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Enhanced sidereal diurnal variation of galactic cosmic rays observed by the two-hemisphere network of surface level muon telescopes

K. Munakata,[1] T. Kitawada,[1] S. Yasue,[1] S. Mori,[1] C. Kato,[1] M. Koyama,[1]
S. Akahane,[1] D. L. Hall,[1] Z. Fujii,[2] K. Fujimoto,[2] J. E. Humble,[3] A. G. Fenton,[3]
K. B. Fenton,[3] and M. L. Duldig[4]

Abstract. Significant enhancements of the cosmic ray sidereal diurnal variation were observed during the period 1992–1995 by the two-hemisphere network of surface-level multidirectional muon telescopes at Hobart (Tasmania, Australia) and Nagoya (Aichi, Japan). The telescopes cover the primary cosmic ray rigidity range of 50–120 GV. Since the enhancement is less prominent in the higher rigidity range (150–550 GV) covered by the shallow underground observations at Misato and Sakashita, it is concluded that the enhancement was caused by significant solar modulation in the lower energy region. Observed sidereal diurnal variations, corrected for spurious variations by a procedure proposed by Nagashima, give a space harmonic vector with amplitude of 0.104 ± 0.008% at 60 GV and maximum at 6.9 ± 0.3 hour local sidereal time. The time of maximum is consistent with northward streaming of cosmic rays perpendicular to the ecliptic plane. Such a north-south anisotropy is expected from cross-field $\xi_{NS} = -\lambda_\perp \mathbf{G}_\theta$ diffusion if both the cross-field mean-free-path $\lambda_\perp$ and the southward directed unidirectional latitudinal density gradient $\mathbf{G}_\theta$ have large enough magnitudes. It is shown that the sector-dependent solar diurnal variations are also enhanced in the period, consistent with $\mathbf{G}_\theta$ being directed south of the ecliptic plane. Magnitudes of $\mathbf{G}_\theta$ and $\lambda_\perp$ derived from the observations are discussed.

1. Introduction

The sidereal daily variation of cosmic ray intensity at energies >100 GeV has been considered to reflect the cosmic ray anisotropy in galactic space or in the outer heliosphere [*Nagashima et al.*, 1985; *Jacklyn*, 1986, and references therein]. Recent studies in the 100–1000 GeV range covered by multidirectional observations of underground muon intensity have revealed the existence of a significant north-south (NS) sidereal asymmetry in which the amplitude of the variation increases as the direction of viewing moves southward over the equator [*Mori et al.*, 1995; *Munakata et al.*, 1995a]. *Nagashima et al.* [1995a, b] have recently proposed a model that explains the NS asymmetry in terms of the coexistence of galactic and heliomagnetic tail-in anisotropies.

At energies below 100 GeV, sidereal diurnal variations caused by solar modulation of galactic cosmic rays in the heliosphere become significant. One such variation results from cosmic ray streaming (or first-order anisotropy) $\mathbf{B} \times \mathbf{G}_r$ perpendicular to the ecliptic plane, where $\mathbf{B}$ is the interplanetary magnetic field (IMF) and $\mathbf{G}_r$ is the radial density gradient of cosmic-rays inside the heliosphere [*Swinson*, 1969, 1976]. This streaming gives rise to a diurnal variation in sidereal time because the Earth's spin axis is tilted with respect to the ecliptic plane. As a consequence, vertical telescopes on Earth look at maximum elevation above the ecliptic plane at 1800 local sidereal time (LST) and at maximum elevation below the plane at 0600 LST, every day. Because of $\mathbf{B} \times \mathbf{G}_r$ streaming, telescopes on Earth record maximum intensity at 1800 LST when the streaming is southward and at 0600 LST when the streaming is northward. Since $\mathbf{G}_r$ is directed radially outward, the streaming reverses direction when the sector polarity of the IMF changes, being directed northward in away IMF sectors and southward in toward IMF sectors. Ground-based telescopes therefore record maximum intensities at 0600 LST in away sectors and at 1800 LST in toward sectors. This "spurious" sidereal diurnal variation is almost canceled out when averaged over a year including away and toward periods of similar length, while it is magnified by subtracting the average variation in one sector from that in the other. The variation is purely NS symmetric, producing identical amplitudes and phases in detectors having the same median primary rigidity and effective latitude of view in opposite hemispheres.

A spurious sidereal diurnal variation also results from the stationary second-order anisotropy responsible for the semidiurnal variation in the solar time. *Fujii* [1971] proposed a model in which the anisotropy is represented by the function $\xi \cos^2\chi$, where ξ is a negative constant and χ is the pitch angle of cosmic rays with respect to the IMF. Intensity deficits occur in the directions parallel and antiparallel to the IMF, producing the solar semidiurnal variation. A solar diurnal variation is also generated, since the Earth's spin axis is generally not perpen-

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[1] Department of Physics, Faculty of Science, Shinshu University, Matsumoto, Japan.

[2] Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya, Japan.

[3] School of Mathematics and Physics, University of Tasmania, Hobart, Tasmania, Australia.

[4] Australian Antarctic Division, Kingston, Tasmania.

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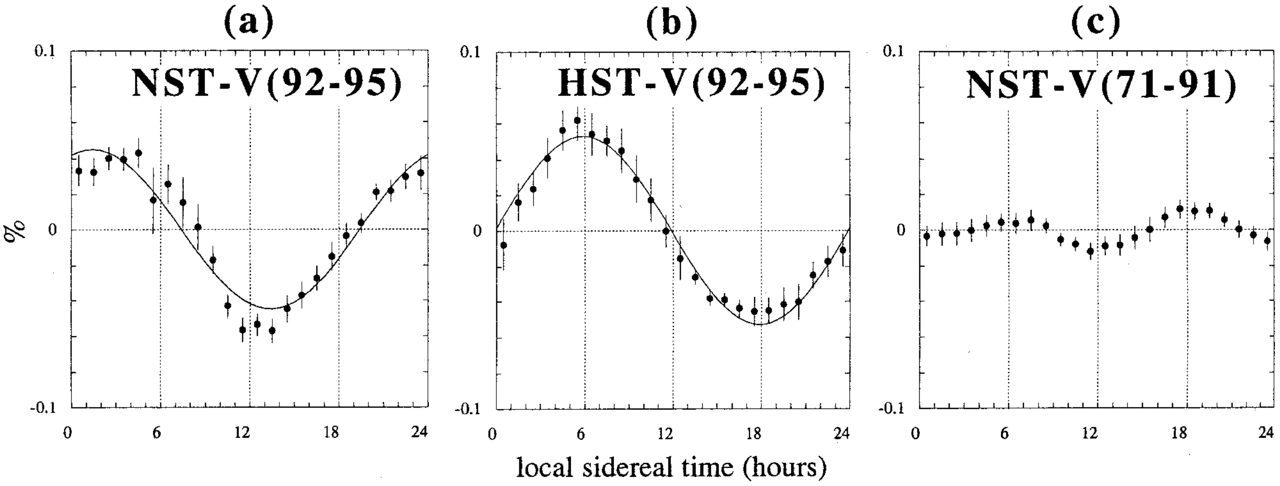

Figure 1. The average daily variations in sidereal time observed by the vertical telescopes of (a) Nagoya scintillation telescope (NST) and (b) Hobart scintillation telescope (HST) over 4 years from 1992 to 1995. (c) The average variation observed by NST over 21 years from 1971 to 1991. The percent deviation of counting rate in each local time from the average rate is plotted. Errors are deduced from the dispersion of yearly-mean counting rates in each hour. Solid curves in Figures 1a and 1b show the first harmonic components (see text).

dicular to the IMF. The geographic direction of the IMF is subject to a systematic annual variation owing to the Earth's orbital motion, causing the solar diurnal variation produced from this anisotropy to show an annual modulation. This can be decomposed into sidereal and antisidereal diurnal components [*Nagashima and Ueno*, 1971; *Nagashima*, 1984]. The sidereal and antisidereal diurnal variations produced by the effect are both purely NS antisymmetric, having maximum phases differing by 12 hours in the two hemispheres. *Nagashima et al.* [1983, 1985] proposed a method to eliminate this spurious variation from the observed sidereal diurnal variation by using the observed antisidereal diurnal variation.

In this paper, we analyze the sidereal diurnal variations observed by the two-hemisphere network of surface-level multidirectional muon telescopes at Hobart (Tasmania, Australia) and Nagoya (Aichi, Japan) to study the solar modulation of galactic cosmic rays with energy less than ~100 GeV. The network covers a wide range of effective latitude of view in both hemispheres and allows us to separate precisely the NS antisymmetric variation from the symmetric one.

2. Data Analysis

The Hobart scintillator telescope (HST) was installed at the Hobart campus of the University of Tasmania (42.85°S, 147.42°E, sea level) in Australia in December 1991. It is part of the north-south network of surface-level multidirectional muon telescopes, in conjunction with the Nagoya scintillator telescope (NST; 35.12°N, 136.97°E), which has been in operation since 1970 [*Sekido et al.*, 1975]. Utilizing the response function of muons in the atmosphere to primary cosmic-rays, the median primary rigidity P_m and the effective latitude of viewing λ_E for each directional telescope may be calculated [see *Munakata et al.*, 1998, Table 1] (hereinafter referred to as paper 1). For the 13 directional telescopes that comprise the HST, P_m ranges from 56 to 81 GV. This overlaps the range (60–119 GV) covered by the NST. The median latitudes λ_E viewed by NST and HST range from 38°N to 47°S (paper 1).

In this paper, we analyze the pressure corrected hourly counting rates observed by NST and HST between January 1992 and December 1995. The data processing method is described in paper 1. The sidereal daily variations in the counting rates recorded by the vertical telescopes in NST and HST averaged over the 4 years are shown in Figures 1a and 1b, respectively. For comparison, Figure 1c shows the average variation observed by NST over the 21 years from 1971 to 1991, immediately preceding the observations shown in Figures 1a and 1b. Errors are deduced from the dispersion of the yearly-mean counting rates in each hour. It is clear that the sidereal diurnal variation is significantly enhanced in both hemispheres between 1992 and 1995. The variations depicted in Figures 1a and 1b are both well represented by simple sinusoidal diurnal curves with an amplitude of 0.045 ± 0.008% and a maximum at 1.4 ± 0.7 hours LST at NST and 0.053 ± 0.007% and 5.9 ± 0.5 hours LST at HST (solid curves). Analyses of the data shown in Figures 1a and 1b confirm that any semidiurnal and tridiurnal variations are insignificant at <0.01%. The amplitudes of the diurnal terms are remarkably large and almost comparable to the amplitudes observed in the higher-energy range recorded by underground muon detectors [*Nagashima et al.*, 1985].

In Figure 2, we show on harmonic dials the amplitudes and phases of the diurnal variations recorded by the 17 and 13 directional telescope components of NST (Figure 2a) and HST (Figure 2b). The harmonic vector observed by each component telescope is plotted as a full circle to which the telescope name is attached. To demonstrate the systematic feature of the variation, solid lines connect the vector end-points to each other. For comparison, Figure 2c shows the average variations observed by NST between 1971 and 1991. The errors in the amplitude for the vertical telescopes deduced from the dispersion of the yearly-mean vectors are 0.012% in Figure 2a, 0.008% in Figure 2b, and 0.004% in Figure 2c. Spurious variations arising from the stationary second-order anisotropy responsible for the semidiurnal variation in solar time have been removed, using the antisidereal diurnal variations observed over the same period. This correction method, proposed by

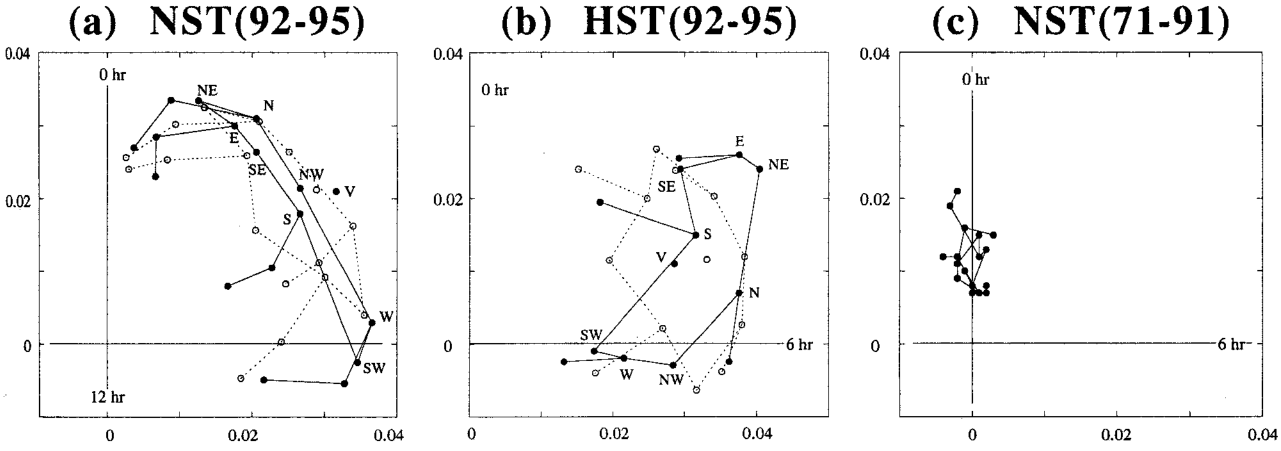

Figure 2. The harmonic dials of the average sidereal diurnal variations observed by (a) NST and (b) HST in 1992–1995. Solid circles indicate the amplitude and phase of the variation observed by each directional component telescope. (c) For comparison, the 21-year average recorded by NST over 1971–1991. The name of each telescope is attached to the head of each vector. The vectors are connected with each other by solid lines to demonstrate the systematic feature of the variation. Errors in the amplitude are deduced for the vertical telescope from the dispersion of the yearly-mean vectors and are 0.012% in Figure 2a, 0.008% in Figure 2b, and 0.004% in Figure 2c. Open circles connected by dotted lines in Figures 2a and 2b show the vectors best fit to the solid circles. In these figures, the obtained common vectors are subtracted from both of the observed and best fit vectors for the corresponding telescopes (see text).

Nagashima et al. [1983], was summarized by *Nagashima* [1984]. In paper 1, we confirmed that both the solar semidiurnal and antisidereal diurnal variations observed by NST and HST for this period were consistent with the model anisotropy proposed by *Nagashima and Ueno* [1971]. Thus the correction method proposed by *Nagashima et al.* [1983] for the spurious sidereal diurnal variation is applicable at least to the average variations over the period 1992–1995. The amplitude of the spurious variation to be removed is ~0.02%, less than half the observed amplitude of the sidereal diurnal variation.

The enhancement was most noticeable in 1992 and 1993 and then rapidly disappeared in 1994 and 1995. It was not observed by NST in 1991. It would be worthwhile to analyze 1992 and 1993 separately, to investigate the temporal development of the sidereal diurnal variation. Such an analysis, however, requires that the correction method proposed by *Nagashima et al.* [1983] be applied over a short period. In doing so, we found that the correction introduced an unexpected NS asymmetry into the corrected sidereal diurnal variation. The relative magnitude of the asymmetry was more than 0.4 times the observed variation. Because of the asymmetry, the observed amplitudes in these 2 years are larger at Nagoya than at Hobart [*Munakata et al.*, 1995b]. On the other hand, in the following 2 years, the asymmetry appears to produce a larger amplitude at Hobart than at Nagoya. Such year-to-year variation of the corrected variation is to some extent due to the counting rate errors of the observations which cause the apparent year-to-year change in the anti-sidereal diurnal variation. Any sporadic changes in interplanetary space can also influence the anti-sidereal diurnal variation, that is, a sporadic change that produces a small effect on the solar diurnal variation can cause large unexpected changes in the associated antisidereal diurnal variation. This can cause the antisidereal diurnal variation to be nonstationary throughout a year. Nagashima's theory does not take this into account. It is believed therefore that data from these instruments are not statistically adequate on timescales of 2 years and thus generated the unexpected asymmetry (K. Nagashima, private communication, 1997). With 4 years data we have much greater confidence in the results. We therefore analyze only the average variation over 4 years between 1992 and 1995.

We next examine if such enhancement is also observed in the higher-energy range monitored by the shallow underground muon telescopes at Misato (36.20°N, 137.83°E) and Sakashita (35.58°N, 137.53°E) in Japan. The vertical depths of Misato and Sakashita are respectively 34 and 80 m water equivalent, corresponding to median rigidities of primary cosmic rays of 145 and 331 GV [*Fujimoto et al.*, 1984]. Figure 3 shows on harmonic dials the average sidereal variations observed by NST (Figure 3a), Misato (Figure 3b) and Sakashita (Figure 3c) from 1992 to 1995. For comparison, Figures 3d–3f show the average vectors for all available observations up to 1991. The vectors shown in these figures have also been corrected for the spurious variation. It is seen from Figures 3d–3f that the long-term average of the sidereal diurnal variation becomes more significant in the higher-energy range. This is qualitatively consistent with a sidereal diurnal variation caused by a galactic anisotropy in high-energy cosmic rays. On the other hand, the variation in 1992–1995 in Figures 3a–3c is most significant in NST, which observes the lowest-energy range, while Sakashita observed no clear enhancement in the highest-energy range. This implies that the enhanced sidereal diurnal variation observed by NST and HST in 1992–1995 did not arise from the galactic anisotropy but was caused by significant solar modulation at lower energies.

To obtain the space harmonic vector that represents the enhanced sidereal diurnal variations in 1992–1995, we make the following best fit calculation for the variations shown in Figures 2a and 2b. We first assume that the variations arose from the NS symmetric anisotropy expressed by $P_1^1(\cos \Theta)$, where P_n^m is the Schmidt seminormalized spherical function [*Chapman and Bartels*, 1940] and Θ is the colatitude of the cosmic ray incident direction measured from the North Pole. The diurnal variation expected for each directional component telescope, is then $D(t) = D_1^1(t)$, where

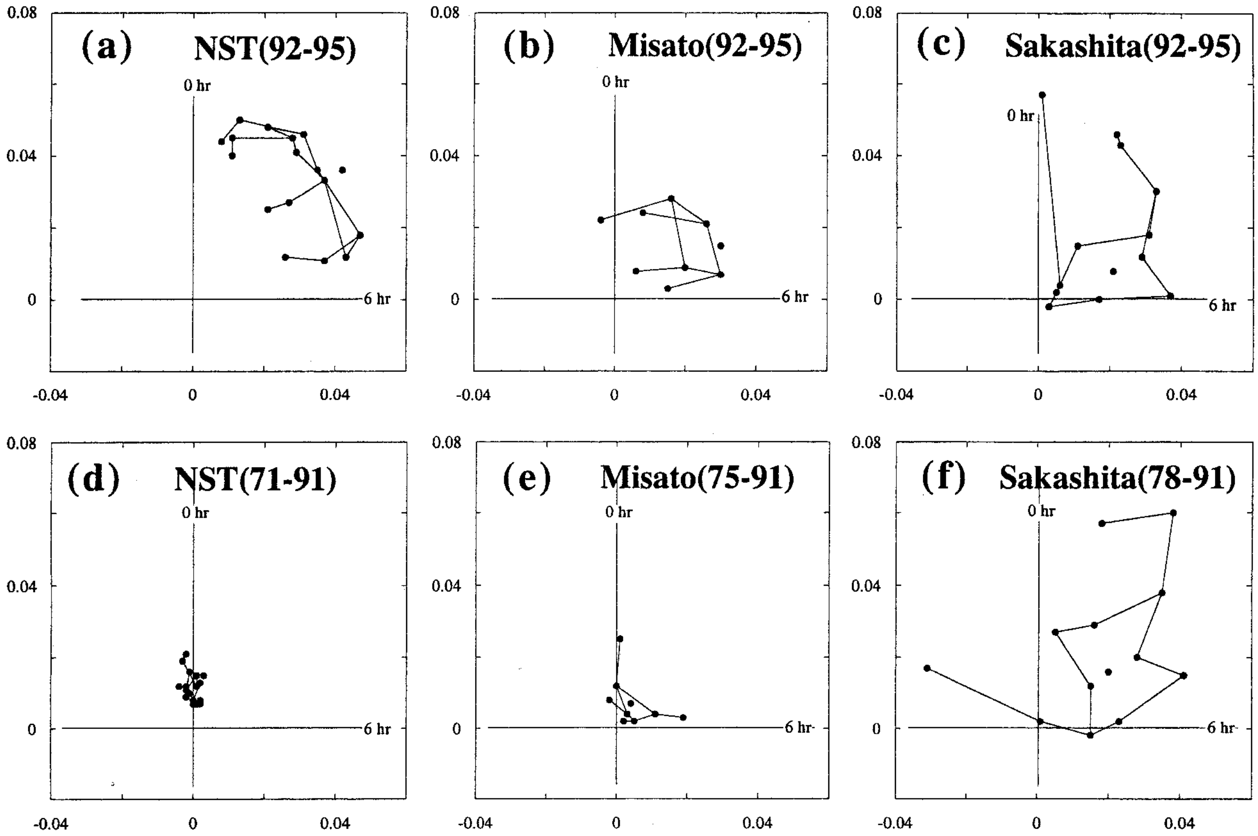

Figure 3. The sidereal diurnal variations observed by (a) NST and the Japanese shallow-underground muon telescopes at (b) Misato and (c) Sakashita over 4 years from 1992 to 1995. (d)–(f) The average variations over a longer period from the beginning of each observation to 1991 (1971–1991) for NST, 1975–1991 for Misato, and 1978–1991 for Sakashita).

$$D_n^m(t) = (A_n^m + a_{com}^m)\cos\frac{2m\pi t}{24} + (B_n^m + b_{com}^m)\sin\frac{2m\pi t}{24}, \tag{1}$$

$$\begin{pmatrix} A_n^m \\ B_n^m \end{pmatrix} = \begin{pmatrix} c_n^m & s_n^m \\ -s_n^m & c_n^m \end{pmatrix} \begin{pmatrix} x_n^m \\ y_n^m \end{pmatrix}, \tag{2}$$

and x_n^m and y_n^m describe the space harmonic vector which represents the observed variations. In these equations, c_n^m and s_n^m are the integral coupling coefficients calculated for each component telescope and "common vectors" (a_{com}^m, b_{com}^m) are introduced as parameters, to be determined, which represent the variation arising from the atmospheric temperature effect (for a more detailed explanation, see paper 1).

In this analysis, we assume for $G_n^m(p)$ a power law rigidity dependence of $(p/60GV)^{\gamma_n^m}$, normalized to unity at 60 GV, with upper cutoff rigidity p_{Un}^m above which $G_n^m(p) = 0$. By comparing $D(t)$ with the observed variation for each component, we obtain the space harmonic vector (x_1^1, y_1^1) for $D_1^1(t)$ as well as γ_1^1 and p_{U1}^1 for $G_1^1(p)$ and the "common vectors" (a_{com}^1, b_{com}^1), all of which give the best fit between the observed and reproduced variations. In Figures 2a and 2b, open circles connected with each other by dotted lines show the best fit diurnal variations. The derived average common vectors, 0.017 ± 0.001% at 1.5 ± 0.2 hours for NST and 0.018 ± 0.002% at 8.6 ± 0.4 hours for HST, are subtracted from both the observed and best fit vectors for the corresponding telescopes. The space harmonic vector obtained for $D_1^1(t)$ has amplitude $\eta_1^1 = [(x_1^1)^2 + (y_1^1)^2]^{1/2} = 0.104 \pm 0.008\%$ at 60 GV and phase $\varphi_1^1 = \tan^{-1}(y_1^1/x_1^1) = 6.9 \pm 0.3$ hours in local sidereal time with $\gamma_1^1 = 0.6$ and $p_{U1}^1 = 80$ GV. This is consistent with the 6.57 hours expected from northward cosmic ray streaming perpendicular to the ecliptic plane. On the basis of calculation by *Tatsuoka and Nagashima* [1985], the magnitude of the NS anisotropy is $\xi_{NS} = 2.412 \times \eta_1^1 = 0.251 \pm 0.019\%$ at 60 GV.

3. Results

If one inspects the theory of cosmic ray modulation (as presented by *Forman and Gleeson* [1975] and *Bieber and Chen* [1991]), one finds that in a coordinate system centered on the Sun, the perpendicular component of the theoretical anisotropy to the IMF will have two components (one from the drift terms of the theory ($\pm\rho G_r \sin\Psi$ in the direction of $\mathbf{B} \times \mathbf{G}_r$) and another from the diffusion terms ($\lambda_\perp G_\theta$). Here the gradients are in a spherical polar coordinate system centered on the Sun and Ψ is the angle between the IMF and the Earth-Sun line. In contrast with $\mathbf{B} \times \mathbf{G}_r$ streaming, cross-field diffusion does not depend on the sector polarity of **B** and can produce an average sidereal diurnal variation independent of IMF sector structure. The existence of $\mathbf{G}_\theta$ has been reported by *Chen et al.* [1991] from neutron monitor observations at ~10 GV (for earlier work on $\mathbf{G}_\theta$, see also *Perona and Antonucci* [1976], *Antonucci and Marocchi* [1976], and *Antonucci et al.* [1978, 1985]). Chen et al. concluded that the magnitude of $\mathbf{G}_\theta$ is typically of order 0.7%/AU and its direction varies in a manner

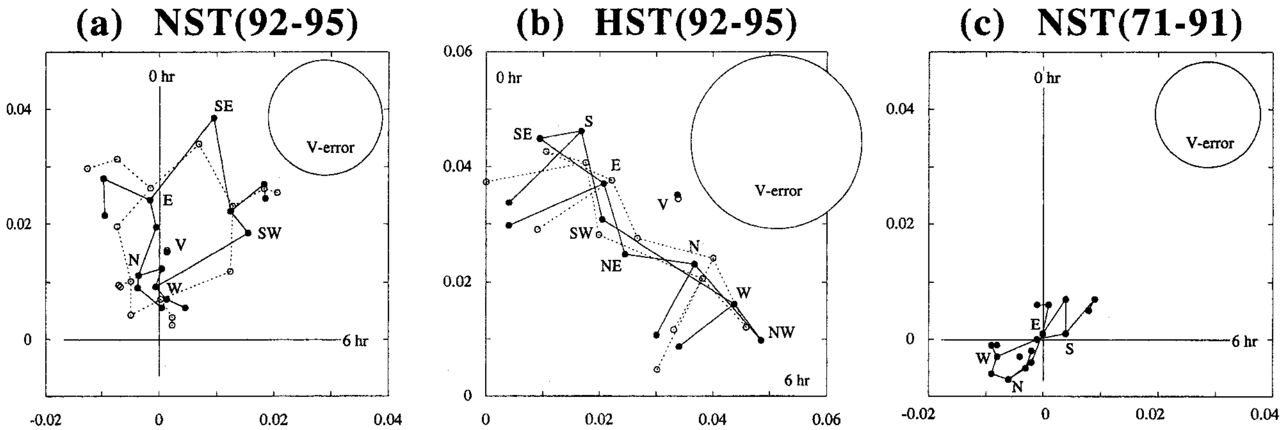

Figure 4. The sector-dependent solar diurnal variation observed by (a) NST and (b) HST in 1992–1995. The amplitude and phase of the difference variations, $[D^T(t) - D^A(t)]/2$, observed by each directional component telescope are plotted by solid circles, while open circles show the vectors best fit to the full circles (see text). In Figures 4a and 4b, the obtained common vectors, which are 0.002 ± 0.002% at 12.4 ± 4.8 hours for NST and 0.012 ± 0.002% at 6.6 ± 0.5 hours for HST on average, are subtracted from both of the observed and best fit vectors for the corresponding telescopes. Errors in the observed amplitude are deduced for the vertical telescope from the dispersion of yearly-mean vectors and are 0.010% in Figure 4a, 0.015% in Figure 4b, and 0.009% in Figure 4c.

not obviously related to either the 11-year sunspot cycle or the 22-year solar magnetic cycle. By using ~2 GeV cosmic ray proton measurements made by the Ulysses space probe, *Simpson et al.* [1996] demonstrated a cosmic ray intensity minimum near the helioequator, with increasing intensity towards both poles. The minimum was offset from the equator, indicating the presence of a northward unidirectional gradient as well as a bidirectional latitudinal one. The northward streaming inferred from φ_1^1 corresponds to $\mathbf{G}_\theta$ directed south of the solar equatorial plane, where the density of cosmic rays is higher than north of the plane. Note that $\mathbf{G}_\theta$ also produces sector-dependent streaming, $\xi_\perp^{TA} = (\rho/B)\ \mathbf{B} \times \mathbf{G}_\theta$, in the ecliptic plane and perpendicular to the IMF, where B is the magnitude of $\mathbf{B}$ and ρ is the gyroradius of cosmic rays in $\mathbf{B}$. This sector-dependent streaming causes the sector-dependent solar diurnal variation in cosmic ray intensity observed at Earth.

To check such a sector-dependent asymmetry of the solar diurnal variation, we first divided the observations into toward and away periods according to the sector polarity given by the Stanford Mean Solar Magnetic Field (Solar-Geophysical Data, 1992–1995). The average solar daily variations, $D^T(t)$ and $D^A(t)$, are then obtained in toward and away periods respectively, and the difference variation $[D^T(t) - D^A(t)]/2$ is calculated. Figures 4a and 4b show the first harmonic vectors $[D^T(t) - D^A(t)]/2$ observed by NST and HST between 1992 and 1995. For comparison, we plot in Figure 4c the average difference variations of NST from 1971 to 1991. Errors of the amplitude deduced for the vertical telescope from the dispersion of yearly-mean vectors are 0.010% in Figure 4a, 0.015% in Figure 4b and 0.009% in Figure 4c. It is clear that the sector-dependent solar diurnal variation is also enhanced between 1992 and 1995. This suggests that the cross-field diffusion model is a better explanation for the enhanced sidereal diurnal variation.

To examine more quantitatively the anisotropy responsible for the variations shown in Figures 4a and 4b, we calculated the best fit to the solar diurnal variations in the same manner as for the sidereal diurnal variations shown in Figures 2a and 2b. We note that the amplitude (0.015 ± 0.010%) of the observed "V" NST vector shown in Figure 4a is not significant while the "V" vector (0.049 ± 0.015%) shown in Figure 4b for HST is significant at 3 sigma. This suggests a contribution from the NS antisymmetric anisotropy. In the fit therefore we assumed that the variation arises from both the NS antisymmetric variation $D_2^1(t)$ in space and the symmetric variation $D_1^1(t)$, where the dependence on Θ is expressed by $P_2^1(\cos\Theta)$. The existence of such an NS antisymmetric term in the sector-dependent solar diurnal variation has already been reported by *Nagashima et al.* [1986]. They found that NST observed the antisymmetric term between 1971 and 1979 and demonstrated that the observed variation was consistent with the sector-dependent second-order anisotropy formulated by *Munakata and Nagashima* [1986] in the framework of the convection-diffusion theory of cosmic-ray transport in the heliosphere. According to *Nagashima et al.* [1986] and *Munakata and Nagashima* [1986], the sector-dependent anisotropy has a similar rigidity spectrum to the second-order anisotropy responsible for the solar semidiurnal variation. For this reason, we use $\gamma_2^1 = 0.5$ and $p_{U2}^1 = 100$ GV, the values used in our analysis of the solar semidiurnal variation (paper 1). From the best fit to the observed variations, we obtain the space harmonic vectors (x_1^1, y_1^1) and (x_2^1, y_2^1) respectively for $D_1^1(t)$ and $D_2^1(t)$, as well as γ_1^1 and p_{U1}^1 for $G_1^1(p)$. In Figures 4a and 4b, open circles connected by dotted lines show the best fit diurnal variations. The amplitudes and phases of the space harmonic vectors obtained for $D_1^1(t)$ and $D_2^1(t)$ are $\eta_1^1 = [(x_1^1)^2 + (y_1^1)^2]^{1/2} = 0.096 \pm 0.007\%$ at 60 GV, $\varphi_1^1 = \tan^{-1}(y_1^1/x_1^1) = 4.8 \pm 0.4$ hours in local solar time and $\eta_2^1 = [(x_2^1)^2 + (y_2^1)^2]^{1/2} = 0.067 \pm 0.005\%$ at 60 GV, $\varphi_2^1 = \tan^{-1}(y_2^1/x_2^1) = 16.9 \pm 0.3$ hours, in local solar time with $\gamma_1^1 = 1.2$ and $p_{U1}^1 = 80$ GV.

The phase φ_1^1 obtained above is 1.8 hours later than the 3.0 hours expected from the streaming caused by $\mathbf{G}_\theta$ directed south of the solar equatorial plane. The phase φ_2^1 is also 1.9 hours later than the 15.0 hours expected from the second-order anisotropy proposed by *Munakata and Nagashima* [1986] and *Nagashima et al.* [1986]. The value observed for φ_1^1 may be explained if the diffusive streaming parallel to the IMF, $\xi_\parallel = -\lambda_\parallel \mathbf{G}_r \cos\Psi$, where $\lambda_\parallel$ is the parallel mean-free-path, is different in toward and away sectors. The $\xi_\parallel$ causes a diurnal variation with a maximum at 21 hours in both toward and away sectors. If the streaming in away sectors exceeds that in toward sectors, the resultant asymmetry can cause a toward-away diurnal variation with a maximum at 9.0 hours, resulting in a shift of φ_1^1 to times later than 3.0 hours. However, at present we have no observational evidence for such an asymmetry of $\xi_\parallel$. In the following discussion, therefore we simply take the projection of the space harmonic vector (x_1^1, y_1^1) onto the direction of 3.0 hours, as $\eta_1^{1^*} = \eta_1^1 \times \cos(1.8\, hr) = 0.086 \pm 0.006\%$ at 60 GV. By using the table given by *Tatsuoka and Nagashima* [1985], the magnitude of $\xi_\perp^{TA}$ is calculated, as $\xi_\perp^{TA} = 1.062 \times \eta_1^{1^*} = 0.091 \pm 0.006\%$ at 60 GV. The other space harmonic vector (x_2^1, y_2^1) obtained above will be discussed elsewhere.

We can estimate the magnitudes of $\mathbf{G}_\theta$ and $\lambda_\perp$ directly from ξ_{NS} and $\xi_\perp^{TA}$ obtained above. First, we obtain the magnitude of the south-pointing unidirectional latitudinal gradient $\mathbf{G}_\theta$ from $\xi_\perp^{TA}$, as $|\mathbf{G}_\theta| = \xi_\perp^{TA}/\rho \sim 0.3\%/\mathrm{AU}$ at 60 GV, where we used $\rho = 0.3$ AU for the gyroradius of a 60 GV proton in a magnetic field with magnitude 5nT. This magnitude of $\mathbf{G}_\theta$ at 60 GV is almost half the representative value of 0.7%/AU at ~10 GV obtained by *Chen et al*. [1991] from neutron monitor observations in the period 1953–1988. If we assume the rigidity dependence of $|\mathbf{G}_\theta| \propto p^{-1}$ found by *Ahluwalia and Dorman* [1997] and use the representative value of 0.7%/AU at ~10 GV by *Chen et al*. [1991], the magnitude of $\mathbf{G}_\theta$ is calculated to be ~0.1%/AU at 60 GV. This therefore implies that $\mathbf{G}_\theta$ in the period 1992–1995 is enhanced by a factor of three from its representative value. *Simpson et al*. [1996] have recently reported the unidirectional latitudinal gradient being observed in the opposite sense (i.e., a north-pointing gradient), but their observation was made during the period between September 1994 and August 1995 when the enhancement of the sidereal diurnal variation in NST and HST had already diminished.

By using the values of $|\mathbf{G}_\theta|$ and ξ_{NS} obtained above, we can also calculate the mean-free-path of cross-field diffusing particles as $\lambda_\perp = \xi_{NS}/|\mathbf{G}_\theta| \approx 0.8$ AU at 60 GV. Assuming isotropic scattering by IMF fluctuations, *Forman and Gleeson* [1975] showed that

$$\kappa_\perp = \frac{\kappa_\parallel}{1+(\omega\tau)^2} \tag{3}$$

where $\kappa_\parallel$, $\kappa_\perp$ are the parallel and perpendicular diffusion coefficients, ω is the gyrofrequency of the particle's orbit, and τ is the mean time between scattering. Using the transformation $\lambda = 3\kappa/v$, where v is the particle speed, it can be shown that

$$\lambda_\perp = \lambda_\parallel \frac{1}{1+(\lambda_\parallel/\rho)^2} = \rho \frac{(\rho/\lambda_\parallel)}{1+(\rho/\lambda_\parallel)^2} < \rho. \tag{4}$$

Thus the magnitude of $\lambda_\perp$ cannot exceed the gyroradius ρ if the isotropic scattering approximation is applicable. The magnitude of $\lambda_\perp$ at 60 GV obtained above is more than twice ρ, implying that the isotropic scattering approximation is not applicable in this energy range. The magnitude of $\lambda_\parallel$ at 60 GV has been evaluated by *Munakata et al*. [1997] from their analysis of the diurnal anisotropy recorded by the surface and underground muon detectors over the period 1978–1995. They found $\lambda_\parallel$ changes with the solar activity and obtained an average value of $\lambda_\parallel = 2.0$ AU at 60 GV in 1992–1995.

Chen and Bieber [1993] derived the upper limit to the ratio ($\alpha = \lambda_\perp/\lambda_\parallel$) as $\alpha_{\max} = 0.16$, beyond which they could not make the observed anisotropy consistent with the cosmic-ray transport equation. Using the above estimate of $\lambda_\parallel$ and assuming α is independent of rigidity, we obtain the upper limit of $\lambda_\perp$ of 0.31 AU, which is much less than the value derived by us. It is concluded that the enhancements in $\xi_\perp^{TA}$ and ξ_{NS} observed in 1992–95 requires the cross-field diffusion mean-free-path $\lambda_\perp$ to be large exceeding the upper limit obtained by Chen and Bieber. It is worth noting that *Hall et al*. [1995] found that in the positive polarity period 1972–1979 of the solar magnetic dipole field, the value of $\alpha_{\max}$ seemed to depend strongly on rigidity.

4. Discussion

Significant enhancement of the sidereal diurnal variation has been observed during the period of 1992–1995 by the two hemisphere network of surface-level multidirectional muon telescopes at Hobart (HST; Tasmania, Australia) and Nagoya (NST; Aichi, Japan). This enhancement is most notable in 1992 and 1993 and then rapidly diminishes in the following 2 years. It is not observed by NST in 1991. Since the enhancement is less prominent in the higher-energy region observed by shallow underground muon observations at Misato and Sakashita, it is concluded that the enhancement is caused by significant solar modulation in the low energy region. The space harmonic vector that represents the enhanced sidereal diurnal variations is found to have an amplitude of 0.104 ± 0.008% and a phase of 6.9 ± 0.3 hours in the local sidereal time at 60 GV. This space harmonic vector is consistent with a northward streaming of cosmic rays with anisotropy $\xi_{NS} = 0.251 \pm 0.019\%$ at 60 GV.

Figures 5a and 5b show respectively the sidereal variations observed by the vertical telescopes in NST and HST from 1992 to 1995, while Figure 5c shows the average variations observed by NST over 21 years from 1971 to 1991. The top and middle panels in each figure show the variations in toward and away sectors, $D^T(t)$ and $D^A(t)$, respectively. In the bottom panels, we show the difference variations, $[D^T(t) - D^A(t)]/2$, to reveal the variations due to the streaming which reverses its direction in accord with the sector alternation. Errors are deduced from the dispersion of yearly-mean counting rates in each hour. From Figures 5a and 5b, it is clear that variations observed by NST and HST over four years from 1992 to 1995 are much larger in away sectors than in toward sectors. Such asymmetry is not seen in Figure 5c for the long-term average by NST. On the other hand, the bottom panels show that there is no clear enhancement in the difference variations in these four years and all the difference variations are consistent. The enhanced away variations in Figures 5a and 5b could be explained by asymmetric $\mathbf{B} \times \mathbf{G}_r$ streaming, but there is no reason for an asymmetry in either $\mathbf{B}$ or $\mathbf{G}_r$ in the two sectors to occur while keeping the difference variations unchanged. Also, an asymmetric $\mathbf{B} \times \mathbf{G}_r$ mechanism cannot explain why the variations in toward sectors (top panels in Figures 5a and 5b) are not out of phase from the variations in away sectors. It seems rather natural therefore to conclude that the northward streaming in these 4 years did not arise from the $\mathbf{B} \times \mathbf{G}_r$ mechanism.

We have shown that the northward streaming ξ_{NS} could be produced by the cross-field diffusion $\xi_{NS} = -\lambda_\perp \mathbf{G}_\theta$, if both the mean-free-path of cross-field diffusion ($\lambda_\perp$) and the south pointing unidirectional latitudinal density gradient ($\mathbf{G}_\theta$) have

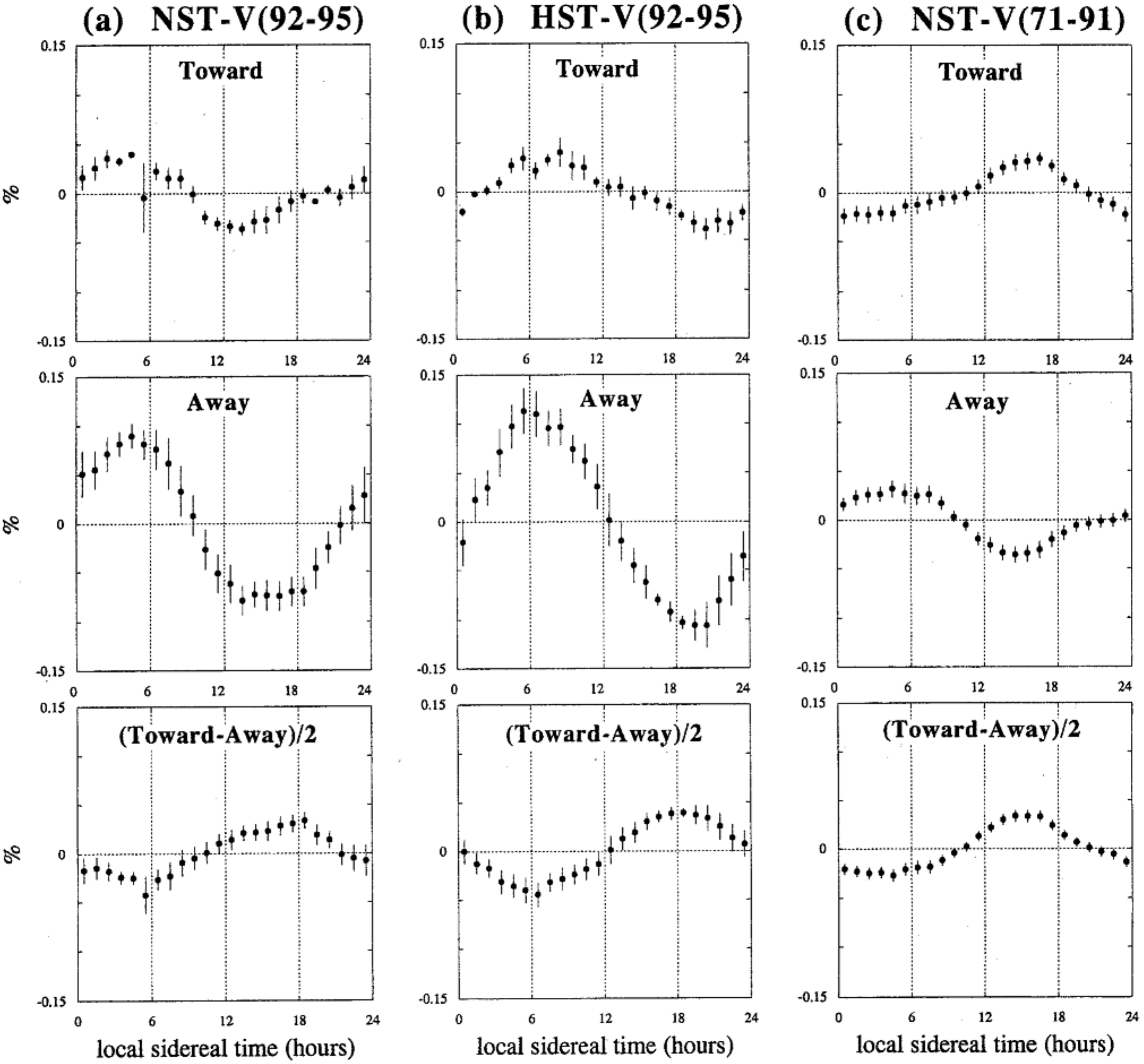

Figure 5. Sidereal daily variation observed in the toward and away sectors of the IMF. The top and middle panels show $D^T(t)$ and $D^A(t)$, respectively, while the bottom panels show the difference variations, $[D^T(t) - D^A(t)]/2$ (see text). (a) and (b), the variations observed by NST and HST in 1992–1995. (c) shows the average variation observed by NST over 21 years from 1971 to 1991. Errors are deduced from the dispersion of yearly-mean counting rates in each hour.

large enough magnitudes. The enhancement of the sector-dependent solar diurnal variations observed over the same period also suggests the existence of a significant $\mathbf{G}_\theta$ and the subsequent sector-dependent streaming $\xi_\perp^{TA} = (\rho/B)\ \mathbf{B} \times \mathbf{G}_\theta$. *Hashim and Bercovitch* [1972] and *Swinson* [1970] have previously shown the existence of a southward unidirectional latitudinal gradient from analysing the solar diurnal variation and other studies have analyzed the annual variation of cosmic ray data and reached the same conclusion [e.g., *Antonucci et al.*, 1985]. This gradient has, however, been shown to change direction at the reversals of the solar dipole magnetic field [*Swinson and Kananen*, 1982].

The space harmonic vectors that represents the diurnal variations are obtained by assuming two types of variation in space, the NS symmetric and antisymmetric variations. Figure 6 shows the amplitudes of the variations recorded by 30 directional telescope components of NST and HST as a function of the effective latitude of view λ_E. In Figure 6, we corrected the observed amplitudes for the difference in the energy response of each telescope. We can obtain the correction factor f for each telescope by using the best fit vector to the observations shown in Figures 4a and 4b, as $f = \{\eta_1^1 P_1^1 (\cos \Theta) + \eta_2^1 P_2^1 (\cos \Theta)\}/a$, where $\Theta = \pi/2 - \lambda_E$, η_1^1 and η_2^1 are respectively the amplitudes of the NS symmetric and antisymmetric space harmonic vectors at 60 GV, and a is the amplitude of variation reproduced in Figures 4a and 4b (open circles). Before plotting the amplitudes as a function of λ_E, we simply multiplied the amplitudes by the values of f. The solid curve in Figure 6 shows the superposition of the expected NS symmetric and antisymmetric variations plotted as two dashed lines. Combining the

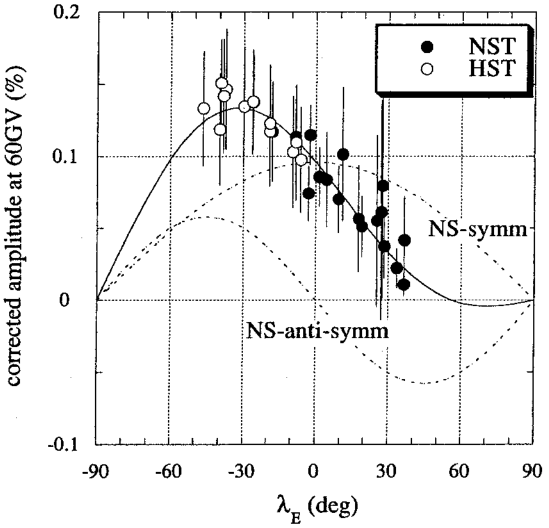

Figure 6. The amplitudes of the sector-dependent solar diurnal variation observed by NST (solid circles) and HST (open circles) are plotted against the effective latitude of viewing direction λ_E. These amplitudes are corrected for the difference in the energy response of each telescope (see text). The solid curve represents the combination of the symmetric and antisymmetric terms, $\eta_1^1 \sin \Theta + \eta_2^1 \sqrt{3} \sin \Theta \cos \Theta$, with the best fit values of $\eta_1^1 = 0.096\%$ and $\eta_2^1 = 0.067\%$ at 60 GV, where $\Theta = \pi/2 - \lambda_E$.

symmetric and antisymmetric terms results in a good fit to the observations. It is also clear that the contribution from the NS antisymmetric variation is significant at mid-latitudes.

The space harmonic vector for the NS symmetric variation in the toward sector is found to have a phase at 4.8 ± 0.4 hours in the local solar time, 1.8 hours later than 3.0 hours expected from the streaming with $\mathbf{G}_\theta$ directed southward. We have used the magnitude of $\xi_\perp^{TA}$ (0.091 ± 0.006% at 60 GV) to obtain a value of $|\mathbf{G}_\theta|$ (0.3%/AU at 60 GV) which is almost half the representative value of 0.7%/AU at ~10 GV obtained by *Chen et al.* [1991] from neutron monitor observations in 1953–1988. By extrapolating their value at ~10 GV to 60 GV using the rigidity spectrum obtained for $\mathbf{G}_\theta$ by *Ahluwalia and Dorman* [1997], the magnitude of $\mathbf{G}_\theta$ is calculated to be only 0.1%/AU at 60 GV, implying that $\mathbf{G}_\theta$ is enhanced in 1992–1995 by a factor of three from its representative value. By analysing the "toward-away" solar diurnal variations observed by neutron monitors and muon telescopes during the 1965–1993 period, *Ahluwalia and Dorman* [1997] showed that $|\mathbf{G}_\theta| = 0$ in 1993 below 67 GV. Their analysis, however, did not take into account the contribution from the NS antisymmetric component of the "toward-away" solar diurnal variation. The results from such analysis do not explain the observed NS asymmetry seen in Figures 4a, 4b, and 6 and cannot be directly compared with our results. It is seen in the figures that the variation observed by the vertical telescope in NST is small while that in HST is quite large, implying that the NS symmetric variation in the northern hemisphere could be almost canceled by the antisymmetric variation. We think that this is the reason that *Ahluwalia and Dorman* [1997] concluded that $|\mathbf{G}_\theta| = 0$ from the neutron monitor observation at Deep River in the Northern Hemisphere. We confirmed that the significant NS asymmetry is also clearly seen in 1-year data of 1993.

By using ξ_{NS} and $|\mathbf{G}_\theta|$, we estimated the mean-free-path of the cross-field diffusing particles to be more than 2 times the gyroradius ($\lambda_\perp \sim 0.8$ AU, $\rho \sim 0.3$ AU) of 60 GV cosmic rays in a 5 nT IMF. This is not consistent with the isotropic scattering model in which $\lambda_\perp$ cannot exceed ρ. To compare the ratio of $\lambda_\perp$ to $\lambda_\parallel$ with that obtained by *Chen and Bieber* [1993], we used $\lambda_\parallel = 2.0$ AU evaluated by *Munakata et al.* [1997] at 60 GV. The ratio $\alpha = \lambda_\perp/\lambda_\parallel$ at 60 GV is estimated to be 0.4 which is more than twice the upper limit of $\alpha_{\max} = 0.16$ derived by *Chen and Bieber* [1993]. It may be concluded that the enhancements in both of $\xi_\perp^{TA}$ and ξ_{NS} require not only a large magnitude of $\mathbf{G}_\theta$ but also a large cross-field diffusion mean-free-path $\lambda_\perp$ and a ratio α exceeding the upper limit obtained by *Chen and Bieber* [1993].

5. Conclusions

In this paper, we have analyzed the significant enhancement of the cosmic ray sidereal diurnal variation observed by the two-hemisphere network of surface-level muon telescopes during the period 1992–1995. Our findings are summarized below.

1. As the enhancement is less significant in the higher-energy range monitored by the shallow underground muon telescopes, it is concluded that the enhanced sidereal diurnal variation did not arise from a galactic anisotropy but was caused by significant solar modulation at energies less than ~100 GeV. The space harmonic vector that represents the sidereal diurnal variation has amplitude 0.104 ± 0.008% at 60 GV and phase 6.9 ± 0.3 hour in local sidereal time. The phase is consistent with the 6.57 hours expected from northward cosmic ray streaming (ξ_{NS}) perpendicular to the ecliptic plane.
2. An enhancement is also observed in the "toward-away" solar diurnal variation in 1992–1995. The variation observed by the two-hemisphere network clearly shows a NS asymmetry in which the amplitude recorded in the southern hemisphere by the vertical component of HST is >3 times larger than that recorded in the Northern Hemisphere by the vertical component of NST.
3. The NS asymmetry in the "toward-away" solar diurnal variation can be reproduced by introducing the NS antisymmetric variation together with the symmetric variation. The space harmonic vector that represents the NS symmetric variation has amplitude 0.096 ± 0.007% at 60 GV and phase 4.8 ± 0.4 hours in local solar time, while the vector that represents the NS antisymmetric variation has amplitude 0.067 ± 0.005% at 60 GV and phase 16.9 ± 0.3 hours local solar time. The latter phase is consistent with the 15.0 hours expected from the second-order anisotropy proposed by *Munakata and Nagashima* [1986] and *Nagashima et al.* [1986].
4. The phase of the space harmonic vector that represents the NS symmetric variation is consistent with the 3.0 hours expected from $\mathbf{B} \times \mathbf{G}_\theta$ streaming with a south pointing unidirectional latitudinal density gradient $\mathbf{G}_\theta$. We estimate the magnitude of $\mathbf{G}_\theta$ to be 0.3%/AU at 60 GV. By extrapolating the representative value of 0.7%/AU at ~10 GV reported by *Chen et al.* [1991] to 60 GV using the rigidity spectrum obtained for $\mathbf{G}_\theta$ by *Ahluwalia and Dorman* [1997], the magnitude of $\mathbf{G}_\theta$ is calculated to be only 0.1%/AU at 60 GV, implying that the magnitude of $\mathbf{G}_\theta$ is enhanced in 1992–1995 by a factor of 3 from its representative value.
5. We have shown that the northward streaming responsible for the enhanced sidereal diurnal variation could be produced by the cross-field diffusion $\xi_{NS} = -\lambda_\perp \mathbf{G}_\theta$, if both the mean-free-path of cross-field diffusion ($\lambda_\perp$) and $\mathbf{G}_\theta$ have large

enough magnitudes. By using ξ_{NS} together with $\mathbf{G}_\theta$ calculated above, we estimated $\lambda_\perp$ to be 0.8 AU at 60 GV and twice the gyroradius of 60 GV cosmic rays in a 5 nT IMF. The ratio of $\lambda_\perp$ to the parallel mean-free-path $\lambda_\parallel$ is also estimated to be 0.4 at 60 GV, which is more than twice the upper limit of $\alpha_{\max} = 0.16$ derived by *Chen and Bieber* [1993] at ~10 GV.

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S. Akahane, D. L. Hall, C. Kato, T. Kitawada, M. Koyama, S. Mori, K. Munakata, and S. Yasue, Department of Physics, Faculty of Science, Shinshu University, 3-1-1 Asahi, Matsumoto, Nagano 390-8621, Japan. (kmuna00@gipac.shinshu-u.ac.jp)

M. L. Duldig, Australian Antarctic Division, Kingston, TAS 7050, Australia.

A. G. Fenton, K. B. Fenton, and J. E. Humble, School of Mathematics and Physics, University of Tasmania, Hobart, TAS 7001, Australia.

Z. Fujii and K. Fujimoto, Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464, Japan.

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