Long-term association of solar activity and cosmic ray intensity for solar cycles 21 and 22

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Received 13 May 2002; revised 26 August 2002; accepted 22 November 2002

Based on the monthly data of solar flare index (SFI), instead of sunspot numbers and cosmic ray intensity (CRI) for the last two solar cycles since 1976, a detailed correlativé study has been made by using the “running cross-correlation” method. It has been found that the anti-correlation between SFI and CRI is strong during ascending and descending phases of the solar cycle. The observed cosmic ray modulation during these periods, when compared with other solar activity indices, shows the appropriateness of the SFI as solar activity index, instead of sunspot numbers or even the grouped solar flares (GSF). The effects are found to be distinctly different in the two solar cycles 21 and 22, when the most appropriate solar activity index SFI is used. The observed depth of cosmic ray modulation in cycle 22 is larger than that in cycle 21 in contrast to reverse tendency in SFI which necessitates further studies on short-term basis.

1 Introduction

Galactic cosmic rays in the energy range from several hundred MeV to tens of GeV are subjected to heliospheric modulation because of solar outputs and its variation that affects their intensity and spectrum during 11-year solar activity cycle. Since the drift modulation processes are charge/polarity dependent, the 22-year solar magnetic cycle is visible in cosmic ray data in the form of different shapes of the maxima of galactic cosmic ray intensity in alternate solar cycles. Long-term cosmic ray modulation can be studied by using the monthly data (averages) of global network of cosmic ray stations (neutron monitors) 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. Earlier results had indicated that the time-lag exists in the anti-correlation between the long-term variation of solar activity and its effect on cosmic rays, and this time-lag may be different in different phases of the solar cycle\(^{16}\). Recently, a new statistical technique, namely, “running cross-correlation” has been used to study the correlation between sunspot number (SSN) and CRI during different phases of the solar activity cycle\(^{7}\). In the present paper, an attempt has been made to study the correlation between CRI and the solar activity (represented by SSN, GSF and SFI) by employing this new statistical technique for the period 1976 -1996 (solar cycles 21 and 22).

2 Data and method of analysis

The variation of cosmic ray intensity is mainly due to the outward convection of solar outputs, which are usually associated with sunspots. However, sunspots are the solar surface features and are not directly connected in any manner with the continuously variable interplanetary medium parameters. On the contrary, the solar flares ejected do have propagational characteristics over long distances in the interplanetary medium and, hence, indices associated with solar flares are expected to be better index for the studies of solar modulation of cosmic rays. The grouped solar flares are routinely generated without giving any weightage to the importance and duration of the solar flares\(^{8}\), whereas the calculation of the solar flare index (SFI) takes care of these two factors\(^{9}\). The SFI was first introduced in 1952 by including \(Q = i.t\), to quantify the daily flare activity over 24 h per day. Here \(i\) represents the intensity scale and \(t\) the duration (in minutes) of the flare. It is expected that this relationship gives (roughly) the total energy emitted by the flares.

For the present study, we have used the monthly mean intensity from the (i) high latitude station Oulu, (ii) two middle latitude stations Climax and Rome and (iii) two low latitude stations Huancayo and Tokyo. For the correlation analysis, earlier investigators have, generally, used the sunspot number as an index of solar activity\(^{7}\) which is available for a long period of time. For the present study, the CRI data have been normalized to the observed counting rates of May
1965 (as 100%) for all the stations. Moreover, all the three solar indices (SSN, GSF and SFI) mentioned earlier have been used for the correlative studies. The method described by Usoskin et al.2 has been used to calculate the ‘running cross-correlation’ between CRI and SFI. For this purpose, a time window of width T centered at time \(t\): \([t-T/2, t+T/2]\) has been used. The cross-correlation coefficient \(C(t)\) is calculated within this window. Then the window is shifted in time by a small time step \(\Delta t<T\), and the new value of cross-correlation is calculated. Here, we have used the time shifting of one month to calculate the correlation coefficient for each month between CRI and SFI. The width of time window, \(T\), has been chosen to be 50 months. This value was found to match two contradictory requirements, i.e. (i) uncertainties of the calculated \(C(t)\) are smaller for large \(T\) and (ii) \(T\) should be small in order to reveal the fine temporal structure of the cross-correlation function. However, no time shift between the two data series has been used while calculating the correlation coefficient.

3 Results and discussion

In the earlier study7, eventhough the correlative analysis has been performed for a much longer period, but that was done by using the SSN and the CRI data of only one station, i.e. Climax. In the present study, the most appropriate SFI has been chosen, which is available from 1976 to 1996. Moreover, to check the long-term reliability of the CRI data we have used the monthly average intensity of Oulu, Climax, Rome, Huancayo and Tokyo neutron monitors. In fact, the data of three pairs of stations have been compared on the basis of their similar cut-off rigidities and a high degree of correlation has been found even for the pair of low latitude stations (Huancayo and Tokyo) as shown in Fig. 1. Therefore, for further analysis we have used the data for only two stations Climax (R=3GV) and Huancayo (R=13GV), which, respectively, represent middle and low latitude stations. The choice of an appropriate solar activity index has been made by comparing the variation of SSN with (i) GSF and (ii) SFI for solar cycles 21 and 22. Figures 2 and 3, respectively, represent the two cross-plots, which show distinctly different behaviour for the solar cycles 21 and 22. It means that when solar activity indices are used, the solar cycles 21 and 22 behave differently. Such a distinction is apparent for both the cases of SFI and GSF. However, GSF index is obtained by just adding numerically all the solar flares, irrespective of their duration and importance, whereas these are considered in generating SFI.

As such, the long-term variations of SFI with CRI for the Climax and Huancayo neutron monitors are shown in Fig. 4 for the period 1976-1996. The general inverse relationship of SFI with CRI is clearly apparent from Fig. 4. Moreover, qualitatively the level of anti-correlation is also seen to be changed with time. To quantitatively observe the changes in correlation coefficient between SFI and CRI for Climax and Huancayo with time, we have performed the ‘running cross-correlation’ analysis between these two parameters. The ‘running cross-correlation’
function \( C(t) \) between SFI and CRI for Climax and Huancayo is shown in Fig. 5. One can see a quasi-periodic behaviour of cross-correlation function with a period of about 5.5 years (half of the 11-year cycle). It is observed from Fig. 5 that the anti-correlation between SFI and CRI is strong \( (|C| = 0.8-0.9) \) during ascending and descending phases of SA cycle, while it becomes weak \( (|C| = 0.2-0.4) \) during maxima and minima of the solar cycle. This is expected, because during maximum and minimum phases of the solar activity cycle the time variations of either of the indices are very small. Earlier investigators \(^7\) had obtained a positive correlation between SSN and CRI during 1981. However, it is seen from Fig. 5 that the anti-correlation between SFI and CRI remains continuously negative, though the level of anti-correlation goes down \( (r = -0.3) \) during this particular period of 1981. It is also clear from Fig. 5 that the behaviour of cosmic ray modulation is quite different during the two solar cycles 21 and 22; the correlation is seen to be significantly different during different phases of the two solar cycles. It is inferred from Fig. 5 that the energetic and long-lived solar flares (suitably included in the preparation of SFI) are much more effective in producing the cosmic ray modulation during solar cycle 22, though the SFI is generally smaller in cycle 22 than in cycle 21 for the same value of SSN. The behaviour of cross-correlation function for two differing cut-off rigidity stations is nearly the same except for the particular
Fig. 4—Monthly average values of solar flare index and cosmic ray intensity (CRI) for Climax and Huancayo, the middle and low latitude monitors, respectively, from the year 1976 to 1996. [The scale for SFI is in reverse order (from top to bottom) to match the variation, being inversely correlated.]

period of 1981-82, an anomaly, which has been discussed earlier also.

The behaviour of cross-correlation function between Climax neutron monitor and SFI, after generating the time-lags up to 8 months between these two series, has also been examined. But there were no significant and systematic differences in the level of anti-correlation, except for the period 1984-87. As such, the results point out that the energetic and long-lived solar flares must be considered with suitable weight to explain the modulation of cosmic rays due to solar outputs and its variation. Moreover, SFI is a better index to choose for any long-term studies of cosmic ray variations. It is also noted that the observed differences in cross-correlation function for the solar cycles 21 and 22 using SFI can be further investigated on a short-term basis for the entire period of 1976-1996 by using the data on a day-to-day basis, particularly, in the light of the fact that the depth of modulation is larger in solar cycle 22 than in cycle 21, though the SFI is showing a reverse tendency.

Acknowledgements

The authors are grateful to Prof. S P Agrawal, ex-Vice-Chancellor, A P S University, Rewa (M P) India, for his encouragement to use appropriate solar
activity index (SFI) and many valuable suggestions to improve the quality of this paper. The NOAA for sunspot data and WDC-C2 for neutron monitors data are also thankfully acknowledged.

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