PERIOD OF UNUSUAL MODULATION OF COSMIC RAY INTENSITY: THE DECLINING PHASE OF CYCLE 20

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ABSTRACT

A running cross-correlation analysis of cosmic ray intensity and solar activity time series has been carried out for the last four solar cycles. Monthly averaged count rates of ground based neutron monitors and monthly sunspot numbers were used as indices of cosmic ray intensity and solar activity, respectively. Time series of several neutron monitors with different geomagnetic cut-off rigidities were analysed. It is shown that, although no rigidity dependence of the running cross-correlation function is found in general, there is a strong rigidity dependence of the correlation coefficient during 1972-1977. The declining phase of cycle 20 has earlier been noted to demonstrate an unusual negative momentary phase. The present results together with these earlier results imply that the cosmic ray modulation by solar activity was very exceptional during declining phase of cycle 20. In particular, the heliosphere became stable very early, resulting in a very fast recovery of the cosmic ray intensity followed by a long plateau-like maximum with a minicycle.

INTRODUCTION

It has been known for a long time that the intensity as well as the energy spectrum of galactic cosmic rays (CR) are modulated by solar activity (SA). The general negative correlation between CR and SA is well pronounced. However, the details of the temporal behaviour of this correlation have not been studied so far. In the present paper we perform a detailed correlative study of the recorded time series of cosmic ray intensity and solar activity for the last four solar cycles. We make use of the running cross-correlation techniques to study the fine temporal behaviour of the connections between CR and SA. We use monthly means of neutron monitor count rates as an index of CR (Figure 1a). The world network of ground based neutron monitors (NM) provides very stable and reliable records of intensities for various energy (rigidity) CR particles for more than 40 years period. Hereafter through the present paper, when speaking on CR particles, we mean particles detected by a ground based neutron monitor (within the energy range from several hundred MeV up to several GeV). We use monthly means of sunspot (Wolf) numbers as an index of SA (Figure 1b). We analyse fine details of the cross-correlation for different CR energies using count rate series of neutron monitors with different geomagnetic cut-off rigidity and discuss the unusual behaviour of the correlation to be unusual during the descending phase of SA cycle 20.

CROSS-CORRELATION BETWEEN CR AND SA AS A FUNCTION OF TIME

In order to study detailed temporal behaviour of the negative correlation between CR and SA as a function of time, we have calculate the running cross-correlation coefficient between the monthly mean NM count rate and monthly sunspot numbers (Wolf series). We use a time window of width T centered at time t : $[t-T/2\ ,\ t+T/2]$. The cross-correlation coefficient, $C(t)$, is calculated for data within this window. Then the window is shifted in time with a small temporal step $\Delta t<T$ and the new value of the cross-correlation coefficient, $C(t+\Delta t)$, is calculated. In this study, we have used the time window of T=50 months. This value was chosen to match two contradictory requirements: (i) uncertainty in the calculated $C(t)$ increases with decreasing T and (ii) T should be small enough in order to reveal the fine temporal structure of the cross-correlation function. No time shift between the two series is used when calculating the cross-correlation coefficients.

Figure 2 presents the running cross-correlation function $C(t)$ calculated for the Climax neutron monitor monthly mean count rates and the series of Wolf numbers. The data covers the period of 1953-1996. The dotted line of Figure 2 denotes the 95% confidence interval for the coefficient $C(t)$. It is of particular interest to study the dependence of CR/SA correlation on the energy (rigidity) of cosmic ray particles. We have calculated the cross-correlation function for neutron monitors with different geomagnetic cut-off rigidities (R). Figure 3 shows the correlation functions for Climax ($R\approx$3 GV), high latitude Oulu (R<1 GV) and equatorial Huancayo ($R\approx$13 GV) neutron monitors.

Figures 2 and 3 show a quasi-periodic behaviour of the correlation function with a period of

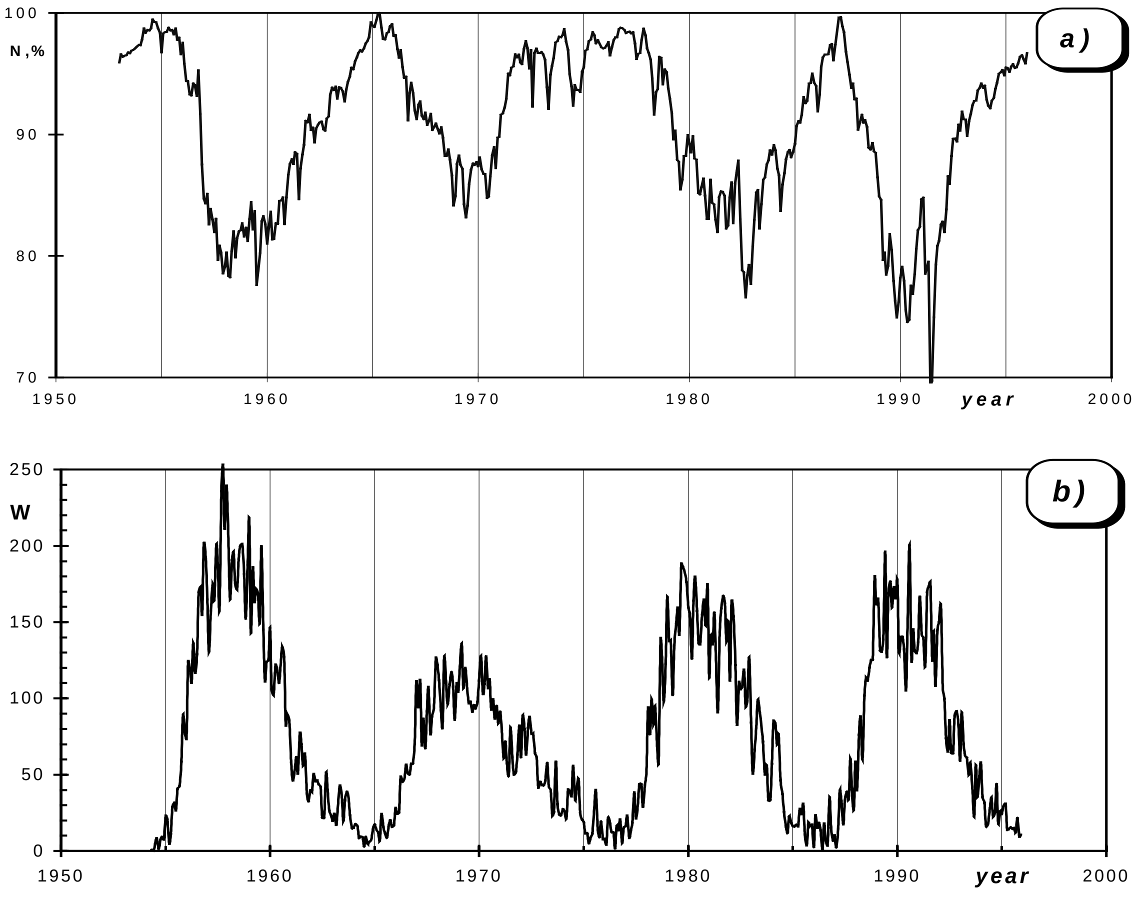

Figure 1. a) Monthly Climax neutron monitor count rate; b) Monthly sunspot (Wolf) numbers

about 5.5 years - i.e. half of 11-year cycle. While the connection between SA and CR is strong ($|C|\approx0.8\div0.9$) during ascending and descending phases of SA cycles, the correlation becomes weak ($|C|<0.2\div0.4$) during extrema (minima and maxima) of SA cycles. This 5.5-year quasi-periodicity in the cross-correlation function can be explained as follows. The actual CR series is delayed in time with respect to SA. Since the time series changes fast during a period of extremum, even a small time shift between two series leads to a weak correlation around extrema.

One interesting feature in Figure 2 is the fact that the correlation coefficient $C(t)$ became significantly positive (C=0.4±0.2) in 1981. This can be explained as follows (see Figure 4). The minimum CR intensity was expected in 1981, about a year after the corresponding SA maximum. However, there was a sudden deep decrease in neutron monitor count rate in 1982 due to a series of strong Forbush decreases in Summer-Fall of 1982. This led to an unexpected delay of the smoothed CR minimum (second half of 1982) with respect to the corresponding SA maximum (end of 1979). Therefore, during the period of 1979-1982, slopes of both series (CR intensity and SA) were negative (Figure 4), leading to a positive correlation.

A very unusual behaviour of the cross-correlation function is observed during the descending phase of cycle 20 (1972-1977). During this period the correlation was weak exceptionally long. Also, the cross-correlation function had an additional local minimum in contrast to a smooth recovery in all other cycles.

One can see in Figure 3 that all the three curves for different neutron monitors with different cut-off rigidities coincide fairly well with each other, within the 95% confidence interval, for the entire interval except for the particular period of 1972-1977. This coincidence means that the overall behaviour of CR modulation is similar for particles with different energies (within the energy range of neutron monitor sensitivity) even if the depth of the modulation changes with particle energy.

DISCUSSION

The fact that the time profiles of the of running cross-correlation CR/SA coefficient were the same (except for the particular period of 1972-1977) for neutron monitors with different geomagnetic cut-off rigidities (Figure 3) implies that the modulation of CR particles with different energy has a similar overall

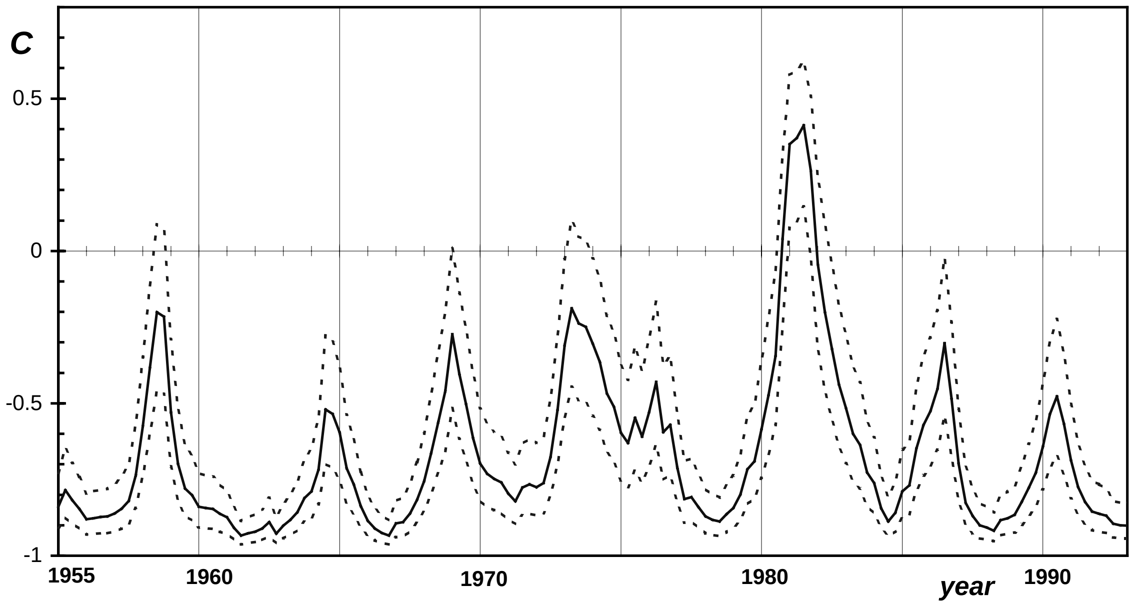

Figure 2. Coefficient of running cross-correlation between SA and CR (Climax monitor). Solid line shows the most probable value and dashed lines border 95% confidence interval.

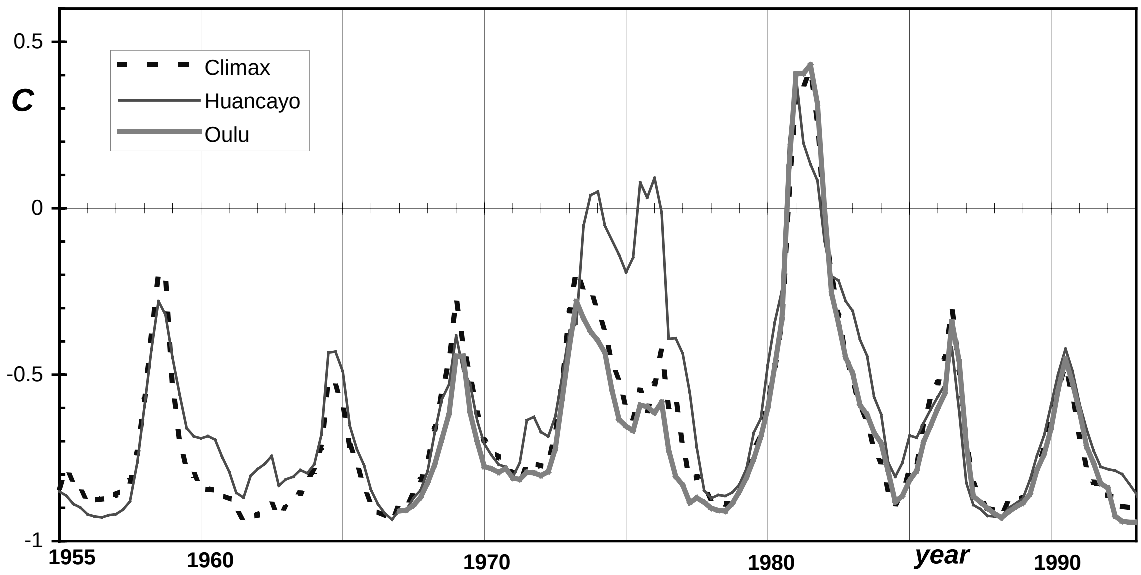

Figure 3. Coefficient of running-cross correlation between SA and CR for monitors with different geomagnetic cut-off rigidities: Huancayo (13 GV), Climax (3 GV), Oulu (<1 GV)

behaviour although the depth of the modulation depends on particle energy. This conclusion can also be supported as follows. Figure 5a shows smoothed CR intensity for mid-latitude Climax and equatorial Huancayo monitors. The data are scaled to exclude the energy dependence of the modulation depth from consideration. One can see that the time profiles are quite similar. As a quantitative measure of this similarity we use value of $\boldsymbol{R}=A\cdot(100\%-N_{Hu})/(100\%-N_{Cl})$, where N_{Hu} and N_{Cl} are count rates (in %) of Huancayo and Climax monitors, respectively, and $A=25/8$ is the scaling factor. Calculated value of $\boldsymbol{R}$ is shown in Figure 5b. One can see that $\boldsymbol{R}\approx1$ during the entire period except for the particular period of 1972-1977. This overall similarity does not contradict with the model calculations of CR modulation: *e.g.* time profiles of calculated intensities for 1 GeV and 10 GeV protons (Figure 3 by Le Roux and Potgieter, 1992) are similar when scaled as given in our Figure 5a. Therefore, the

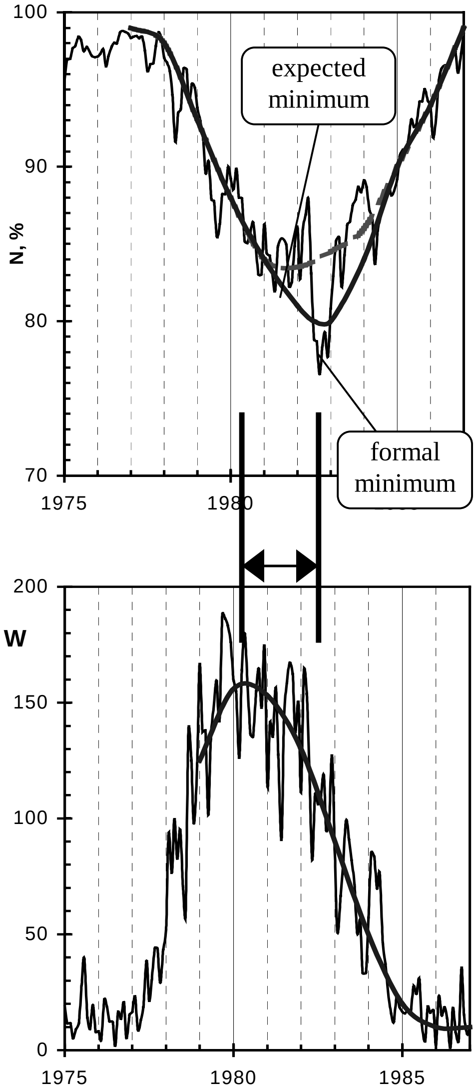

Figure 4. Illustration of positive correlation between CR and SA in 1981. Top panel: Climax monitor count rate, solid line - formally smoothed and dashed line - expected time profile. Bottom panel - sunspot numbers. Double arrow within vertical solid lines denotes the period of negative slope for both series.

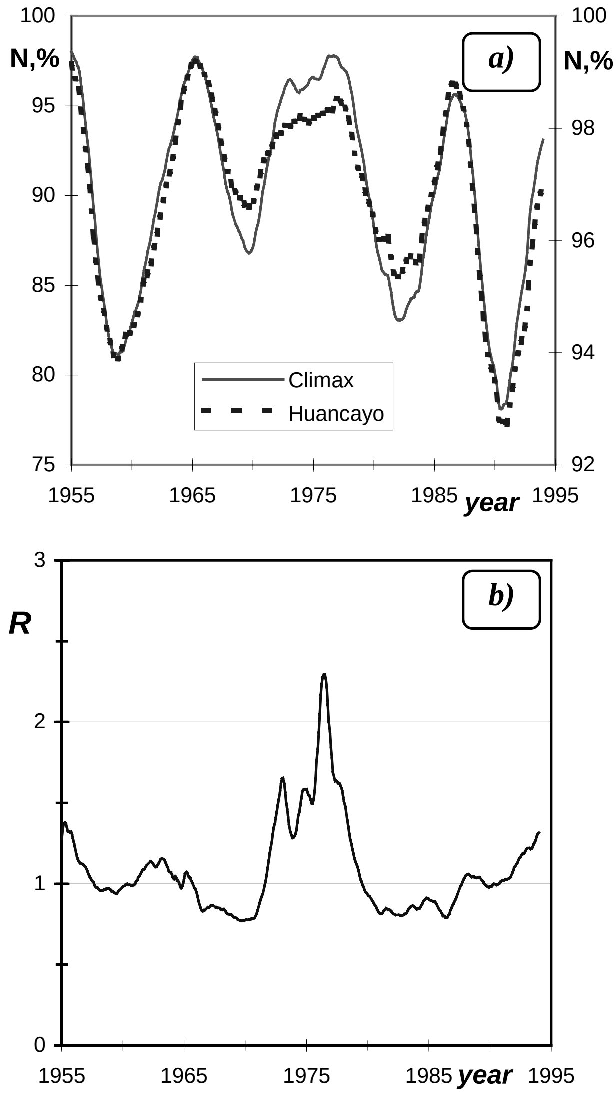

*Figure 5. a) Two years smoothed series of Climax (solid line) and Huancayo (dashed line) count rates. b) Value of **R** (see text).*

modulation of GCR particles of different energy is driven on the same time scale and the same spatial scale by the same heliospheric processes, which may be merged interaction regions (*e.g.* Perkko and Burlaga, 1992), waviness of the heliospheric neutral sheet (*e.g.* Kota and Jokipii, 1983; Le Roux and Potgieter, 1992) or multiple solar eruptions (Cliver and Cane, 1996). Let us note that we deal with long-term global processes. Short-time variations like solar protons events or Forbush decreases are beyond the scope of the present study.

The behaviour of CR/SA correlation shows a qualitatively different behaviour during the descending phase of 20th cycle of SA. A strong energy dependence of the modulation is found in the descending phase of cycle 20 (Figure 3). The intensity of CR particles with rigidity harder than 13 GV (Huancayo monitor) was independent on SA during 1973-1976. Correlation between SA and CR of lower energy was also weak for a longer time than usual, about four years compared to usual 1-1.5 years. The fact that the negative correlation was systematically weaker for Climax (3 GV) than for

Oulu (<1 GV) monitor serves as additional indication for energy dependence of modulation. Note that we have recently found this period to be unusual also in the phase evolution of CR and SA cycles (Usoskin et al., 1997a, b). Besides, an unusual “minicycle” in CR during 1973-1974 has been reported earlier (*e.g.* Webber and Lockwood, 1988).

The CR modulation is controlled by the global solar activity affecting the conditions of CR propagation in the heliosphere. Most likely, the very low SA of the cycle 20 is responsible for the unusual properties found. This implies that the perturbation of the heliosphere is weaker and less widely spread during cycle 20 than during other cycles. This might lead to a situation where the heliospheric perturbations are relatively “thin” for higher energy particles (Huancayo monitor in our case), allowing those particles to reach the Earth as if it was a minimum SA period. On the other hand, the perturbations could be still “thick” enough for lower energy particles (Oulu monitor) to be driven by the weak SA. Such a situation could result in energy dependence of modulation as well as other peculiarities found. Thus, the heliosphere recovered after the 20th maximum more quickly than usual. This implies that the heliospheric perturbations caused by SA in the descending phase of cycle 20 were quite local and could not result in global modulation of CR. Therefore, CR reached its maximum level already in 1972 although the actual SA minimum was found only in 1976. It is also known that the solar dipole tilt decreased very rapidly from the maximum level of about 90º in late 1970 to about 30º in 1971 (Wang, 1993), and that the heliospheric neutral sheet was very flat as early as in 1973 (and probably even earlier) (*e.g.* Kojima and Kakinuma, 1990). These results demonstrate that the heliosphere reached the quiet time structure very early in the declining phase of cycle 20, implying an exceptionally fast recovery of the CR level and a long flat CR maximum during 1972-1977. It is likely that, although the SA was of average level (and even a very strong solar event of August 1972 occurred), the expansion of the SA related perturbations in the heliosphere was not wide enough to effectively modulate GCR particles within the neutron monitor energy range, leading to the observed singularities in the CR modulation in the descending phase of cycle 20.

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