

Three dimensional structure of correlations between intensity variation of cosmic rays and solar wind velocity

H. Kojima[‡], T. Fujii^{*}, Y. Hayashi^{*}, S. Kawakami^{*}, M. Minamino^{*}, H. Miyauchi^{*}, T. Nonaka^{*},
S. Ogio^{*}, T. Okuda^{*}, H. Tanaka^{*}, E. Usui^{*}, Y. Yamashita^{*}, A. Oshima[†], H. M. Antia[†],
S. R. Dugad[†], U. D. Goswami[†], S. K. Gupta[†], P. K. Mohanty[†], P. K. Nayak[†],
P. Subramanian[†], S. C. Tonwar[†], S. Shibata[§] and I. Morishita[¶]

^{*} Graduate School of Science, Osaka City University, Osaka, Japan

[†] Tata Institute of Fundamental Research, Bombay, India

[‡] Faculty of Engineering, Aichi Institute of Technology, Toyota, Japan

[§] College of Engineering, Chubu University, Kasugai, Japan

[¶] Department of Information Management, Asahi University, Hozumi, Japan

Abstract. A three dimensional structure of a solar wind effect on the intensity variation of cosmic rays has been investigated by using the regression analysis method in this paper. The solar wind effect discussed here is represented by the regression coefficients between the intensity variation of cosmic rays and the solar wind velocity. The data of cosmic ray intensity used in the analysis have been measured by the multi directional muon telescope (GRAPES3) at Ooty in southern India during the period from 2000 to 2007. The data of solar wind velocity have been referred to the ACE level 2 data set. In order to examine the three dimensional structure of the solar wind effect, we have classified the data of the cosmic ray intensity into 12 directional components.

From this analysis, we have clearly confirmed the existence of the solar wind effect on the intensity variation of cosmic rays and the regression coefficients around $-0.001\%/(km/s)$ have been obtained. By the analysis with the data divided into two periods of a solar active side (from 2000 to 2003) and a solar quiet side (from 2003 to 2007), we have found that the solar wind effect in the direction of the sun is clearly weaker (with a smaller absolute value of the regression coefficient) than those in the other directions for the data of the northern telescopes observed during the period from 2004 to 2007. On the other hand, the data observed during the period from 2000 to 2003 have shown almost constant effects. This result might reflect the alterations of the streaming of cosmic rays in the heliosphere depending on the polarity of the solar magnetic field.

Keywords: intensity variation, solar wind velocity, heliosphere

I. 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. The dependencies especially on the directions of the cosmic ray propagation have seldom been studied.

The reason is as follows. 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 recorded 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], we have successfully removed 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 activity on the solar wind effect on the intensity variation of cosmic rays. In this analysis, we have used the similar filtering method which will be described in the next section.

In order to investigate the three dimensional structure of the solar wind effect, the data of cosmic ray intensity measured by the multi directional muon telescope (GRAPES3) with large effective area and fine angular resolution of seven degree at Ooty in southern India near equator ($76^{\circ}40'$ E, $11^{\circ}23'$ N, 2200 m *asl*) have been used. The muon telescope of GRAPES3 consists of 16 modules with the effective area of 35 m^2 for each. In 1998, we have started to observe the time variation of muon intensity. The incident direction of each muon have been recorded since Apr., 1999.

II. ANALYSIS AND RESULT

In this analysis, we have used the data obtained by the one of the GRAPES3 modules which has only been recorded the incident direction of each muon in the all 8 years during the period from 2000 to 2007. The data observed by the neutron monitor at Kiel have been used as the references. Solar wind velocities and other plasma parameters of the interplanetary magnetic field in the corresponding period are referred to the ACE level 2 data set.

A. Preprocessing

In this analysis, at first, all the data have been prepared for hourly values. In order to reject some kinds of interference between several variations caused by the different origins described in the previous section, the data we used have been preprocessed as the following way. At first, differences from 27-day running average have been taken to remove the long term effects in both the data of cosmic ray intensity and the solar wind velocity. Variations of the cosmic ray intensity exceeding a lower limit of -4% or an upper limit of 3% have been rejected from the analysis as abnormal data. The duration of a transient event, such as a Forbush decrease, have been estimated using the data observed by the neutron monitor at Kiel by an indication of the decrease greater than -2% . Then, the corresponding data have been rejected.

B. Classification to the directional components

In order to examine the three dimensional structure of the solar wind effect, the data of the cosmic ray intensity preprocessed as described before have been classified into 12 directional components as follows.

By incident directions of muons, the data have been divided into 3 latitudinal directions. The original data divided into 225 directions as shown in Fig. 1 have been

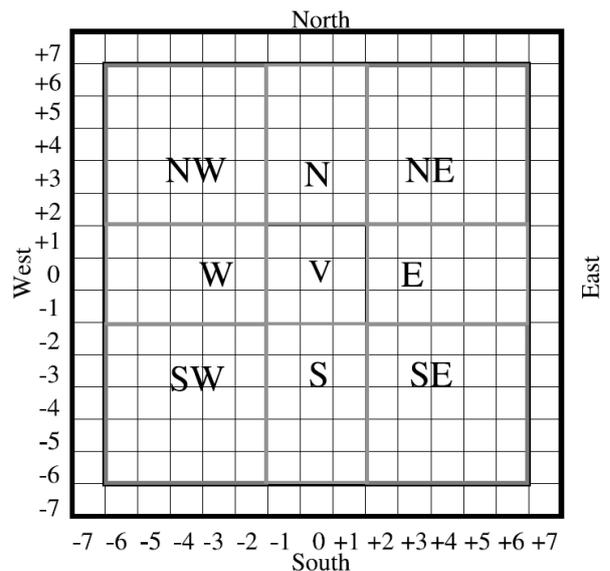


Fig. 1: Schematic diagram of the multi directional muon telescope (GRAPES3) viewed from above.

combined into 3 directions of the north (NW+N+NE), the vertical (W+V+E), and the south (SW+S+SE).

To see the directional dependencies relative to the sun, after taking the running average of three hours, the data combined as above have been classified into local time of 0 h, 6 h, 12 h, and 18 h, these are correspond to the midnight, the dawn, the noon, and the dusk of GSE, respectively.

The data of intensity variation of cosmic rays and the corresponding data of the velocity of the solar wind thus classified have been used for the regression analyses.

For the analysis of dependencies on the solar activity, the data prepared as described above have been divided into the period from 2000 to 2003 correspond to a solar active side and the period from 2003 to 2007 correspond to a solar quiet side.

C. Confirmation of the solar wind effect

From the regression analysis using the data of the whole period from 2000 to 2007, we have clearly confirmed the existence of the solar wind effect on the intensity variation of cosmic rays and the regression coefficients around $-0.001\% / (\text{km/s})$ have been obtained as shown in Fig. 2 and Fig. 3. By these results, our previous results [8] [9] concerning to the solar wind effect on the intensity variation of cosmic rays have been confirmed.

D. Activity dependence of the solar wind effect

From the regression analyses using the data from the midnight direction of GSE, we have observed a weak dependence on the solar activity. On the other hand, the data from the noon direction of GSE have shown a rather strong dependence on the solar activity as in Fig. 4 and Fig. 5.

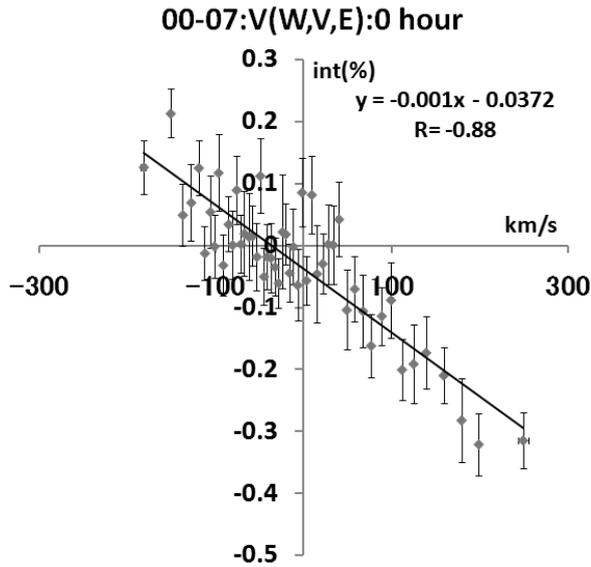


Fig. 2: Scatter diagram of the cosmic ray intensity at Vertical telescope vs. solar wind velocity (from 2000 to 2007).

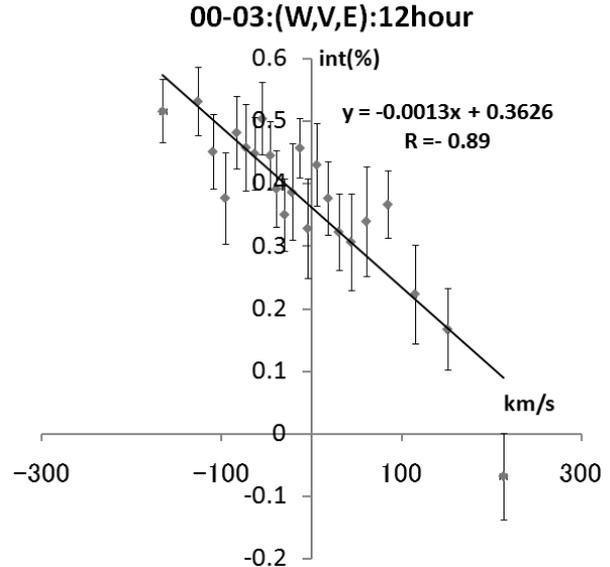


Fig. 4: Scatter diagram of the cosmic ray intensity at Vertical telescope vs. solar wind velocity (from 2000 to 2003).

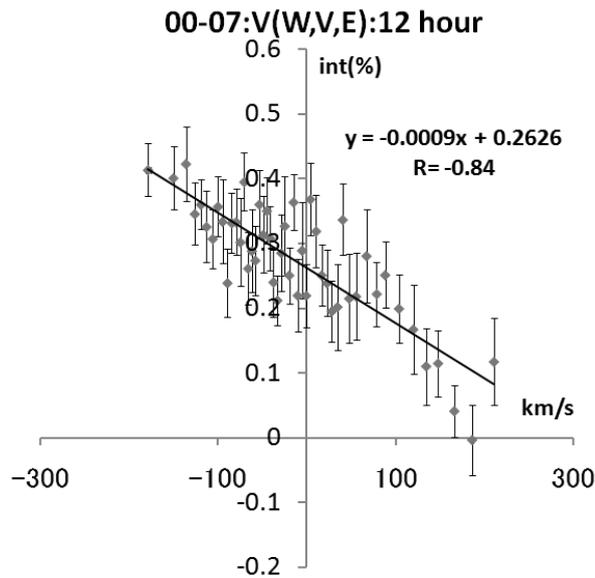


Fig. 3: Scatter diagram of the cosmic ray intensity at Vertical telescope vs. solar wind velocity (from 2000 to 2007).

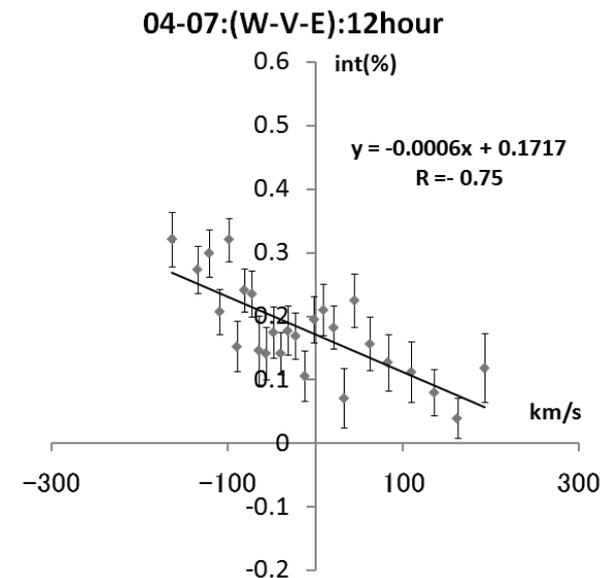


Fig. 5: Scatter diagram of the cosmic ray intensity at Vertical telescope vs. solar wind velocity (from 2004 to 2007).

E. Three dimensional structure of the solar wind effect

By comparing the regression coefficients of all categories as shown in Fig. 6, Fig. 7, and Fig. 8, we have found that the solar wind effect in the direction to the sun (the noon direction of GSE) is clearly weaker (with a smaller absolute value of the regression coefficient) than those in the other directions for the data of the northern telescopes observed during the period from 2004 to 2007. On the other hand, the data observed during the period from 2000 to 2003 have shown almost constant effects. This result might reflect the alterations of the

streaming of cosmic rays in the heliosphere depending on the polarity of the solar magnetic field.

III. CONCLUSION

In this paper, as the result of the analysis of data, we have clearly confirmed the existence of the solar wind effect on the intensity variation of cosmic rays and the regression coefficients around $-0.001\%/(km/s)$ have been obtained using the data of whole period from 2000 to 2007. By the analysis with the data divided into two periods from 2000 to 2003 (solar active) and from 2004

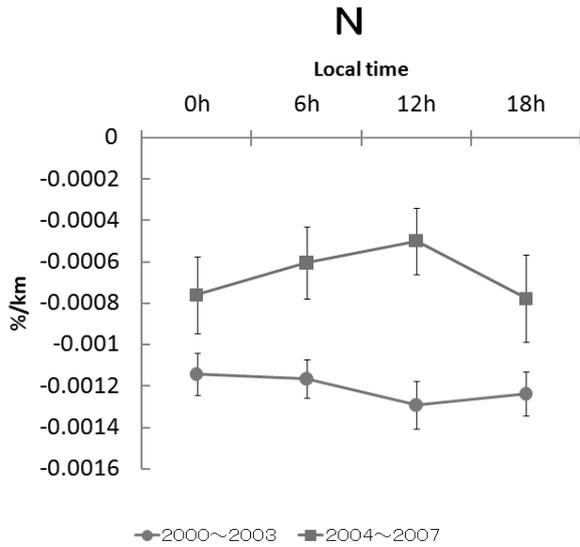


Fig. 6: Directional (local time) dependence of the regression coefficients between the cosmic ray intensity at North telescope and solar wind velocity (circle: 2000-2003 and square: 2004-2007).

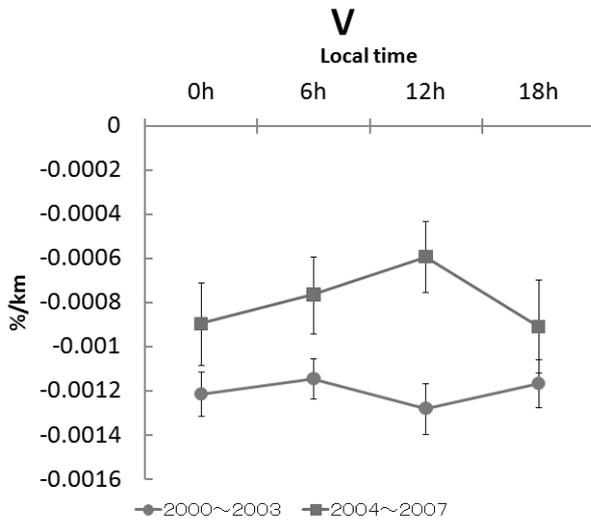


Fig. 7: Directional (local time) dependence of the regression coefficients between the cosmic ray intensity at Vertical telescope and solar wind velocity (circle: 2000-2003 and square: 2004-2007).

to 2007 (solar quiet), we have found that the solar wind effect at noon in GSE is clearly weaker than those in the other directions for the data of the northern telescopes observed during the solar quiet period. On the other hand, the data observed during the solar active period have shown almost constant solar wind effects. This result suggests the alterations of the streaming of cosmic rays in the heliosphere depending on the polarity of the solar magnetic field.

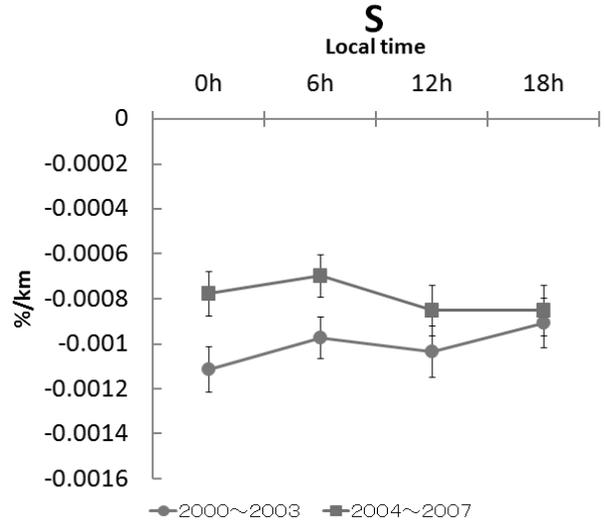


Fig. 8: Directional (local time) dependence of the regression coefficients between the cosmic ray intensity at South telescope and solar wind velocity (circle: 2000-2003 and square: 2004-2007).

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