Rigidity dependence of the solar-wind-effect on cosmic-ray intensities associated with Solar activity

H. KOJIMA[1], S. SHIBATA[2], A. OSHIMA [3], H. TAKAMARU[2], H. M. ANTIA[4], S. R. DUGAD[4], T. FUJII[5], S. K. GUPTA[4], Y. HAYASHI[5], N. ITO[5], A. IYER[4], P. JAGADEESAN[4], A. JAIN[4], S. KAWAKAMI[5], K. KURAMOTO[5], D. MATSUMIYA[5], T. MATSUYAMA [5], M. MINAMINO[5], P. K. MOHANTY [4], I. MORISHITA[6], S. D. MORRIS[4], P. K. NAYAK[4], T. NONAKA[7], S. OGIO[5], T. OKUDA[5], B. S. RAO[4], K. C. RAVINDRAN[4], K. SIVAPRASAD[4], P. SUBRAMANIAN[4], H. TANAKA[5], S. C. TONWAR[4], Y. YAMASHITA[5], K. YAMAZAKI[5]

[1]*Faculty of Engineering, Aichi Institute of Technology, Toyota, Aichi, 470-0392, Japan*
[2]*College of Engineering, Chubu University, Kasugai, Aichi, 487-8051, Japan*
[3]*National Astronomical Observatory of Japan, Mitaka, Tokyo, 181-8588, Japan*
[4]*Tata Institute of Fundamental Research, Homi Bhabha Road, Munbai, 400005, India*
[5]*Graduate School of Science, Osaka City University, Sumiyoshi, Osaka, 558-8585, Japan*
[6]*Department of Information Management, Asahi University, Hozumi, Gifu, 501-0296, Japan*
[7]*Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, 277-8582,Japan*
shibata@isc.chubu.ac.jp
DOI: 10.7529/ICRC2011/V11/0982

Abstract: We presented the Solar activity dependence of the solar-wind-effect on cosmic ray intensity variations at 30th ICRC. At that time, we showed the results obtained mainly by using the data of Kiel neutron monitor and Nagoya muon telescope. We now utilise the data of large GRAPES-3 tracking muon telescope collected during 9 years from 2000 to 2008. From the field of view of this telescope, we obtained the cosmic ray intensities corresponding to the median rigidity from 64.4 to 92.0 GV. We have investigated the rigidity dependence of the solar-wind-effect using this data together with the data of neutron monitors at Keil (17.2 GV) and at Mexico City (25.8 GV) for lower rigidity, and these are discussed in detail.

Keywords: Cosmic ray intensity variations, Solar-wind-effect, Solar activity dependence, Rigidity dependence, Solar modulation

1 Introduction

According to the diffusion-convection theory [1] [2] [3] [4], it is expected that the cosmic ray intensity varies with the solar wind velocity. If their relationship is quantitatively clarified, it will become observationally possible to obtain the diffusion coefficient for the propagation of galactic cosmic rays flown into the heliosphere from inter stellar space.

Since the beginning of direct measurements of solar wind with satellites (Oct. 1963), there have been several studies [5] [6] [7] that had pointed out the effect of solar wind on the variations of the cosmic ray intensities, so called the solar-wind-effect; *i.e.* the intensity of cosmic rays decreases as the velocity of solar wind increases. These analyses have mainly concentrated on the relationship between time variations of the cosmic ray intensities and high speed streaming of the solar wind. There have been few analyses that have clarified the quantitative relationship between the intensity variation of the cosmic rays and the velocity variation of the steady state solar wind. Especially, the rigidity dependence of the solar-wind-effect has seldom been studied.

The difficulty of the analysis is mainly due to following reason. Since the intensity of cosmic rays varies with several causes, it shows a very complicated time profile which is composed of many different variations with different time periods. For example, it contains a long term intensity variation of eleven-year period. Transient variations like Forbush decreases are also contained. There also exist the intensity variation of cosmic rays caused by the anisotropy due to the earth's rotation or revolution around the sun. In our observation, the intensity variation of the cosmic rays has been recoded as the mixture of these different phenomena.

As for the variation of the solar wind velocity, it is also known that there exist several components of the variation such as a high speed flow accompanied by a solar flare, a recurrent variation with a period of around 27 days (13.5 days) corresponding to the solar rotation, or a long term variation with a period of several years.

Thus for the both of variations of the cosmic ray intensity and the solar wind velocity, it is very difficult to separate each component of variation with different cause in a simple way. Then we are not always able to obtain an acceptable result from a simple correlation analysis between these data of the cosmic ray intensity and the solar wind velocity in an extended period.

In our previous investigations [8] [9] [10], we have successfully shown the solar-wind-effect on the intensity variations of cosmic rays by removing both the long term variations and the transient ones which might cause the problems described above, then we have obtained the clear dependence of the solar-wind-effect on the Solar activity. In this paper, we extend these analysis to examine the rigidity dependence of the solar-wind-effect and the year-to-year variation of it by using the same filtering method which will be described in the next section.

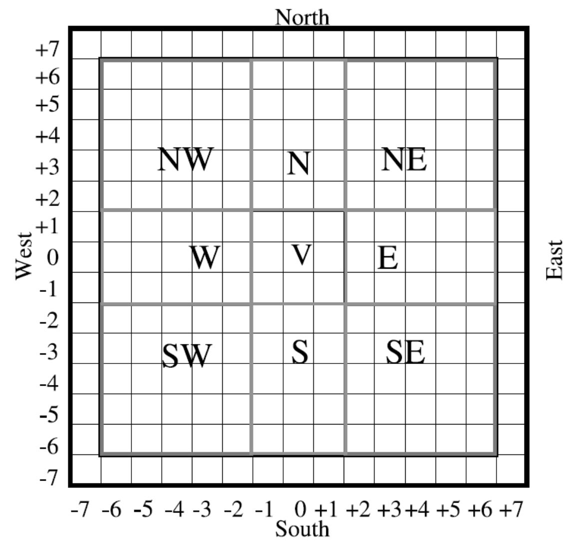

Figure 1: The field of view of the GRAPES-3 tracking muon telescope.

Component	Rigidity (GV)
NE	92.0
N	73.5
NW	73.2
E	82.9
V	66.3
W	64.4
SE	88.7
S	69.9
SW	70.9
Kiel NM	17.2
Mexico City NM	25.8

Table 1: Median rigidities of the data.

2 Analysis and Result

In order to investigate the rigidity dependence of the solar-wind-effect, the data of cosmic ray intensity observed by the GRAPES-3 tracking muon telescope with large effective area and fine angular resolution of seven degree are used. This telescope consists of 16 modules with the effective area of $35\,\mathrm{m}^2$ for each and is installed at Ooty in southern India near equator ($76°40'$ E, $11°23'$ N, $2200\,\mathrm{m}\,asl$). In 1998, we have started to observe the time variation of muon intensity with this telescope and the incident direction of each muon have been recorded since Apr., 1999. For the analysis described here, we utilise the data of this telescope measured during 9 years from 2000 to 2008. The data observed by the neutron monitors at Kiel and at Mexico City during the corresponding period are also used. Solar wind velocities we used are referred to the OMNI 2 data set.

2.1 Median rigidities of the data

The GRAPES-3 tracking muon telescope detects muons of energy above $1\,\mathrm{GeV}$. The field of view of the telescope consists of $15 \times 15 = 225$ direction bins as shown in Fig.1. For the analysis, we adopted the inner $13 \times 13 = 169$ bins as the effective field of view and reconfigured them into nine bins labeled as NE, N, NW, E, V, W, SE, S, and SW according to the incident direction of muons shown in the same figure. The median rigidity of corresponding primary proton to each bin was estimated from Monte Carlo simulations carried out using CORSIKA package. The values of median rigidities thus calculated are listed in Table1. The rigidities of neutron monitors derived from the coupling coefficients [11] are also shown in the same table.

2.2 Data processing

In this analysis, the method of data processing we adopted is similar to that reported at the 30th and 31st ICRCs [8] [9] [10]. At first, for the data of the GRAPES-3 tracking muon telescope, the number of muons collected for one hour is combined for each of nine bins. Thereafter, the hourly muon rate expressed as fractional percentage change from the average of the entire data set for the corresponding bin are obtained. Next, the hourly rate is corrected for changes in the atmospheric pressure. Then, for each bin, the data with values exceed ten times of the root mean square are rejected as abnormal. For the data of neutron monitors, the hourly counting rate is also converted to the fractional percentage change from the average of the entire data set. The same rejection criteria for abnormal as above is also applied to the data of neutron monitors.

After those processes, in order to reject some kinds of interference between several variations caused by the different origins described in the previous section, the data are treated as the following way. The duration of a transient event, such as a Forbush decrease, is estimated using the daily av-

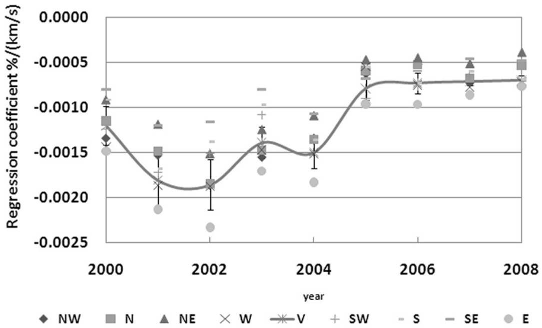

Figure 2: Year-to-year variation of the regression coefficients of cosmic-ray intensities vs solar wind velocities (for the data of the GRAPES-3 tracking muon telescope).

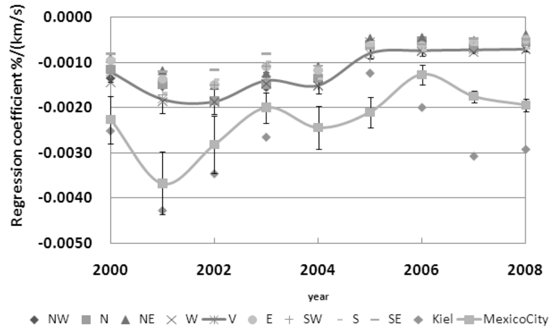

Figure 3: Year-to-year variation of the regression coefficients of cosmic-ray intensities vs solar wind velocities (for the all data).

eraged counting rate of the Kiel neutron monitor. The day with the rate less than $-4\,\%$ compared to the average of the three preceding days is presumed as a day in a transient event, and the corresponding data are rejected. For the indication of the recovery after the transient event, more than $70\,\%$ from the minimum rate is required. After this, the differences from 648-hour (27-day) running average are taken to remove the long term effects in both the data of cosmic ray intensity and the solar wind velocity. Then, daily averages of all the data are obtained from hourly counting rates processed as above.

2.3 Regression analysis

To get the year-to-year variation of the solar-wind-effect on cosmic-ray intensities, the regression analysis of the cosmic-ray intensities vs solar wind velocities is done year by year from 2000 to 2008 on daily basis. The regression coefficients obtained are around $-0.0010\,\%/(\mathrm{km/s})$ for nine bins of the GRAPES-3 tracking muon telescope and around $-0.0025\,\%/(\mathrm{km/s})$ for neutron monitors as shown in Figures 2 and 3. In Fig.2, the regression coefficients obtained only from the data of the GRAPES-3 tracking muon telescope are shown. The regression coefficients obtained form the data of neutron monitors are combined in Fig.3.

2.4 Solar activity dependence of the solar-wind-effect

Though this is a reconfirmation of our previous results [8] [9], the Solar activity dependence of the solar-wind-effect on cosmic-ray intensities can be seen from Fig.2 or Fig.3. The correlation between the regression coefficients and the Solar activity indices such as the sunspot numbers is negative, $i.e.$ the magnitudes of regression coefficients are large before 2004 (active term) and small after 2004 (quiet term), and the ratio of coefficients is about 2 (see also [9]).

2.5 Rigidity dependence of the solar-wind-effect

As noticed in the previous subsection, the magnitudes of regression coefficients derived from the data of neutron monitors are about the twice as large as those derived from the data of the GRAPES-3 tracking muon telescope. This means that there exist the rigidity dependence of the solar-wind-effect on cosmic-ray intensities. In Figures 4 and 5, the regression coefficients are re-plotted with a new abscissa of corresponding median primary rigidities given in Table1. From these figures, you can easily see the rigidity dependence. For the guide of eyes, the regression lines for the data points plotted in Fig.5 are separately drawn in Fig.6. From the figure, as far as observing the inclinations of the lines correspond to 2001, 2003, 2005, there seems to be the Solar activity dependence. However, the relation becomes not so simple when the line of 2007 is included. So,

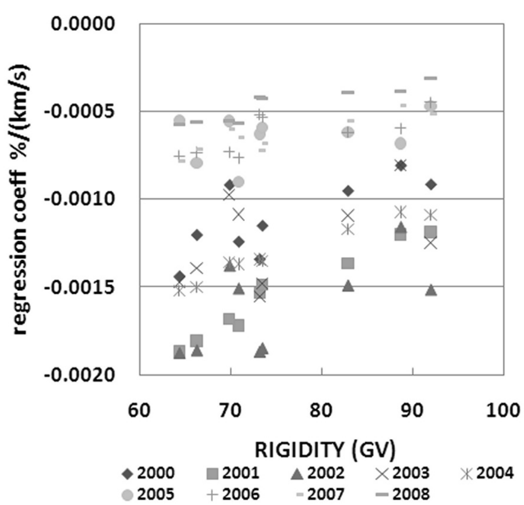

Figure 4: Rigidity dependence of the regression coefficients of cosmic-ray intensities vs solar wind velocities (for the data of the GRAPES-3 tracking muon telescope).

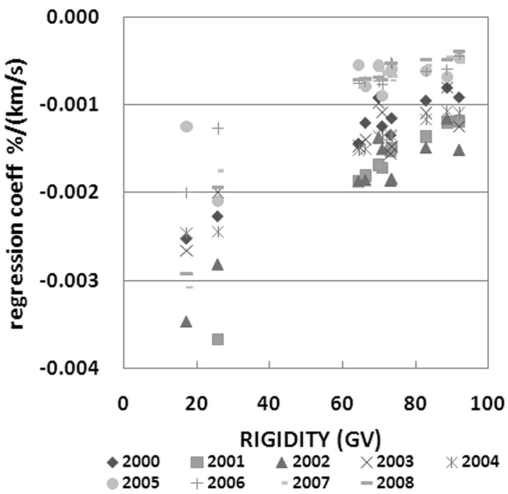

Figure 5: Rigidity dependence of the regression coefficients of cosmic-ray intensities vs solar wind velocities (for the all data).

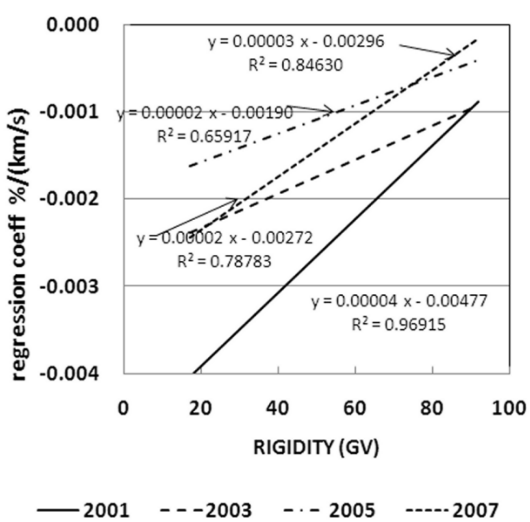

Figure 6: Regression lines of the data points for odd years shown in Fig.5 (2001, 2003, 2005, 2007).

at this time, the existence of their Solar activity dependency is inconclusive.

3 Conclusion

In this paper, the existence of the solar-wind-effect on cosmic-ray intensity variations is confirmed and the regression coefficients around $-0.0010\,\%/(\mathrm{km/s})$ are obtained using the data of GRAPES-3 tracking muon telescope observed during 9 years from 2000 to 2008. From the year-to-year regression analyses, we can deduce the Solar activity dependency of the solar-wind-effect. The correlation is negative, and the magnitudes of regression coefficients are large before 2004 (active term) and small after 2004 (quiet term).

The rigidity dependence of the solar-wind-effect are clearly observed by this analysis, but the existence of their Solar activity dependency is inconclusive at this time.

Acknowledgements

The authors express our thanks to the staff of the neutron monitor stations at Kiel and at Mexico City for providing the cosmic ray data used in this analysis. The staffs of Space Physics Data Facility (SPDF) and National Space Science Data Center (NSSDC) are also acknowledged for allowing us to use the data in OMNI 2 data set.

This work is partly supported by the grant in aid of the Solar Terrestrial Environment Laboratory of Nagoya University and the Institute for Cosmic Ray Research of University of Tokyo.

References

[1] E. N. Parker, The Passage of Energetic Particles through Interplanetary Space, Planet. Space. Sci., 13, 9, 1965

[2] E. N. Parker, The effect of adiabatic deceleration on the cosmic ray spectrum in the solar system, Planet. Space. Sci., 14, 371, 1966

[3] L. J. Gleeson and W. I. Axford, Cosmic Rays in the Interplanetary Medium, Astrophys. J., 149, L115, 1967

[4] L. J. Gleeson and W. I. Axford, Solar Modulation of Galactic Cosmic Rays, Astrophys. J., 154, 1011, 1968

[5] Y. Munakata and K. Nagashima, Correlation Analysis between Cosmic Ray Intensity Variation and Interplanetary Plasma Parameters, Proc. 16th Int. Conf. Cosmic Rays, Kyoto, 3, 530, 1979

[6] K. Fujimoto, H. Kojima and K. Murakami, Cosmic Ray Intensity Variations and Solar Wind Velocity, Proc. 18th Int. Conf. Cosmic Rays, Bangalore, 3, 267, 1983

[7] K. Fujimoto, H. Kojima and K. Murakami, The Solar Wind Effect on Cosmic Rays and the Solar Activity, Proc. 19th Int. Conf. Cosmic Rays, San Diego, 3, 262, 1985

[8] H. Kojima et al., The Change in Cosmic Rays Intensity Variation with the Solar Wind Velocity, Proc. 30th Int. Conf. Cosmic Rays, Merida, 1, 557, 2007

[9] H. Kojima et al., A Solar Wind Effect on Cosmic Ray Intensity Variations, Proc. 30th Int. Conf. Cosmic Rays, Merida, 1, 561, 2007

[10] H. Kojima et al., Three Dimensional Structure of Correlations Between Intensity Variation of Cosmic Rays and Solar Wind Velocity, Proc. 31st Int. Conf. Cosmic Rays, Lodz, #1102, 2009

[11] S. Yasue et al., Coupling Coefficients of Cosmic Ray Daily Variations for Neutron Monitor Stations, Report of Cosmic-Ray Research Laboratory, **7**, Nagoya University, 1982