Solar modulation of galactic and heliotail-in anisotropies of cosmic rays at Sakashita underground station (320 ∼ 650 GeV)

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(Received November 4, 2003; Revised March 8, 2004; Accepted Marth 16, 2004)

The sidereal daily variation of cosmic rays with energies less than 10^4GeV is produced by two kinds of anisotropy, one is the galactic anisotropy with deficient intensity in the direction with right ascension $\alpha_G = 12$ hours and declination $\delta_G = 20°$ and the other is the heliotail-in anisotropy with excess intensity in the direction of $\alpha_T \sim 6$ hours and $\delta_T \sim -24°$ (Nagashima *et al.*, 1998). It will be shown that the variation of the galactic origin with energy less than ∼500 GeV is greater in the negative polarity state of solar magnetic field at the north pole than in the positive state owing to the different motion of cosmic rays in the two polarity states and shows a considerably good agreement with its simulation. On the contrary, the variation of the tail-in origin does not show such a polarity dependence. Instead, it becomes greater in the active period of solar cycle than in the quiet period, suggesting the existence of cosmic-ray acceleration due to the interaction between galactic and solar magnetic fields in the heliotail region.

Key words: Heliomagnetic polarity, polarity-dependent cosmic-ray sidereal daily variation of galactic origin, polarity-independent variation of heliotail origin.

1. Introduction

It was shown in the previous paper (Nagashima *et al.*, 1998, hereafter called Ref. 1) that the two anisotropies described in Abstract can be observed with muon telescopes at underground stations Sakashita (median primary energy $E_m \sim 350$ GeV, latitude $\lambda = 36°$ N, longitude $\phi = 138°$E) and Hobart ($E_m = 184$ GeV, $\lambda = 43°$S, $\phi = 147°$E) and even in very low energy region with muon telescopes at the ground station Nagoya ($E_m \sim 65$ GeV, $\lambda = 35°$N, $\phi = 137°$E). The existence of the anisotropies was supported shortly afterward by the two-hemisphere observations in Japan and Australia (Hall *et al.*, 1998).

However, it is not certain why the galactic anisotropy could produce the sidereal daily variation in such a low energy region with the same form as that observed with air showers at Mt. Norikura ($E_m \sim 10^4$GeV, $\lambda = 35°$N, $\phi = 137°$E) in spite of its modulation anticipated in the heliomagnetosphere (cf. Nagashima *et al.*, 1981), and also it is not certain whether the heliotail-in anisotropy is due to the excess inflow of galactic cosmic rays from the heliotail side or the acceleration of cosmic rays inside the heliotail region. In an attempt to solve these questions, the modulation of these anisotropies due to the solar activity and the polarity reversal of solar magnetic field is studied.

2. Analysis

Data used for the present analysis of the sidereal daily variations of cosmic rays are those obtained with six components (S3, S2,. . ., NE) of the muon telescope at Sakashita underground station in 1971–2000. The characteristics of each component are listed in Fig. 1. These data are classified into five periods ALL, A, Q, P and N. The symbol ALL is all the period of observation, A and Q are the active and quiet period in solar cycle, and P and N the periods of positive and negative polarity state of solar magnetic field at the north pole. The selection of data into A and Q is so arranged that each group is not heavily one-sided in number in order to maintain statistical accuracy of each group. P and N states were quoted from Howard (1974) and Solar Geophysical Data published monthly by U.S. Department of Commerce. From these data, the sidereal and anti-sidereal daily variations are derived in the following combined periods AP, AN, QP and QN, which express respectively 'Active and Positive' period, 'Active and Negative' period and so forth. The influence of the solar diurnal variation on the sidereal variation is eliminated by using the anti-sidereal variation (cf., Ref. 1).

In the following, the corrected sidereal variation is expressed with $I(t)$ or $I(X; Y)$ where X is the component telescope (S3, S2,. . .) or the simulation (SIM), and Y is the period (ALL, A, AP, AN,. . .). Similarly, the variations produced by the galactic and heliotail-in anisotropies are expressed respectively with $G(t)$ or $G(X; Y)$ and $T(t)$ or $T(X; Y)$. The anisotropies are expressed respectively with G and T anisotropies.

3. Sidereal Daily Variation

Figure 1 shows sidereal variation $I(X; ALL)$ which suggests coexistence of G and T anisotropies, as it can be interpreted as a composite variation consisting of $T(t)$ with a

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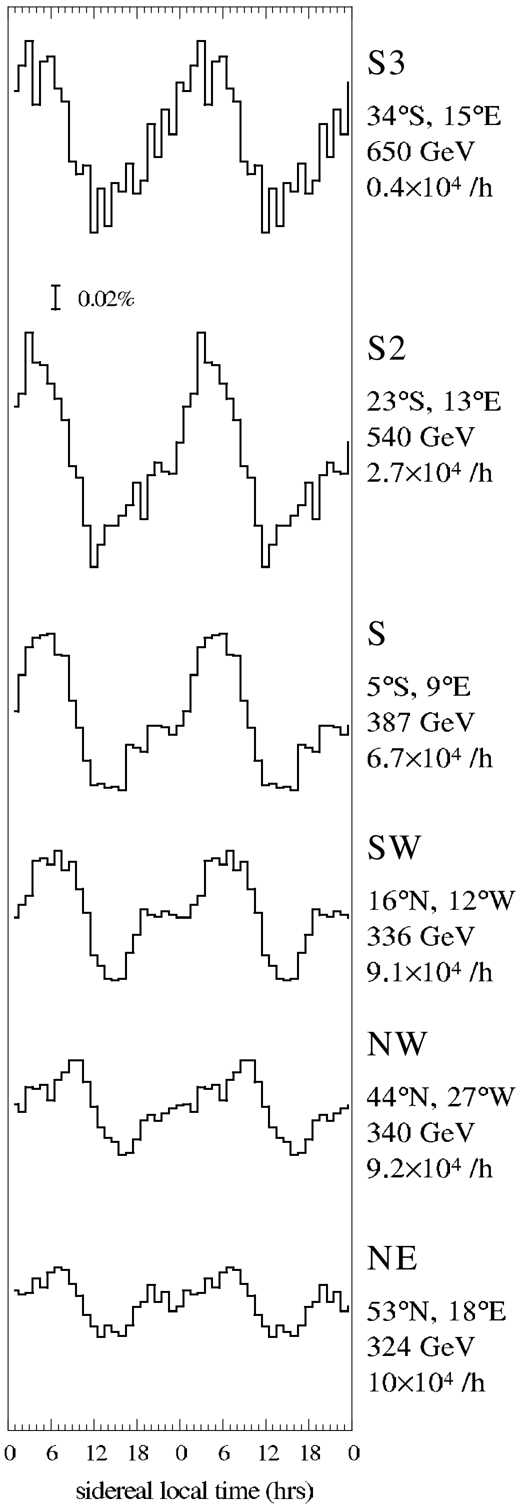

Fig. 1. Cosmic-ray sidereal daily variations at Sakashita underground station in '*ALL*' period (1971–2000). The 24-hour variation is repeatedly plotted so as to extend for a 2-day period. The viewing direction (geographic lat. and long.) of the component telescope (S3, S2, S,. . ., NE) and the hourly count and median energy (GeV) of cosmic rays are attached to each variation.

sharp peak at ~6 hours superposed on $G(t)$ of plateau-type with a valley at ~12 hours. The variation $I(SW; ALL)$ is the most typical example of the superposition. However, such a variation becomes obscure in the southern hemisphere owing to the enhancement of $T(t)$ and/or the reduction of $G(t)$, because G- and T-anisotropies are located respectively in the northern and southern hemisphere (cf. Ref. 1).

The directions of the two anisotropies can be estimated respectively from the times of maximum and minimum phase of $I(t)$ by adjusting longitudinal deviation of the viewing direction of the telescope from the meridian plane. These directions derived from all $I(X; ALL)$s are as follows,

$$t_{\max} = 6.1 \pm 0.5 \text{ hours (Tail-in anisotropy)}, \quad (1)$$
$$t_{\min} = 13.1 \pm 0.3 \text{ hours (Galactic anisotropy)},$$

which almost coincide respectively with those derived in Ref. 1.

For the study of the solar modulation of $T(t)$ and $G(t)$, it is desirable for $I(t)$ to have the form showing clearly the existence of $T(t)$ and $G(t)$. In this respect, the S- and SW-variations are most preferable (cf. Fig. 1). These variations are classified into four periods (QP, QN, AP, AN) as shown in Fig. 2. $T(t)$s due to the tail-in anisotropy show the solar-activity dependence that they are greater in A period than in Q period regardless of the polarity state (P or N) of the solar magnetic field. This relation is symbolically expressed as

$$T(X; A) > T(X; Q). \quad (2)$$

On the other hand, $G(t)$s due to the galactic anisotropy show the polarity dependence that they are greater in N state than in P state regardless of the solar activity (A or Q). This relation is expressed as

$$G(X; N) > G(X; P). \quad (3)$$

Table 1 shows the magnitudes of $T(X; Y)$ and $G(X; Y)$ estimated from the peak, the plateau and the bottom of $I(X; Y)$, each of which is the average of 3 ~ 6 hourly values. The polarity (P or N) dependence of $G(X; Y)$ and the solar-activity (A or Q) dependence of $T(X; Y)$ are clearly seen in the table even though their magnitudes are rough estimates owing to the uncertainty especially for the determination of the plateau level.

4. Interpretation of the Modulation

The polarity dependence of $G(t)$ is due to the different motion of galactic cosmic rays in the positive and negative polarity states of the heliomagnetosphere, as will be shown by the following simulation. Owing to the existence of the heliomagnetosphere, the modulation depends on the following parameters, the direction (α_G, δ_G) and structure of the anisotropy, the polarity state (P or N) of solar magnetic field at the north pole, the interplanetary magnetic field (B_E) at the Earth's orbit, the heliolatitudinal amplitude (λ_W) of the wavy neutral sheet, the radial and energy dependences of cosmic-ray mean free path in heliomagnetosphere and the declination (δ_e) of the viewing direction of detector. Generally, as far as δ_G of the anisotropy is not near the geographic north pole, the modulation making $G(t)$ greater in N state than in P state can be simulated without any restriction on other parameters in the above (Nagashima *et al.*, 1981, 1982; Nagashima and Morishita, 1983). Figure 3 shows some examples of the simulation of $G(t)$ modulated in the spherical heliomagnetosphere with a radius of 10^2AU. The

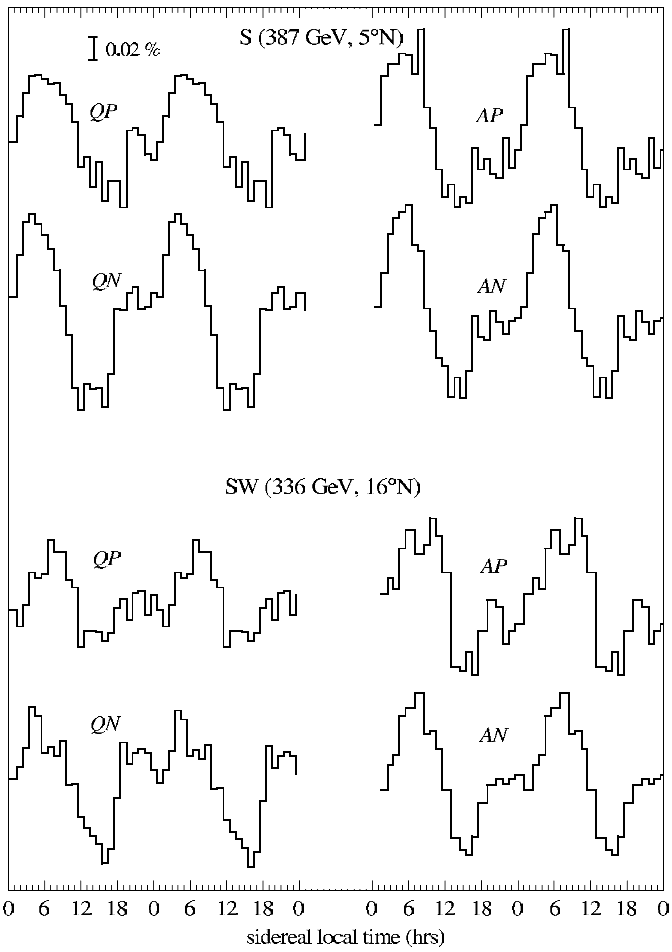

Fig. 2. Cosmic-ray sidereal variations of S and SW telescopes in QP, QN, AP and AN periods. Caption is the same as that in Fig. 1.

Table 1. Magnitudes of $T(X;Y)$ and $G(X;Y)$ for X = S and SW in units of $10^{-2}\%$ estimated from Fig. 2 in the period of $Y = AP$, AN, QP and QN which express respectively 'Active and Positive' period, 'Active and Negative' period and so forth (see text).

Telescope	$T(X;Y)$				$G(X;Y)$			
	A		Q		N		P	
	AP	AN	QP	QN	QN	AN	QP	AP
S (5°S, 387 GeV)	~8	~8	~5	~6	~7	~5	~4	~3
SW (16°N, 336 GeV)	~7	~6	~5	~2	~8	~5	~2	~3

solid and dashed curves express respectively $G(SIM;N)$ and $G(SIM;P)$ for several energies in N and P states at $\delta_e = 0°$ for $\lambda_W = 0°$ and $B_E = 6$ nT in the absence of magnetic statistical scatterings of cosmic rays. The simulation is made on the assumption that G anisotropy has the spatial form $F(\chi)$ given by Eq. (4), its minimum being in the direction of $\delta_G = 20°$ and $\alpha_G = 12$ hours specified in Abstract.

$$F(\chi) = \eta_1 P_1(\cos\chi) + \eta_2 P_2(\cos\chi) \qquad (4)$$
$$= -\cos\chi - 0.25(3\cos^2\chi - 1),$$

where χ is measured from the center direction of the deficient cone and $\eta_1(=-1)$ and $\eta_2(=-0.5)$ are so chosen that $F(\chi)$ is nearly constant outside the cone, as shown in Fig. 3. The simulated $G(t)$ in N state considerably well maintains the original form of the cone even at very low energy (50 GeV), but in P state it is extremely deformed from the original owing to strong attenuation in the heliomagnetosphere. This deformation in P state can be seen in the observed variations in Fig. 2. Quantitative comparison of the simulation with the observations can be made as follows. The ratio $R(P/N)$ of $|G(SIM;P)|$ to $|G(SIM;N)|$ is about 0.45 at E = 500 GeV and does not depend so much on the parameters such as δ_e, λ_W and so forth, although $G(t)$ itself depends on these parameters. This ratio R is not affected also by the statistical scatterings of cosmic rays with the heliomagnetic irregularities, because the same scattering effect on $G(X;P)$ and $G(X;N)$ is expected as far as the solar activities in P and N states are equal to each other. The ratio (0.45) in the above approximately coincides with those observed at Sakashita (cd. Table 1). This indicates that the observed variation is produced by G anisotropy and subject to the polarity-dependent modulation in the heliomagnetosphere. Therefore, by using the simulation, the magnitude of G anisotropy can be estimated inversely from the observation. As the modulation factor $M(N/F)$, which is defined by the ratio of $|G(SIM; N)|$ to $|F(\chi)|$, is ~0.8 at $E = 500$ GeV, the magnitude of G anisotropy derived from $G(SW; QN)$ in Table 1 is ~0.10%. This value is almost comparable with the magnitude (0.13%) of $G(t)$ observed with air showers ($E \sim 10^4$GeV) at Mt. Norikura (Nagashima *et al.*, 1989), denying the previous conclusion that the spectrum of G anisotropy increases sharply with energy (cf. Ref. 1). The estimated magnitude would increase more by the following reason. As mentioned in the above, $G(t)$ is influenced also by the statistical scattering of cosmic rays with the magnetic irregularities. According to Yasue *et al.* (1983), the influence is almost negligible in high energy region (≥500 GeV), but cannot be neglected at low energies (≤200 GeV). However, such an influence can be seen even in the energy region (300 ~ 500 GeV), especially in the difference between $G(X; QN)$ and $G(X; AN)$ in Fig. 2 and Table 1. This indicates that the influence of the scatterings cannot be neglected in the energy region of 300 ~ 500 GeV. If we take into consideration this effect for the estimation of G anisotropy, the value (~0.10%) further increases.

Prior to the present analysis, Bercovitch (1984) tried to find out the polarity dependence of the galactic anisotropy by using the first harmonic components of $I(t)$s observed with Ottawa Muon Array (90 ~ 660 GeV; $\delta = 45°$N, $\phi = 76°$W) in the positive (1976–1979) and negative (1981–1984) polarity states, but could not confirm its existence expected from the simulation (Nagashima *et al.*, 1981). This would be mainly due to the following reason that the first harmonic component of $I(t)$ contains the contamination due to the polarity-independent $T(t)$, which disturbs the detection of the polarity dependence of $G(t)$, and furthermore his observation was made almost in the enhanced period of $T(t)$ (cf. Fig. 2). Unfortunately, the influence of $T(t)$ could not be eliminated in his analysis, as its existence was not known in those days.

The modulation of $T(t)$ does not depend on the polarity but on the solar activity. This polarity independence cannot be produced by any galactic anisotropy in this energy region as shown by the simulation described in the above (cf. Fig. 3). These facts suggest that the anisotropy responsible for $T(t)$ is produced in the heliotail region by some unknown heliotail acceleration mechanism of cosmic rays such as that probably due to the interaction between the galactic and solar magnetic fields like the geotail acceleration of ionized low-energy particles.

5. Conclusion

On the basis of the observation of cosmic rays with 300 ~ 500 GeV, it is concluded that the galactic anisotropy produces the polarity-dependent sidereal daily variation with the maximum phase at ~1.1 hours (sidereal local time) which is greater in the negative polarity state of the solar magnetic field at the north pole than in the positive state. The observed polarity dependence shows a considerably good agreement with the simulation. The magnitude of the galactic anisotropy derived from the observed variation with the aid of the simulation is about 0.1% which is almost comparable with that (0.13%) observed with the air showers ($E \sim 10^4$GeV) at Mt. Norikura.

The heliotail-in anisotropy produces the solar-activity-dependent sidereal variation with the maximum phase at ~6.1 hours, which is greater in the active period of solar cycle than in the quiet period. As the variation does not depend on the polarity, the anisotropy seems to be produced in the heliotail region by some acceleration mechanism of cosmic rays such as that probably due to the interaction between the galactic and solar magnetic fields.

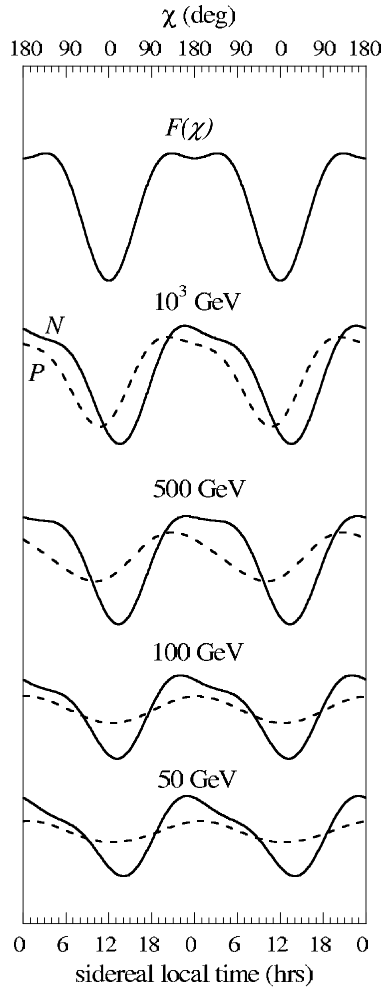

Fig. 3. Simulation of polarity-dependent sidereal variations $G(SIM; PorN)$ for $E = 50 \sim 10^3$GeV on the Earth ($\delta_e = 0°$) produced by the solar modulation of galactic anisotropy ($\alpha_G = 12$ hours; $\delta_G = 20°$) in the heliomagnetosphere ($B_E = 6$ nT; $\lambda_W = 0°$). F: Evolution of the anisotropy in the plane through the axis of minimum flux. P and N: Variation in the positive and negative polarity states.

Acknowledgments. The authors express their sincere appreciation to the members of Cosmic-Ray Section, Solar-Terrestrial Environment Laboratory, Nagoya University for the maintenance of muon observation at Sakashita and for the kind discussions.

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