Solar Diurnal and Semi-Diurnal Variations of Cosmic Rays Observed by the North-South Network of Surface-Level Multi-Directional Muon Telescopes

Z. FUJII¹, K. FUJIMOTO¹, S. SAKAKIBARA¹, H. UENO¹, K. MUNAKATA², S. YASUE², C. KATO²,
S. AKAHANE², S. MORI², J. E. HUMBLE³, K. B. FENTON³, A. G. FENTON³, and M. L. DULDIG⁴

¹*Solar-Terrestrial Environment Laboratory, Nagoya University, Nagoya 464-01, Japan*

²*Department of Physics, Faculty of Science, Shinshu University, Matsumoto 390, Japan*

³*Physics Department, University of Tasmania, Hobart, Tasmania 7001, Australia*

⁴*Australian Antarctic Division, Kingston, Tasmania 7150, Australia*

(Received December 5, 1994; Accepted March 9, 1995)

A scintillator muon telescope was installed at the Hobart Campus of the University of Tasmania (42.85°S, 147.42°E), Australia in December 1991. It is part of a North-South Network of Multi-Directional Cosmic Ray Muon Surface Telescopes, in conjunction with the Nagoya Cosmic Ray Muon Telescope (35.12°N, 136.97°E). Using two years of data from the North-South Network, we have investigated the average features of the solar diurnal and semi-diurnal variations. Preliminary results of the analysis show that two years averages of the observed diurnal variations are composed of a north-south symmetric and an asymmetric variations. The north-south asymmetric diurnal variation is consistent with that expected from the semi-diurnal anisotropy which produces the observed semi-diurnal variation. It is shown that the reference axis of the anisotropy is in the direction of about 7°S sunward from the ecliptic.

1. Introduction

Studies of solar daily variations of cosmic rays provide valuable information on the physical process of cosmic ray modulation in the heliosphere. Nagashima (1971) and Nagashima and Ueno (1971) formulated a model of the cosmic ray daily variations arising from a generalized axis-symmetric anisotropy, to give the basis of analysis in the three dimensional space. In this framework, many investigations have been made of the origin of the solar semi-diurnal variation, and it was shown that the observed semi-diurnal variation can be interpreted by the pitch angle distribution ($F_2(X) \propto \sin^2 X$) of cosmic ray particles about the interplanetary magnetic field line (Nagashima *et al.*, 1972; Fujii, 1972). This second space distribution also produce a special diurnal anisotropy represented by a spherical $P_2^1(\cos\theta)$ -type function whose latitudinal dependence is north-south asymmetric. On the other hand, it is known that there exists the diurnal variation due to the so called co-rotational anisotropy with a relatively large amplitude. Observed diurnal variations are composed of these two space harmonic components which have different latitudinal dependences (Fujimoto *et al.*, 1973). To study these diurnal variations, it is important to analyse simultaneously data observed in both hemisphere. In this report, we present briefly the solar diurnal and semi-diurnal variations observed by the North-South Network of Surface-Level Multi-Directional Muon Telescopes.

2. The North-South Network of Surface-Level Multi-Directional Muon Telescopes

A scintillator muon telescope was installed at the Hobart Campus of the University of Tasmania (42.85°S, 147.42°E, sea level), Australia, in December 1991. It is part of a North-South Network of Multi-Directional Cosmic Ray Surface Muon Telescope, in conjunction with the Nagoya cosmic ray muon

telescope (35.12°N , 136.97°E , Sekido *et al.*, 1975) which have been in operation since 1970. The Hobart telescope are of similar design of those at Nagoya and telescope consist of two layers of $3\text{ m} \times 3\text{ m}$, one-quarter of Nagoya telescopes in detector area. The telescopes record 13 different directional intensities, taking coincidence between pulses from a specified pair of detectors of $1\text{ m} \times 1\text{ m}$ in the upper and lower layers. The asymptotic directions of five directional telescopes, Vertical, 30°North , 30°South , 30°East and 30°West are shown in Fig. 1, together with those of the Nagoya telescopes. Characteristics of the Hobart and Nagoya telescopes are listed in Table 1 (comp.: Component telescope, λ_E : declination of effective viewing direction, P_c : geomagnetic cutoff rigidity, I : hourly counting rate, P_m : effective median rigidity).

Fig. 1. The asymptotic orbital direction of the cosmic rays with the rigidity P incident parallel to each telescope at Nagoya (top) and Hobart (bottom), its direction (V , E , ...) being schematically shown in Fig. 1. The axis of ordinates and abscissas show the geographic latitude and the geographic longitude in degree, respectively.

Table 1. Characteristics of the Nagoya and Hobart Multi-Directional Surface Muon Telescopes.

Nagoya Scintillator Telescope

Comp.	λ_E	P_c (GV)	I_{obs} (10^4 c.p.h.)	I_{cal} (10^4 c.p.h.)	P_m (GV)
V	18.0°N	11.5	276	243	60.0
N	38.0°N	12.9	125	110	66.0
S	4.0°N	11.3	123	112	64.0
E	9.0°N	16.2	120	108	67.0
W	25.0°N	9.4	126	113	63.0
NE	19.0°N	17.6	58.0	52.0	73.0
NW	37.0°N	11.0	62.0	54.4	68.0
SE	2.0°S	15.0	58.0	53.1	71.0
SW	11.0°N	9.2	60.0	54.9	67.0
N2	33.0°N	12.9	61.1	53.8	87.0
S2	6.0°S	10.9	59.9	54.6	85.0
E2	1.0°N	21.0	58.1	52.1	91.0
W2	27.0°N	9.3	61.7	55.2	84.0
N3	36.0°N	11.0	17.8	13.4	112.0
S3	18.0°S	10.8	17.6	13.5	111.0
E3	3.0°S	25.1	17.3	12.9	119.0
W3	36.0°N	8.7	18.0	13.6	110.0

Hobart Scintillator Telescope

Comp.	λ_E	P_c (GV)	I_{obs} (10^4 c.p.h.)	I_{cal} (10^4 c.p.h.)	P_m (GV)
V	30.0°S	2.5	89	64	56.4
N	19.0°S	2.5	32	23	61.6
S	37.6°S	2.5	33	23	61.6
E	20.0°S	2.5	33	23	61.6
W	38.6°S	2.5	32	23	61.6
NE	9.4°S	2.5	12	9.0	66.8
NW	26.3°S	2.5	12	9.0	66.8
SE	26.1°S	2.5	13	9.0	66.8
SW	46.8°S	2.5	13	9.0	66.8
N2	6.0°S	2.5	8.7	5.6	81.1
S2	40.0°S	2.5	9.4	5.6	81.1
E2	8.1°S	2.5	8.9	5.6	81.1
W2	39.8°S	2.5	8.6	5.6	81.1

3. Observed Solar Diurnal and Semi-Diurnal Variations

The Hobart muon telescope started continuous observations of cosmic ray intensities in late December, 1991. More than two years of data are now available from the North-South Network of surface-level muon telescopes. Observed hourly value intensities are corrected for pressure changes, and analysed by harmonic analysis to derive the diurnal and semi-diurnal harmonic coefficients on a daily basis. The obtained diurnal vectors are corrected for Compton-Getting effect due to the earth's orbital motion around the sun, and the diurnal and semi-diurnal vectors are averaged for the observed period of two complete years of 1992 and 1993. The mean vectors thus derived for Nagoya and Hobart are shown in harmonic dial in Fig. 2. In the figure, the end-points of vectors are connected by solid and dotted lines, to show the relative relation of amplitudes and phases observed by the directional telescopes.

Fig. 2. Average solar diurnal and semi-diurnal variations observed with 17 and 13 directional muon telescopes at Nagoya and Hobart, respectively. Symbol expresses the directional telescope (cf. Table 1).

4. Analysis

The axis-symmetric distribution is expressed by the following equation,

$$\frac{J(X, P)}{J(P)} = F(X)G(P) = G(P) \sum_{n=0}^{\infty} F_n(X) = G(P) \sum_{n=0}^{\infty} \eta_n P_n(\cos X)$$

where P is the cosmic ray rigidity, $G(P)$ is the differential rigidity dependence of the anisotropy and X defines the cosmic ray incident direction (OJ) relative to the reference axis of the anisotropy (OR) as shown in Fig. 3. The m -th space distribution $F_n(X)$ is transformed into the projected component $f_n^m(X)$ as

Fig. 3. Equatorial and ecliptic coordinates systems. N: Equatorial north pole, P: Ecliptic north pole.

$$F_n(X) = \sum_{n=0}^{\infty} f_n^m(X) = \sum_{n=0}^{\infty} \eta_n P_n^m(\cos \theta_J) P_n^m(\cos \theta_R) \cos m(\alpha_J - \alpha_R)$$

where (θ_J, α_J) and (θ_R, α_R) represent the direction of the cosmic rays and the reference axis in equatorial coordinate respectively. The m -th harmonic component $D_n^m(t)$ of the daily variation at a station is related to $f_n^m(X)$ and $G(P)$ as

$$D_n^m(t) = A_n^m \cos \frac{2m\pi t}{24} + B_n^m \sin \frac{2m\pi t}{24}$$

$$\begin{pmatrix} A_n^m \\ B_n^m \end{pmatrix} = \begin{pmatrix} c_n^m & s_n^m \\ -s_n^m & c_n^m \end{pmatrix} \begin{pmatrix} x_n^m \\ y_n^m \end{pmatrix} \quad \begin{pmatrix} x_n^m \\ y_n^m \end{pmatrix} = \eta_n P_n^m(\cos \theta_R) \begin{pmatrix} \cos \frac{2m\pi t}{24} t_R \\ \sin \frac{2m\pi t}{24} t_R \end{pmatrix}$$

where t_R is the local time of the reference axis, and c_n^m and s_n^m are the coupling coefficients. The harmonic components, D_1^1 and D_2^2 are calculated for Hobart, using the coupling coefficients, and are shown in Fig. 4 for the typical rigidity dependences of the diurnal and semi-diurnal variations. It should be noted that the observed semi-diurnal vectors shown in Fig. 2 are quite similar to the configuration of the calculated D_2^2 . On the other hand, the observed diurnal vectors have the configuration deformed from that of the calculated D_1^1 , suggesting a contribution by the harmonic component D_2^1 . In the following, we assumed a power law rigidity dependence of P^γ with an upper cut-off rigidity P_U for $G(P)$. The semi-diurnal anisotropy was first determined by the best fit between the observed and the expected values. The obtained amplitude of the semi-diurnal anisotropy is $0.100 \pm 0.003\%$ at 10 GV with $P_U = 100$ GV and $\gamma = 0.5$, and the phase is 3.05 and 15.05 ± 0.05 hr. Using the rigidity dependence of D_2^2 for D_2^1 , the observed diurnal variations are analysed, assuming the existence of two harmonic components D_1^1 and D_2^1 . The obtained amplitudes and the phases of D_1^1 in space are $0.37 \pm 0.1\%$ and 15.3 hr with $P_U = 100$ GV and $\gamma = 0$, and those of D_2^1 are $0.023 \pm 0.007\%$, 15.3 ± 1.3 . It should be pointed out here that the obtained phase of D_2^1

HOBART

 D_1^1 D_2^2

Fig. 4. D_1^1 and D_2^2 calculated for Hobart telescope. The phase and the rigidity dependence are assumed to be 15 hr and P^0 with $P_U = 100$ GV for D_1^1 , and 3 hr and $P^{0.5}$ with $P_U = 100$ GV for D_2^2 respectively.

coincides with that of D_2^2 within the accuracy of the observations. This implies that D_2^1 and D_2^2 are produced by the pitch angle distribution of $F_2(X)$ whose reference axis is almost parallel to the average direction of the interplanetary magnetic field. The ratio of the obtained amplitudes indicates that the average reference axis of the anisotropy is in the direction of about 7° S sunward from the ecliptic.

In summary, we have investigated the average features of the solar diurnal and semi-diurnal variations, using two years of data from the North-South Network of Multi-Directional Cosmic Ray Surface Telescopes. It is shown that the observed diurnal variations are composed of a north-south symmetric variation and an asymmetric variation. Preliminary results of analysis indicate that the reference axis of the semi-diurnal anisotropy is in the direction of about 7° S sunward from the ecliptic.

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