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SOLAR CYCLE VARIATIONS OF MODULATION PARAMETERS OF GALACTIC COSMIC-RAYS IN THE HELIOSPHERE

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ABSTRACT

Solar cycle variations of modulation parameters are derived from cosmic-ray anisotropy observed by a network of multidirectional muon telescopes. The network covers wide ranges of median rigidity of primary cosmic-rays and effective latitude of viewing. It was found that the radial density gradient varies with a good correlation with the solar activity, while the parallel mean-free-path of the cosmic-ray diffusion varies with an anti-correlation with the solar activity. These features are both in accord with the conventional modulation theory incorporating convection and diffusion processes. The correlation coefficients of yearly mean values of radial density gradient and parallel mean-free-path with the sunspot number were respectively 0.7 and 0.6. The bi-directional latitudinal gradient showed a clear 22-year solar magnetic cycle as predicted by the drift model for the cosmic-ray transport in the heliosphere. The unidirectional latitudinal gradient, on the other hand, showed 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. We also analyze temporal variations of modulation parameters derived from neutron monitor observations at ~10 GV. By comparing with those obtained from muon observations at 60 GV, we discuss the rigidity dependence of temporal variations of modulation parameters .

INTRODUCTION

By analyzing the diurnal anisotropy of cosmic-ray intensity observed by neutron monitors and ion chambers over a period of about 50 years, a series of studies revealed long term variations of the local modulation parameters such as radial and latitudinal gradients of cosmic-ray density in the heliosphere and mean-free-paths of cosmic-ray scattering by magnetic irregularities (Swinson *et al.*, 1991, Bieber and Chen, 1991, Chen *et al.*, 1991, Chen and Bieber, 1993, Hall *et al.*, 1996, 1997, Ahluwalia and Dorman, 1997). These studies give us the important information on the large scale distribution of high energy cosmic-rays and enable us to make crucial tests of physical models for the modulation of galactic cosmic-rays in the heliosphere. In this report, we summarize results derived from our two hemisphere observations of the solar diurnal anisotropy by a network of four muon telescopes at Nagoya (surface), Hobart (surface), Misato (30 m.w.e. underground) and Sakashita (80 m.w.e. underground), each of which is multi-directional. The network, which consists of total 50 directional component telescopes observing in various directions along with various depths of overburden, covers wide ranges of median rigidity of primary cosmic-rays (from 60 GV to 595 GV) and effective latitude of viewing (from 38°N to 47°S). It allows us to precisely determine both the rigidity spectrum and the north-south asymmetry of the anisotropy in space (Munakata *et al*, 1997, 1998, 1999a).

RESULTS

Figure 1 shows the long term variations of modulation parameters derived at 60 GV from the network observation by muon telescopes during 18 years from 1978 to 1995. For the detail of our analysis, reader can refer to our previous papers (Munakata *et al.*, 1997, 1999b) and a review paper by Hall *et al.* (1996). In our analyses of modulation parameters in this paper, we assumed a value of 0.01 for the perpendicular to parallel mean free path ration (α) following the results by Chen and Bieber (1993). It is also reported by Hall et al. (1997) that modulation parameters do not strongly depend on α in $0.01 \le \alpha \le 0.1$. In Figure 1, yearly mean values of radial density gradient (G_r) in %/AU, parallel diffusion mean-free-path ($\lambda_{//}$) in AU and bi-directional and uni-directional latitudinal density gradients ($G_{|Z|}$ and G_θ respectively) in %/AU are plotted versus year. Errors are deduced from the dispersion of 14 solar rotation (Bartels rotation) averages in each year. $G_{|Z|}$ represents the density distribution symmetric above and below the heliospheric current sheet (HCS) and a local maximum ($G_{|Z|}$<0) or minimum ($G_{|Z|}$>0) of the cosmic-ray density on the HCS. On the other hand, G_θ represents the asymmetric distribution above and below the HCS and higher (G_θ<0) or lower (G_θ>0) density in the northern hemisphere above the HCS than in the southern hemisphere below the HCS. Figures 2a and 2b show respectively G_r and $\lambda_{//}$ in Figure 1 as functions of yearly mean sunspot number. It is clear that G_r varies with a good correlation with the solar activity, while $\lambda_{//}$ varies with an anti-correlation with the solar activity. Correlation coefficients of Figures 1a and 1b are 0.70 and 0.60, respectively. These features of G_r and $\lambda_{//}$ are both in accord with the conventional modulation theory incorporating the convection and diffusion processes.

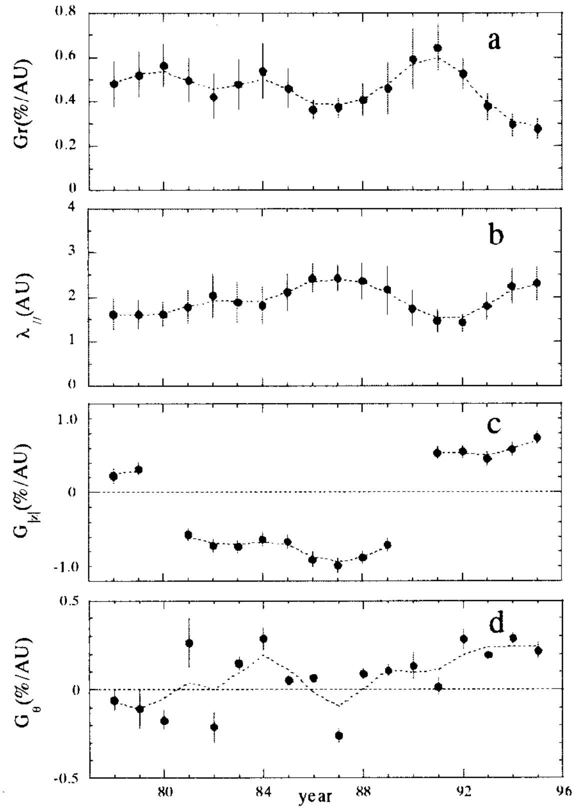

Fig. 1. Yearly averages of modulation parameters derived at 60 GV from network observations by multidirectional muon telescopes during the period from 1978 to 1995.

In Figure 2c showing G_r as a function of $\lambda_{//}$, we note that $\lambda_{//}$ in 1992 in the declining phase of the cycle 22 remained at the minimum level in 1991 when G_r started to decrease. Due to this, an apparent hysteresis effect between $\lambda_{//}$ and G_r is seen during a period from 1991 to 1993. We also note that the network observed an enhancement of the sidereal diurnal variation in 1992 and 1993, possibly arising from the northward cosmic-ray streaming, $-\lambda_\perp G_\theta$, perpendicular to ecliptic plane and the IMF (Munakata *et al.*, 1999a).

The bi-directional latitudinal gradient $G_{|Z|}$ in Figure 1c shows a clear 22-year solar magnetic cycle variation with local maximum (minimum) of cosmic-ray density on the HCS during the period of negative (positive) solar magnetic polarity, as predicted by the drift model for the cosmic-ray transport in the heliosphere. The mean value of $\lambda_{//}$ in Figure 1b was slightly larger in the negative polarity period than in the positive polarity period, as reported by Chen and Bieber (1993), but the difference was not significant. There was no polarity dependence found in G_r in Figure

1a.

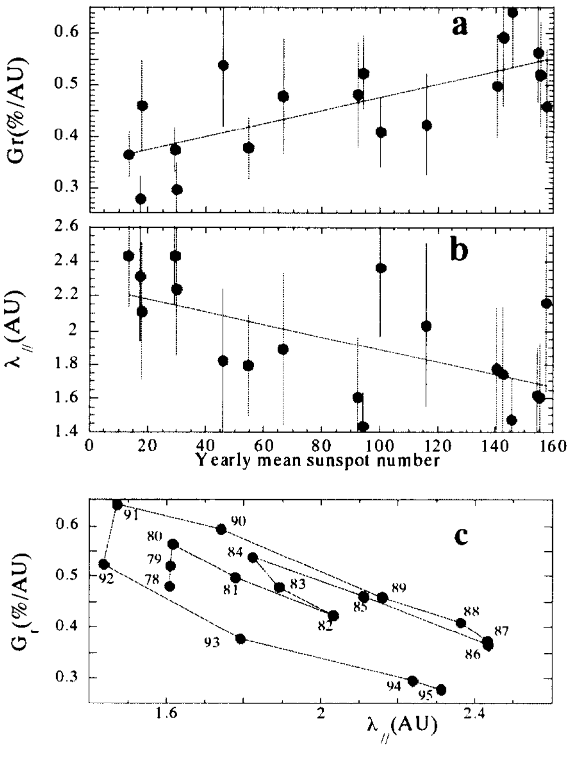

Fig. 2. Correlations of G_r(a) and $\lambda_{//}$(b) with yearly mean sunspot number. The correlation between G_r and $\lambda_{//}$ is shown in (c).

It is also interesting to compare modulation parameters in Figure 1 derived from muon observations with those obtained from neutron monitor observations in lower rigidity region (median rigidity of primary cosmic-rays is ~10 GV). An extensive analysis of neutron monitor and ion chamber data has already been made by Chen and Bieber (1993). In processing the pressure corrected muon count rate, we basically followed a procedure adopted by Bieber and Chen (1991). To confirm the performance of our analysis, we also analyzed neutron monitor data recorded at Thule, McMurdo and Deep River following the procedure by Bieber and Chen (1991). Figure 3 shows variations of modulation parameters derived from neutron monitor data during a period from 1971 to 1994. We have confirmed that the derived anisotropy in each year is quite consistent with Chen and Bieber (1993). The correlations seen in Figure 1 between sunspot number and modulation parameters were not significant in Figure 3. By comparing Figure 3 with Figure 1, we also note larger errors in Figure 3 from neutron monitor data than those in Figure 1 from muon data. In both cases, we deduced errors from the dispersion of 14 solar rotation averages in each year. The difference in error sizes is partly due to the difference in procedures to derive the anisotropy from the observed diurnal variation. The anisotropy from which modulation parameters in Figure 1 are derived in every solar rotation is calculated from a best-fitting for diurnal variations recorded by total 50 directional component telescopes in the muon observation network. The anisotropy used in Figure 3, on the other hand, is deduced directly from observed data without any best-fitting. That is, the intensity difference between Thule and McMurdo is used to derive the north-south component of the anisotropy perpendicular to the equatorial plane, while Deep River data are used to obtain component in the equatorial plane. The difference in error sizes is also due to the difference in cosmic-ray responses to temporal changes of the physical condition in interplanetary space. Lower rigidity (~10 GV) cosmic-rays observed by neutron monitors could be more sensitive to such temporal changes than higher rigidity (60 GV) cosmic-rays. This causes larger dispersions (errors) of 14 solar rotation averages in lower rigidity region covered by neutron monitors. It is noted that this difference in responses to temporal changes is also seen in variations of yearly mean values and temporal variations of modulation parameters in Figure 1 are more smooth than those in Figure 3.

Another interesting difference is seen in temporal variations of $G_{|Z|}$ in Figures 1c and 3c. It is clear that the 22-year solar magnetic cycle is more significant in Figure 1c at 60 GV than in Figure 3c at ~10 GV. This may be interpreted in terms of rigidity dependence of the drift effect, as follows. The quasi-linear theory of pitch angle scattering of cosmic-rays by magnetic irregularities predicts $\lambda_{//} \propto P^2$ for $P \geq 10\text{GV}$, where P is particle's rigidity. On the other hand, the gyration radius (ρ) of particle in interplanetary mean magnetic field is proportional to P. Thus, the ratio $\lambda_{//} / \rho$ representing the mean number of gyrations of a particle between pitch angle scatterings increases with increasing P. This implies that particles with higher rigidity are allowed to gyrate more times than particles with lower rigidity and the drift effect of guiding center of gyration motion could be more pronounced in muon observations monitoring higher rigidity region than in neutron monitor observations.

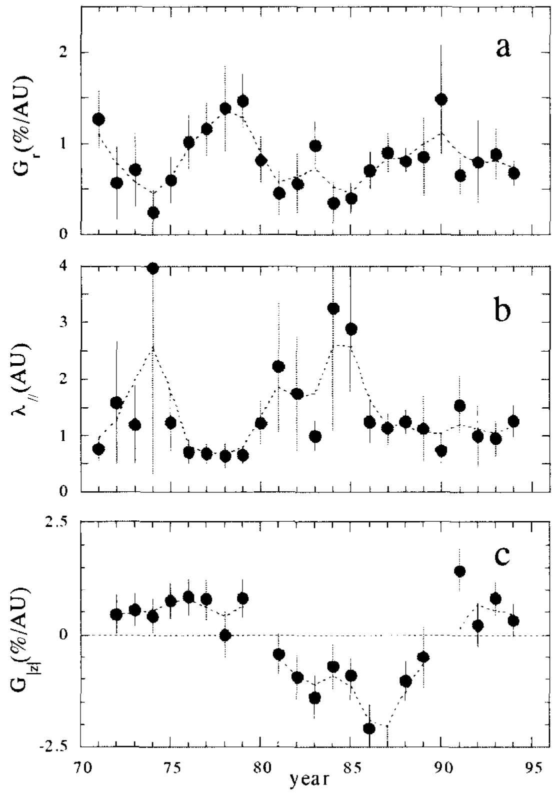

Fig. 3. Modulation parameters derived at ~10 GV from neutron monitor observations at Thule, McMurdo and Deep River during a period from 1971 to 1994.

The two hemisphere network of muon observations in 1992-1995 also confirmed a significant north-south (NS) asymmetry in the "sector-dependent" diurnal variation from which the unidirectional latitudinal density gradient (G_θ) is derived (Munakata, *et al.*, 1999a). The "sector-dependent" variation can be deduced by subtracting the diurnal variation during the period of away IMF sector from the variation during the period of toward IMF sector. Due to the asymmetry, the amplitude recorded in southern hemisphere by the vertical component of Hobart is more than three times larger than that recorded in northern hemisphere by the vertical component of Nagoya (Munakata *et al.*, 1999a). Such NS-asymmetry has been reported by Swinson *et al.* (1986) and Nagashima *et al.* (1986). Particularly, Nagashima *et al.* (1986) found a purely NS anti-symmetric variation being observed by muon telescopes at Nagoya in 1971-1979 and demonstrated that the observed variation was consistent with the variation arising from a second-order anisotropy formulated by Munakata and Nagashima (1986) in the framework of the convection-diffusion theory of cosmic-ray transport in the heliosphere. It was also shown by Munakata et al. (1999a, 1999b) that the amplitude of anti-symmetric component is almost comparable with that of symmetric component and the contribution from the anti- symmetric component is not negligible in this rigidity region. To derive an accurate value of G_θ from the observed diurnal variation, therefore, it is important to analyze the NS symmetric variation separately from the anti-symmetric one. Figure 1d shows the first result of such analysis of data observed by muon detector network. For the NS symmetric variation, the phase of maximum intensity was found around 1700 local solar time (LST) in five years of 1978, 1979, 1980, 1982 and 1987, while the phase was found around 0500 LST in the remaining years. For the NS anti-symmetric variation, on the other hand, the phase was always found around 1700 LST in northern hemisphere. During the period from 1992 to 1995, therefore, the NS symmetric and anti-symmetric variations cancel each other in northern hemisphere, while those amplify each other in southern hemisphere. This explains the significant NS asymmetry found by Munakata *et al.* (1999a). G_θ in Figure 1d 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 HCS (Munakata *et al.*, 1999b).

DISCUSSION

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. We still have no clear idea to explain the discrepancy at present, but it 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. It is noted that such energy dependence was actually seen between modulation parameters derived from muon observations at 60 GeV and neutron monitor observations at ~10 GeV (see Figures 1 and 3).

By analyzing the sector-dependent solar diurnal variations observed by neutron monitors and muon telescopes in 1965-1993, Ahluwalia and Dorman (1997) showed that $G_\theta=0$ 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 found by Munakata *et al.* (1999a) and cannot be directly compared with our results. As described above, the NS symmetric variation in the northern hemisphere is almost canceled by the anti-symmetric variation in 1992-1995. We think that this is the reason that they concluded $G_\theta=0$ from the neutron monitor observation at Deep River in the northern hemisphere. For better understanding the energy dependence of G_θ, therefore, it is important to analyze the sector-dependent solar diurnal variation observed by neutron monitors taking account of both NS symmetric and anti-symmetric components of diurnal variation.

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