR solar differential relative intensity "$D(t)$" by χ^2-fitting with a cosinusoidal curve in three samples. The fourth column shows the χ^2.

energy/TeV	$A_D \times 10^{-4}$	ϕ_D/hour	χ^2/ndf
4.0	2.19±0.11	−0.97±0.20	27.02/22
6.2	1.33±0.14	−0.08±0.40	11.28/22
12.0	1.14±0.15	−0.52±0.50	6.98/22

Table 2. Amplitude $A_{\rm R}$ and phase $\phi_{\rm R}$ of CR solar relative intensity "$R(t)$" in three samples.

energy/TeV	$A_{\rm R}$ expected$\times 10^{-4}$	$A_{\rm R}$ observed$\times 10^{-4}$	$\phi_{\rm R}$ expected/hour	$\phi_{\rm R}$ observed/hour
4.0		8.39±0.42		5.03±0.20
6.2	4.00	5.09±0.53	6	5.92±0.40
12.0		4.35±0.57		5.48±0.50

5 Summary

In conclusion, we report on the latest sidereal and solar time modulation of multi-TeV CRs by using the east-west method with updated Tibet III air shower array events during the period from November 1999 to December 2008. The results agree very well with the previous paper. This agreement also indicates that the sidereal and solar modulation are fairly stable from 1999–2008. The solar anisotropy at 4.0 TeV disagrees with the expected CG effect, which may be due to solar modulation or the characteristics of the experimental device in the near threshold energy.

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