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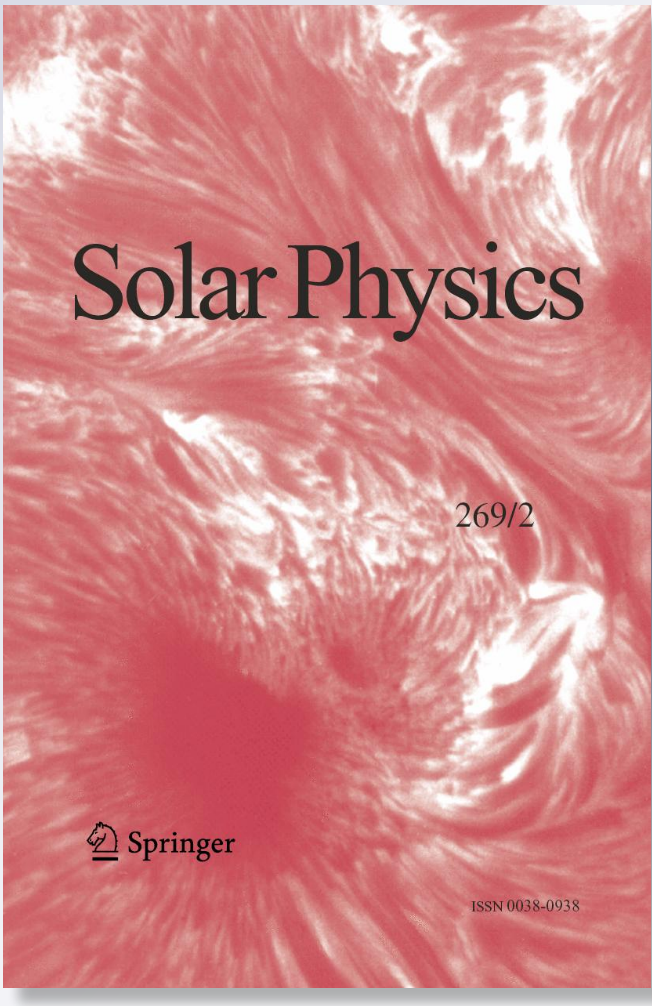

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Hysteresis of Cosmic Rays with Respect to Sunspot Numbers During the Recent Sunspot Minimum

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Abstract Cosmic ray neutron monitors show intensity changes (counts) anti-correlated with sunspot number R_z, but with a lag of a few months. The lag is ~ 3 months for even cycles and $\sim 9 - 15$ months for odd cycles. Thus, for the recently started even Cycle 24, a lag of ~ 3 months was expected. However, for Cycle 24, whereas R_z had a minimum value (zero) in August 2009, cosmic ray intensity decreased only after March 2010, with a lag of seven months with respect to R_z. Thus, Cycle 24 did not conform to the known pattern of even cycles (lag of ~ 3 months). It may be noted that the minimum at the juncture of Cycle 23-24 was abnormally long, tens of months instead of few months as in earlier cycles. Also, in this solar minimum, the cosmic ray intensity was much higher than in previous cycles.

Keywords Cosmic rays · Hysteresis · Cycle 24

1. Introduction

Cosmic rays (CR) are mostly of extra-galactic origin and should show a constant intensity level at the Earth. But the intensity is considerably modulated by the heliospheric environment and considerable changes are observed. On shorter time scales, there are the Forbush decreases of several percent, lasting for a few days. On a longer time scale, there is a distinct 11-year variation, anti-correlated with sunspot activity R_z. The CR intensity is maximum at sunspot minimum and *vice versa*, but not exactly. The CR *lags* behind R_z and the CR – R_z plots show *hysteresis* loops. Details are shown in Kane (2007) and references therein.

The CR modulation starts with a delay with respect to sunspot number and the delay is larger in odd cycles as compared to the delay in even cycles. The delays in previous cycles were, denoting cycle(months): 17(9); 18(1); 19(10 – 11); 20(2); 21(16); 22(4); 23(14) (Mavromichalaki, Paouris, and Karalidi, 2007). The mechanism for CR modulation consists of time-dependent heliospheric drifts and outward propagating diffusive barriers,

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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, MIRs; Burlaga *et al.*, 1985; Burlaga, McDonald, and Ness, 1993). The convection – diffusion mechanism is independent of the sign of the solar magnetic field and operates similarly in every 11-year sunspot cycle (Dorman, 1959; Parker, 1963, and others). On the other hand, the drift mechanism gives opposite effects with the changing sign of the solar magnetic field in alternate cycles (Jokipii and Davila, 1981; Jokipii and Thomas, 1981; Lee and Fisk, 1981; Potgieter and Moraal, 1985, and many other further papers). 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 $A > 0$ epochs, the inflows of CR 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). The delays (different in odd and even cycles) are displayed as hysteresis plots of CR *versus* sunspot numbers, where the hysteresis loops are broad in odd cycles and narrow in even cycles (Dorman, 2001; Dorman *et al.*, 2001, Dorman, Iucci, and Villoresi, 2001, and references therein). In the recently ended cycle 23 (1996 – 2009), the hysteresis loop was broad, as expected (Kane, 2007). It was also mentioned in Kane (2007) that the lag between CR and R_z was $\sim$3 months in even cycles and 9 – 15 months in odd cycles. Presently, the new Cycle 24 has commenced, and it is time to check with what time lag the CR modulation started with respect to R_z. The present communication reports such a study.

2. Plots

Figure 1 shows a plot of Climax (39°N, 254°E) cosmic ray neutron monitor counts (ordinate) *versus* sunspot number R_z (abscissa). The odd cycles (a) 19, (c) 21, (e) 23 are shown in the left column and depict broad hysteresis loops. The even cycles (b) 20, (d) 22 are shown in the right column and depict narrow hysteresis loops. For Cycle 24, a loop would be seen only in the next 11 years. For the present, the plot (f) shows the CR percentage count (upper plot, location Kiel, 54°N, 10°E) and sunspot number R_z (lower plot) and the abscissa is months January 2009 to August 2010. The following may be noted.

i) The sunspot number R_z showed a minimum (actually zero, an unusual thing) in the month of August 2009 and then increased rapidly to the value of 19 by February 2010.

ii) The CR neutron monitor counts (Cycle 24) at the mid-latitude location Kiel were at a steady level up to March 2010 and thereafter started decreasing and the drop was $\sim$4% by September 2010. Thus, in Cycle 24, the CR modulation started about seven months later than the R_z minimum. In earlier even cycles, the lags were only $\sim$3 months. Probably, the abnormal duration of the sunspot minimum resulted in a longer lag.

3. Conclusions

Cosmic ray neutron monitors show intensity changes (counts) anti-correlated to sunspot number R_z, but with a lag of a few months. The lag is $\sim$3 months for even cycles and $\sim$9 – 15 months for odd cycles. Thus, for the even Cycle 24, a lag of $\sim$3 months was expected. However, whereas R_z had a minimum value (zero) in August 2009 and increased rapidly thereafter, CR intensity at the mid-latitude location Kiel remained at a high level up to March

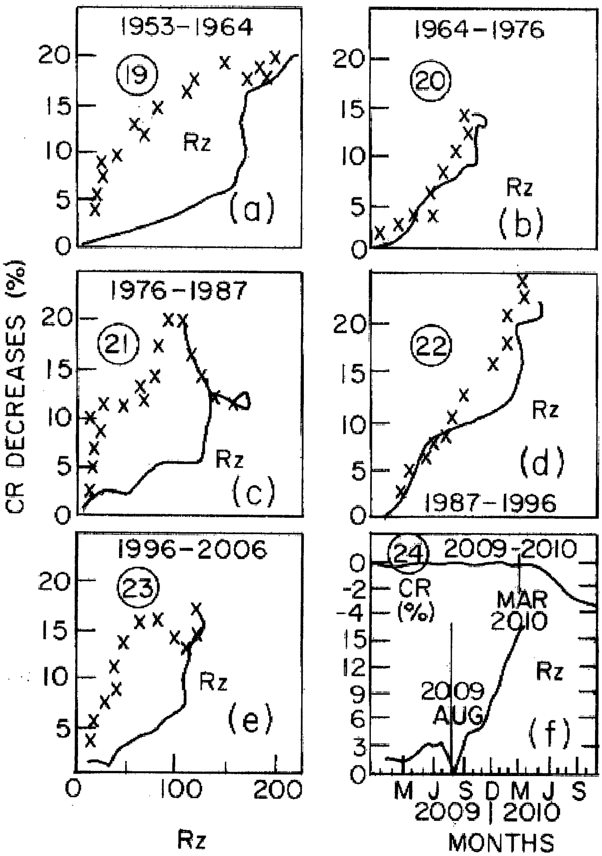

Figure 1 Hysteresis plot of cosmic ray (CR) decreases at Climax (39°N, 254°E) *versus* sunspot number R_Z for cycles (a) 19, (b) 20, (c) 21, (d) 22 and (e) 23. For Cycle 24, no hysteresis is possible as the full cycle will be available only after 11 years, but for the initial stage of Cycle 24, Figure 1(f) shows a plot of CR (upper plot, intensity at the location Kiel, 54°N, 10°E) and R_Z (lower plot) for the interval January 2009 – August 2010. R_Z minimum occurred in August 2009, while CR decrease started with a 7-month lag, in March 2010.

2010 and started decreasing thereafter. Thus, CR showed a lag of seven months with respect to R_z and Cycle 24 did not conform to the known pattern of even cycles (lag of ~ 3 months). It may be noted that the minimum at the juncture of Cycle 23-24 was abnormally long, tens of months instead of few months. Also, in this solar minimum, the cosmic ray intensity was much higher than in previous cycles.

To check whether other neutron monitors (besides Kiel) showed similar results, some other mid-latitude neutron monitor data were examined and showed a start of the modulation in a small way in February 2010 and in a big way thereafter. For example, the neutron monitor at Newark (40°N, 76°W) operated by the Bartol Research Foundation (supported by the United States National Science Foundation under grants ANT-0739620) showed relative percentage values for the month of January 2010 as zero, followed by -0.6% in February and more than -1% in March onwards, dropping to -4% by September 2010. Thus, the lag in Cycle 24 appears to be 6 – 7 months.

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