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Rigidity dependence of the intensity variations of galactic cosmic rays

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For the investigation of the interactions of galactic cosmic rays with the solar wind plasma and/or interplanetary magnetic field, it is important to know the rigidity dependence of the intensity variations of galactic cosmic rays in detail. In this paper, we have performed a regression analysis between the cosmic ray intensity variations and the relative solar wind velocity and obtained the rigidity dependence of the resultant regression coefficients. We have divided the data into two durations of active and calm by a criteria which is based on the data of neutron monitor of the lowest geomagnetic cut-off rigidity on the Earth.

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1. Introduction

To understand the mechanism of propagation of the galactic cosmic rays in the universe, detail physical process of interactions of the galactic cosmic rays with the interplanetary magnetic field have to be studied. The study on the cosmic ray propagation have been performed mainly focused on the cosmic ray intensity and its anisotropy in the heliosphere. The knowledge of this historic study of the cosmic ray propagation has been expanded its application to the region of an extra heliospheric, namely interstellar space. We know that there are several kinds of anisotropy that vary timewise and spacewise in different scale. Such variations might be observed as results of any effects on the cosmic ray propagation.

It's not obvious how such basic physical mechanisms which could control the cosmic ray propagation behave in different scale. To make this question clear, we investigated the mechanism of cosmic ray intensity variation during two specific periods, namely during so called Forbush Decrease (FDs) as "Active period" and other periods as "Calm period", and made comparison each other. Since it is difficult to dissociate the anisotropy during the FDs, we adopted the solar wind velocity and the cosmic ray intensity as suitable parameters both are less affected by the directional variation.

2. Observational sites and median rigidities

In the present analysis, the data obtained by the worldwide network of neutron monitors (NM) [4] and the data from the large area 560 m^2 tracking muon telescope of the GRAPES-3 experiment [5] located at Ooty, India were used. The 17 NM stations are listed with their corresponding median primary rigidities ($R_m = 10.0 \sim 31.6$ GV), which were calculated from the Tables provided by Yasue and co-workers [6], below in Table.1.

The GRAPES-3 muon telescope consists of 4 super-modules, each in turn having 4 modules. Each module [5] consists of a total of 232 proportional counters (PRCs) arranged in 4 layers, with alternate layers separated by 15 cm thick concrete and placed in orthogonal directions. One module has a sensitive area of 35 m^2 and has the energy threshold of 1 GeV for vertical muons by means of a total of 15 layers of concrete blocks (total thickness $\sim$550 g.cm^{-2}) above the top Layer. This configuration enable us to use the muon detector as telescope. The 9 directional components of large area tracking muon telescope in the GRAPES-3 experiment and the corresponding median primary rigidities ($R_m = 64.4 \sim 92.0$ GV) calculated by Nonaka and co-workers [7] are also listed in Table.2.

3. Selection of Forbush decrease events

In this paper, we have divided the data into two durations of Active period and Calm period. Active period is only the period of during Forbush Decrease and remaining period after excluding all possible FDs is defined as Calm period. The daily averaged rates from February 2000 to October 2006 observed by the NM stations and the GRAPES-3 muon telescope were used in this analysis. To define the Active period, the following criteria was applied for the FD selection and totally

Table 1: List of NM stations and corresponding median primary rigidities (R_{m} in GV).

NM station	R_{m} (GV)
Alma-Ata	15.8
Apatity	12.6
Athens	25.1
Beijing	25.1
Haleakala	31.6
Inuvik	12.6
Kiel	15.8
Lomnicky Stit	12.6
McMurdo	12.6
Mexico	25.1
Moscow	15.8
Novosibirsk	15.8
Potchefstroom	20.0
SouthPole	10.0
Tbilisi	20.0
Thule	12.6
Yakutsk	12.6

Table 2: List of directional components of GRAPES-3 muon telescope and corresponding median primary rigidities (R_{m} in GV).

Direction	R_{m} (GV)
NW	73.2
N	73.5
NE	92.0
W	64.4
V	66.3
E	82.9
SW	70.0
S	69.9
SE	88.7

36 FD events which are listed in Table.3 have been passed the selection filter. All the Active period used in this analysis is defined as a period of 10 days including 3 days in advance of a FD starts.

For the averaged cosmic ray intensity variation with McMurdo and Thule NM stations, if the variation shows > 3 % decrease when compared to the average counting rate of the preceding three days, we define the decrease as a FD event.

Table 3: List of date of Forbush decreases and their Date.

No.	Date of FDs	No.	Date of FDs
1	2000.02.12	19	2002.07.20
2	2000.06.09	20	2003.05.30
3	2000.07.15	21	2003.10.22
4	2000.09.18	22	2003.10.30
5	2000.11.07	23	2004.01.22
6	2000.11.27	24	2004.07.24
7	2000.03.28	25	2004.07.27
8	2001.04.09	26	2004.09.14
9	2001.04.12	27	2004.11.08
10	2001.04.29	28	2005.01.03
11	2001.08.18	29	2005.01.18
12	2001.08.28	30	2005.05.09
13	2001.09.26	31	2005.05.15
14	2001.10.12	32	2005.07.17
15	2001.10.22	33	2005.08.24
16	2001.11.06	34	2005.09.11
17	2001.11.24	35	2006.12.08
18	2001.12.31	36	2006.12.15

4. Solar wind velocity and cosmic ray intensity variation

The effects of solar wind velocity on the cosmic ray intensity must be through interactions between the interplanetary magnetic field which is frozen in the solar wind and the galactic cosmic ray particles, so we expected it depends on the rigidity of the galactic cosmic rays through the scattering mean free path or the diffusion coefficients of galactic cosmic rays. To investigate such a possible relationship, we chose solar wind velocity as a feasible parameters. Before studying solar wind velocity and cosmic ray intensity correlation, interference by unrelated periodic and transient phenomena in interplanetary space had to be identified and their contribution minimized. Periodic effects include 27 d solar rotation, annual, 11 yr solar activity, 22 yr solar magnetic cycle etc. Transient phenomena include FDs that cause irregular, short-term CR changes characterized by a sudden drop in a day and a slow recovery spread over days to weeks. Figure.1 shows the variation of the daily mean solar wind velocity (in km/s), which had already been applied the 27-day high pass filter, provided by the OMNIweb[9]. Figure.2 shows the variation of cosmic ray intensity observed by the Mowcow neutron monitor and the GRAPES-3 muon telescope.

5. Analysis

At first, we have taken a correlation between cosmic ray intensity variation and the solar wind velocity and applied regression analysis to obtain the regression coefficient which is the slope of

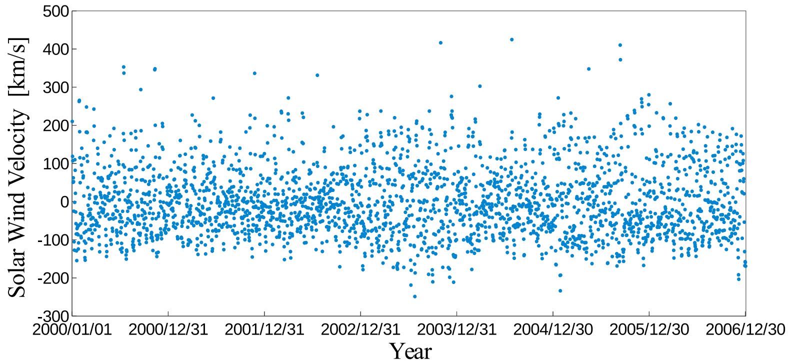

Figure 1: Daily variation in Solar Wind Velocity V_{SW} from 2000 and 2006, provided by OMNIweb.

the straight line fitted onto the scatter plot of data. The regression coefficients, C_{sw} (%/(km/s)), between the cosmic ray intensity variations and relative solar wind velocity were obtained for each station. For each station, a scatter plot was drawn using all the daily values of all the events with the cosmic ray intensity variations on the y-axis and corresponding relative solar wind velocity on the x-axis respectively. Therefore 26 regression coefficients, C_{sw}, were obtained finally. The same procedure has been applied to obtain the regression coefficients $C_{sw,\sigma}$ (%/(km/s)) for the correlation between cosmic ray intensity variation and deviation of the solar wind velocity.

We looked into the rigidity dependence of both the regression coefficients C_{sw} and $C_{sw,\sigma}$ as a interested parameters during the Active period and Calm period. C_{sw} shows a relationship between the cosmic ray intensity variation and relative solar wind velocity, $C_{sw,\sigma}$ shows a relationship between the cosmic ray intensity variation and irregularity of relative solar wind velocity.

Using these 26 regression coefficients, the rigidity dependence of them were investigated. A set of C_{sw}s was used to draw a scatter plot using the corresponding median rigidity on the x-axis and applied the further regression analysis to find rigidity dependence as shown in Figure.4. The same procedure was applied to the $C_{sw,\sigma}$ and the rigidity dependence were obtained as shown in Figure.5.

6. Summary

For the investigation of the interactions of galactic cosmic rays with the solar wind plasma, it is important to know the rigidity dependence of the intensity variations of galactic cosmic rays in detail. In this paper, we have performed a regression analysis between the cosmic ray intensity variations and the relative solar wind velocity and obtained the rigidity dependence of the resultant regression coefficients. We have investigated the rigidity dependence of regression coefficients, C_{sw} and $C_{sw,\sigma}$, during two specific periods, namely during Forbush Decrease (FDs) as "Active period" and the period after excluding all FDs as "Calm period", We used the World Wide Neutron Monitor stations for the rigidity regions from 10.0 to 31.6 GV and GRAPES-3 muon telescope from 64.4 to 92.0 GV. We obtained clear rigidity dependencies in both the Active and Calm periods even in

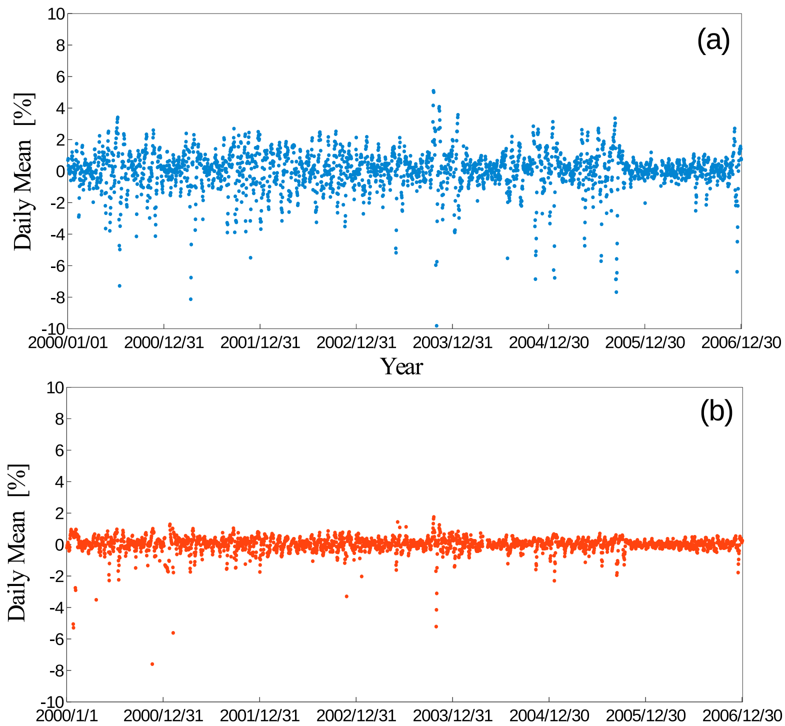

Figure 2: Daily variation in Cosmic ray intensity observed by (a) the Moscow neutron monitor and (b) the GRAPES-3 vertical component from 2000 to 2006.

the low and high rigidity regions. This results might help us to understand the mechanism of the interaction of galactic cosmic rays with the solar wind plasma.

7. Acknowledgment

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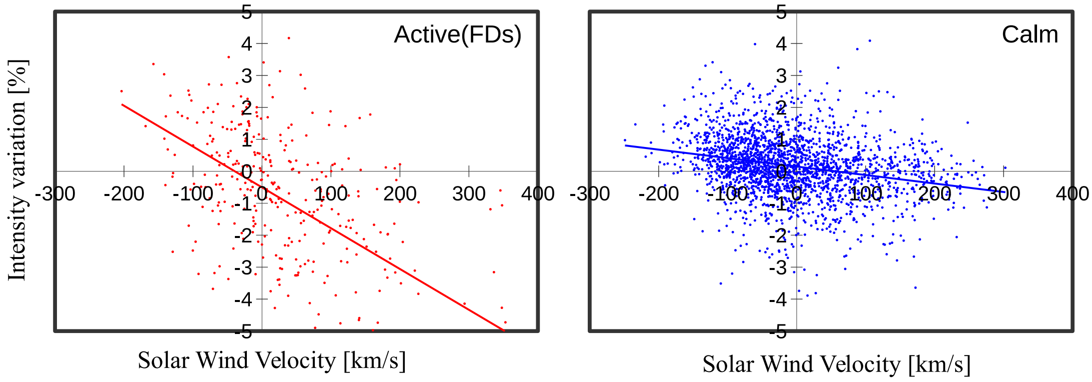

Figure 3: The relationship between cosmic ray intensity variation and the relative solar wind velocity observed by Moscow neutron monitor. The slope of the solid line in both the figures show a regression coefficient, C_{sw} in $\%/(\mathrm{km/s})$, for (a) Active period and (b) Calm period.

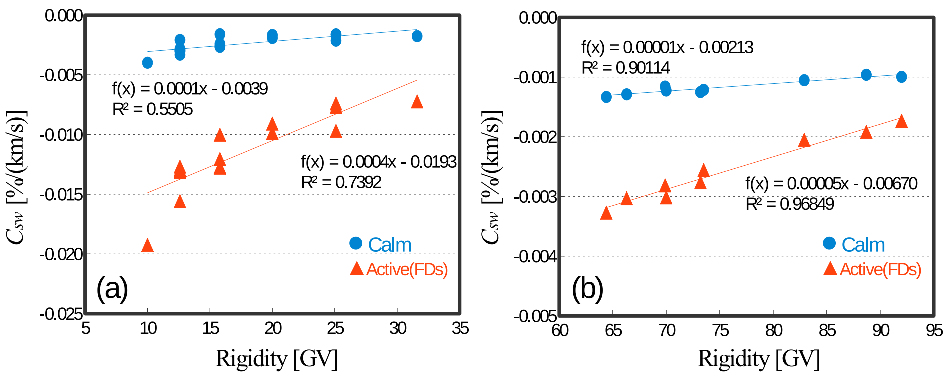

Figure 4: Rigidity dependence of the regression coefficient C_{sw} in $\%/(\mathrm{km/s})$; (a) Worldwide network of Neutron Monitors, (b) GRAPES-3 Muon telescope

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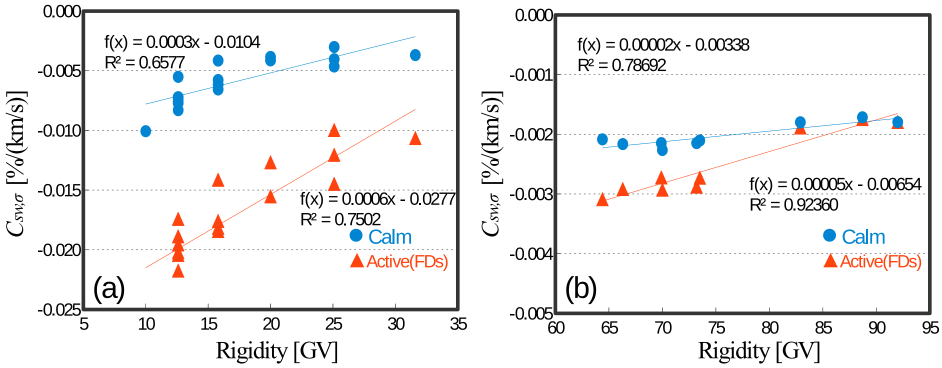

Figure 5: Rigidity dependence of the regression coefficient $C_{sw,\sigma}$ in $\%/(\mathrm{km/s})$; (a) Worldwide network of Neutron Monitors, (b) GRAPES-3 Muon telescope

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