DEPENDENCE OF COSMIC RAYS ON SOLAR ACTIVITY FOR ODD AND EVEN SOLAR CYCLES

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ABSTRACT

We study the relationship between solar activity and cosmic ray intensity for the last four full cycles, using the time delayed component method (Usoskin et al., 1998) in a $2D$ phase space. We present a new method to define the cosmic ray cycle which is free from ambiguousness related to the exact timing of cosmic ray maxima and minima. Using this definition, we confirm that the evolution of cosmic ray intensity is different for odd and even cycles and we show that odd cosmic ray cycles are longer and have longer autocorrelation interval lengths than even cycles. The momentary time lag between cosmic ray intensity and sunspot activity is about one year for odd cycles and small or negative for even cycles. This reflects the difference in the cosmic ray modulation conditions for odd and even cycles and is probably associated with the influence of drift effects.

INTRODUCTION

Galactic cosmic rays (GCR) in the energy range from several hundred MeV to tens of GeV are subject to heliospheric modulation which changes their intensity and spectrum during the 11-year solar cycle. Since the drift modulation processes are charge/polarity dependent, the 22-year solar magnetic field cycle is visible in cosmic ray data, e.g., in the different shapes of maxima of galactic cosmic ray intensity cycles.

Long-term cosmic ray modulation can be studied by the global network of cosmic ray stations (neutron monitors) located at different geomagnetic cut-off rigidities and altitudes. Neutron monitors are sensitive to cosmic rays of about 0.5-20 GeV which coincides with the energy range of most effective solar modulation. Neutron monitor records are a unique data set to study the detailed time behaviour of modulation since 1950s. Earlier studies have established the overall anti-correlation between solar activity (SA) and cosmic ray intensity (e.g., Dorman and Dorman, 1967; Nagashima and Morishita, 1979; Webber and Lockwood, 1988). It was shown that a time lag exists between the long-term variations of solar activity and cosmic rays, and that this time lag may vary in time (e.g., Nagashima and Morishita, 1979; Mavromichalaki and Petropoulos, 1984; Nymmik and Suslov, 1995; Storini et al., 1995).

We have recently introduced concepts of momentary phase and time lag using the delayed component method (Usoskin et al., 1997, 1998). Analyzing the evolution of the time lag, we showed that it is large (more than one year) during odd cycles 19 and 21 and small or even negative during the even cycle 20. A negative time lag implies that the recovery of cosmic ray intensity during cycle 20 was faster than sunspot activity. GCR modulation during the decrease of cycle 20 is known to be quite unique (Usoskin et al., 1997a, 1998) most probably because of the unusual reversal of the global solar magnetic field (Howards,

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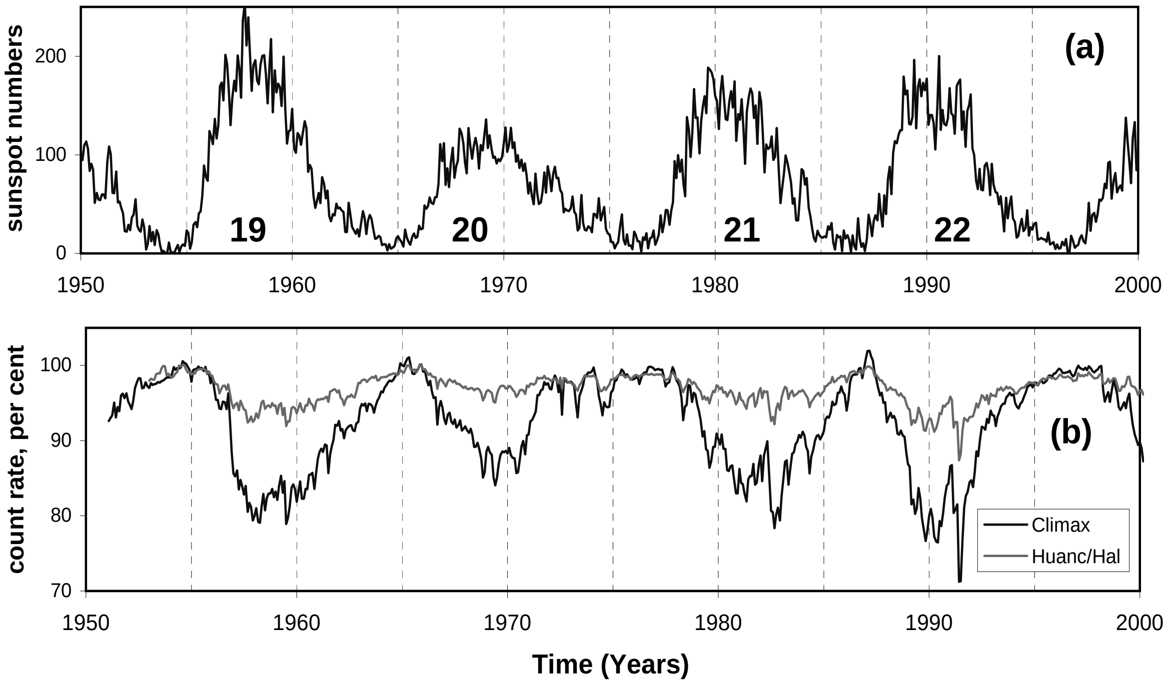

Fig. 1. (a) Monthly sunspot numbers (NOAA), solar cycles are numbered. b) Normalised count rate of Climax and Huancayo/Haleakala neutron monitors (NOAA). The normalisation is to 100% in May 1965.

1974; Benevolenskaya, 1998), leading to an unusual heliospheric structure (Ustinova, 1983). Soon after the maximum of solar cycle 20, when SA was still at a medium level, the heliosphere became rather quiet resulting in a long flat maximum of cosmic ray intensity. Moreover, the heliosphere was relatively "thin" or transparent for energetic particles (above some 13 GeV) but was still "thick" for low-energy cosmic rays leading to an energy-dependent modulation during cycle 20.

Since cycle 22 was not yet completed in its $2D$ dynamics by the time of publication of Usoskin et al. (1998), the results for this cycle presented there were preliminary. Therefore, it was unclear if the negative time lag of cycle 20 was a general feature for all even CR cycles. In the present paper, we extend our analysis to include the complete cycle 22 and generalize the study for the last four complete cycles. In this study we use a new formal definition of a 2D CR cycle, without reference to SA cycles.

DATA ANALYSIS

We use the monthly Wolf sunspot number series as index of solar activity (Figure 1(a)). Cosmic ray intensity is given by the monthly count rates of neutron monitors in Huancayo/Haleakala (geomagnetic cut-off 13 GV) and Climax (3 GV). Their normalized (per May 1965) count rates are shown in Figure 1(b).

When displaying the SA and CR evolutions in a $2D$ phase space, we use the delayed component method (see, e.g., Usoskin et al., 1997, 1998). The method can be briefly described as follows. First, one can construct an $n-$dimensional vector W_i from a time series w_i:

$$\{w_i\} \rightarrow \{W_i \equiv (w_i,\ w_{i+\tau},\ \dots\ ,\ w_{i+(n-1)\tau})\} \tag{1}$$

where τ is the time delay. The evolution of $\{W_i\}$ is topologically similar to the evolution of the actual system in an $n-$dimensional phase space (Takens, 1981) and allows to study the multidimensional topology of a system using its one-dimensional time realization w_i. The value of the time delay τ should be close to the first zero of the autocorrelation function of w_i, which is about $\frac{1}{4}$ of the period for a periodic signal.

The two-dimensional phase evolution curves of the 30-month running averaged SA for the four last solar cycles are shown in Figure 2 for τ = 30 months. The time interval for each solar cycle was defined as the time when the corresponding curve in Figure 2 makes one full revolution of 2π. These time intervals correspond to min-to-min SA cycles 19-22: 1953-1964, 1964-1974, 1975-1985, and 1986-1996, respectively.

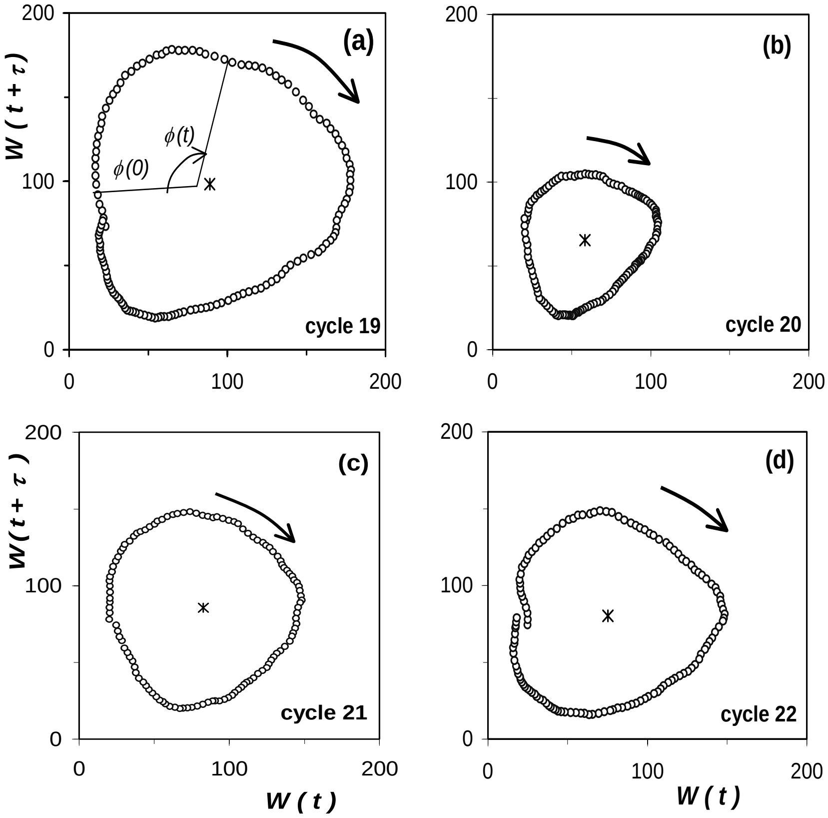

Fig. 2. Two-dimensional phase evolution curves of sunspot activity for the four last solar cycles 19-22 (panels (a)-(d), respectively) for $\tau = 30$ months. Arrows denote the direction of the evolution, asterisks denote cycle centers. A scheme of the momentary phase concept (see text) is shown in (a).

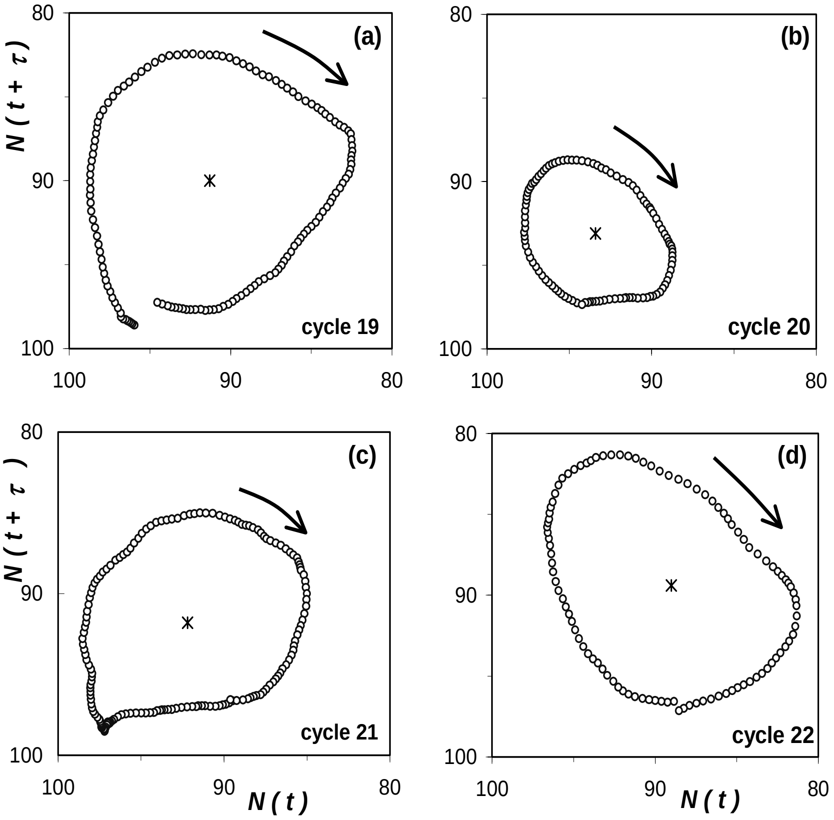

Fig. 3. Two-dimensional phase evolution curves of cosmic ray intensity (in percent) as detected by Climax NM for the four last solar cycles 19-22 (panels (a)-(d), respectively) for $\tau = 30$ months. Arrows denote the direction of the evolution, asterixes denote cycle centers.

Cycles evolve clockwise and quite uniformly around their centers. The center of each cycle was defined as the mass center of the cycle shape. E.g., the abscissa of the center is given as (denoting $x_i = w_i$, $y_i = w_{i+\tau}$)

$$x_c = \frac{\sum\left[(x_i + x_{i+1}) \cdot dist(i, i+1)\right]}{2\sum dist(i, i+1)} \tag{2}$$

where $dist(i, i+1) = \sqrt{(x_i - x_{i+1})^2 + (y_i - y_{i+1})^2}$ is the distance between points W_i and W_{i+1}. One can see that the phase space curves of SA cycles are pretty round and symmetric, the evolution is uniform along a cycle and the curves have a roughly equal length and shape. In particular, we noted that cycles 21 and 22 are very similar to each other in their evolution. The residual correlation between the actual and the delayed sunspot series is about zero ($R_{19} = 0.13 \pm 0.09$, $R_{20} = 0.14 \pm 0.09$, $R_{21} = -0.02 \pm 0.09$, $R_{22} = 0.09 \pm 0.09$ for cycles 19-22, respectively). This shows that the average delay of $\tau = 30$ months applies separately for each solar cycle. This is also reflected in the round shape of SA cycles.

The two-dimensional phase evolution curves of the 30-month running averaged cosmic ray intensity as detected by Climax NM for the four last solar cycles are shown in Figure 3 for $\tau = 35$ months, the first zero of the autocorrelation function for the entire series. We note that a definition of CR cycles is not straightforward. Max-to-max CR intensity cycles are ambiguous because of long flat maxima for $qA > 0$ epochs (e.g., in 1970s). On the other hand, the shape of CR intensity minima is distorted by major Forbush decreases (e.g., in early 1980s, see Figure 3 in Usoskin et al., 1998) leading to an ambiguous min-to-min CR cycle identification. We defined CR cycles as intervals of full 2π revolution in 2D phase space. These CR cycles form intervals of 1952-1962, 1963-1971, 1972-1983, and 1983-1992. Other choice for CR cycles would lead to underdeveloped ($< 2\pi$) or overdeveloped ($> 2\pi$) phase space curves. Thus, the CR cycles are well determined by the method. First years of the cycles roughly correspond to the year of completed reversal of the global Sun's magnetic field for $qA > 0$ epochs and is 1-2 years after the completed reversal for $qA < 0$ epochs (Bazilevskaya and Svirzhevskaya, 1998). As seen in Figure 3, the topological features of CR phase space curves are quite different for odd and even cycles. E.g., the length of odd cycles is 11-12 years, while even cycles are significantly shorter, about 8.5-9 years. Also, odd $2D$ cycles are slightly elongated along the main diagonal, but even cycles are elongated in the perpendicular direction. This reflects the fact that there remains a non-zero residual correlation between the original and delayed series, and this correlation is positive for odd cycles ($R_{19} = 0.17 \pm 0.09$, $R_{21} = 0.37 \pm 0.08$) and negative for even cycles ($R_{20} = -0.27 \pm 0.1$, $R_{22} = -0.29 \pm 0.1$). Moreover, the autocorrelation length (time delay at which the first zero of the autocorrelation function appears) is different for odd and even cycles. While the autocorrelation length is about 35 months for the entire series, it is about 45 months for odd cycles, and 30-33 months for even cycles (see Figure 4). This leads to the different $2D$ curves for odd and even cycles.

Using the $2D$ curves and the coordinates of the cycle centers (Eq. 2), one can introduce the momentary phase of a cycle as shown in Figure 2 (for details see Usoskin et al., 1998). Using the momentary phase, one can calculate the time lag between moments of equal phase in SA and CR cycle evolution. This time lag (Figure 5) is calculated for Climax and Huancayo/Haleakala neutron monitors.

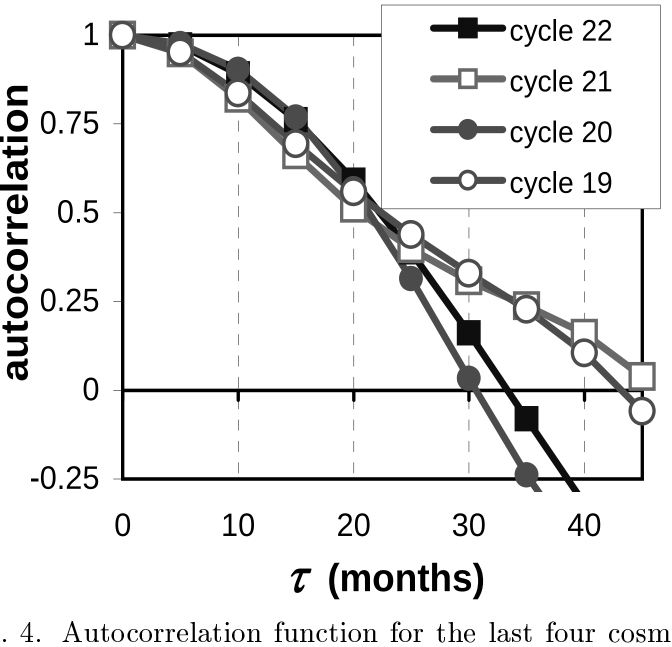

Fig. 4. Autocorrelation function for the last four cosmic ray cycles.

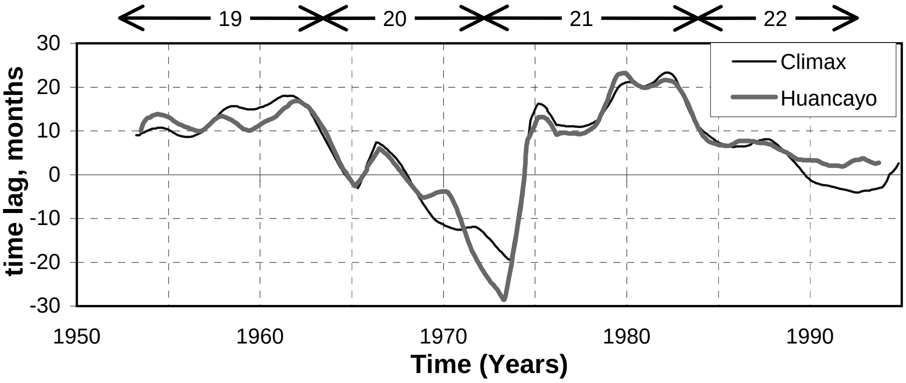

Fig. 5. Time lag between moments of equal phases of SA and CR cycles (see text) for Climax and Huancayo/Haleakala neutron monitors. Intervals of CR cycles are shown on the top.

Table 1. Features of Cosmic Ray Intensity Cycles.

feature	odd cycles	even cycles
length	11-12 years	≈9 years
shape	elongated along the main diagonal	elongated along the opposite diagonal
auto-correlation length	≈45 months	30-33 months
time lag vs. SA	$\geq$ 1 year	≤ 0

DISCUSSION AND CONCLUSIONS

We have studied the evolution of SA and CR cycles in $2D$ phase space for the last four cycles. While the cyclic evolution of SA was quite regular and topologically similar for all cycles (see Figure 2), CR cycles show rather different topology and time characteristics for odd and even cycles (see Figure 3). We defined CR cycles in a formal way of the full 2π revolution which allows for a study of the length of CR cycles, irrespective of the SA cycles. The parameters of the CR cycles are summarized in Table 1. We would like to note particularly that while SA cycles 21 and 22 were very similar in their phase space evolution, the corresponding CR cycles were rather different. These differences are related to the 22-year cycle in heliospheric modulation of cosmic rays (e.g., le Roux and Potgieter, 1995; Potgieter, 1998) leading to the different shape of CR maxima and the hysteresis effect for odd and even cycles (Nagashima and Morishita, 1979; Jokipii, 1991). Accordingly, drift effects dependent on the polarity of the global solar magnetic field (see, e.g., Jokipii and Levy, 1977; Fisk et al., 1998) may play a significant role for the observed differences between odd and even cycles. The drift mechanism is enhanced during periods of low to moderate SA, i.e., around solar cycle minima, during negative polarity periods, when $qA < 0$ (e.g., le Roux and Potgieter, 1995). The drift effects may lead to the found 22-year changes in the modulation of cosmic rays in the neutron monitor energy range (e.g., Kudela et al., 1991; Mavromichalaki et al., 1998). Since cosmic ray particles can use the heliospheric neutral sheet to enter the inner heliosphere during negative polarity minima (e.g., McDonald et al., 1998), their intensity at 1 AU is more sensitive to the warpedness of the neutral sheet during the recovery phase of odd solar cycles than even cycles. This leads to a slower recovery of CR flux for $qA < 0$ cycles, and therefore to the observed fact that odd CR cycles are longer than even CR cycles.

If the recovery of CR intensity is faster than the declining rate of SA level, the corresponding time lag becomes negative as happened in 1968-1974 and 1989-1995. We note that the difference in time lags for odd and even cycles is consistent throughout the studied interval. The time lag is as large as 1-1.5 years for odd cycles and zero or negative for even cycles, leading to the different cycle lengths. (Note also that the expected zero or small negative time lag during the second half of cycle 20 was aggravated to its large negative value due to the very unusual features of the global solar magnetic field and heliosphere structure for cycle 20 (Ustinova, 1983; Benevolenskaya, 1998).) Moreover, the time profile of the lag is similar for the two 22-year cycles (19-20 and 21-22 solar cycles). These results imply that there is a significant difference in the solar modulation of CR during positive and negative polarity magnetic cycles. The fact that CR series obtained at different rigidities show a very similar behaviour implies that the found odd/even cycle differences reflect a persistent feature of the modulation in the energy range up to several tens of GeV.

Concluding, we have shown that there is a systematic difference in cosmic ray intensity cyclic evolution for odd and even cycles which is ascribed to the possible role of drift effects in heliospheric modulation of cosmic rays. The odd CR cycles are longer than even cycles and the momentary time lag between equal phases of cosmic ray and sunspot activity cycles is large for odd cycle and small or negative for even cycles.

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