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Dependence of cosmic ray intensity on variation of solar wind velocity measured by the GRAPES-3 experiment for space weather studies

H. Kojima
Faculty of Engineering, Aichi Institute of Technology, Toyota City, Aichi 470-0392, Japan[*]

H. M. Antia, S. R. Dugad, S. K. Gupta,[†] P. Jagadeesan, A. Jain, P. K. Mohanty, and B. S. Rao
Tata Institute of Fundamental Research, Mumbai 400 005, India[*]

Y. Hayashi, S. Kawakami, and T. Nonaka
Graduate School of Science, Osaka City University, Osaka 558-8585, Japan[*]

A. Oshima and S. Shibata
College of Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan[*]

K. Tanaka
Graduate School of Information Sciences, Hiroshima City University, Hiroshima 731-3194, Japan[*]
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The space weather impacts propagation of galactic cosmic rays (CRs) in the heliosphere as explained by the diffusion-convection mechanism which predicts that the variation in CR intensity should be anticorrelated with changes in solar wind velocity (V_{SW}). Several unrelated solar phenomena, including periodic ones such as 27 d solar rotation, annual, 11 yr solar activity, 22 yr solar magnetic cycle etc., and transient ones, for example, Forbush decreases (FDs), and ground level enhancements generally caused by solar flares or coronal mass ejections also affect CR intensity on Earth. These solar phenomena make a quantitative study of dependence of CR intensity on V_{SW} rather difficult. Here, the high statistics muon data of six years (2000–2005) from the large GRAPES-3 muon telescope have been used to study the correlation between V_{SW} and CR intensity. Data gathered during these six years were used after minimizing the contribution of various unrelated solar phenomena outlined above. We observed a strong anticorrelation between the variations in V_{SW} and CR intensity at a significance of 19σ.

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I. INTRODUCTION

The Sun produces a continuous stream of charged particles called solar wind [1] that carries the magnetic field into the heliosphere. The heliosphere comprises an interplanetary region where outward flow of solar wind impedes inflow of galactic cosmic rays (CRs) and also contains an interplanetary magnetic field (IMF) connected to the Sun. Due to high electrical conductivity of solar wind, the IMF gets frozen into it. Outflow of solar wind coupled with solar rotation forces the IMF into a spiral form and convects charged particles away from the Sun. Irregularities in the IMF influence convection of CRs through interaction with the solar wind. Resultant diffusion and convection of particles is affected by gradient and curvature drift in the IMF causing a radial density gradient of galactic CRs away from the Sun [2]. Recently GRAPES-3 had measured radial density gradient of CRs, averaged over six years (2000–2005), to be 0.65% AU^{-1} at a median rigidity of 77 GV [3].

Space weather involves the study of interplanetary medium including the solar wind, IMF, Earth's magnetosphere etc. Space weather studies aim to forecast dangerous processes in the near-Earth environment because of their influence on performance and reliability of space, and ground based technological systems [4]. Sudden changes in space weather can disrupt electrical grids, communication satellites, and endanger lives of astronauts [5]. Space weather is driven by solar wind and especially the changes occurring in V_{SW} [6]. Since IMF is frozen into solar wind, change in V_{SW} reflects the turbulence in IMF which in turn influences the diffusion of CRs into the heliosphere. Thus a study of correlation between V_{SW} and CR intensity offers an excellent probe of space weather. It affects geomagnetic field and our atmosphere through a set of complex processes. The study of intimate but poorly understood connection between space weather and its influence on Earth is the main motivation for launch of a large number of civilian satellites by various space agencies [7].

Galactic CRs incident on the atmosphere produce secondary particles. However, among secondaries, neutrons because being neutral and muons due to their large penetration reach the surface of Earth, and thus, these two

[*]GRAPES-3 Experiment, Cosmic Ray Laboratory, Raj Bhavan, Ooty 643 001, India.
[†]gupta@grapes.tifr.res.in

secondary components of CRs may be studied by ground based detectors. Any phenomenon occurring in interplanetary space that influences the flux of galactic CRs would also affect intensity of neutrons and muons on the ground. The radial density gradient of CRs reflects the mean value of V_{SW}. Solar wind is known to display rapid changes in its velocity V_{SW} and a measurement of variation in muon intensity in response to changes in V_{SW} offers a powerful handle to probe the space weather, wherein muons act as a proxy for galactic CRs.

The V_{SW}-CR correlation has been long studied, especially during the active phase of the Sun. In an early work neutron data showed fast streams originating in coronal holes caused reduced CR intensity [8]. Anticorrelation between V_{SW} and CRs was shown from neutron data of 1965–1975 [9]. Using muon and neutron data for 1973–1978 short-term changes were shown correlated with high speed streams from active solar regions [10]. For the first time, using a 27 d high-pass filter, an anticorrelation was observed in neutron data (1965–1975) during solar maximum [11]. Similar anticorrelation between CR intensity and coronal mass ejections (CMEs) was also shown by other groups [12].

However, earlier correlation studies of V_{SW} and CR intensity, some of them summarized above, focused on contribution of active regions or specific events such as flares and CMEs that could have easily resulted in correlated changes between V_{SW} and CRs. However, in the present paper this correlation has been studied during low solar activity by eliminating data influenced by Forbush decreases (FDs), ground level enhancements (GLEs) and by various periodic phenomena. The objective being that if the contribution of change in V_{SW} on CR intensity could be shown under quiescent solar conditions, then a key space weather phenomenon would be established at a more fundamental level. Data from the GRAPES-3 experiment with the large (560 m^2) muon telescope [13] that allowed tiny changes in muon flux to be measured were used in this study.

II. GRAPES-3 EXPERIMENT

GRAPES-3 is located at Ooty (11.4 °N, 76.7 °E, 2.2 km altitude) in India. It comprises two major detector components, first a dense air shower array with 8 m distance between adjacent scintillation detectors (1 m^2) [13–15]. The present array operating with ~400 detectors was designed to measure the energy of primary CRs from 10 TeV to 100 PeV [16]. The second component is a large (560 m^2) muon telescope to measure muon content of CR showers [13] to determine their composition and energy spectrum [17]. It is also used to measure CR variation due to solar activity [18,19]. It contains 16 modules (each 35 m^2) consisting of proportional counters (PRCs) of size 600 cm × 10 cm × 10 cm. A module contains 232 PRCs arranged in four layers of 58 PRCs each, with alternate layers arranged in mutually orthogonal directions as shown in Fig. 1. Successive PRC layers were separated by 15 cm concrete shown as the shaded region in Fig. 1. The direction of each muon can be reconstructed with $\lesssim 6°$ accuracy in two orthogonal planes.

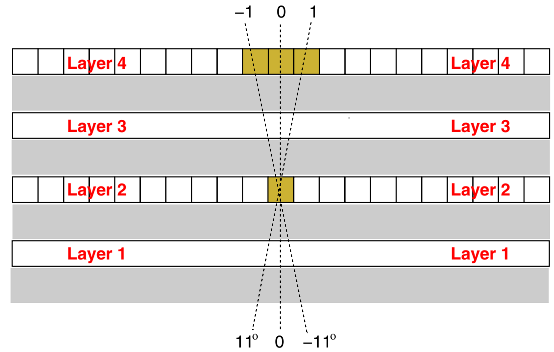

FIG. 1 (color online). Schematic view of muon direction based on triggered PRCs, one in the lower and the second from three PRCs in the upper layer.

The thickness of the concrete absorber above Layer 1 shown in Fig. 1, was ~550 g cm^{-2} resulting in an energy threshold of 1 GeV for vertical muons that varies as $\sec\theta$ GeV for muons arriving at an angle θ. The muon direction is measured for a triggered PRC in the lower layer, and then binned in three directions based on triggered PRC in the upper layer from three PRCs, one above, and one on either side of the PRC in the lower layer as shown in Fig. 1. This generated a $3 \times 3 = 9$ map of muons in two projection planes that were combined to form the vertical (V) direction. The number of incident muons were recorded once every 10 s.

III. REMOVAL OF TRANSIENT AND PERIODIC EFFECTS

Muon data of six years from 1 January 2000 to 31 December 2005 were used here. The muons correspond to primary CRs of a median rigidity ~66 GV, estimated using the IGRF-11 model of the geomagnetic field [20] and CORSIKA Monte Carlo simulations [21]. A total of 7×10^{12} muons were used in this analysis. Cuts were designed to remove data affected by instrument problems. After dead-time correction, a two step cut was used to identify and remove gaps in data, because gaps could distort real dependence of CR intensity on V_{SW}. The root mean square (rms) deviation σ_1 was calculated and hourly data with deviation $\geq 10\sigma_1$ were rejected as abnormal. This cut was repeated after recalculating mean and σ_2 and data with deviation $\geq 5\sigma_2$ were rejected. This eliminated poor quality data segments including gaps, gain variation, instrument failures etc. Hourly muon rates were converted into fractional change (%) from the six-year mean after correcting for atmospheric pressure variation [22]. In 2000 only four modules were operating, but from 2001 all 16 began operation. Thus, our results are based on data from four modules in 2000 and 16 modules thereafter.

Before studying solar wind–CR 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. Due to its lower cutoff rigidity, the Kiel neutron monitor records large amplitude even for small magnitude events, and was thus used to identify transient events [23]. The impact of these two classes of phenomena were minimized by cuts described below [24].

The 24 h intensities in each day were combined to obtain daily values for 2192 d in six years. Hourly data on neutrons from Kiel [23] for 2185 d, and V_{SW} from NASA site [25] for full 2192 d were available. Days that did not contain muon data for all 24 h were rejected as incomplete and only 2117 d survived. Muon intensity $\Delta I_\mu(\%)$ relative to the six-year mean is shown in Fig. 2(a). The data display a variation of $\pm 2\%$ from mean for $\sim 1.5 \times 10^{12}$ muons. Similarly daily mean V_{SW} is shown in Fig. 2(b).

To minimize the contribution of periodic variations (27 d, annual, 11 yr, and 22 yr) an indirect high-pass filter was used. A running mean $H(\text{low})_i$ of hourly rates h_i was calculated for each day from 13×24 h on either side of a given hour for muon and V_{SW}, respectively. The running mean provides low-pass filter $H(\text{low})_i$ of hourly rates. Low-pass filter outputs $H(\text{low})_i$ for muons, and V_{SW} are shown as continuous lines in Figs. 2(a) and 2(b), respectively. In both cases low-pass outputs closely follow the actual profile, indicating accurate reproduction of observed slow variation in data. Thereafter, running mean $H(\text{low})_i$ was subtracted from corresponding hourly rates h_i to extract hourly high-pass output $H(\text{high})_i$. Hourly high-pass outputs were combined to generate the daily mean shown in Fig. 3. Remaining periodic effects such as solar diurnal and sidereal variations got suppressed due to use of daily rates.

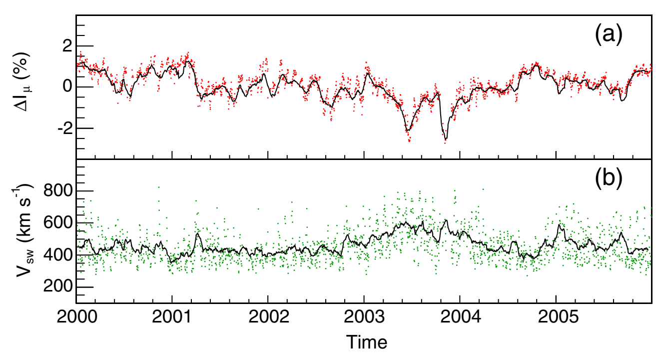

FIG. 2 (color online). Daily variation in (a) muon intensity ΔI_μ (%), (b) solar wind velocity V_{SW} [25]; relative to respective 6 yr mean.

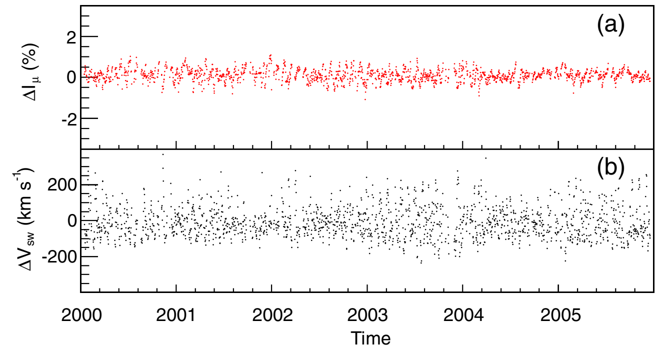

FIG. 3 (color online). Daily variation after high pass filter, (a) muon intensity ΔI_μ (%), (b) solar wind velocity V_{SW} [25]; relative to respective 6 yr mean.

The effect of transient phenomena such as FDs and GLEs that cause irregular, short-term variations were identified as follows. Due to a lower cutoff rigidity, Kiel data recorded a large amplitude for transients of relatively small magnitude and were used to identify such events. If on day "i" intensity was I_i, mean neutron intensity $I3d_i$ for the previous three days was calculated. A decrease in intensity was $M_i = (I3d_i\text{-}I_i)$ for day i. If $M_i \geq 2$ % then data for day i were rejected as influenced by an FD. Data for the following days $(i+1), (i+2), \ldots, (i+n)$ were rejected as they were assumed to lie in the FD recovery phase, where n corresponded to the day when, $I_{i+n} \leq 0.3I_i + 0.7I3d_i$, i.e. recovery was 70% complete. The same cut for an increase in intensity was used to remove GLEs. After the above cuts data for muons and V_{SW} were examined and only days when data on all three observables, muons, neutrons, V_{SW} were present were included in further analysis. Only 1763 d passed this cut. Variations in muon intensity and ΔV_{SW} are shown in Figs. 3(a) and 3(b), respectively. Muons display a flat profile due to effective removal of periodic and transient effects. Similar featureless behavior is seen in V_{SW} from Fig. 3(b) that highlights the success of this analysis approach.

IV. SOLAR WIND–COSMIC RAY INTENSITY CORRELATION

After applying cuts described in Sec. III to minimize the contribution of unrelated transient and periodic effects, the GRAPES-3 data were analyzed to investigate the correlation of CR intensity with variation of V_{SW}. A scatter plot for 1763 d shown in Fig. 4 displays the variation of muon intensity (ΔI_μ) relative to ΔV_{SW}, by using data from Figs. 3(a) and 3(b). A linear fit to this data shown as a dashed line highlights the anticorrelation between ΔV_{SW} and ΔI_μ. A similar value of anticorrelation was reported earlier from a less rigorous analysis of the data, where its dependence on muon direction and epoch of observation were emphasized [24].

To obtain a quantitative estimate of this anticorrelation, data for 1763 d shown in Fig. 4 were combined into 41 bins,

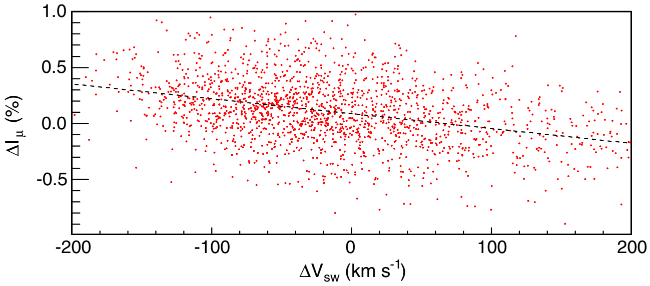

FIG. 4 (color online). Correlation of muon intensity variation ΔI_μ (%) and solar wind velocity V_{SW}.

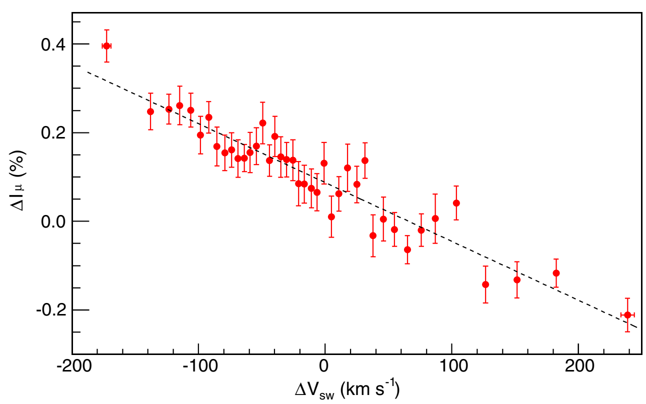

FIG. 5 (color online). Muon intensity variation ΔI_μ (%) correlated with solar wind velocity V_{SW} after binning into 41 intervals.

each containing data of 43 d sorted in order of ascending V_{SW}. The resultant plot for ΔI_μ and ΔV_{SW} is shown in Fig. 5. The error bar on each point represents rms spread of corresponding parameter. Since rms spread in ΔV_{SW} is tiny, corresponding horizontal error bars are invisible except for two extreme data points. A linear fit to data yielded a slope of $(-1.33 \pm 0.07) \times 10^{-5}\%/\ (\mathrm{km\,s^{-1}})$ with a significance of 19σ for a median rigidity of 66 GV. This analysis based on novel use of high-pass filter has demonstrated anticorrelation between variation in V_{SW} and CR intensity measured using muons over a long interval of six years.

V. SUMMARY

A key space weather phenomenon that the variation in galactic CR intensity in heliosphere is anticorrelated with solar wind velocity has been investigated using GRAPES-3 muon data. Historically, interference of two classes of solar phenomena, namely, periodic (27 d, annual, 11 yr, 22 yr), and transient (FD and GLE) events had made unambiguous establishment of the above phenomenon under quiescent solar conditions extremely difficult. The contribution of periodic phenomena was largely eliminated by employing an efficient high-pass filter and that of transient events by eliminating affected days by exploiting higher sensitivity of the Kiel neutron monitor. A clear anticorrelation between ΔI_μ and ΔV_{SW} has been established using GRAPES-3 muon data at a rigidity of 66 GV with a slope of $(-1.33 \pm 0.07) \times 10^{-5}\%/\ (\mathrm{km\,s^{-1}})$ at a significance of 19σ. The high sensitivity of GRAPES-3 has allowed this important space weather phenomenon to be established.

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