New estimation of the power-law index of the cosmic-ray energy spectrum as determined by the Compton-Getting anisotropy at solar time frame

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***Abstract*. The amplitude of the Compton-Getting anisotropy is known for involving the power-law index of the cosmic-ray energy spectrum. Based on this relation, the Tibet air-shower experiment measures the cosmic-ray spectral index to be $-3.09 \pm 0.44_{\rm stat} \pm < 0.45_{\rm syst}$ between 6 TeV and 40 TeV, which is consistent with -2.7 from direct energy spectrum measurements using instruments on board satellites and balloons. Potentially, this Compton-Getting anisotropy analysis can be utilized**

to confirm the astrophysical origin of the knee of the cosmic-ray energy spectrum, against theoretical models for non-standard hadronic interactions in the atmosphere.

***Keywords*: cosmic rays, anisotropy, knee**

I. Introduction

The cosmic-ray (CR) energy spectrum features a power law $\mathrm{d}N/\mathrm{d}E \propto E^{-\gamma}$ in the energy range between 30 GeV and 100 EeV, where N denotes the number of cosmic rays at the top of the atmosphere, E the cosmic-ray particle energy. The spectral index γ changes from 2.7 to 3.1 around the "knee" at $E \simeq 4$ PeV. Conventional methods for measuring the power-law index of the cosmic-ray energy spectrum above 100 TeV are indirect measurements with air-shower arrays, in which cosmic-ray particles' energy is one by one determined from their shower size. The relation between the two is deduced from air-shower simulations, assuming hadronic interaction models to be reasonable extrapolation of accelerator experiments' results up to the higher energy range. The spectral index thus obtained is valid only if no violation of the standard hadronic interaction takes place in the relevant energy range. This fact leaves room for an argument whether or not non-standard high-energy nucleon interactions in the atmosphere cause the knee of the cosmic-ray energy spectrum [1].

One potential method to confirm the astrophysical origin of the knee is observing the Compton-Getting (CG) anisotropy due to the terrestrial orbital motion around the Sun. When a detector observing cosmic rays moves relative to the rest frame of the CR plasma along the Earth orbit around the Sun, a fractional CR intensity variation ΔI can be observed in the solar time frame. For a presumed power-law CR energy spectrum, this CG anisotropy is expressed as

$$\frac{\Delta I}{< I >} = (\gamma + 2)\frac{v}{c}\cos\theta, \qquad (1)$$

where I denotes the CR intensity, γ the power-law index of the cosmic-ray energy spectrum, v the orbital velocity, c the speed of light and θ the angle between the arrival direction of CRs and the moving direction of the observer [2][3]. At multi-TeV energies, Cutler and Groom first reported clear evidence for the CG anisotropy in the solar diurnal variation [4]. The observed variation was in reasonable agreement with a sinusoidal curve expected from the CG anisotropy, except the maximum phase of the curve deviated from 6:00 h by $+2$ hours at 2σ significance. This deviation was ascribed to meteorological effects on the underground muon intensity. The Tibet air-shower experiment conducted the first study on energy dependence of the solar diurnal variation and proved its consistency with the CG anisotropy above multi-TeV energies [5][6].

As is seen in equation (1), the spectral index γ can be measured directly from the amplitude of the CG anisotropy, which does not strongly depend on the accuracy of the energy determination of the cosmic-ray particles. This method, therefore, does not include the procedure of converting the shower size of each cosmic-ray particle to its energy. The power-law index γ can then be measured virtually without being affected by hadronic interaction models, as air-shower simulations are used only for the purpose of making a rough estimation as to the energy range where the observation of the Compton-Getting anisotropy is being made.

This method is a new approach to measure the spectral index of high-energy cosmic rays and can be utilized as pass-fail criteria of the knee as caused by the non-standard hadronic interaction.

II. Tibet Air-Shower Experiment

The Tibet air-shower array, located at 90.522° E, 30.102° N and 4300 m above sea level, has been operating successfully since 1990. The Tibet III array, consisting of 533 scintillation counters of 0.5 m^2 each, was completed in November 1999 after several times expansion [7][8]. The counters are equipped with fast-timing (FT) photomultiplier tubes and placed on a 7.5 m square grid within an area of 22,050 m^2 [9]. A 0.5 cm thick lead plate is put on top of each counter to improve fast-timing signals by converting gamma rays into electron-positron pairs. Event trigger signals are issued on condition of any fourfold coincidence taking place in the FT counters which record more than 0.6 particles. The trigger rate is approximately 680 Hz at a few TeV energy threshold. The energy of primary CR particles is estimated from $\sum \rho_{\mathrm{FT}}$: the sum of the number of particles/m^2 for each FT counter.

III. Cosmic-Ray Data Analysis

For analysis, we use 11.3×10^{10} events accumulated during 1912 live days from November 1999 to December 2008. The events remaining after the conventional data selection criteria [10] are histogrammed in hourly bins in the local solar time. The number of events for each month is corrected, taking into account monthly variations of the live time. The daily and yearly event rates vary by $\pm$ 2% and $\pm$ 5% respectively [9], mostly affected by meteorological effects. To remove these temporal variations, the East$-$West subtraction procedure is adopted [11]. The daily variations at solar time frame for East and West incident events, $E(t)$ and $W(t)$, are calculated, according to the geographical longitude of incident directions. Dividing $E(t) - W(t)$ by $2\delta t$, the hour-angle separation between the mean directions of E- and W-incident events, leads to $D(t)$: the differential of the physical variation at solar time frame $R(t)$.

$$D(t) \equiv \frac{E(t) - W(t)}{2\delta t} = \frac{R(t+\delta t) - R(t-\delta t)}{2\delta t} = \frac{\mathrm{d}}{\mathrm{d}t}R(t) \qquad (2)$$

The main advantage of the East$-$West method is that meteorological effects and possible detector biases, which are expected to produce common variations for both E- and W-incident events, can be removed.

IV. Results and Discussion

The CR events are divided into eight $\sum \rho_{\rm FT}$ bins in order to find out the energy region where the observed solar daily variation is considered to be free from effects other than the CG anisotropy. The observed solar daily variation in each $\sum \rho_{\rm FT}$ bin is fitted with the equation:

$$f(\lambda) = \alpha \cos\left(\frac{\pi}{12}(\lambda - \phi)\right), \quad (3)$$

where α denotes the amplitude of the CG anisotropy, λ [hr] the local solar time and ϕ [hr] the phase at which the sinusoidal curve reaches its maximum. Note that in a differential form, the phase ϕ is shifted earlier by 6 hours (1/4 cycle) relative to the corresponding actual daily variation, and that the amplitude α is π/12 times that of the physical CG anisotropy.

Figure 1(a) shows $\sum \rho_{\rm FT}$ dependence of the phase ϕ. There exists deviation from the expected CG anisotropy due to some contamination in the region of $\sum \rho_{\rm FT} < 50$, whereas the measured phases are consistent with the expected value in $\sum \rho_{\rm FT} \geq 50$. We thus consider the observed variation in $\sum \rho_{\rm FT} \geq 50$ to be due to the CG anisotropy only. Figure 1(b) shows $\sum \rho_{\rm FT}$ dependence of the observed amplitude α. Since the CR energy spectrum in the multi-TeV region is expressed by a single power law, the amplitude should be consistent with a flat line insofar as there is no contamination. Figure 1(b) confirms that the solar daily variation we observe in the region of $\sum \rho_{\rm FT} \geq 50$ can be solely attributed to the CG anisotropy. We report here on the spectral index γ using events with $\sum \rho_{\rm FT} \geq 50$. This energy region is roughly between 6 TeV and 40 TeV, corresponding to 20% and 80% of the median energy distribution, respectively.

Figure 2(a) shows the observed solar daily variation together with the best-fit sinusoidal curve, which leads to $\alpha = (11.05 \pm 0.96_{stat}) \times 10^{-5}$. The value of γ can be calculated using the equation:

$$\alpha = (\gamma + 2)\frac{v}{c}\frac{\pi}{12}F, \quad (4)$$

where α denotes the amplitude, $v = 2.978 \times 10^4$ [m/s] the average orbital velocity of the Earth, and $F = 0.827$ an effective geometrical factor by which α decreases, calculated according to the latitude at Yangbajing site [10]. The factor π/12 appears as the anisotropy is measured in the differential form given in equation (2). In equation (4), we use the average value of the orbital velocity of the Earth. It is equivalent to neglecting its time dependency of ±2%, which may need to be taken into account when more data are accumulated.

Seasonal changes of the sidereal daily variation due to the galactic anisotropy could produce spurious variations in the solar time frame, which must be taken into account as a systematic error of γ. Figure 2(b) shows the differential variation in the local extended-sidereal time (367.2422 cycles/yr). The χ^2-fitting results are summarized in Table I. The insignificant variation in the extended-sidereal time with an amplitude of $(0.16 \pm 0.96_{stat}) \times 10^{-5}$ assures that contamination in the solar daily variation due to the seasonal changes of the sidereal daily variation is less than 9% of the CG anisotropy. We thus find $\gamma = 3.14 \pm 0.44_{stat} \pm < \ 0.45_{syst}$. This systematic error would become smaller in the future when more data are accumulated.

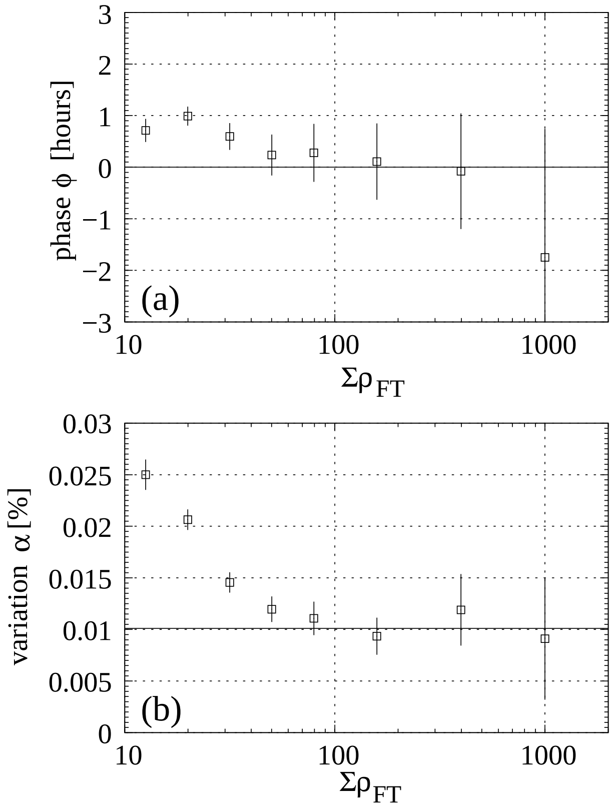

Fig. 1. (a) : $\sum \rho_{\rm FT}$ dependence of the phase ϕ, (b) : $\sum \rho_{\rm FT}$ dependence of the amplitude α. Both are evaluated in a differential form. The solid lines show the expected values from the CG anisotropy, assuming the spectral index to be -2.7. The error bars are statistical only.

As the detection efficiency of the Tibet air-shower array depends on CR nuclei in this energy range (6 − 40 TeV), the correction for it must be taken into account. Air-shower simulations employing direct observational data for primary cosmic rays [12] prove that -0.05 should be added to the value of γ above. This correction can be left out of consideration above ∼60 TeV where the detection efficiency reaches ∼100% independent of nuclei.

Finally, we find the spectral index γ between 6 and 40 TeV to be $3.09 \pm 0.44_{stat} \pm < \ 0.45_{syst}$, which is consistent with 2.7 from direct energy spectrum measurements using instruments on board satellites and balloons.

The CG anisotropy analysis will enable future high-statistics experiments with huge effective areas to measure the power-law index of the cosmic-ray all-particle

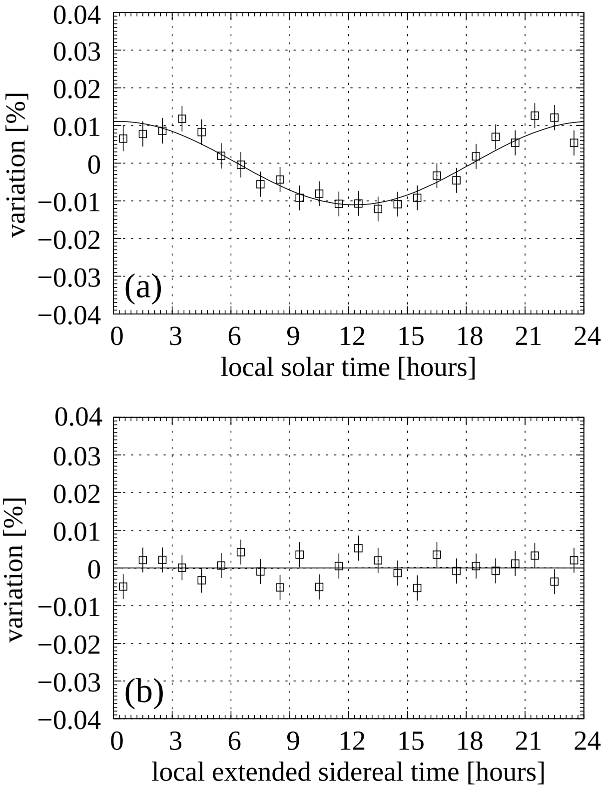

Fig. 2. The differential variation of the relative CR intensity in the local solar time (a) and in the local extended-sidereal time (b). The solid lines are the sinusoidal curves best fitted to the data. The error bars are statistical only.

TABLE I

THE χ^2-FITTING RESULTS OF THE DIFFERENTIAL VARIATION IN THE LOCAL SOLAR TIME (A) AND IN THE LOCAL EXTENDED-SIDEREAL TIME (B), ASSUMING THE SINUSOIDAL CURVE GIVEN BY EQUATION (3). THE ERROR BARS ARE STATISTICAL ONLY.

	α ($\times$ 10^{-3}%)	ϕ [hr]	χ^2/d.o.f.
(a)	11.05 ± 0.96	0.31 ± 0.33	13.9/22
(b)	0.16 ± 0.96	-6.7 ± 22.4	21.1/22

energy spectrum at higher energies. The spectral index γ measured by this method can be compared not only with the γ values from the direct measurements below $\sim$100 TeV but also with those from the indirect air-shower analyses above $\sim$100 TeV. These comparisons will check the mutual consistency between different ways of measuring the CR energy spectrum. Following the same strategy, the CG anisotropy analysis can be applied to much higher energies to confirm the astrophysical origin of the knee.

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