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# Odd and even cycles in cosmic rays and solar activity

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**Abstract.** We present here a new method to define the evolution of cosmic ray and solar activity cycles using the time delayed component method in a $2D$ phase space. This method is free from the ambiguousness related to the exact timing of cosmic ray maxima and minima. We study the relationship between solar activity and cosmic ray intensity for the last four 11-year cycles. We confirm that the evolution of cosmic ray intensity is different for odd and even cycles and show that odd cosmic ray cycles are longer and have longer autocorrelation 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.

## 1 Introduction

The global network of neutron monitors (NMs) is a good tool to study the long-term modulation of galactic cosmic rays (GCR) since the effective energy range of GCR as detected by NMs (0.5-20 GeV) coincides with the energy range of heliospheric modulation (e.g., Belov (2000)). Earlier studies have established the overall anti-correlation between solar activity (SA) and cosmic ray intensity (e.g., Dorman & Dorman (1967); Nagashima & Morishita (1979); Webber & 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 & Morishita (1979); Mavromichalaki & Petropoulos (1984); Nymmik & Suslov (1995); Storini et al. (1995)). In order to study the details of the varying relation between CR and SA we have recently introduced concepts of momentary phase and time lag using the delayed component method (Usoskin et al., 1997a, 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. 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 thus covering the last four complete cycles. While Usoskin et al. (1998) tied the $2D$ CR cycle in time with the corresponding SA cycle, we present here a new definition for the $2D$ CR cycle which is independent of the SA cycle (see also Usoskin et al. (2001)). The new definition allows to study CR and SA cycles independently, giving a more correct comparison between them.

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## 2 Data analysis

We use the monthly Wolf sunspot number series as index of solar activity. 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).

When displaying the SA and CR evolutions in a $2D$ phase space, we use the delayed component method (see, e.g., Usoskin et al. (1997a, 1998) and references therein). The method can be briefly described as follows (see also Usoskin et al. (2001)). First, one can construct an $n-$dimensional vector $W_i$ from a time series $w_i$:

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

where $\tau$ 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 $\tau$ 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.

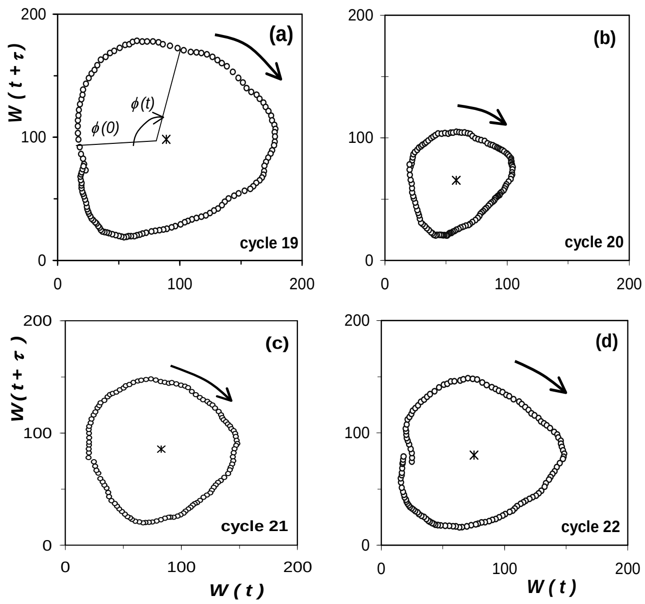


**Fig. 1.** Two-dimensional phase evolution curves of sunspot activity for the four last solar cycles 19-22 (panels (a)-(d), respectively) for $\tau = 30$ months. Arrows denote the direction of the evolution, asterisks denote cycle centers. A scheme of the momentary phase concept (see text) is shown in (a).

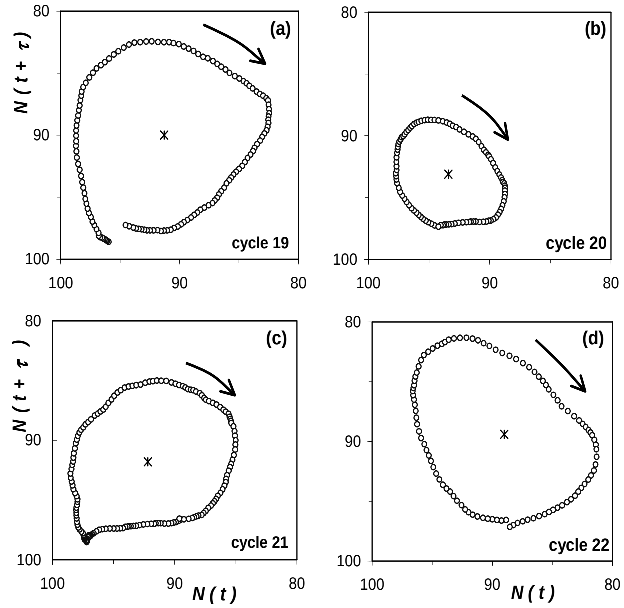


**Fig. 2.** Two-dimensional phase evolution curves of cosmic ray intensity (in percent) as detected by Climax NM for the four last cosmic ray cycles 19-22 (panels (a)-(d), respectively) for $\tau = 35$ months.

The two-dimensional phase evolution curves of the 30-month running averaged SA for the four last solar cycles are shown in Fig. 1 for $\tau = 30$ months. The time interval for each solar cycle was defined as the time when the corresponding curve in Fig. 1 makes one full revolution of $2\pi$. These time intervals correspond to min-to-min SA cycles 19-22: 1953-1964, 1964-1974, 1975-1985, and 1986-1996, respectively. 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 note 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 consistent with 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 time delay of $\tau = 30$ months applies separately for each solar cycle. This is also reflected in the round shape of SA cycles. We have used the following measure to test the cycle shape with a circle:

$$S = \sqrt{\frac{\Sigma(1 - r/r_o)^2}{N}} \tag{3}$$

where $r$ is the distance from the cycle center (Eq. 2), $r_o$ is the mean distance, and $N$ is the number of points in the cycle. The values of $S$ are 0.08, 0.09, 0.05, 0.07 for SA cycles 19–22, respectively.

The two-dimensional phase evolution curves of the 30-month running averaged cosmic ray intensities as detected by Climax NM for the four last cosmic ray cycles are shown in Fig. 2 for $\tau = 35$ months, the first zero of the autocorrelation function for the entire series. We note that the 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 define CR cycles as intervals of full $2\pi$ revolution in 2D phase space. These CR cycles form intervals of 1952-1962, 1963-1971, 1972-1983, and 1983-1992 for CR cycles 19-22, respectively. 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.

Unlike SA, CR cycles deviate significantly from a circular shape. The values of $S$ (Eq. 3) are 0.11, 0.11, 0.12, 0.14 for CR cycles 19–22, respectively. As seen in Fig. 2, 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 shorter, about 9

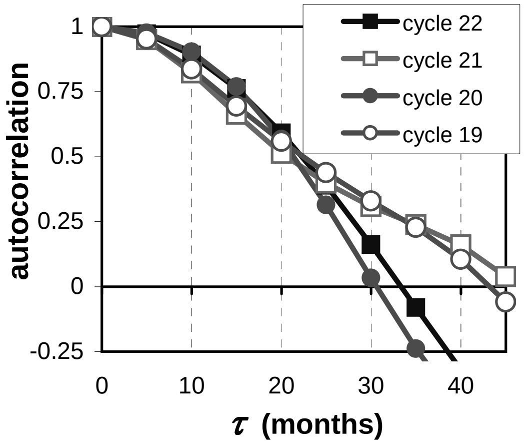


**Fig. 3.** Autocorrelation function for the last four cosmic ray cycles.

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, but only 30-33 months for even cycles (see Fig. 3). 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 Fig. 1 for SA (for details see Usoskin et al., 1998). However, the overall relative phase between the SA and CR cycles has to be defined. This was fixed by the minimum of the cross-correlation function which was found at 10 months for the whole time interval. Then the momentary time lags are calculated with respect to to this overall delay between SA and CR. Fig. 4 depicts the momentary time lags for Climax and Huancayo/Haleakala NMs.

## 3 Discussion and conclusions

We have studied the evolution of SA and CR cycles in $2D$ phase space for the last four cycles. We defined the CR cycles as cycles of the full $2\pi$ revolution, allowing us to study the length of CR cycles irrespective of the SA cycles. The parameters of the CR cycles are summarized in Table 1. While the cyclic evolution of SA was quite regular and topologically similar for all cycles (see Fig. 1), CR cycles show a rather different topology and time characteristics for odd and even cycles (see Fig. 2). In particular, we would like to note that while SA cycles 21 and 22 were very similar in their phase space evolution, the corresponding CR cycles were

**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 opposite diagonal |
| auto-correlation length | ≈45 months | 30-33 months |
| time lag vs. SA | $\geq$ 1 year | $\leq 0$ |

rather different. These differences are therefore most probably related to the 22-year cycle in heliospheric modulation of cosmic rays (le Roux & Potgieter, 1995; Potgieter, 1998), leading to the different shape of CR maxima and the hysteresis effect for odd and even cycles (Nagashima & Morishita, 1979; Jokipii, 1991). Accordingly, the drift effects dependent on the polarity of the global solar magnetic field (see, e.g., Jokipii & Levy (1977); Fisk et al. (1998)) seem to 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 $qA < 0$ (see, e.g., le Roux & Potgieter (1995)). The drift effects may also lead to the 22-year variations in the modulation of cosmic rays in the neutron monitor energy range (see, 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 (see, 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 (see Fig. 4). We note that the difference in time lags between odd and even cycles is consistent throughout the studied interval. The time lag is as large as 1-1.5 years for odd cycles but roughly zero or negative for even cycles. (Note also that the expected zero or small negative time lag during the second half of cycle 20 was aggravated to a large negative value due to the very unusual features of the global solar magnetic field and heliospheric structure for (Ustinova, 1983; Benevolenskaya, 1998).) Moreover, the time profile of the lag is fairly 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 detected 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 are systematic differences in cosmic ray evolution between odd and even cycles which are probably due to the drift effects in heliospheric

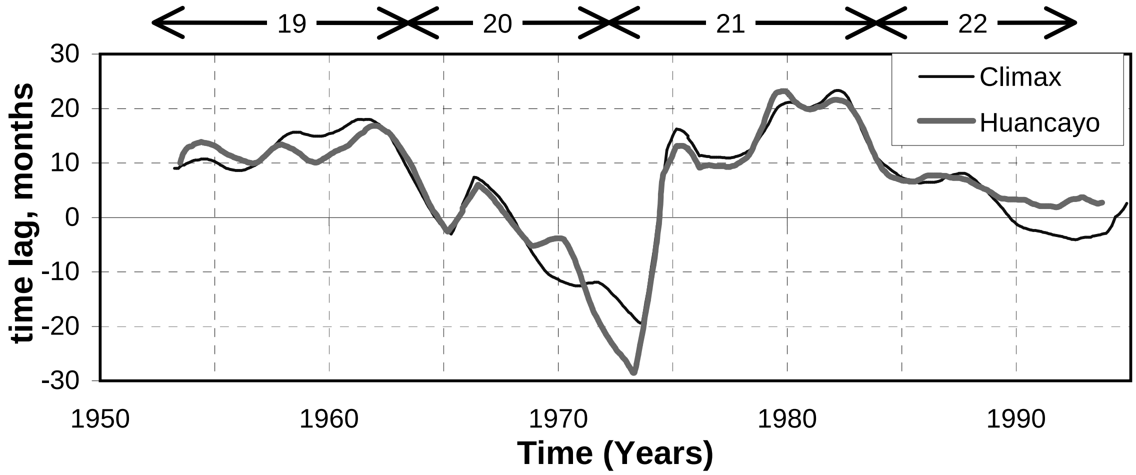


**Fig. 4.** Time lag between moments of equal phases of SA and CR cycles (see text) for Climax and Huancayo/Haleakala neutron monitors. Intervals of CR cycles are shown on the top.

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 (see Table 1).

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