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Sidereal Anisotropy of Galactic Cosmic-Ray Intensity Observed with the Tibet Air Shower Array

The Tibet ASγ Collaboration

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We report the large-scale sidereal anisotropy of galactic cosmic-ray intensity in the multi-TeV region obtained with the Tibet III air shower array in the period from 1999 through 2003. The sidereal daily variation of cosmic rays observed with Tibet III clearly indicates the excess of relative intensity around $4 \sim 7$ hours local sidereal time, as well as the deficit around 12 hours local sidereal time. The amplitude of the excess is not significant when averaged over the declination, however it becomes larger and clearer as the declination of viewing direction moves toward the south. The maximum phase of the excess intensity shifts from $\sim$7 to $\sim$4 hours according to the declination moving from the northern hemisphere to the equatorial region. Furthermore,

it is shown that both the amplitude and the phase of the first harmonic vector of the daily variation are almost independent of primary energy denoting no considerable energy dependence in the multi-TeV region.

1. Introduction

The directional anisotropy of galactic cosmic-ray intensity in the multi-TeV region gives us valuable information on the magnetic structure of the heliosphere and/or the local interstellar space surrounding the heliosphere. The galactic anisotropy has been investigated via the sidereal daily variation (SDV) of cosmic-ray intensity observed in a fixed directional channel of the detector on the spinning Earth. It is found that the SDV of 10 TeV cosmic-ray intensity exhibits a deficit with a minimum around 12 hours local sidereal time (LST) by a long-term observation with an air-shower (AS) detector at Mt. Norikura in Japan [1]. Such a deficit has also been seen in the sub-TeV region by underground muon detectors [2](NFJ). In addition to this anisotropy, NFJ has also found a new anisotropy component causing an excess of intensity with a maximum around 6 hours LST in the sub-TeV region. Since this new anisotropy component was not observed by the omnidirectional measurement of the Norikura AS array at $\sim$ 10 TeV, NFJ prospected that the amplitude of the new anisotropy reduces 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 coming from the heliotail direction($\sim$ 6 hours in LST), the new component has been named "Tail-In" anisotropy (NFJ).

In this paper, we show an analysis of the SDV obtained by the Tibet III air shower array, investigating the precise form of both the full 24-hour profile and the energy and declination dependences of the SDV. It should be noted that successful observation of the Compton-Getting (CG) anisotropy due to terrestrial orbital motion around the Sun [3] ensures the reliability of the present analysis.

2. Experiment

The Tibet air shower experiment has been successfully operating at Yangbajing ($90.522°$E, $30.102°$N, 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 [4, 5]. The Tibet III array, used in the present work, was completed in the late fall of 1999. This array consists of 533 scintillation counters of $0.5\mathrm{m}^2$ each placed on a $7.5\mathrm{m}$ square grid with an enclosed area of $22,050\mathrm{m}^2$ and each viewed by a fast-timing (FT) photomultiplier tube. A $0.5\mathrm{cm}$ 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.

3. Analysis

The obtained air shower events are subsequently histogrammed into hourly bins in LST (366 cycle/year), according to the incident direction, time, and air shower size of each event. For the purpose of checking the seasonal change in the daily variation, the histograms for each month are constructed and then corrected for the observation live time varying month to month. Following [3], we first derive the daily variation for each of East and West (E- and W-) incident events and then adopt the "East-West"(E-W) subtraction method to eliminate meteorological effects as well as possible detector biases. By dividing the difference by the hour angle separation between the mean E- and W-incident directions, one can obtain the "differential" variation "$D(t)$" in sidereal time. The physical variation "$R(t)$"can be easily 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 using 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.A spurious variation in sidereal time also could be produced from a seasonal change of the daily variation in solar time. However, it is confirmed that the variations with non-physical frequencies, i.e., the variations in the anti-sidereal time (364 c/y) (also called the psuedo-sidereal time) and in the extended-sidereal time (367 c/y), are negligibly small. Thus, the seasonal changes of the solar and sidereal daily variation can be neglected.

Then, 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 derived as the mode value of the logarithmic energy of each event obtaied by the MC simulation.

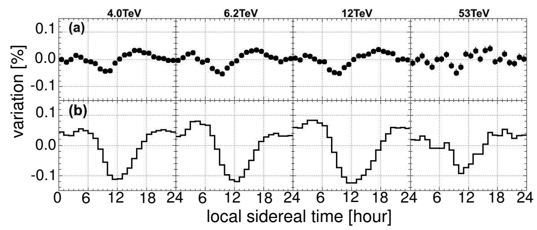

Figure 1. The SDVs averaged over all declinations as a function of representative primary energies of 4.0, 6.2, 12, and 53 TeV. The panels (a) show the differential variations $D(t)$'s, while the panels (b) indicate the physical variations $R(t)$'s. The error bars are statistical.

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 $\sim$ 6 hours LST reduces with increasing primary cosmic-ray energy above $\sim$ 1 TeV, while "Galactic" anisotropy with a minimum at $\sim$ 12 hours LST remains constant. However the result from the present work is apparently inconsistent with their suggestion. Figure 1 shows the SDV averaged over all declinations ($-15°$ to $75°$). As can be seen clearly, there is no significant energy dependence in the 24-hour profile of the SDV in this energy region. Furthermroe, this is confirmed in Figure 2 which depicts the energy dependence of the amplitude and the phase of the first harmonic vector measured 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.

Figures 3(a) and 3(b) show the full 24-hour profile of the SDV averaged over all declinations and primary energies by the present work and Norikura AS experiment(NFJ). It is found that the present results are in a fairly good agreement with the Norikura data as far as the SDV averaged over all declinations is concerned. In Figures 3(b) showing $R(t)$s, both results have the intensity deficit with a minimum around 12 hours. However, the remarkable new features are obtained by the Tibet III measurement become evident, when we look at the SDV in each declination band separately. As can be seen in Figure 3(c), it is evident that there is also an excess intensity with a maximum earlier than $\sim$ 7 hours LST. The phase of maximum shifts from $\sim$ 7 hours to $\sim$ 4 hours 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 [2, 6, 7]. 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 discoveries might require an alternative interpretation of the origin of this anisotropy, since particle acceleration causing a $\sim 0.1\%$ anisotropy of the multi-TeV cosmic rays seems unlikely in the heliotail.

5. Acknowledgements

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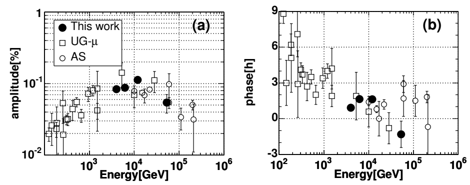

Figure 2. The first harmonics of the SDVs obtained by underground muon observations(UG-μ) and by air-shower array experiments(AS). The amplitude (a) and the phase (b) are plotted as a function of the primary cosmic-ray energy. Shown are Tibet III (*filled circles*), underground muon observations (*open squares*), and other air shower experiments (*open circles*). The amplitude is divided by $\cos\delta$ for correction of the difference in the representative declination (δ). The data by Tibet III are averaged over all declinations.

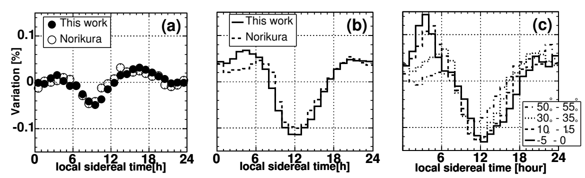

Figure 3. The SDVs averaged over all primary energies. The panel (a) and (b) show the differential variation $D(t)$ and the physical variation $R(t)$ averaged over all declinations respectively, while the panel (c) shows the physical variation $R(t)$'s in the four declination bands of $50° - 55°$(*dash-dotted line*), $30° - 35°$(*dotted line*), $10° - 15°$(*dashed line*), and $-5° - 0°$(*solid line*). The open circles in (a) and dashed histograms in (b) indicate the SDV of the Norikura AS experiment [1].

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