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# Multi-parametric Effect of Solar Activity on Cosmic Rays

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**Abstract.** The long-term modulation of cosmic ray intensity (CRI) by different solar activity (SA) parameters and an inverse correlation between individual SA parameter and CRI is well known. Earlier, it has been suggested that the concept of multi-parametric modulation of CRI may play an important role in the study of long-term modulation of CRI. In the present study, we have tried to investigate the combined effect of a set of two SA parameters in the long-term modulation of CRI. For this purpose, we have used a new statistical technique called "Running multiple correlation method", based on the "Running cross correlation method". The running multiple correlation functions among different sets of two SA parameters (e.g., sunspot numbers and solar flux, sunspot numbers and coronal index, sunspot numbers and grouped solar flares, etc.) and CRI have been correlated separately. It is found that the strength of multiple correlation (among two SA parameters and CRI) and cross correlation (between individual SA parameter and CRI) is almost similar throughout the period of investigation (1955–2005). It is also found that the multiple correlations among various SA parameters and CRI is stronger during ascending and descending phases of the solar cycles and it becomes weaker during maxima and minima of the solar cycles, which is in accordance with the linear relationship between SA parameters and CRI. The values of multiple correlation functions among different sets of SA parameters and CRI fall well within the 95% confidence interval. In the view of odd–even hypothesis of solar cycles, the strange behaviour of present cycle 23 (odd cycle), as this is characterized by many peculiarities with double peaks and many quiet periods (Gnevyshev gaps) interrupted the solar activity (for example April 2001, October–November 2003 and January 2005), leads us to speculate that the solar cycle 24 (even cycle) might be of exceptional nature.

*Key words.* Sun—solar parameters—cosmic ray modulation—running multiple correlation method.

## 1. Introduction

The history of cosmic ray (CR) modulation studies is as long as the history of regular CR observations. Initially, these studies were strictly tied to ground-based neutron monitors. Even now in the epoch of Voyager and Ulysses satellite missions, when successful CR experiments have been performed into the distant heliosphere, the neutron monitor is still the best detector to investigate CR modulation. Long-term modulation of cosmic rays can be studied by using the monthly data (averages) of global network of neutron monitor stations having different geomagnetic cut-off rigidities. Neutron monitors are most sensitive to cosmic rays in the energy range 0.5–20 GeV, which coincides with the maximum energy response and effective solar modulation. It has been known for a long time that the intensity as well as the energy spectrum of galactic cosmic rays is modulated by solar activity (SA). The details of the CR modulation and variation of time-lag factor are still a matter of great interest. Among various solar activity parameters, the sunspot number (SSN) has been considered as a primary indicator to define the level of solar activity, which in general follows an 11-year periodicity. Therefore, the sunspot numbers are used as a representative solar index for the study of cosmic ray modulation and solar-terrestrial relationship (Dorman & Dorman 1967; Pomerantz & Duggal 1971; Rao 1972; Webber & Lockwood 1988; Ahluwalia 1998). Later on, in addition to SSN, a variety of solar indices (solar flares, solar flux, coronal index, etc.) have been used as a proxy index to represent the solar activity (Kane 2005; Gupta *et al.* 2005, 2006).

Galactic cosmic rays in the energy range from several hundreds MeV to tens of GeV are subjected to heliospheric modulation, under the influence of solar output and its variation. The heliospheric modulation of cosmic ray intensity and spectrum are associated with 11-year solar activity cycle. The charge/polarity dependence of drift mechanism is clearly observed in cosmic ray modulation in terms of 22-year solar magnetic cycle, showing different shapes of cosmic ray maxima in the alternate solar cycles. Long-term cosmic ray modulation in the high-energy range is studied using the monthly mean data of global network of cosmic ray neutron monitoring stations having different geomagnetic cut-off rigidities. Neutron monitors are most sensitive to cosmic rays in the energy range 0.5–20 GeV, which coincides with maximum energy response for effective solar modulation. Though, the anti-correlation between solar activity and flux of galactic cosmic rays reaching the earth is a well established fact, the degree of anti-correlation is found to vary during the different phases of solar cycles (Dorman & Dorman 1967; Pomerantz & Duggal 1971; Rao 1972; Nagashima & Morishita 1979; Mavoromichalaki & Petropoulos 1984; Webber & Lockwood 1988; Nymmik & Suslov 1995; Storini *et al.* 1995; Ahluwalia & Wilson 1996; Dorman *et al.* 2001; Usoskin *et al.* 2002).

In fact, it is unreasonable to expect a single index of solar activity or some heliospheric parameter to affect the cosmic ray variation. The observed CR variations are integrated phenomena by their nature and it is expected that many factors will have an influence in the modulation process of cosmic rays. Hence, a more realistic model of long-term modulation should combine several solar-heliospheric indices (Belov 2000). In the present study, considering the above idea, we have tried to investigate the effect of a set of solar-heliospheric parameters in the modulation of cosmic rays. For such a study, we have performed a detailed correlative analysis between CRI and a different set of SA parameters, using "Running multiple correlation method". The results obtained by this method have also been compared with the results of correlative analysis between CRI and individual SA parameters.

## 2. Data and method of analysis

In the earlier studies of cosmic ray modulation a variety of solar-heliospheric parameters have been used to study the linear relationship between CRI and these parameters. In general, sunspot numbers (SSN), solar flux (SF), coronal index (CI), solar flare index (SFI), grouped solar flares (GSF), tilt angle of heliospheric neutral current sheet (TA), etc., have been used (Gupta *et al.* 2006). The results of different SA parameters have also been compared (Mishra *et al.* 2006).

In the present study, we have used the monthly mean values of SSN, SF, CI, GSF and TA as solar-heliospheric parameters for the cycles 19–23. The CRI data has been taken from the mid latitude neutron monitor station located at Kiel. To observe the effect of multiple parameters on CR modulation, we have used a new statistical technique called "Running multiple correlation method" based on the method of running cross correlation (Usoskin *et al.* 1998; Mishra & Tiwari 2003). In the said method, we have calculated the multiple correlation coefficients between different sets of SA parameters and CRI by the following formula

$$R = \surd[(r_{yx_1})^2 + (r_{yx_2})^2 - 2r_{yx_1}r_{yx_2}r_{x_1x_2}]/\surd[1 - (r_{x_1x_2})^2],$$

where $r_{yx_1}$ is the cross correlation coefficient between dependent variable $y$ and independent variable $x_1$, $r_{yx_2}$ is the correlation coefficient between $y$ and independent variable $x_2$, and $r_{x_1x_2}$ is the correlation coefficient between independent variables $x_1$ and $x_2$. Here, the different SA parameters have been assumed as independent variables and CRI as dependent variable. Firstly, $r_{yx_1}$, $r_{yx_2}$ and $r_{x_1x_2}$ have been calculated by the running cross correlation method for every month and then the multiple correlation coefficients have been calculated by putting these values into the formula. As such, the value of $R$ has been obtained for each month of 1955–2004.

## 3. Results and discussion

For the present study, we have chosen the CRI data observed at Kiel ($R_c \sim 3\,\text{Gv}$), a middle latitude neutron monitor station. The overall anti-correlation between CRI and different SA parameters is well known, however the magnitude (strength) of correlation varies with time (Gupta *et al.* 2006). To observe these variations and to see the effect of multiple parameters in the modulation of CRI, the running multiple correlation function between CRI and different sets of independent SA parameters (CRI-SSN-SF, CRI-SSN-GSF, CRI-SSN-TA, CRI-SF-CI & CRI-CI-GSF) is illustrated in Fig. 1.

This type of analysis is useful to explain the momentary behaviour of multiple correlation coefficient with respect to time. Unlike the cross correlation coefficient $r$, which gives an estimate of both the strength and direction of the association, multiple correlation coefficient $R$, tells only the strength of the association. It is observed from Fig. 1 that the strength of multiple correlation is different for the different phases of particular solar cycle and it varies with time. It is seen that the general behaviour of multiple correlation coefficient for different sets of SA parameters is similar except for cycle 23, which confirms the peculiar behaviour of cycle 23 in relation to previous cycles. Moreover solar cycle 21 also looks peculiar in terms of correlation coefficient among different sets of solar parameters and CRI, which is unexpected and needs further investigation in this direction. It is also evident that the strength of correlation is stronger during ascending and descending phases of solar cycle and it becomes

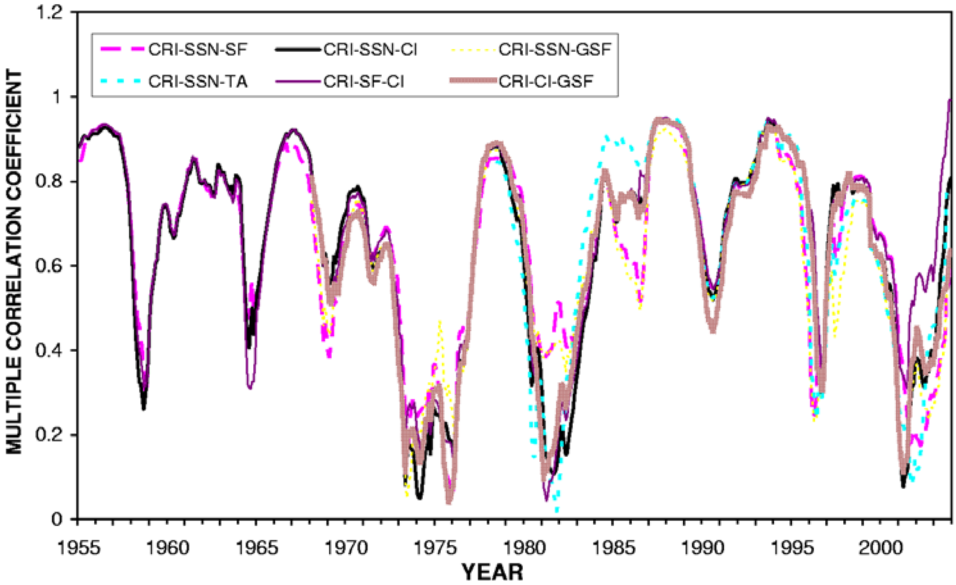


**Figure 1.** Shows multiple correlation coefficient between CRI and different sets of solar activity parameters during the period 1955–2004.

weaker during maxima and minima of solar cycle, which is in accordance with the results obtained by the running cross correlation method (Gupta *et al.* 2006). Since the variation in sunspot activity which determines the behaviour of a particular cycle depends on solar dynamo process, hence the peculiar behaviour of cycle 23 gives an idea to speculate the behaviour of solar cycle 24. Many authors have speculated the behaviour of solar cycle 24 in contradiction with each other. On the one hand, a group of scientists have speculated it to be exceptionally low (Choudhuri *et al.* 2007) and on the other hand, scientist have urged it to be of high activity (Dikpati *et al.* 2006).

Further, we have compared the results of linear relationship of CRI and SSN (obtained by the running cross correlation method) with the results obtained by the multiple correlation analysis (Fig. 2).

It is obvious from Fig. 2 that there is no significant difference in the results of these two types of analysis throughout the entire period of investigation. The values of multiple correlation coefficients among various sets of SA parameters and CRI falls well within the 95% confidence interval.

The understanding of the solar modulation of galactic cosmic rays is still based on the standard model of diffusion, convection and adiabatic deceleration effect, where the path of individual particles through the heliosphere is determined by the interplanetary magnetic field lines including drift processes. This leads to characteristic differences between adjacent solar cycles due to the different polarity of the solar and large-scale interplanetary magnetic fields. The polarity of the solar magnetic field reverses sign once every 11-year near the time of maximum solar activity. Thus successive activity maxima are characterized by different solar field polarity. However, for a better understanding of odd–even cycle's differences, the influence of curvature of interplanetary magnetic field on the transport of cosmic ray should also be considered.

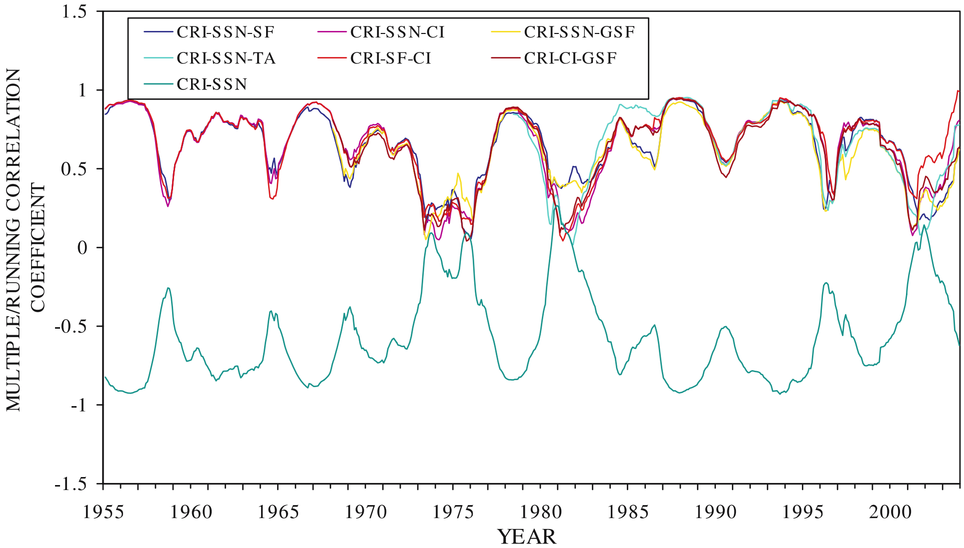


**Figure 2.** Multiple correlation coefficient between CRI and different sets of solar activity parameters (upper panel) and running cross correlation coefficient between CRI and SSN (lower panel).

## 4. Conclusions

Based on the observational results presented above, the following conclusions are drawn:

- The strength of multiple correlation is different for the different phases of the solar cycle.
- The strength of multiple correlation is stronger ($\sim$ 0.8–0.9) for the ascending and descending phases of solar cycle and it becomes weaker ($\sim$ 0.2) during the maxima and minima, which is in accordance with the results obtained by the running cross correlation method, where it is found to be $\sim$ 0.8–0.9 and $\sim$ 0.1–0.2 for both the cases respectively (Gupta *et al.* 2006).
- The overall behaviour of multiple correlation function for different sets of SA parameters is almost similar throughout the period of investigation, except for solar cycle 23 (1996–2005).
- No significant difference in the results of running cross correlation analysis and multiple correlation analysis has been observed, however, some more sets of parameters (interplanetary and heliospheric) such as solar wind velocity, plasma temperature, coronal holes area, etc., are required to generalize these results.
- In the view of even–odd hypothesis, the strange behaviour of cycle 23 (odd cycle) lead us to speculate that solar cycle 24 might be of an exceptional nature as mentioned above.

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