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LONG TERM VARIATION OF COSMIC RAY LATITUDE GRADIENT IN THE HELIOSPHERE

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ABSTRACT

We examine the long-term change in the unidirectional latitude gradient (G_θ) of galactic cosmic-rays in the heliosphere, by analyzing the "Toward-Away" solar diurnal variation (SDV) of cosmic-ray intensity recorded by a network of Japanese multi-directional muon telescopes during 18 years from 1978 to 1995. In our analysis, we take into account not only the north-south (NS) symmetric SDV (S^{sym}) but also the NS anti-symmetric SDV ($S^{anti-sym}$), which was first observed by the Nagoya surface muon telescope in 1971-1979 and well confirmed by the two hemisphere observations at Nagoya and Hobart in 1992-1995. The phase of the yearly mean S^{sym} in space is found at ~0500 or ~1700 hours local solar time depending on the year, while the phase of $S^{anti-sym}$ is always found at ~1700 hours in the northern hemisphere. G_θ derived from the component of S^{sym} perpendicular to the interplanetary magnetic field shows no clear variation related to the 11-year solar activity- or 22-year solar magnetic-cycles, but it remains positive after the late 80's implying a higher density of cosmic-rays in the southern hemisphere below the heliospheric current sheet.

INTRODUCTION

The unidirectional latitude gradient (G_θ) represents the asymmetry of cosmic-ray density above and below the heliospheric current sheet (HCS). Particles approaching Earth in the ecliptic plane as they gyrate around the interplanetary magnetic field (IMF) come from regions on both sides of the HCS. If there is an asymmetry of cosmic-ray densities above and below the HCS, the asymmetry can be detected as a cosmic-ray streaming, $\xi_\perp^{TA} = (\rho / B)\boldsymbol{B} \times \boldsymbol{G}_\theta$, in the ecliptic plane and perpendicular to the IMF ($\boldsymbol{B}$), where B is the magnitude of $\boldsymbol{B}$ and ρ is the gyro-radius of cosmic rays in $\boldsymbol{B}$. This streaming reverses direction when the sector polarity of the IMF ($\boldsymbol{B}$) changes and causes the "sector-dependent" solar diurnal variation (SDV) in cosmic-ray intensity observed at Earth (Hashim and Bercovitch, 1972; Swinson, 1970; Chen et al., 1991, Ahluwalia and Dorman, 1997). The variation is almost cancelled 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. It is noted that the variation arising from the above mentioned streaming, $\xi_\perp^{TA}$, 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.

In our separate paper (Munakata et al., 1998, hereafter refered to as Paper 1), we have analyzed the sector-dependent SDV observed by the two hemisphere network (THN) of the surface muon telescopes at Hobart (Tasmania, Australia) and Nagoya (Aichi, Japan) during a period of 1992-95. It was shown that the variation

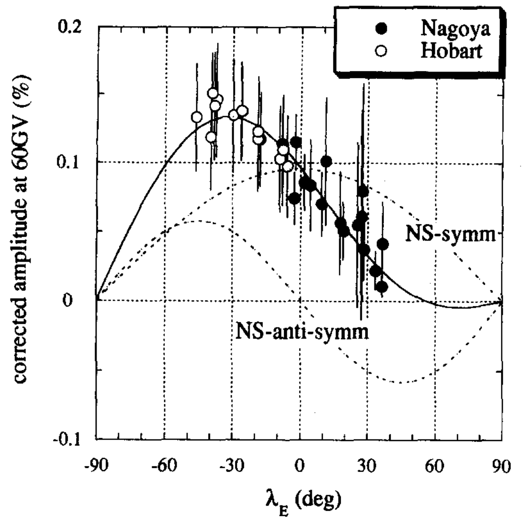

Fig. 1. The amplitudes of the sector-dependent SDV observed by Nagoya (full circles) and Hobart (open circles) are plotted against the effective latitude of viewing direction λ_E. The solid curve shows the superposition of the expected NS symmetric and anti-symmetric variations plotted as two broken lines (Paper 1).

observed by the THN clearly shows a NS asymmetry in which the amplitude recorded in the southern hemisphere by the vertical component of Hobart is more than three times larger than that recorded in the northern hemisphere by the vertical component of Nagoya. The existence of the NS anti-symmetric term in the variation has already been reported by Nagashima et al. (1986). They found that Nagoya observed the purely anti-symmetric variation between 1971 and 1979 and demonstrated that the observed variation was consistent with the variation arising from the sector-dependent second-order anisotropy formulated by Munakata and Nagashima (1986). Figure 1 taken from Paper 1 shows the amplitudes of the variation recorded by 30 directional telescope components in the THN as a function of λ_E. The amplitudes in this figure are corrected for the difference in the energy response of each telescope. The solid curve in the figure shows the superposition of the expected NS symmetric and anti-symmetric variations plotted as two broken lines. Combining the symmetric and anti-symmetric terms results in a good fit to the observations. In deriving G_θ from the observed diurnal variation, therefore, it is important to analyze the NS symmetric variation separately from the anti-symmetric one.

In this paper, we examine the long term variation of G_θ by analyzing the SDV observed by a network of Japanese muon telescopes during 18 years from 1978 to 1995. The network consists of the total 37 directional component telescopes covering a wide range of λ_E and enables us to examine the NS symetric variation separately from the anti-symmetric one (Munakata et al., 1997).

DATA ANALYSIS AND RESULTS

We analyze the SDV in the hourly count rates recorded by the network over an 18 year period from 1978 to 1995. The network consists of the surface-level (Nagoya), shallow underground (Misato) and deep underground (Sakashita) muon telescopes each of which is multi-directional. The total 37 directional components in the network cover wide ranges of the median primary cosmic-ray rigidity (P_m) from 60GV to 595GV and λ_E from 60°N to 18°S. For the detail of the raw data processing, the reader can refer to our previous papers (Munakata et al., 1997, Paper 1). The average first harmonic vector of the observed SDV in each of the Toward (T) and Away (A) IMF sector periods was calculated in solar time for all component telescopes. The "sector-dependent" vector for the j-th telescope at the i-th station was then calculated from the vectors, $D^T_{i,j}$ and $D^A_{i,j}$ respectively in T and A periods, as $\Delta D_{i,j} = (D^T_{i,j} - D^A_{i,j})/2$ in each of 14 intervals (Bartel's solar rotations) every year.

The first harmonic vector $d_{i,j}$ of the solar diurnal variation expected for the j-th component telescope at the i-th station is related to the space harmonic vectors as, $d_{i,j} = C^{sym}_{i,j} S^{sym} + C^{anti-sym}_{i,j} S^{anti-sym} + d^{com}_i$, where S^{sym} and $S^{anti-sym}$ are the space harmonic vectors representing respectively the NS symmetric and anti-symmetric variations and $C^{sym}_{i,j}$ and $C^{anti-sym}_{i,j}$ are matrices of the coupling coefficients defined for each component telescope with assumed rigidity spectra of S^{sym} and $S^{anti-sym}$. d^{com}_i is introduced to represent the unknown vector due to the atmospheric temperature effect which is supposed to be common for all the telescopes in the i-th station. In this report, we adopt a power-law spectrum ($|S| \propto (p/60GV)^\gamma$) normalized at 60GV for each of S^{sym} and

$S^{anti-sym}$ with an exponent (γ) and an upper cut-off rigidity (P_u) above which $|S| = 0$. We simply assume $\gamma = 0$ for S^{sym}, following the rigidity spectrum of cosmic-ray streaming expected in the convection-diffusion framework at high rigidities. P_u for S^{sym} is left as one of the free parameters to be determined in the analysis. 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 $\gamma = 0.5$ and P_u=200GV for $S^{anti-sym}$, the values used in the analysis of the solar semidiurnal variation. For every solar rotation (Bartel's rotation) in each year, we obtain S^{sym} and $S^{anti-sym}$ as well as P_u for S^{sym} and d_i^{com}, all of which give the best fit between the observed ($\Delta D_{i,j}$) and reproduced ($d_{i,j}$) variations (for more detail, see Paper 1).

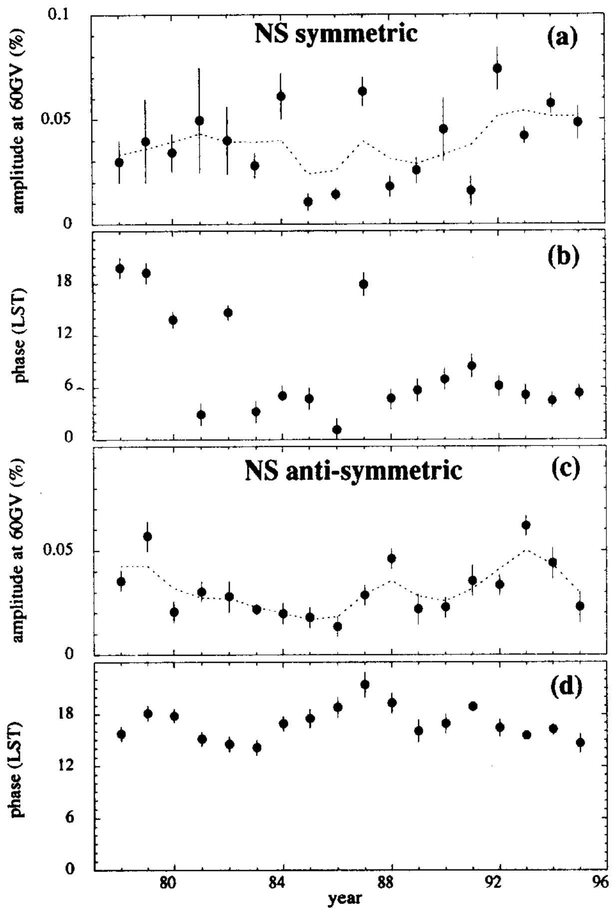

Fig. 2. The yearly mean amplitudes and phases of the space harmonic vectors representing the sector dependent SDV between 1978 and 1995. Figures (a) and (b) show the NS symmetric vector (S^{sym}) while Figures (c) and (d) show the NS anti-symmetric vector ($S^{anti-sym}$). The amplitudes are normalized at 60GV. Note that Figures (b) and (d) represent the phases in the toward sector and those are reversed (±12 hours) in the away sector.

Figure 2 shows the yearly mean amplitudes and phases of the space harmonic vectors, S^{sym} and $S^{anti-sym}$, at 60GV obtained for each of 18 years from 1978 to 1995. Errors are deduced from the dispersion of 14 space harmonic vectors obtained for 14 solar rotations in every year. We first note in the figure that S^{sym} has the phase around 1700 local solar time (LST) in five years of 1978, 1979, 1980, 1982 and 1987 while it has the phase around 0500 LST in the remaining years. The NS anti-symmetric variation, $S^{anti-sym}$, on the other hand, has the phase always around 1700 LST (0500 LST) in the northern (southern) hemisphere. It is also clear that the amplitude of $S^{anti-sym}$ is almost comparable with that of S^{sym} and the contribution from $S^{anti-sym}$ is not negligible in this rigidity region. We also note that the phase of S^{sym} is around 0500 LST during the period from 1992 to 1995 covered by the THN of Nagoya and Hobart. In the period, therefore, the variations due to S^{sym} and $S^{anti-sym}$ cancel each other in the northern hemisphere, while those amplify each other in the southern hemisphere. This explains the significant NS asymmetry in Figure 1. By using S^{sym} obtained above and the Parker's spiral angle of the IMF, we then calculated the component of the anisotropy perpendicular to the IMF, $A_{\perp}^{sym}$, which is directly related to the unidirectional latitude density gradient, G_θ, by $A_{\perp}^{sym} = -\rho G_\theta$ where ρ is the gyration radius of the cosmic-ray particle in the IMF. Figure 3 shows G_θ obtained from $A_{\perp}^{sym}$ at 60GV with ρ=0.2AU in 5nT magnetic field. It is seen in this figure that G_θ shows no clear variation related to the 11-year solar activity- or 22-year solar magnetic cycles, but it remains positive after the late 80's implying a higher density of cosmic rays in the southern hemisphere below the heliospheric current sheet.

By analyzing the sector-dependent solar diurnal

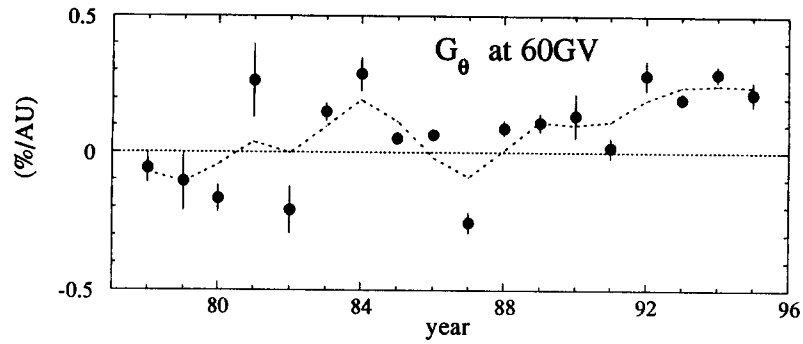

Fig. 3. The unidirectional latitudinal gradient G_θ at 60GV calculated from S^{sym} in Figure 2. In the calculation, we used the gyration radius ρ=0.2AU in 5nT magnetic field.

variations observed by neutron monitors and muon telescopes during the 1965 to 1993 period, Ahluwalia and Dorman (1997) showed that G_θ=0 in 1993 below 67 GV. Their analysis, however, did not take into account the contribution from the NS anti-symmetric component in the variation. The results from such analysis do not explain the observed NS asymmetry seen in Figure 2 and cannot be directly compared with our results.

By using ~2 GeV cosmic-ray proton measurements made by the ULYSSES space probe during the period between September 1994 and August 1995, Simpson et al.(1996) demonstrated a cosmic-ray intensity minimum near the helio-equator, 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 bi-directional latitudinal one. Their result is just in the opposite sense to ours in Figure 1d showing positive G_θ and the southward unidirectional gradient in 1994 and 1995. This may suggest that the large scale distribution of high energy (~60 GeV) particles is different from that of low energy (~2 GeV) particles in the heliosphere.

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