

LARGE-SCALE SIDEREAL ANISOTROPY OF GALACTIC COSMIC-RAY INTENSITY OBSERVED BY THE TIBET AIR SHOWER ARRAY

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ABSTRACT

We present the large-scale sidereal anisotropy of Galactic cosmic-ray intensity in the multi-TeV region observed with the Tibet-III air shower array during the period from 1999 through 2003. The sidereal daily variation of cosmic rays observed in this experiment shows an excess of relative intensity around 4–7 hr local sidereal time as well as a deficit around 12 hr local sidereal time. While the amplitude of the excess is not significant when averaged over all declinations, the excess in individual declination bands becomes larger and clearer as the viewing direction moves toward the south. The maximum phase of the excess intensity changes from ~ 7 hr at the Northern Hemisphere to ~ 4 hr at the equatorial region. We also show that both the amplitude and the phase of the first harmonic vector of the daily variation are remarkably independent of primary energy in the multi-TeV region. This is the first result determining the energy and declination dependences of the full 24 hr profiles of the sidereal daily variation in the multi-TeV region with a single air shower experiment.

Subject headings: cosmic rays — diffusion — ISM: magnetic fields

1. INTRODUCTION

The directional anisotropy of Galactic cosmic-ray intensity in the multi-TeV region gives us an important piece of information about the magnetic structure of the heliosphere and/or the local interstellar space surrounding the heliosphere, through which cosmic rays propagate to the Earth. The Galactic an-

isotropy has been measured via the sidereal daily variation (SDV) of cosmic-ray intensity recorded in a fixed directional channel of the detector on the spinning Earth. On the basis of the SDV observed in the 1–100 TeV region, most of the previous investigations reported on the first harmonic vector with small amplitude [$(1-10) \times 10^{-4}$ or 0.01%–0.1%] and a phase of maximum somewhere between 23 and 3 hr in the local sidereal time (LST; Jacklyn 1966; Cutler et al. 1981; Alexeenko & Navarra 1985; Jacklyn 1986; Nagashima et al. 1989; Bergamasco et al. 1990; Cutler & Groom 1991; Aglietta et al. 1996; Munakata et al. 1997). Based on a harmonic analysis, these observations are consistent with the large-scale diffusive propagation of cosmic rays in the Galaxy (Shibata et al. 2004), but there is no consensus currently for a production mechanism in the local interstellar region surrounding the heliosphere that would reproduce the full 24 hr profile of the SDV (Jacklyn 1966; Alexeenko & Navarra 1985; Nagashima et al. 1989; Bergamasco et al. 1990). This is partly due to the lack of the information on the dependence of the anisotropy on declination. Also, the first harmonic vector is not always sufficient to precisely represent the full 24 hr profile of the SDV, since the SDV often has significant higher order harmonics, including but not limited to a second harmonic. Both the 24 hr profile of the SDV and its declination dependence can only be obtained by utilizing multiple high-count observations of the celestial sphere, which has not been possible until recently.

A continuous observation of the 24 hr profile of the SDV over 12 years with an air shower (AS) detector at Mount Norikura in Japan revealed that the SDV of 10 TeV cosmic-ray intensity exhibits a deficit with a minimum around 12 hr LST (Nagashima et al. 1989). Similar profiles have been reported

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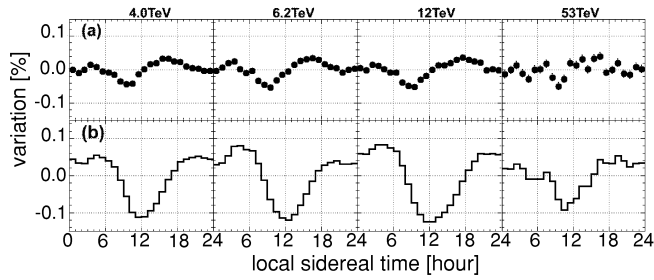


FIG. 1.—Sidereal daily variations averaged over all declinations as a function of representative energies of 4.0, 6.2, 12, and 53 TeV. The upper panels (a) show the differential variations $D(t)$, while the lower panels (b) display the physical variations $R(t)$. The error bars are statistical.

by several other experiments in the same energy region (Alexeenko & Navarra 1985; Bergamasco et al. 1990; Aglietta et al. 1996; Munakata et al. 1997). The intensity deficit has also been seen in the sub-TeV region, below 1 TeV covered by underground muon detectors (Nagashima et al. 1998, hereafter NFJ). In addition to this anisotropy, which they named “Ga-

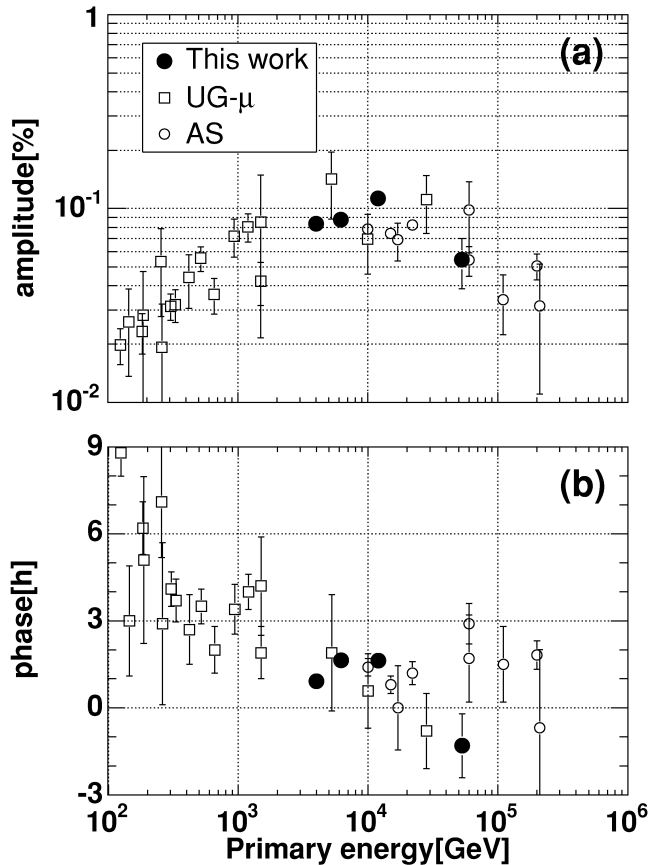


FIG. 2.—First harmonics of the sidereal daily variations obtained by underground muon observations (Bercovitch & Agrawal 1981; Thambyahpillai 1983; Nagashima et al. 1985; Swinson & Nagashima 1985; Andreyev et al. 1987; Lee & Ng 1987; Ueno et al. 1990; Cutler & Groom 1991; Fenton et al. 1995; Mori et al. 1995; Munakata et al. 1995, 1997; Ambrosio et al. 2003) and by air shower array experiments (Gombosi et al. 1975; Alexeenko et al. 1981; Nagashima et al. 1989; Bergamasco et al. 1990; Aglietta et al. 1995, 1996; NFJ). The amplitude (a) and the phase (b) of the first harmonics are plotted as a function of the primary cosmic-ray energy. Shown are Tibet III (filled circles), underground muon observations (open squares), and other air shower experiments (open circles). For clarity, the points are not labeled with citation information. The observed amplitude is divided by $\cos \delta$ for provisional correction of the difference in the representative declination (δ). The data by Tibet III are averaged over all declinations.

TABLE 1
AMPLITUDES AND PHASES OF THE FIRST HARMONIC VECTOR OBTAINED WITH THE TIBET III

Energy (TeV)	Amplitude (10^{-3} %)	Phase (hr)	χ^2
4.0	83.4 ± 5.2	0.9 ± 0.2	338.1
6.2	87.7 ± 6.2	1.6 ± 0.3	342.0
12	112.6 ± 6.7	1.6 ± 0.2	200.3
53	54.4 ± 15.8	-1.3 ± 1.1	58.2

NOTE.—The amplitudes and phases were observed by the Tibet III and are plotted in Fig. 2. The χ^2 -values are deduced from harmonic analyses of the differential variations $D(t)$ for 22 degrees of freedom.

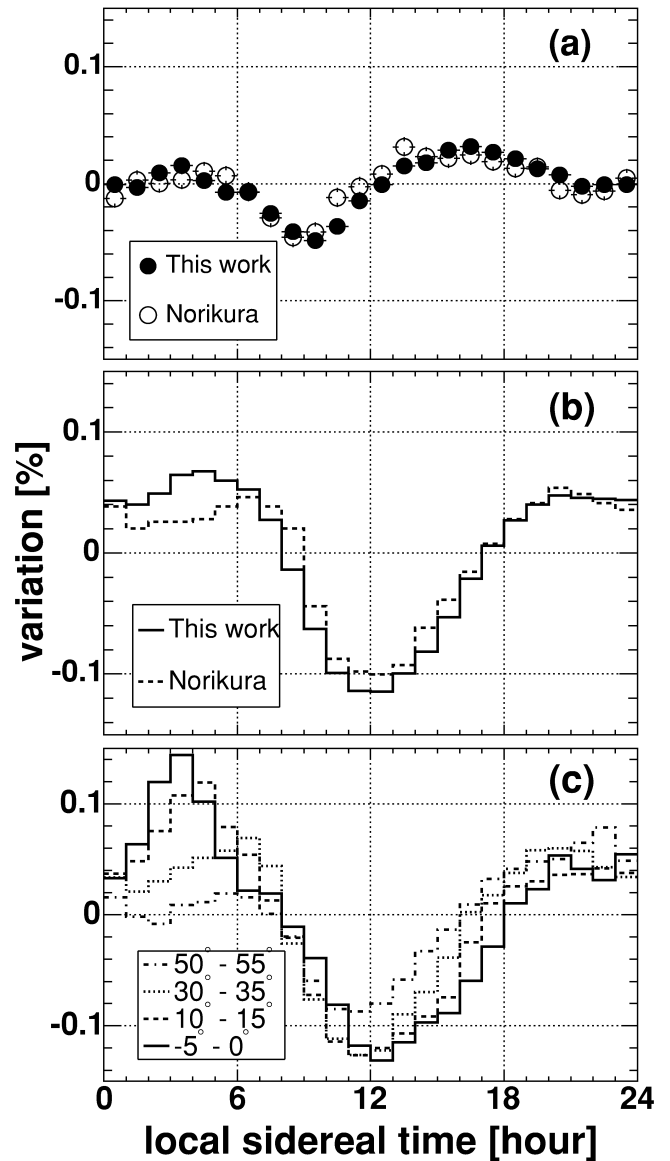


FIG. 3.—Sidereal daily variations averaged over all primary energies. Panels a and b show, respectively, the differential variation $D(t)$ and the physical variation $R(t)$ averaged over all declinations, while panel c shows the physical variation $R(t)$ in the four declination bands of 50° – 55° (dash-dotted line), 30° – 35° (dotted line), 10° – 15° (dashed line), and -5° – 0° (solid line). The open circles in (a) and the dashed histograms in (b) display the variations reported from the Norikura AS experiment (Nagashima et al. 1989).

lactic” anisotropy, NFJ has also found a new anisotropy component causing an excess of intensity with a maximum around 6 hr LST in the sub-TeV region. The amplitudes of both of these anisotropy components increase with increasing energy up to ~ 1 TeV, as higher energy particles become less sensitive to the solar modulation effects masking the Galactic anisotropy. An analysis of the SDVs recorded in a total of 48 directional channels of the underground muon detectors monitoring both the northern and southern sky indicated that the maximum phase of the new anisotropy component, which is ~ 6 hr in the Northern Hemisphere, shifts toward earlier times as the declination of the incident cosmic rays moves south toward the equator (Hall et al. 1998, 1999).

Since this new anisotropy component was not seen by the omnidirectional measurement of the Norikura AS array at ~ 10 TeV, which was not capable of resolving the declination of the incident direction, NFJ suggested that the amplitude of this anisotropy decreases with increasing energy between 1 and 10 TeV. As such an energy spectrum is consistent with an anisotropy due to the possible acceleration of particles arriving from the heliotail direction, i.e., ~ 6 hr in LST, this new component has been named the “tail-in” anisotropy (NFJ).

A two-dimensional map of the SDV obtained with the Tibet III air shower array has been published elsewhere (Amenomori et al. 2005; Wu et al. 2005). In this Letter, we present an analysis of the SDV observed by the Tibet III air shower array, examining the precise form of both the full 24 hr profile and the energy and declination dependences of the SDV with high statistics and a good angular resolution of the incident direction of primary particles. The reliability of both the measurement and the analysis in the Tibet III experiment in the multi-TeV region is assured by the successful observation of the Compton-Getting (CG) anisotropy due to the orbital motion of the Earth around the Sun (Amenomori et al. 2004, hereafter Paper I).

2. EXPERIMENT

The Tibet air shower experiment has been successfully operating at Yangbajing (90°522 east, 30°102 north, 4300 m above sea level) in Tibet, China since 1990. The array, originally constructed in 1990, was gradually upgraded by increasing the number of counters (Amenomori et al. 2000, 2002). The Tibet III array, used in the present analysis, was completed in the late fall of 1999. This array consists of 533 scintillation counters of 0.5 m², each placed on a 7.5 m square grid with an enclosed area of 22,050 m² 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 γ -rays into electron-positron pairs.

An 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. We collected 5.4×10^{10} events by the Tibet III array during 918 live days from 1999 November to 2003 November. After some simple data selections (software trigger condition of any fourfold coincidence in the FT counters recording more than 0.8 particles in charge, zenith angle of arrival direction $< 45^\circ$, air shower core position located in the array, etc.), 3.0×10^{10} events remained for further analysis. The declination of incident direction of these events ranges from -15° to 75° .

The performance of the Tibet III array is also examined by employing a full Monte Carlo (MC) simulation in the energy range from 0.3 to 1000 TeV. We use the CORSIKA version 6.004 code (Heck et al. 1998) and the QGSJET model (Kal-

mykov et al. 1997) for the generation of air shower events and the EPICS UV8.00 code²⁰ of shower particles with scintillation counters. Primary cosmic-ray particles are sampled from the energy spectrum made by a compilation of direct observational data. The primary cosmic-ray energy is estimated by $\sum \rho_{\text{FT}}$, which is the sum of the number of particles per square meter for each FT counter. According to the result of the simulation, $\sum \rho_{\text{FT}} = 100$ corresponds approximately to 10 TeV primary cosmic-ray energy (Amenomori et al. 2003).

3. ANALYSIS

The selected air shower events are subsequently histogrammed into hourly bins in LST (366 cycles per year), according to the time, incident direction, and air shower size of each event. In order to check the seasonal change in the daily variation, we constructed the histogram for each month and corrected it for the observation live time varying month to month. Following Paper I, we first obtain the daily variation for east- and west-incident events and adopt the “east-west”(E-W) subtraction method to eliminate meteorological effects and possible detector biases. By dividing the difference by the hour angle separation between the mean E- and W-incident directions averaged over the E- and W-incident events, we obtain the “differential” variation “ $D(t)$ ” in sidereal time. The physical variation “ $R(t)$,” which is expected to be free from spurious effects, can be reconstructed by integrating $D(t)$ in sidereal time t . Hereafter, we make statistical arguments on the basis of the differential variation $D(t)$ to avoid the difficulty in estimating the error in $R(t)$. By adopting this method, the spurious variation contained in the average daily variation is reduced to $\leq 0.01\%$, which is less than 20% of the CG anisotropy with the amplitude of $\sim 0.05\%$ in the solar time. A spurious variation in sidereal time also could be produced from a seasonal change of the daily variation in solar time. We confirmed, however, that the variations with nonphysical frequencies, i.e., the variations in the antisidereal time (364 cycles per year, also called the pseudosidereal time) and in the extended-sidereal time (367 cycles per year), are negligibly small. This ensures that the seasonal changes of the solar and sidereal daily variation are both negligible. For more details of the method, readers are referred to Paper I and Nagashima et al. (1989).

The data are divided into four data samples according to representative primary energies of 4.0, 6.2, 12, and 53 TeV. Each of these representative energies is calculated as the mode value of the logarithmic energy of each event produced by the MC simulation.

In our analysis, we first calculate the harmonic vector by making a best fit of the “differential variation” $D(t)$ with the harmonic function

$$D^{\text{cal}}(t) = A_D \cos \frac{2\pi}{24} (t - \Phi_D), \quad (1)$$

where A_D and Φ_D are the amplitude and phase of the first harmonic vector of $D(t)$ and t is local sidereal time in hours. By integrating equation (1) in time t , we arrive at the amplitude and phase of the physical variation $R(t)$, respectively, as

$$A_R = \frac{24}{2\pi} A_D, \quad \Phi_R = \Phi_D + 6. \quad (2)$$

²⁰ See <http://cosmos.n.kanagawa-u.ac.jp/EPICSHome>.

The errors of A_R and Φ_R are deduced from errors of the observed $D(t)$.

4. RESULTS AND DISCUSSIONS

On the basis of the SDV observed by the Norikura AS experiment, NFJ concluded that the amplitude of the tail-in anisotropy, with a maximum at ~ 6 hr LST, decreases with increasing primary energy above ~ 1 TeV, while the Galactic anisotropy, with a minimum at ~ 12 hr LST, remains constant. Furthermore, they suggested that the phase of the composite first harmonic vector turns counterclockwise from ~ 3 to ~ 0 hr with increasing energy (the composite amplitude is also expected to decrease by $\sim 30\%$ when the amplitudes of two anisotropy components are equal at ≤ 1 TeV). The result from the present experiment, however, is apparently inconsistent with their model, as seen in Figure 1. This figure showing the SDV averaged over all declinations (-15° to 75°), observed by the Tibet III, indicates that there is no significant energy dependence in the 24 hr profile of the SDV in this energy region. This is further confirmed in Figure 2, which depicts the energy dependence of the amplitude A_R and the phase Φ_R of the first harmonic vector observed by the Tibet III, together with those from other experiments. It is readily seen that the first harmonic vector of the SDV is remarkably independent of the primary cosmic-ray energy in the multi-TeV region, contrary to the suggestion of NFJ. The amplitude and phase observed by the Tibet III are also summarized in Table 1, together with the χ^2 -values for making the best fit of the first harmonic. The large χ^2 -values indicate that the first harmonic vector is not sufficient for a precise representation of the full 24 hr profile.

Figures 3a and 3b show the full 24 hr profile of the SDV averaged over all declinations and primary energies, together with the results of the Norikura AS experiment (NFJ), which was not capable of resolving the declination of the incident direction. We find that the Tibet III results are in fairly good

agreement with the Norikura data as far as the SDV averaged over all declinations is concerned. In Figure 3b displaying $R(t)$, both results show the intensity deficit with a minimum around 12 hr, which is referred to as the Galactic anisotropy by NFJ. The remarkable new features of the Tibet III measurement, however, become more apparent when one looks at the SDV in each declination band separately, as shown in Figure 3c. It is evident that there is also an excess intensity with a maximum earlier than ~ 7 hr LST. The phase of maximum changes from ~ 7 to ~ 4 hr LST, and the amplitude of the excess increases as the viewing direction moves from the Northern Hemisphere to the equatorial region. This is qualitatively consistent with the anisotropy component first found in the sub-TeV region by underground muon detectors and referred to as tail-in anisotropy (Hall et al. 1998, 1999; NFJ). The Tibet III experiment clearly shows that the tail-in anisotropy continues to exist in the multi-TeV region covered by AS experiments. The present findings might require an alternative interpretation of the origin of this anisotropy, since particle acceleration resulting in an $\sim 0.1\%$ anisotropy of the multi-TeV cosmic rays seems unlikely in the heliotail. Finally, we note that the observations presented in this Letter have been made possible by the high statistics and good angular resolution provided by the Tibet III experiment. A more detailed study of the SDV based on the two-dimensional map is in progress. It seems also desirable to lower the energy threshold to the sub-TeV region, which would allow the precise measurement of the heliospheric modulation of the sidereal anisotropy and may lead to a better understanding of the large-scale magnetic structure of the heliosphere.

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