32ND INTERNATIONAL COSMIC RAY CONFERENCE, BEIJING 2011

On temporal variations of the multi-TeV cosmic ray anisotropy using the Tibet III Air Shower Array

M. Amenomori[1], X. J. Bi[2], D. Chen[3], W. Y. Chen[2], S. W. Cui[4], Danzengluobu[5], L. K. Ding[2], X. H. Ding[5], C. F. Feng[6], Zhaoyang Feng[2], Z. Y. Feng[7], Q. B. Gou[2], H. W. Guo[5], Y. Q. Guo[2], H. H. He[2], Z. T. He[4,2], K. Hibino[8], N. Hotta[9], Haibing Hu[5], H. B. Hu[2], J. Huang[2], W. J. Li[2,7], H. Y. Jia[7], L. Jiang[2], F. Kajino[10], K. Kasahara[11], Y. Katayose[12], C. Kato[13], K. Kawata[3], Labaciren[5], G. M. Le[2], A. F. Li[14,6,2], C. Liu[2], J. S. Liu[2], H. Lu[2], X. R. Meng[5], K. Mizutani[11,15], K. Munakata[13], H. Nanjo[1], M. Nishizawa[16], M. Ohnishi[3], I. Ohta[17], S. Ozawa[11], X. L. Qian[6,2], X. B. Qu[2], T. Saito[18], T. Y. Saito[19], M. Sakata[10], T. K. Sako[12], J. Shao[2,6], M. Shibata[12], A. Shiomi[20], T. Shirai[8], H. Sugimoto[21], M. Takita[3], Y. H. Tan[2], N. Tateyama[8], S. Torii[11], H. Tsuchiya[22], S. Udo[8], H. Wang[2], H. R. Wu[2], L. Xue[6], Y. Yamamoto[10], Z. Yang[2], S. Yasue[23], A. F. Yuan[5], T. Yuda[3], L. M. Zhai[2], H. M. Zhang[2], J. L. Zhang[2], X. Y. Zhang[6], Y. Zhang[2], Yi Zhang[2], Ying Zhang[2], Zhaxisangzhu[5], X. X. Zhou[7] (The Tibet ASγ Collaboration)

[1] *Department of Physics, Hirosaki University, Hirosaki 036-8561, Japan*
[2] *Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China*
[3] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan*
[4] *Department of Physics, Hebei Normal University, Shijiazhuang 050016, China*
[5] *Department of Mathematics and Physics, Tibet University, Lhasa 850000, China*
[6] *Department of Physics, Shandong University, Jinan 250100, China*
[7] *Institute of Modern Physics, SouthWest Jiaotong University, Chengdu 610031, China*
[8] *Faculty of Engineering, Kanagawa University, Yokohama 221-8686, Japan*
[9] *Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan*
[10] *Department of Physics, Konan University, Kobe 658-8501, Japan*
[11] *Research Institute for Science and Engineering, Waseda University, Tokyo 169-8555, Japan*
[12] *Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan*
[13] *Department of Physics, Shinshu University, Matsumoto 390-8621, Japan*
[14] *School of Information Science and Engineering, Shandong Agriculture University, Taian 271018, China*
[15] *Saitama University, Saitama 338-8570, Japan*
[16] *National Institute of Informatics, Tokyo 101-8430, Japan*
[17] *Sakushin Gakuin University, Utsunomiya 321-3295, Japan*
[18] *Tokyo Metropolitan College of Industrial Technology, Tokyo 116-8523, Japan*
[19] *Max-Planck-Institut für Physik, München D-80805, Deutschland*
[20] *College of Industrial Technology, Nihon University, Narashino 275-8576, Japan*
[21] *Shonan Institute of Technology, Fujisawa 251-8511, Japan*
[22] *RIKEN, Wako 351-0198, Japan*
[23] *School of General Education, Shinshu University, Matsumoto 390-8621, Japan*

zhangyi@mail.ihep.ac.cn

DOI: 10.7529/ICRC2011/V01/1167

Abstract: We analyze the large-scale two-dimensional sidereal anisotropy of multi-TeV cosmic rays by Tibet Air Shower Array, with the data taken from 1999 November to 2008 December. To explore temporal variations of the anisotropy, the data set is divided into nine intervals, each in a time span of about one year. The sidereal anisotropy of magnitude about 0.1% appears fairly stable from year to year over the entire observation period of nine years. This indicates that the anisotropy of TeV Galactic cosmic rays remains insensitive to solar activities since the observation period covers more than a half of the 23rd solar cycle.

Keywords: cosmic rays — diffusion — ISM: magnetic fields — solar neighborhood — Sun: activity

1 Introduction

Galactic cosmic rays (GCRs) are high-energy nuclei (most protons) believed to be accelerated by supernova remnants (SNRs) in our Galaxy and continuously propagate to the Earth. The intensity of GCRs is nearly isotropic due to deflections in the Galactic magnetic field (GMF). However, extensive observations do show a slight anisotropy on the overall isotropic background [9, 15, 7, 16, 3, 14, 6, 2, 1].

From the analysis of numerous experiments, both the amplitude and the phase of the best-fit first harmonic are obtained with cosmic ray (CR) energy in a wide range from tens of GeV to PeV [8, 1]. Below several tens of GeV, solar modulation effects are most notable for GCRs. GCRs interact with the solar wind magnetic field, both ordered field and irregular field components, after entering the heliosphere. The spatial distribution of GCRs can reflect the magnetic structure in the solar wind. With increasing energy, CRs become less sensitive to the solar modulation. It is well known that the flux of GCRs with energy per nucleon in the energy range of $\sim 10^{11} - 10^{14}$ eV has a sidereal anisotropy on the order of 10^{-3}. The gyro radius r_L of CRs in this energy range in a GMF of 3 μG is about several AU ($\sim$ 0.03 pc), much smaller than the size of the Galaxy. In the multi-TeV range, the gyro radius of hundreds of AU becomes comparable to the spatial scale of the heliosphere in the nose direction toward the upstream side of the interstellar medium flow [19]. However, the heliosphere has a long heliotail, and the modulation in the heliotail remains possible. Therefore, the large-scale sidereal anisotropy of CRs in this energy range gives us an important clue about the magnetic field structure in the heliosphere or the local interstellar space surrounding the heliosphere.

The solar cycle shows a quasi-period of about 11 yr and the global magnetic polarity reverses with a quasi-period of two solar activity cycles [18]. Since GCRs are modulated by solar activities in the mentioned energy range above, the sidereal anisotropy may follow the variation of solar cycle. Many experiments devoted to the study of temporal variations of GCR sidereal anisotropy. [16] found that both the amplitude and the phase of the sidereal anisotropy with the rigidity $\sim 10^{13}$V had no significant changes for more than ten years, except that the phase changed at the epoch (1979-1980) when the polar magnetic field of the Sun reversed its polarity. At primary energy as low as 2 TeV, [10] demonstrated that the sidereal anisotropy was constant within the accuracy of the experiment, with observations in the subsequent ten years (1982-1991) after this epoch of polarity reversal. Recently, underground muon observations showed that yearly mean harmonic vectors of the sidereal anisotropy in the sub-TeV region are more or less stable in phase and amplitude over 20 years since 1985 without showing any significant correlation with the solar activity and magnetic-cycles [13]. However, Milagro experiment recently reported an amplitude increase of the sidereal anisotropy at 6 TeV in the latter half of the 23rd solar cycle (from 2000 July to 2007 July), while the phase remains stable [2]. The contradiction needs further checks from other experiments.

In this paper, we analyze temporal variations of sidereal anisotropy of multi-TeV GCR intensity using the data of Tibet III array from 1999 November to 2008 December. At this point, we cannot investigate the influence of the polarity reversal of the global solar magnetic field on the sidereal anisotropy due to the lack of data before the current magnetic field reversal.

2 Tibet Air Shower Array Experiment

The Tibet Air Shower Array experiment has been operating successfully at Yangbajing (90.522° E, 30.102° N; 4300 m above the sea level) in Tibet, China since 1990. The Tibet III array was completed in the late fall of 1999 [4] by gradually upgrading. The array is composed of 497 fast timing(FT) detectors and 36 density (D) detectors, covering a surfacearea of 22,050 m^2. 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 $\sum \rho_{\mathrm{FT}}$ is regarded as an estimator for the primary particle energy, where the size of $\sum \rho_{\mathrm{FT}}$ is defined as the sum of particles per m^2 for each FT detector.

In the present analysis, CR events are selected based on the following four criteria: (1) estimated air shower core location should be inside the array; (2) the zenith angle of the incident direction should be less than $45°$; (3) any fourfold coincidence in the FT counters should record a signal of more than 0.8 particles; (4) when $10 \leq \sum \rho_{\mathrm{FT}} < 178$ is satisfied, corresponding to a modal energy of about 5 TeV.

In total, about 4.91×10^{10} CR events are used in the present analysis.

3 Analysis and Results

Tibet ASγ experiment has showed that no other periodicity of modulation was significant enough from 1 hour to 2 years in the energy range from ~ 3.0 TeV to ~ 12.0 TeV, besides the well-known solar diurnal, sidereal diurnal and sidereal semi-diurnal modulations at a level of $\sim 10^{-3}$[11],by using Lomb-Scargle Fourier transformation method [12, 17].

When applying the all distance equi-zenith angle method (detailed in [5]), the intensity in the function natural contain both sidereal time and solar time modulation components. The alternative method to separate these modulations was to properly fold the data according to the sidereal time or solar time periodicity. This method was used in [5, 6] when we analyzed CR intensity variations in the sidereal time frame with several years data samples. In this method, each event had to be re-weighted to form an exactly one year long and uniformly distributed data series before folding. Therefore, the disadvantage of this method is that more than one year's data are needed, which can not be followed in current work. In this case, we adopt a new method of fitting all modulation components simultaneously to perform the year-by-year analysis of CR anisotropy.

Based on the results of Lomb-Scargle Fourier transformation, in the present analysis, we assume that at any moment t, the relative intensity of CRs at any given direction (θ, ϕ) in the horizontal coordinate, is modulated as a product of $I_{sid}(\alpha_{sid}, \delta_{sid})$ and $I_{sol}(\alpha_{sol}, \delta_{sol})$. Here $(\alpha_{sid}, \delta_{sid})$ and $(\alpha_{sol}, \delta_{sol})$ are positions corresponding to the celestial coordinate in the local sidereal time frame and the local solar time frame of the same point (t, θ, ϕ) in horizontal coordinate, I_{sid} and I_{sol} denote the CR intensity in the sidereal time frame and the solar time frame respectively. So substituting I by $I_{sid}(\alpha_{sid}, \delta_{sid}) \times I_{sol}(\alpha_{sol}, \delta_{sol})$, the total χ^2 can be written as

$$\begin{aligned}\chi^2 = \sum_{t,\theta,\phi} \Bigg(\Bigg\{ & \frac{N_{obs}(t,\theta,\phi)}{I_{sid}(\alpha_{sid},\delta_{sid}) \times I_{sol}(\alpha_{sol},\delta_{sol})} - \\ & \frac{1}{(\sum\limits_{\phi\neq\phi'} 1)} \sum_{\phi\neq\phi'} \frac{N_{obs}(t,\theta,\phi')}{I_{sid}(\alpha'_{sid},\delta'_{sid}) \times I_{sol}(\alpha'_{sol},\delta'_{sol})} \Bigg\}^2 \\ & \times \Bigg\{ \frac{N_{obs}(t,\theta,\phi)}{I^2_{sid}(\alpha_{sid},\delta_{sid}) \times I^2_{sol}(\alpha_{sol},\delta_{sol})} + \\ & \frac{1}{(\sum\limits_{\phi\neq\phi'} 1)^2} \sum_{\phi\neq\phi'} \frac{N_{obs}(t,\theta,\phi')}{I^2_{sid}(\alpha'_{sid},\delta'_{sid}) \times I^2_{sol}(\alpha'_{sol},\delta'_{sol})} \Bigg\}^{-1} \Bigg).\end{aligned}$$

Here, $N_{obs}(t, \theta, \phi)$ denotes the number of observed events in the "window" (θ, ϕ) in the horizontal coordinate at the moment t. After minimizing the χ^2 function, $I_{sid}(\alpha_{sid}, \delta_{sid})$ and $I_{sol}(\alpha_{sol}, \delta_{sol})$ can be obtained simultaneously.

The data were acquired by the Tibet III Array for 1915.5 live days from Nov. 1999 to Dec. 2008. It covers all nine running phases of the Tibet III Air Shower Array. As described in Equation (1), for any direction in the horizontal coordinate at any moment in the observation period, a χ^2 function can be constructed. Covering all nine phases of Tibet III array, we got a total χ^2 accumulated over the entire observation period. By minimizing it, the CR intensity maps in the frame of the local sidereal time and the local solar time averaged over all nine phases were obtained simultaneously.

To study the temporal variation of the sidereal anisotropy, the data was divided into nine subsets, corresponding to nine running phases of Tibet III array each in a time scale of about one year, as summarized in Table 1.

Using data samples recorded during each separated phase, the GCR relative intensity maps in the local sidereal time frame averaged over each phase were obtained according to Equation (1). The two-dimensional (2D) relative intensity maps of GCRs with modal energy around 5 TeV in the local sidereal time frame of different phases are displayed in Fig. 1, and the corresponding one-dimensional (1D) projections over all declinations are also shown. The solid red markers in each plot denote the relative intensities of GCRs in the local sidereal time frame over the corresponding observation period, while the blue dashed smooth curves in plots represent variations of GCR relative intensity averaged over all nine phases of Tibet III array. From the comparison of GCR sidereal anisotropy in different phases from 1999 November to 2008 December, it can be seen that the CR intensity variation in the local sidereal time appears fairly stable year by year.

Furthermore, we take a χ^2 test to check the consistency among different phases. As shown in Equation (1), the CR intensity variation along the local sidereal time averaged over all nine phases contains contributions of each single phase. To avoid the correlation between the two plots which are used in the test, we compare the result of each single phase with the average one of all the other eight phases except the single one instead of the average one of all nine phases. The obtained χ^2/ndf value and the probability of each comparison were labeled in Fig. 1. The test also indicates stability for the sidereal anisotropy with time.

The observation period of Tibet III Array covers more than a half of the 23rd solar activity cycle from the maximum to the minimum. So it implies that the sidereal anisotropy of multi-TeV GCRs is insensitive to the solar activity. It disagrees with the recent result of Milagro experiment [2], which shows an increase in the amplitude of the sidereal anisotropy with time while the phase remains stable.

4 Conclusions

In this work, we investigate temporal variations of the large-scale sidereal anisotropy of GCR intensity using the data of Tibet III Air Shower Array from 1999 November to 2008 December. Totally $\sim 4.91 \times 10^{10}$ CR events are used. The data is divided into nine intervals, each in a time span of about one year. We find that, in the multi-TeV energy range, the sidereal anisotropy is fairly stable year by year over all nine phases of Tibet III Array, which covers more than a half of the 23rd solar cycle from the maximum to the minimum. It indicates that the anisotropy in this energy range appears insensitive to solar activities. This feature can give some constraints on the origin of the sidereal anisotropy, which has no convincing and widely accepted explanations so far.

5 Acknowledgements

The collaborative experiment of the Tibet Air Shower Arrays has been performed under the auspices of the Ministry of Science and Technology of China and the Ministry of Foreign Affairs of Japan. This work was supported in part

Table 1: Definition of nine phases of Tibet III from 1999 November to 2008 December

Phase	Start time	End time	Live days	Number of used CR events
1	Nov. 18, 1999	Jun. 29, 2000	173.1	5.16×10^9
2	Oct. 28, 2000	Oct. 11, 2001	283.7	8.14×10^9
3	Dec. 05, 2001	Sep. 19, 2002	201.8	5.59×10^9
4	Nov. 18, 2002	Nov. 18, 2003	259.1	6.34×10^9
5	Dec. 14, 2003	Oct. 10, 2004	123.6	3.07×10^9
6	Oct. 19, 2004	Nov. 15, 2005	277.6	6.79×10^9
7	Dec. 07, 2005	Nov. 03, 2006	114.5	2.71×10^9
8	Nov. 06, 2006	Feb. 25, 2008	269.2	6.36×10^9
9	Mar. 02, 2008	Dec. 03, 2008	212.9	4.91×10^9

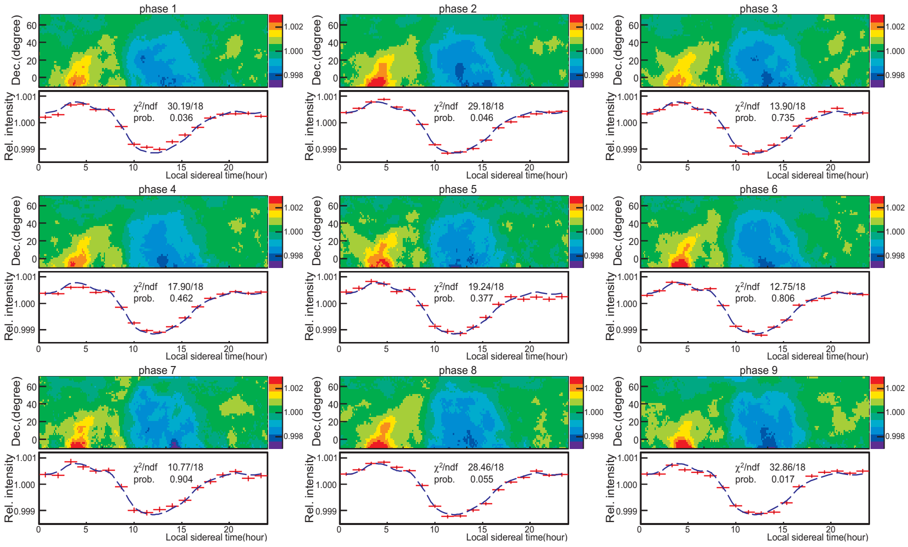

Figure 1: Cosmic ray intensity variation in the local sidereal time frame for CRs with the modal energy around 5 TeV in the 9 phases of Tibet III Array. Top: 2D intensity map of each phase; Bottom: 1D projection averaged over all declinations. In bottom plots of each panel, the red crosses in each plot show the intensity variation over each phase respectively, while the dashed blue lines represent the intensity averaged over all nine phases of Tibet III array.

by Grants-in-Aid for Scientific Research on Priority Areas (712) (MEXT), by the Japan Society for the Promotion of Science (JSPS), by the National Natural Science Foundation of China, the Chinese Academy of Sciences and the Ministry of Education of China.

References

[1] Abbasi, R. U., et al. 2009, arXiv:0907.0498
[2] Abdo, A. A., et al. 2009, Apj, 698, 2121
[3] Aglietta, M., et al. 1996, ApJ, 470, 501
[4] Amenomori, M., et al. 2002, Proc. 27th Int. Cosmic Ray Conf. (Hamburg), 2, 573
[5] Amenomori, M., et al. 2005, Apj, 633, 1005
[6] Amenomori, M., et al. 2006, Science, 314, 439
[7] Cutler, D. J., Bergeson, H. E., Davies, J. F., & Groom, D. E. 1981, ApJ, 248, 1166
[8] Guillian, G., et al. 2007, Phys. Rev. D, 75, 062003
[9] Jacklyn, R. M. 1966, Nature, 211, 690
[10] Kozyarivsky, V. A., et al. 1995, Bull. Russ. Acad. Sci., Phys., 59, 714
[11] Li., A. F., et al. 2008, Proc. 30th Int. Cosmic Ray Conf. (Mexico City), 1, 609
[12] Lomb, N. R. 1976, Astrophys, Space Sci., 39, 447
[13] Munakata, K., et al. 2008, arXiv:0811.0422v2
[14] Munakata, K., et al. 1997, Phys. Rev. D, 56, 23
[15] Nagashima, K., et al. 1975, Proc. 14th Int. Cosmic Ray Conf. (Munich), 4, 1503
[16] Nagashima, K., et al. 1989, Nuovo Cimento C, 12, 695
[17] Scargle, J. D. 1982, Apj, 263, 835
[18] Solanki, S. K., Inhester, B., & Schüssler, M. 2006, Rep. Prog. Phys., 69, 563
[19] Washimi, H., & Tanaka, T. 1996, Space Sci. Rev., 78, 85