PHASE EVOLUTION OF SOLAR ACTIVITY AND COSMIC-RAY VARIATION CYCLES

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Abstract. Cycles of phase evolution of solar activity and cosmic-ray variations are reconstructed by means of the delay component method, which allows us to study the temporal behaviour of time lag between solar activity and cosmic-ray cycle phases. It is shown that the period of the late 20th cycle was very unusual. We have found a delay in the phase of the solar activity cycle with respect to that of cosmic rays and discuss the heliospheric conditions responsible for this delay.

1. Introduction

It has been known for a long time that there exists an inverse correlation between cosmic-ray intensity variations (CR) and solar activity (SA). The details of the CR modulation by SA are still a subject of study. A general time lag in CR vs SA has been found (e.g., Dorman and Dorman, 1967). Both amplitude and lag of the modulation vary from cycle to cycle (e.g., Nagashima and Morishita, 1979; Marmatsouri *et al.*, 1995). A detailed study of the temporal behaviour of the lag would be of great value for further investigation of the modulation process. However, earlier studies dealt only with the mean value of the lag over a cycle. In the present paper we reconstruct the evolution of both SA and CR cycles in a two-dimensional plane by means of the method of time delay components. Such an approach allows us to study, in detail, the temporal behaviour of the phase lag between SA and CR cycles. We use records of monthly means of the counting rate of the Oulu neutron monitor. This monitor has a series of very stable and reliable routine records of CR since 1963. These data have been extended backwards to the 19th cycle of SA with the series of monthly means of the Climax neutron monitor during 1953 – 1965 (WDC-C2). CR data are normalized to the counting rate in May 1965. We consider the monthly sunspot number as an index of SA.

2. Method of Analysis

The method of analysis based on the Packard – Takens procedure (Packard *et al.*, 1980) has become quite common recently and can be briefly shown as follows. From a time series of observations $\{x_i\}$, a formal series of n-dimensional vectors

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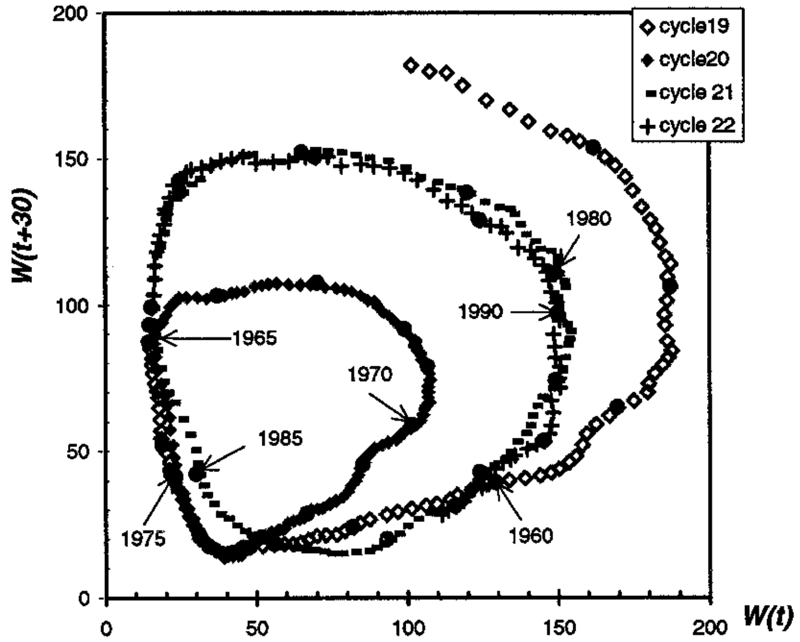

Figure 1. Evolution of solar activity cycles in a plane $W(t+\tau)$ vs $W(t)$.

$\{\mathbf{X}_i \equiv (x_i, x_{i+\tau}, \ldots, x_{i+(n-1)\tau})\}$ can be constructed. According to the theorem by Takens (1981), the evolution of $\{\mathbf{X}_i\}$ is similar, from the topological point of view, to that of the actual evolution of the data in n-dimensional phase space. In other words, the evolution of $\{\mathbf{X}_i\}$ is of the same temporal behaviour as the actual evolution. Thus, the method allows one to study the evolution of an n-dimensional dynamical system as a time series in one dimension. This method, together with methods of fractal analysis, has been applied earlier to an analysis of SA (Mundt *et al.*, 1991; Ostryakov and Usoskin, 1991; Kremliovsky, 1994).

In Figure 1 we present the evolution of SA in a two-dimensional plane $W(t)$ vs $W(t+\tau)$ reconstructed by this method. For the plot we used monthly sunspot numbers smoothed over 30 months. The delay $\tau = 30$ months (the first zero of the auto-correlation function) is close to $\frac{1}{4}$ of the main period of ≈ 11 years. Dark points denote the months of January of each year. Figure 2 shows the evolution of CR plotted in the same way. A cycle of $\sim$11 years is clearly seen in both figures. In order to analyse the evolution, we consider the phase φ of a cycle which corresponds to the rotation of the evolution curve in a cycle. The value of $\varphi = 0$ marks the beginning of each cycle. Months of minimum and maximum monthly means are chosen as the start of the cycles for SA and CR, respectively. Let us consider a time lag between the moments of equal phases of the SA and CR cycles. Figure 3 shows the temporal behaviour of the phase lag. We used the following approach: (i) for a certain time t_s, the value of φ for the SA cycle is determined

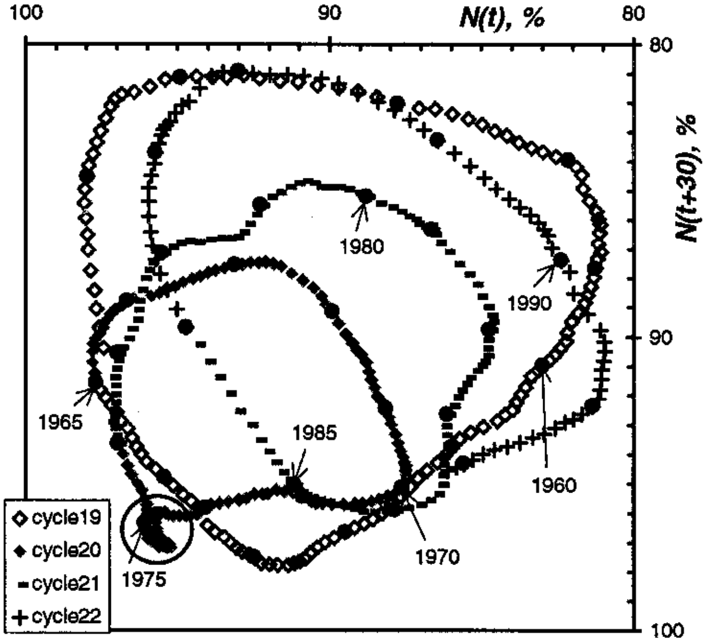

Figure 2. Evolution of cosmic-ray intensity cycles in a plane $N(t+\tau)$ vs $N(t)$.

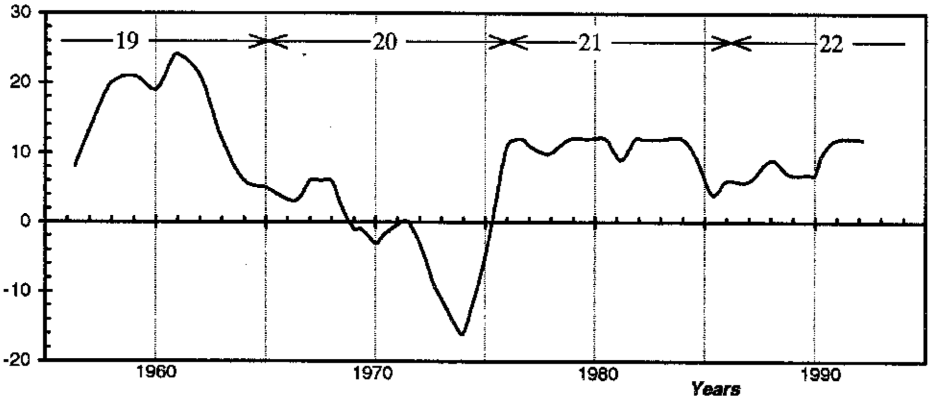

Figure 3. Time lag between the moments of equal phases of CR and SA cycles.

(Figure 1); (ii) the time t_c of the same value of φ for the CR cycle (Figure 2) is found; (iii) the phase lag $t_c - t_s$ is plotted vs t_s.

3. Results and Discussion

The evolution of SA (Figure 1) shows the general ~11-year cycle behaviour. The evolution curve is quite smooth and regular for the entire period. There is no singularity in the evolution of the cycles, while the cycle magnitudes differ significantly from each other. The large 19th cycle is followed by the small 20th cycle. Cycles 21 and 22 are of equal magnitude. All four cycles are of the same shape, and the angular speed of the evolution along a cycle is in general constant during the period. The evolution of a CR cycle (Figure 2) shows qualitatively a different behaviour. As in the case of SA, the 20th CR cycle is smaller than the 19th cycle. In contrast to SA, the magnitude of the 22nd CR cycle differs from that of the 21st cycle which supports the idea about different modulation for odd and even cycles (Webber and Lockwood, 1988; Ahluwalia, 1994). Besides, the shapes of the four cycles differ from each other. During 1973 – 1975, a singularity, circled in Figure 2, took place in the evolution of CR. The evolution curve leaves the smooth cycle in the beginning of 1973, makes a loop and returns to the cycle in early 1975. To make sure that the loop is not an observational artifact, we have checked records of other neutron monitors (Lomnický Štít, Moscow, Deep River) during the period and found the same effect. Note that a 'minicycle' in CR during 1973 – 1974 has been reported (e.g., Webber and Lockwood, 1988). During this period nothing special in the SA cycle evolution is observed. The comparison of general evolution of CR vs SA shows the relationships to be much more complicated than a simple negative correlation with some constant lag, during one cycle. Note that the phase lag we study (Figure 3) is not completely the same lag as reported by Nagashima and Morishita (1979), Lopate and Simpson (1991), Nymmik and Suslov (1995). Their studies are based, mainly, on the minimisation of the cross-correlation function. Such a method deduces a lag value averaged over a period of one cycle, only. Moreover, since a minimum of the cross-correlation function, in its dependence on the lag value, is usually wide, the accuracy of the lag obtained is not high. The method we use gives the value of the CR delay with respect to the SA cycle for every moment of time. Such a momentary phase lag, integrated over a SA cycle, is in good agreement with that obtained by other authors. Figure 3 shows the fine temporal behaviour of the phase lag. During the 19th cycle an increase is seen in the lag value up to $\sim$20 months, followed by a decrease to $\sim$5 months, showing an average lag of 10 – 12 months, which is typical for odd cycles (e.g., Lopate and Simpson, 1991). The next odd cycle, cycle 21, reveals the same average value, the lag being roughly constant during the cycle. One can see from Figure 3 that the phase lag time became negative in 1970 – 1975. Formally, this means that the phase of the SA cycle was 'late' with respect to the CR cycle. A negative lag means that the CR recovery was faster during the period after 1970, than the decrease of SA (compare Figures 1 and 2). The yearly dark circles 'rotate' faster along the 20th CR cycle than those along the SA cycle. During 1973 – 1975, the phase of the CR cycle was 'waiting' for that of SA, which is seen as the loop in Figure 2. This period corresponds to the fast increase in the phase lag time from (-15) to 10 months (Figure 3), because the CR phase stops while SA normally rotates in the cycle. We name this process as a 'fast phase recovery'. The CR modulation is controlled by the global solar activity affecting the conditions of CR propagation in the heliosphere. The sunspot number series are considered to follow, in general, the behaviour of overall solar activity. Therefore, it is probable that the very low SA of cycle 20 is responsible for the strange phase properties found. This implies that, during the active phase of the 20th cycle, the perturbation in the heliosphere is weaker and less widely spread than during the respective periods of more active cycles. Thus, the heliosphere recovers, with declining solar activity, more quickly after the 20th maximum than during the other cycles studied. The decline of the 20th cycle starts with a period of very fast decrease, from the monthly sunspot number of about 130 in mid-1970 to 50 in mid-1971. This decline is seen, with a delay of a few months, as the corresponding fast increase in CR. Note that the CR maximum level is attained already in early 1972, although the sunspot minimum is found several years later. This implies that the inverse correlation between sunspot numbers and CR is only approximate, i.e., the CR level depends not only on the local SA level at some period of time slightly earlier, but on the previous activity level on a longer time scale. Accordingly, the CR level shows a kind of 'hysteresis' behaviour (e.g., Nagashima and Morishita, 1979), i.e., a nonlinear dependence on sunspot activity which is visible during the declining phase of SA cycle 20. Note also that, together with decreasing sunspot activity, the solar dipole tilt is known to decrease very rapidly from the maximum level of about 90° in late 1970 to about 30° in 1971 (Wang, 1993). Moreover, interplanetary scintillation observations (e.g., Kojima and Kakinuma, 1990) made since 1973 show that the heliosheet was very flat as early as in 1973 (and probably even earlier). These results demonstrate that the heliosphere evolved to 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. This exceptional heliospheric evolution led to the negative lag between CR and SA cycles observed in the late declining phase of solar cycle 20. A detailed analysis of the phase evolution of CR and SA cycles is postponed to a later paper.

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