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Lags and Hysteresis Loops of Cosmic Ray Intensity *Versus* Sunspot Numbers: Quantitative Estimates for Cycles 19 – 23 and a Preliminary Indication for Cycle 24

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Abstract Hysteresis plots between cosmic-ray (CR) intensity (recorded at the Climax station) and sunspot relative number R_Z show broad loops in odd cycles (19, 21, and 23) and narrow loops in even cycles (20 and 22). However, in the even cycles, the loops are not narrow throughout the whole cycle; around the sunspot-maximum period, a broad loop is seen. Only in the rising and declining phases, the loops are narrow in even cycles. The CR modulation is known to have a delay with respect to R_Z, and the delay was believed to be longer in odd cycles (19, 21, and 23; about 10 months) than the delay in even cycles (20 and 22; about 3 – 5 months). When this was reexamined, it was found that the delays are different during the sunspot-minimum periods (2, 6, and 14 months for odd cycles and 7 and 9 months for even cycles) and sunspot-maximum periods (0, 4, and 7 months for odd cycles and 5 and 8 months for even cycles). Thus, the differences between odd and even cycles are not significant throughout the whole cycle. In the recent even cycle 24, hysteresis plots show a preliminary broadening near the sunspot maximum, which occurred recently (February 2012). The CR level (recorded at Newark station) is still high in 2013, indicating a long lag (exceeding 10 months) with respect to the sunspot maximum.

Keywords Cosmic rays · Interplanetary physics · Sunspots

1. Introduction

Cosmic rays (CR) are of galactic origin (originating in supernovae and their remnants) and enter the heliosphere almost isotropically. However, the heliosphere is pervaded with the solar wind, and interplanetary magnetic fields modify the CR intensity recorded at the Earth's surface. The CR intensity shows variations on several time scales, such as diurnal variation, Forbush decreases occurring over several days, and 27-day variations. On a longer time scale, there is a year-to-year variation almost out of phase with the 11-year sunspot cycle, showing differences in the even and odd cycles (22-year modulation). The CR modulation

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is known to have a delay with respect to the sunspot number, and the delay was believed to be longer in odd cycles (19 and 21) than the delay in even cycles (20 and 22) (Dorman and Dorman, 1967; Nagashima and Morishita, 1979; Usoskin *et al.*, 1998; Singh, Badruddin, and Ananth, 2005). The mechanism for CR modulation consists of time-dependent heliospheric drifts and outward-propagating diffusive barriers, which are formed by merging of coronal mass ejections (CMEs), shocks, and high-speed flows at 10 – 15 AU from the Sun (merged interaction regions, or MIRs; Burlaga *et al.*, 1985). All MIRs are effective in modulation but in varying degrees. Since very strong MIRs are very effective in modulating CRs throughout the heliosphere (Burlaga, McDonald, and Ness, 1993), global MIRs (GMIRs) were conceived, which are regions extending 360° around the Sun, occur mostly in the ecliptic plane, and are responsible for step-like changes in CR counting rates. As mentioned in Kane (2007), the convection–diffusion mechanism is independent of the sign of the solar magnetic field and operates similarly in every 11-year sunspot cycle (*e.g.* Dorman, 1959; Parker, 1965). On the other hand, the drift mechanism causes opposite effects with the changing sign of the solar magnetic field in alternate cycles (*e.g.* Jokipii and Davila, 1981; Jokipii and Thomas, 1981; Lee and Fisk, 1981; Potgieter and Moraal, 1985). At the sunspot maximum of odd cycles, the solar north-polar magnetic field reverses, from outward directed ($A > 0$) to inward directed ($A < 0$) during an interval of a few months. A few months later, the solar south-polar magnetic field also reverses from inward directed ($A < 0$) to outward directed ($A > 0$) during an interval of a few months. In even cycles, the opposite occurs. In the $A > 0$ epochs, the inflows of CRs into the inner heliosphere are faster from over the poles than from along the heliospheric current sheet. When $A < 0$, the opposite occurs (Wibberenz, Richardson, and Cane, 2002). Cane *et al.* (1999) have reported a very good anti-correlation between CR intensity and interplanetary total magnetic field B for the two consecutive cycles 21 and 22, and a very close relationship between CR intensity and the tilt angle (latitudinal extent) of the heliospheric current sheet (HCS) compiled by Hoeksema (1995). The tilt of the wavy current sheet in the heliosphere has been claimed to be a very successful proxy for solar activity in CR modulation models that include particle drifts (Ferreira and Potgieter, 2002). The difference in delays between the odd and even cycles is best displayed in hysteresis plots of CR intensity and sunspot relative number; the hysteresis loops are broad in odd cycles and narrow in even cycles (Dorman, 2001; Dorman, Iucci, and Villoresi, 2001; Dorman *et al.*, 2001; and references therein).

Variations in CR intensity are contributed from processes occurring in the whole heliosphere, and depend on solar activity not at one moment, but during a rather long previous period (for example, Nagashima and Morishita, 1979; Belov, 2000). Nagashima and Morishita (1979) summarized the CR delays as follows: “When the polar magnetic field of the Sun is parallel to the galactic magnetic field, they could easily connect with each other so that galactic CRs could intrude more easily into the heliosphere along magnetic lines of force, as compared with those in the antiparallel state of the magnetic fields.... The transition between the two states has a time lag behind the polarity reversal, depending on the rigidity of the observed CRs; such as about 1 year for a neutron monitor and about 3.5 year for low rigidity components.”

In the present communication, the lags between CR intensity and sunspot relative number for cycles 19 – 23 are studied quantitatively by using the hysteresis plots between CR intensity and sunspot relative number. Furthermore, a preliminary examination is made for sunspot cycle 24, which seems to have reached a peak value of the sunspot relative number of about 68 (12-month running mean) in February 2012, with a decline thereafter, while CR intensity depression has not yet reached a peak.

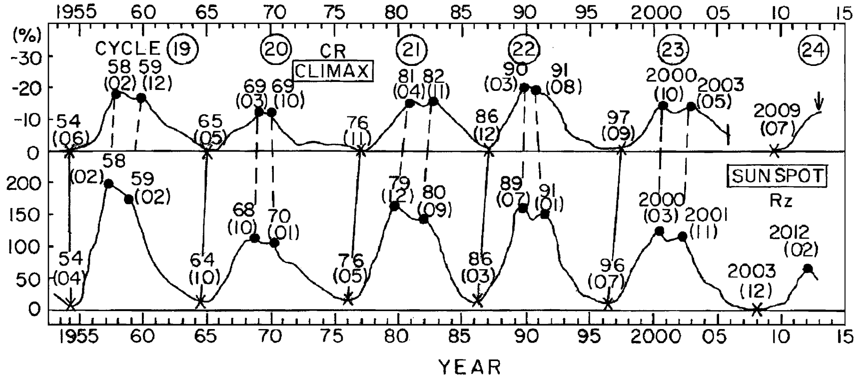

Figure 1 Plot of the 12-month running mean of the CR intensity in the upper half, and the sunspot relative number R_Z in the lower half. The vertical scale for the CR intensity is reversed. The years (months in parentheses) of the peaks and troughs of the curves are marked with dots and crosses, respectively; their values are given in Table 1.

2. Estimation of Lags

The sunspot data were obtained from the NOAA website ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/. For the CR intensity, the longest series available is from the Climax station (latitude 39.4N, longitude 106.2W, altitude 3400 m; rigidity in 1965 is 2.99 GV), from about 1953 to 2006 (when the station was terminated). The data were obtained from the website http://cr0.izmiran.rssi.ru/clmx/main.htm. For 2008 onward, we used CR data from the Newark station (latitude 39.9N, longitude 75.4W, altitude 80 m; rigidity in 1965 is 1.92 GV), available at the Bartol Research Institute (ftp://ftp.bartol.udel.edu/pyle/BRIData/).

Figure 1 shows a plot of the 12-month running mean of CR intensity in the upper half and the sunspot relative number R_Z in the lower half. Since the changes in CR intensity are expected to be anti-correlated with R_Z, the vertical scale for CR is reversed (the peaks in the CR curve representing maximum percentage depressions, matching with sunspot number maxima). The years and months of the peaks and troughs are marked and their values are given in Table 1. In each cycle, there are two adjacent peaks near the sunspot maximum. The values in Table 1 refer to the first peaks in the sunspot relative number as well as CR intensity data.

The following points may be noted:

i) Comparing the R_Z minimum and the corresponding minimum in the CR depression, CR lagged behind R_Z by 2, 6, and 14 months (average ≈ 7 months) in the odd cycles (19, 21, and 23) and 7 and 9 months (average ≈ 8 months) in the even cycles (20 and 22). Thus, there is no significant difference in the lags between the odd and even cycles.

ii) Comparing the R_Z maximum and the corresponding maximum in the CR depression, CR lagged behind R_Z by 0, 4, and 7 months (average ≈ 4 months) in the odd cycles and 5 and 8 months (average ≈ 6 months) in the even cycles. Thus, there is some indication that the lags are longer for the even cycles. This is in contradiction with other reports that mentioned longer lags for odd cycles (Dorman and Dorman, 1967; Nagashima and Morishita, 1979; Usoskin *et al.*, 1998; Singh, Badruddin, and Ananth, 2005). The range of lag values in the odd cycles (19, 21, and 23) is very broad; 2 – 14 months for the R_Z

Table 1 Dates of maxima and minima of CR depressions and sunspot relative number R_Z and their difference for odd cycles (19, 21, and 23) in the upper half and even cycles (20, 22, and 24 (partial)) in the lower half. The month of the year is given in parentheses.

	CR minimum depression	R_Z minimum	CR later by (months)	CR maximum depression	R_Z maximum	CR later by (months)
Odd cycles						
19 1953 – 1964	1954 (06)	1954 (04)	2	1958 (02)	1958 (02)	0
21 1976 – 1987	1976 (11)	1976 (05)	6	1981 (04)	1979 (12)	4
23 1996 – 2006	1997 (09)	1996 (07)	14	2000 (10)	2000 (03)	7
Even cycles						
20 1964 – 1976	1965 (05)	1964 (10)	7	1969 (03)	1968 (10)	5
22 1987 – 1996	1986 (12)	1986 (03)	9	1990 (03)	1989 (07)	8
24 2008 onwards	2009 (07)	2008 (12)	7	2012 (12)	2012 (02)	> 10

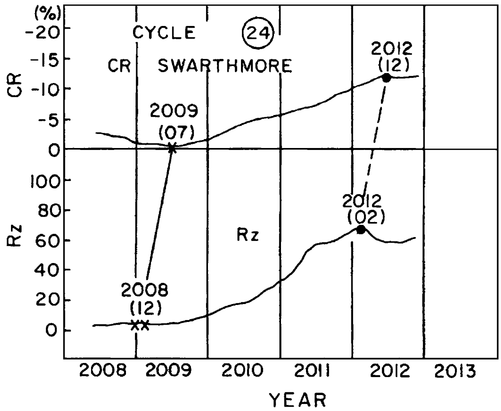

Figure 2 A detailed plot for cycle 24, 2008 onward. Whereas R_Z peaked in 2008 (12) at a value of ≈ 68 (12-month running mean), the CR plot continues with high negative values at a level of $-12\ \%$ in 2013, while it had a zero level in 2008.

minimum periods, and 0 – 7 months for the R_Z maximum periods. Also, these authors have not given lags separately for the R_Z maximum and minimum periods.

iii) In cycle 24, R_Z reached a peak in 2012 (12). Unfortunately, CR data from Climax were terminated in 2006. Hence, data from Newark were used, and they show that the CR level has remained high even in 2013. Thus, the lag would be at least 10 months, if not more, an unexpectedly long lag for an even cycle.

For cycle 24, Figure 2 shows a detailed plot of the same data from 2008 onward. Whereas R_Z peaked in 2012 (02) at a value of ≈ 68 (12-month running mean), the CR intensity depression continues at a level of $-12\ \%$. At 2012 (12), the lag is already 10 months. If this level continues, the lag will increase further, exceeding 10 months.

Figure 3 shows the hysteresis plots between CR intensity (Climax) and R_Z for the odd cycles (19, 21, and 23) on the left side, and for the even cycles (20, 22, and part of 24) on the right side. Values during the rising phase of a sunspot cycle are shown with full

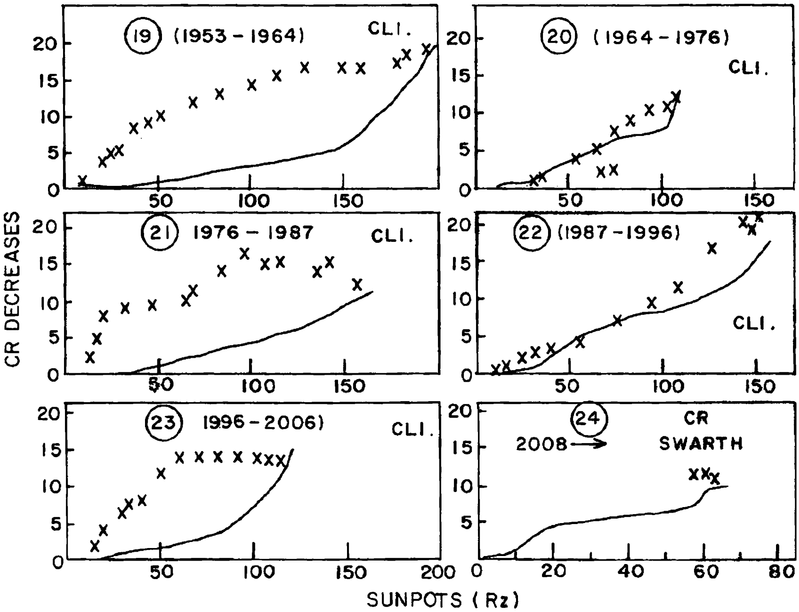

Figure 3 Hysteresis plots between CR intensity (data from Climax) and R_Z for the odd cycles (19, 21, and 23) on the left side and the even cycles (20, 22, and part of 24) on the right side. Values during the rising phase of a sunspot cycle are shown with full lines, while values during the declining phase of a sunspot cycle are shown with crosses. As can be seen, the loops are broader in the odd cycles.

lines, while values during the declining phase of a sunspot cycle are shown with crosses. As can be seen, the loops are broader in the odd cycles, as was previously reported by many authors. However, in the even cycles, though the loops are narrower overall, the loops show broadening near sunspot maxima. Only in the rising and declining phases, the loops merge into a thin pattern. Thus, even in these even cycles, some diffusion effects must have been present around the sunspot-maximum periods. For cycle 24 (right side bottom plot), the full line (rising phase of cycle 24) has ended and a few crosses (declining phase) have appeared. The tendency seems to indicate a broad structure, but this will be shown clearly only after data of a few more years in the declining phase (2012 onward) become available.

3. Conclusions and Discussion

Hysteresis plots between CR intensity and sunspot relative number are known to show broad loops in odd cycles (19, 21, and 23) and narrow loops in even cycles (20 and 22). However, we found that in the even cycles, the loops are not narrow throughout. Around the sunspot-maximum periods, broad loops are seen, which subsequently become narrow in the declining and rising phases.

It has been known that the maximum and minimum of CR depression are delayed with respect to the corresponding maximum and minimum of R_Z. The delays were longer in odd cycles (19, 21, and 23; about 10 months) than the delays in even cycles (20 and 22; about 3 – 5 months). The magnitude of the delays slightly depends on the methods adopted by different authors for data analysis. However, when the data were reexamined after a 12-month running mean, it was found that the delays are different for sunspot-minimum periods

(2, 6, and 14 months for odd cycles and 7 and 9 months for even cycles) and for sunspot-maximum periods (0, 4, and 7 months for odd cycles and 5 and 8 months for even cycles). This means that the delays for the odd and even cycles are not significantly different.

In the recent even cycle 24, the hysteresis plots show a preliminary broadening near the sunspot maximum, which occurred recently (February 2012). The CR data from Newark show that the CR intensity depression is still high in 2013 at a level of $-12\ \%$. This indicates a long lag exceeding 10 months, which is an unexpected result for an even cycle.

In the present analysis, only one CR dataset from Climax was used. This is mainly because Climax has provided the longest data series available. However, for a shorter interval, the data from other locations (Calgary, Thule, and others) were examined and gave qualitatively the same results. Similarly, for the solar index, only the sunspot relative number was used. Another index used by some authors (Belov, 2000; Wibberenz, Richardson, and Cane, 2002) is the 2800 MHz flux. In an earlier communication (Kane, 2007), both these indices were used and it was shown that they had almost the same characteristics (the correlation between the two solar indices is higher than $+0.90$).

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