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Solar modulation of galactic cosmic rays during the last five solar cycles

M. Singh[a,b], Y.P. Singh[a,c], Badruddin[a,*]

[a]Department of Physics, Aligarh Muslim University, Aligarh 202 002, India
[b]Department of Physics, Hindustan Institute of Technology, Greater Noida 201 306, India
[c]Department of Physics, Mangalayatan University, Beswan, Aligarh, India

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Abstract

We study the cosmic ray modulation during different solar cycles and polarity states of the heliosphere. We determine (a) time lag between the cosmic ray intensity and the solar variability, (b) area of the cosmic ray intensity versus solar activity modulation loops and (c) dependence of the cosmic ray intensity on the solar variability, during different solar activity cycles and polarity states of the heliosphere. We find differences during odd and even solar cycles. Differences during positive and negative polarity periods are also found. Consequences and implications of the observed differences during (i) odd and even cycles, and (ii) opposite polarity states ($A<0$ and $A>0$) are discussed in the light of the modulation models, including drift effects.

Keywords: Cosmic rays; Solar cycle variation; Sun; Solar activity; Solar polarity; Heliosphere

1. Introduction

The ~11-year variation in cosmic ray intensity observed at the earth is anti-correlated with solar activity with some time lag. Using ionization chamber data for solar cycles 17 and 18, Forbush (1954, 1958) first demonstrated that cosmic ray variations lagged behind sunspot activity by 6–12 months. Simpson (1963) attributed the observed lag as due to the dynamics of the build up and subsequent delayed relaxation of the modulating region. In some subsequent studies (e.g. Dorman and Dorman, 1967; Simpson and Wang, 1967; Wang, 1970) the observed time lag was used to infer the size of the modulating region (the heliosphere). Hatton (1980), using neutron monitor data, found a large difference between the time lags during cycles 19 and 20; smaller (by 6 months) for solar cycle 20 than for cycle 19. This observation had led Hatton (1980) to question the use of time lag to estimate the modulation boundary and to doubt that sunspot number (SSN) is an appropriate index of solar activity.

Hysteresis effect between long-term variations in cosmic ray intensity and solar activity is being studied since long (e.g. Neher and Anderson, 1962). In most of the studies of the long-term variations and hysteresis effects, SSN has been used as a

*Corresponding author. Tel.: +91 5712701001;
fax: +91 57127201001.
E-mail address: badr_phys@yahoo.co.in (Badruddin).

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parameter of solar activity (e.g. Storini, 1990; Jakimiec et al., 1999; Van Allen, 2000; Usoskin et al., 2001; Dorman et al., 2001; Cliver and Ling, 2001; Kane, 2003, 2006a). However, other solar indices, e.g. coronal green line intensity (Pathak and Sarabhai, 1970; Wang, 1970), solar flares (Hatton, 1980; Ozguc and Atac, 2003) and solar proton events (Mavromichalaki and Petropoulos, 1984), have also been used in the past for studies of the relationship between solar variability and cosmic ray intensity. Such studies provide information about the time lags between the solar activity indices and cosmic ray intensity in various solar cycles. For example, time lags of 2–4 months for even solar cycles and 9–16 months for odd solar cycles have been observed between solar activity and cosmic ray intensity (e.g. see Mavromichalaki and Petropoulos, 1984; Mavromichalaki et al., 1998 and references therein). However, geomagnetic activity index $A_{\rm p}$ is correlated with cosmic ray intensity without any phase lag (e.g. see Balasubrahmanyan, 1969; Mavromichalaki et al., 1998). Badruddin et al. (2007) used another parameter (tilt of the heliospheric current sheet) and studied its relationship with cosmic ray intensity during various solar cycles.

Thus, in order to study the dynamics of the cosmic ray modulation, several solar activity parameters have been used in the past and many interesting results have been obtained. However, some recent studies of the time lag and hysteresis effect (e.g. Mavromichalaki et al., 1998; Jakimiec et al., 1999; Van Allen, 2000; Usoskin et al., 2001; Cliver and Ling, 2001; Dorman et al., 2001; Ozguc and Atac, 2003; Kane, 2003; Singh et al., 2005; Sabbah and Rybansky, 2006; Mishra et al., 2006; Badruddin et al., 2007) have suggested interesting interpretations (in terms of drift/diffusion effects), implications and consequences (for modulation models) of the observed differences in time lags as well as differences in shapes, sizes, etc. of the hysteresis loops during odd and even cycles. In an elegant study of modulation loops, Van Allen (2000) argued that the differences in certain features of modulation loops in odd and even cycles give support to the inclusion of gradient and curvature drifts in the theories of cosmic ray transport in the heliosphere. He also put forward some interpretive ideas, although he remarked that his interpretive contributions may not be definitive but will stimulate more detailed consideration of the significance of modulation loops.

In this paper, we have studied certain aspects of solar modulation during solar cycles 19–23 utilizing cosmic ray neutron monitor data from two locations on the earth (Climax and Oulu) and three solar activity indices (SSN, 10.7 cm solar radio flux (SRF) and solar flare index (SFI)).

2. Theoretical considerations: a brief overview

Most of the earlier studies of time lag/hysteresis phenomena between solar activity and long-term variation in cosmic ray intensity (e.g. Simpson and Wang, 1967; Nagashima and Morishita, 1980; Hatton, 1980; Mavromichalaki et al., 1998) have tried to explain their results on the basis of convection–diffusion and adiabatic deceleration theory of galactic cosmic ray modulation into a spherically symmetric solar wind model (Parker, 1965; Gleeson and Axford, 1967). According to this model, the cosmic ray intensity I $(R,\ \beta,\ t)$ at heliocentric radial distance 'r' and at time 't' in terms of intensity I_∞ (R, β) beyond the modulating region is given by

$$I(R,\beta,t) = I_\infty(R,\beta)\exp\left[-\int_r^{L(t)} \frac{V_{\rm s}(\vec{r},t)}{K(R,\beta,\vec{r},t)}\,{\rm d}\vec{r}\right], \tag{1}$$

where $V_{\rm s}(\vec{r},t)$ is the solar wind velocity, $K(R,\beta,\vec{r},t)$ is the isotropic diffusion coefficient and $L(t)$ is the effective distance over which the modulation is effective in time t. The dependence of isotropic diffusion coefficient $K(R,\beta,\vec{r},t)$ on the particle rigidity R and particle velocity $\beta(=v/c)$ is determined by the shape of the magnetic field power spectrum (Jokipii, 1967; Wang, 1970).

Based on Parker's theory, Nagashima and Morishita (1980) have shown that cosmic ray modulation can be described by the expression

$$I(t) = I_\infty - \int F(\tau)S(t-\tau)\,{\rm d}\tau, \tag{2}$$

where I_∞ and $I(t)$ are the galactic (unmodulated) and modulated cosmic ray intensities, $S(t-\tau)$ is the source function representing a proper solar activity index at a time $t-\tau$ $(\tau>0)$ and $F(\tau)$ is the characteristic function, which expresses the time dependence of solar disturbance represented by $S(t-\tau)$. Using this expression and different source functions, e.g. sunspots (Nagashima and Morishita, 1980), solar flares of importance $\geqslant 1$ (Hatton, 1980) and a combination of SSN, solar flares and

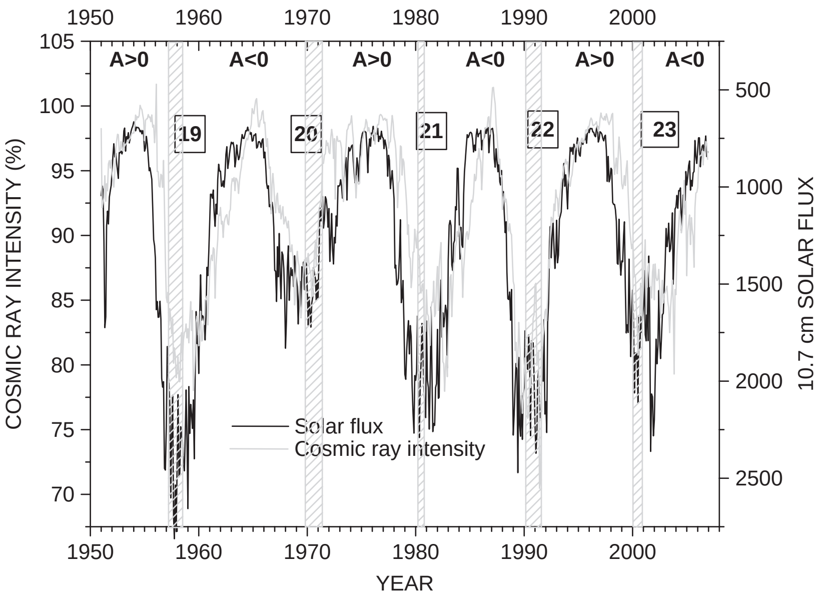

Fig. 1. Cosmic ray intensity (Climax NM) and 10.7 cm solar flux variation (scale inverted) from 1951–2006.

geomagnetic index (Mavromichalaki and Petropoulos, 1984), modulated intensity has been calculated. Although the agreements between observed intensity and calculated intensity using Eq. (2) were found to be impressive, need for the improvement in this model by introducing a source function that takes care of solar polarity dependence in modulation was suggested (Mavromichalaki et al., 1998).

Since the charge/polarity-dependent effect in the modulation is ascribed to the gradient in and curvature of the interplanetary magnetic field, for the interpretation of every aspect of hysteresis curve, one may require the solution of the basic equation for the transport and modulation of cosmic rays in the heliosphere that includes all four terms representing (i) outward convection of the cosmic rays due to the solar wind, (ii) particle drift due to the curvature and gradient of the interplanetary magnetic field, (iii) inward diffusion and (iv) adiabatic energy loss. Current modulation models are based on the solution of the transport equation (Parker, 1965):

$$\frac{\partial f}{\partial t} = -\vec{V}.\vec{\nabla}f - \vec{V}_{\mathrm{d}}.\vec{\nabla}f + \vec{\nabla}.\left(\vec{K}.\vec{\nabla}f\right) + \frac{1}{3}\left(\vec{\nabla}.\vec{V}\right)\frac{\partial f}{\partial(\ln\ R)}, \quad (3)$$

where $f(r,R,t)$ is the cosmic ray distribution function. Terms on the right-hand side represent convection, gradient and curvature drift, diffusion and adiabatic energy loss respectively. Numerical solutions of Eq. (3) have been obtained including the effect of tilt in heliospheric current sheet

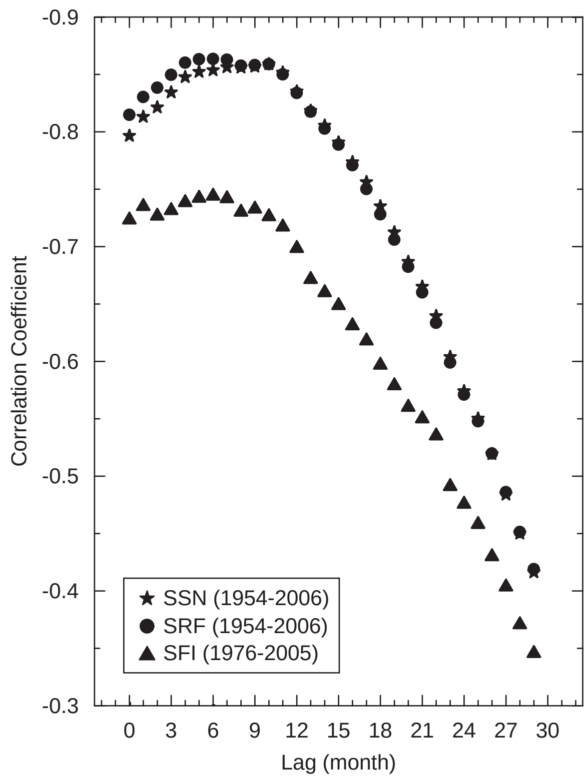

Fig. 2. Average time lag correlation between cosmic ray intensity and solar indices (sunspot number, 10.7 cm solar flux and flare index).

(e.g. Kota and Jokipii, 1983; Potgieter et al., 2001 and references therein).

3. Results

Fig. 1 shows the monthly averaged Climax neutron monitor data (in percent) against the monthly values of 10.7 cm solar flux for the period 1951–2006. Solar cycles, solar polarity epochs ($A<0$ and $A>0$) and solar polarity reversal periods are indicated in the figure. From an overview of this long-term plot, certain differences in the behavior of the cosmic ray flux variations during odd and even cycles are worth mentioning (see also Storini, 1990; Otaola et al., 1985; Ahluwalia, 1995; Mavromichalaki et al., 1998).

The time lag between the cosmic ray intensity (CRI) and the solar flux appears larger in odd solar

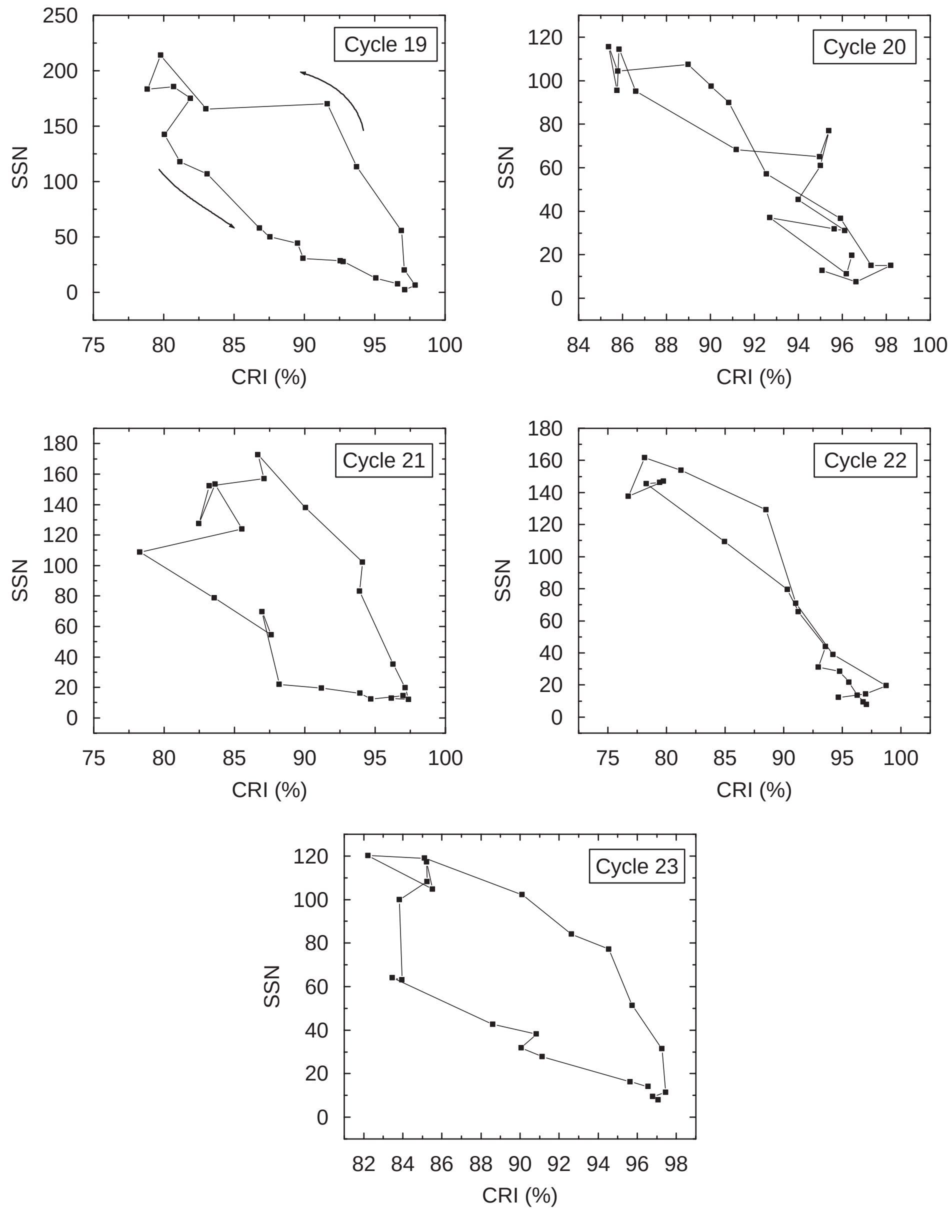

Fig. 3. Hysteresis plots between cosmic ray intensity (CRI) as recorded by Climax neutron monitor and sunspot number (SSN) for solar cycles 19–23.

cycles than in even cycles. In even solar cycles 20 and 22, the cosmic ray intensity reached higher values shortly after the maxima of solar flux and remains high for several years (~5 and 3 years, respectively, in cycles 20 and 22). In odd cycles 19, 21 and 23, the intensity increases slowly and peaks early (around the solar cycle minimum) only for a year or so. Thus the recoveries of cosmic ray intensity during even cycles are rather rapid, whereas during odd cycles recoveries are slow and took longer periods to recover completely. More precisely, the recovery during odd solar cycles completes in 5–6 years, while only in 2–3 years during even cycles. It is to be mentioned that in odd cycles the decreasing phase lies during the $A>0$ state and the recovery phase lies in the $A<0$ polarity state of the heliosphere. In even cycles, the opposite is the case, i.e. decreasing phase lies in the $A<0$ state and the recovery phase in the $A>0$ polarity state.

Another feature worth noting in Fig. 1 is that the time lag between solar activity and cosmic ray

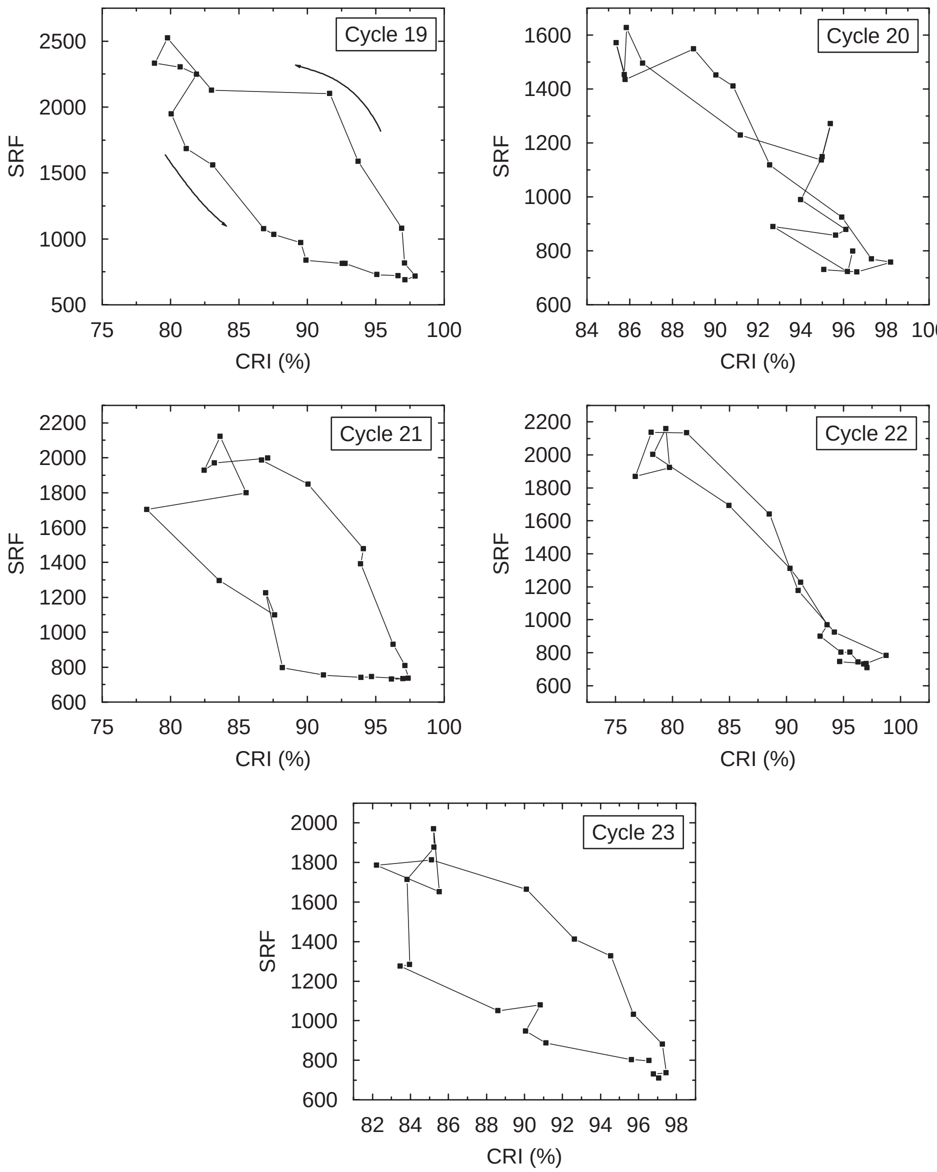

Fig. 4. Hysteresis plots between CRI and 10.7 cm solar radio flux (SRF) for solar cycles 19–23.

intensity is larger in odd cycles than in even cycles. The cycle-averaged lags were calculated earlier (Nymmik and Suslow, 1995) and were found to be 3.7, 12.6 and 3.2 months for cycles 20, 21 and 22, respectively. Ozguc and Atac (2003) also determined time lags for solar cycles 20, 21 and 22 and found them to be 7, 10 and 2 months, respectively. Cliver and Ling (2001) observed that the 11-year cosmic ray cycle appears to lag the sunspot cycle by ~1 year for odd numbered cycles (such as 19 and 21), while for the even numbered cycles, SSN and cosmic ray intensity curves were essentially in phase. Usoskin et al. (2001) also found similar differences in time lags during odd and even cycles. Ozguc and Atac (2003) used SFI as a measure of solar activity and observed that their results partly confirm the findings of Nymmik and Suslow (1995) and Cliver and Ling (2001) but were not in agreement with those of Dorman et al. (2001), who found that with increasing relative role of drift effects, the time lag for odd cycles decreases but increases for even cycles.

In most of the earlier studies of hysteresis effect (e.g. Mavromichalaki et al., 1998; Van Allen, 2000; Kane, 2003), yearly means of cosmic ray intensity and a solar activity parameter have been used and many interesting results have been obtained. However, there does not appear to be any specific reason

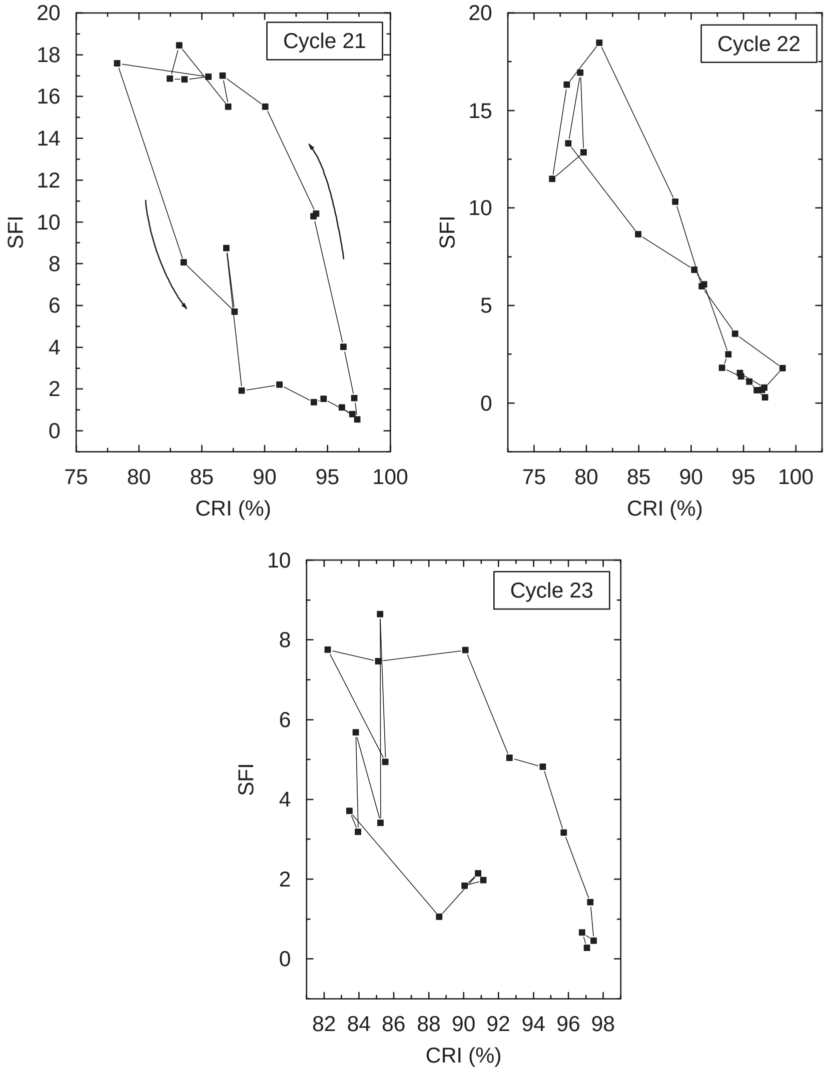

Fig. 5. Hysteresis plots between CRI and solar flare index (SFI) for solar cycles 21–23 (up to 2005).

for taking 12-month average of the data for such studies. In an attempt to find the more suitable interval over which the data should be averaged for the better insight of the hysteresis loops and the modulation, we have determined the average time lag for a long period (1954–2006) between cosmic ray intensity and three indices of solar activity, namely SSN, 10.7 cm SRF and SFI. To determine these, we have calculated the correlation coefficients between a solar parameter and cosmic ray intensity by introducing successive time lags of 0–29 months and obtained the time lag corresponding to optimum correlation. It is found to be 6 months (Fig. 2). Thus, in the present study, we have used 6-monthly averages of cosmic ray intensity and solar data to plot the hysteresis curves for solar cycles 19–23.

In Fig. 3 we have shown the hysteresis plots of 6-monthly averaged cosmic ray intensity from Climax neutron monitor (cutoff rigidity $R_c = 2.97$ GV, latitude $\lambda = 39.37°$N) versus SSN for solar cycles 19, 20, 21, 22 and 23. Similar plots between cosmic ray intensity and 10.7 cm solar flux are shown in Fig. 4. Hysteresis plots between cosmic ray intensity and SFI for cycles 21–23 are plotted in Fig. 5. Differences in phase lags, loop areas and rate of change of CRI with change in solar parameters during odd and even cycles are evident. To show that these observed features and differences between odd and even cycles are not limited to any one neutron monitoring station but are observed at other neutron monitors also, we have plotted the hysteresis curves using CRI neutron monitor data

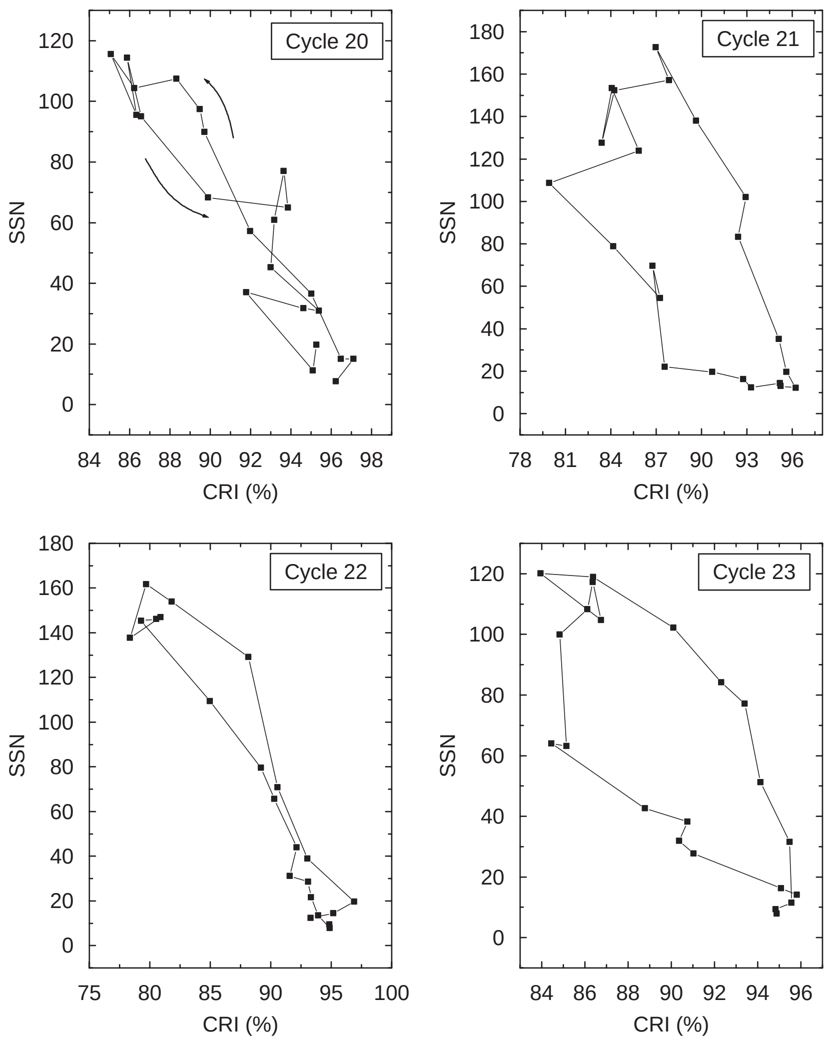

Fig. 6. Hysteresis plots between CRI as recorded by Oulu neutron monitor and SSN for solar cycles 20–23.

from Oulu ($R_c = 0.81$ GV, $\lambda = 65.06°$N) in Figs. 6–8. An interesting and additional feature of these 6-monthly averaged modulation loops is the appearance of secondary loops near/around the solar maximum/polarity reversal in almost each solar cycle; this feature was not apparent in yearly averaged modulation loops of any of the solar cycles (e.g. see Van Allen, 2000).

In order to find the phase lag between cosmic ray intensity and a solar parameter, we have calculated the correlation coefficients between the two by introducing time lags systematically from 0 to 29 months for different solar cycles and plotted the results in Fig. 9. The time lags so obtained are summarized in Table 1. From these tabulated values we see that (a) the time lags between CRI and solar indices (SSN/SRF/SFI) during odd cycles are 10–14 months, while they are only 1–3 months during even cycles, and (b) the difference, if any, in time lag for different solar activity parameters (SSN/SRF/SFI) is small in a particular solar activity cycle.

In order to provide further insight into the observed time lags during various solar activity cycles, adopting the same procedure as for Fig. 9, we have determined the time lags during positive ($A>0$) and negative ($A<0$) polarity epochs excluding the periods of polarity reversal, i.e. during 1952–1956 ($A>0$), 1961–1968 ($A<0$), 1973–1979 ($A>0$), 1982–1989 ($A<0$), 1992–1999 ($A>0$) and 2001–2006 ($A<0$). The lag correlation plots are shown in Fig. 10 and the results are summarized in Table 2. It is found that the time lags are 9–14

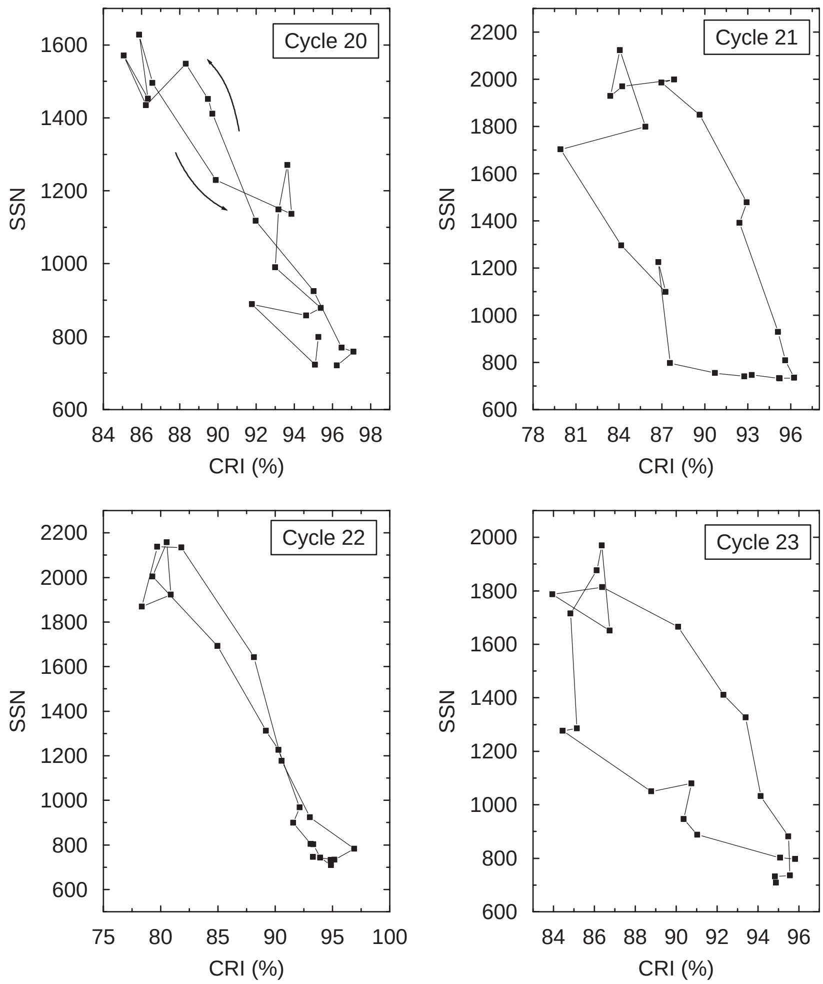

Fig. 7. Hysteresis plots between CRI and 10.7 cm SRF for solar cycles 20–23.

months during the $A<0$ epoch (see Table 2), the exception being 1982–1989 period with one solar activity parameter (SFI). However, the time lags between CRI and solar activity are much smaller (1–5 months) in opposite polarity condition of the heliosphere ($A>0$). It is worth mentioning that in periods of longer time lags (1961–1968, 1982–1989 and 2001–2006), the cosmic ray intensity recovers during $A<0$ polarity conditions. It is also interesting to note that time lags are longer (see Table 1) during odd solar activity cycles; in these solar cycles intensity recovers during the negative polarity state of the heliosphere ($A<0$).

We have also determined the area of the various modulation loops (see Table 3). It is clear from this table that the areas of the odd cycle loops are much larger than the areas of the even cycle loops (also see Van Allen, 2000).

From the hysteresis plots, it appears that the rate of change of CRI with solar activity is different in odd and even cycles. Linear regression analysis has been done for the quantitative estimation of the rate of CRI decrement with SRF during the increasing phase of each solar cycle (Table 4). It is clear from this table that intensity decreases, with solar activity, at a faster rate during initial phase of even solar cycles than of the odd solar cycles. This difference appears to be related to the polarity states of the heliosphere.

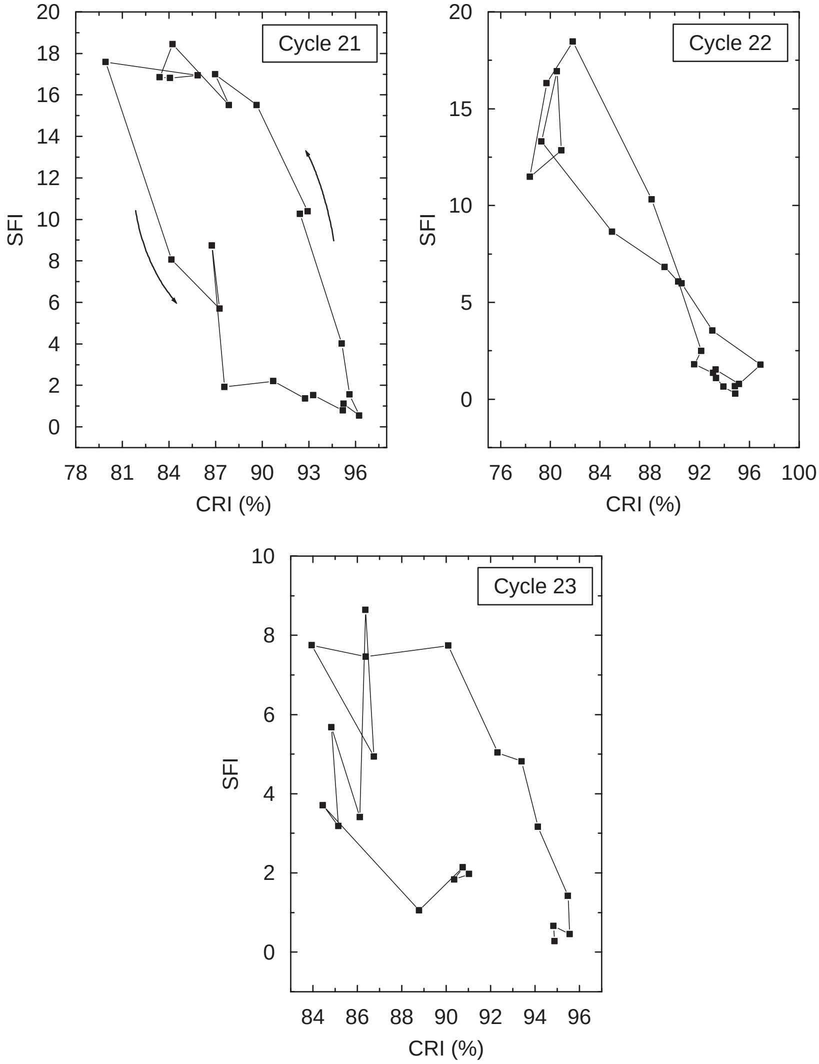

Fig. 8. Hysteresis plots between CRI and SFI for solar cycles 21–23 (up to 2005).

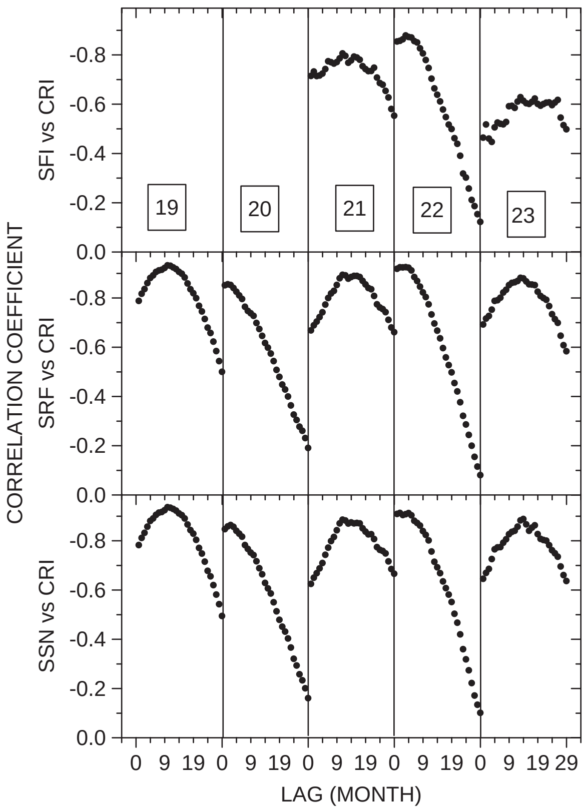

Fig. 9. Time lag correlation of CRI with different indices SSN, SRF and SFI during 19–23.

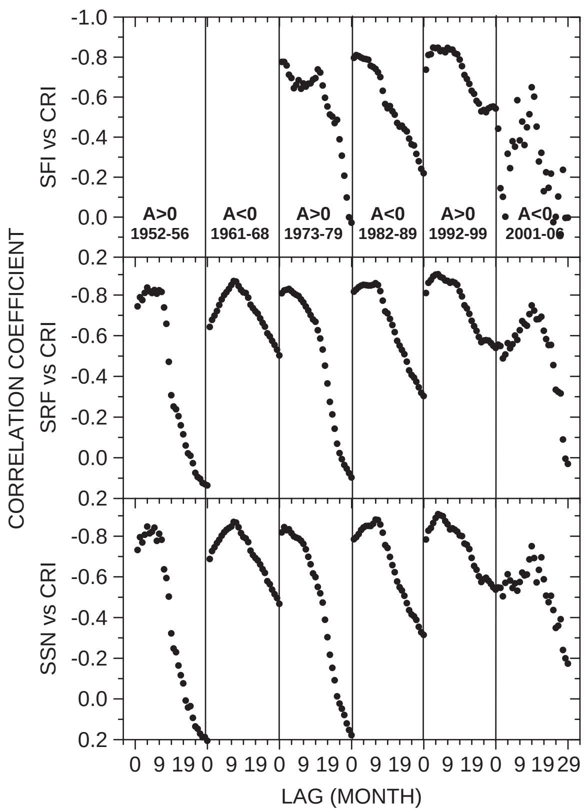

Fig. 10. Time lag correlation of CRI with different indices SSN, SRF and SFI during different polarity states $A>0$ and $A<0$.

Table 1
Time lags between solar activity indices (sunspot number (SSN), solar radio flux (SRF) and solar flare index (SFI)) and CRI (Climax NM) with maximum correlation coefficient (r) for solar cycles 19–23

Solar cycle	Lag (months)			Maximum value of 'r'		
	SSN	SRF	SFI	SSN	SRF	SFI
19	10	10	–	−0.936	−0.932	–
20	02	01	–	−0.863	−0.855	–
21	11	11	11	−0.885	−0.893	−0.806
22	01	03	03	−0.913	−0.925	−0.878
23	15	14	14	−0.832	−0.814	−0.519

Table 2
Time lags between solar activity indices and cosmic ray intensity with maximum correlation coefficient (r) during different polarity epochs ($A<0$ and $A>0$)

Solar polarity	Lag (months)			Maximum value of 'r'		
	SSN	SRF	SFI	SSN	SRF	SFI
$A>0$ (1952–1956)	04	04	–	−0.847	−0.836	–
$A<0$ (1961–1968)	10	10	–	−0.869	−0.868	–
$A>0$ (1973–1979)	01	03	00	−0.844	−0.829	−0.775
$A<0$ (1982–1989)	09	09	01	−0.881	−0.857	−0.809
$A>0$ (1992–1999)	05	05	03	−0.908	−0.902	−0.847
$A<0$ (2001–2006)	14	14	14	−0.750	−0.748	−0.648

It has been reported in some papers that sunspot cycle 23 (an odd numbered) is developing in a manner that is generally similar to cycle 20, an even numbered cycle (e.g. Ozguc and Atac, 2003). For example, heliospheric quantities during the rising phase of cycle 23, in general, better follow the averages and deviations of cycle 20 (Dmitriev et al., 2002). Ozguc and Atac (2003) compared the hysteresis loop of cycle 20 with that of just half of cycle 23 and observed that cosmic rays and flare index have almost same values in these two cycles. On the other hand, Van Allen (2000) and Cliver and Ling (2001) reported that the early phase of cycle 23 resembles more those of cycles 19 and 21.

Table 3
Areas of the solar cycle modulation loops using Climax and Oulu neutron monitor data and sunspot number and solar radio flux

Solar cycle	Sunspot number		Solar radio flux	
	Climax NM	Oulu NM	Climax NM	Oulu NM
19	1599		14,809	
20	108	146	286	1589
21	1262	1067	10,741	9689
22	389	386	1542	1937
23	773	584	7842	5166
Odd cycle average	1211	826	11,131	7428
Even cycle average	249	266	914	1763

Table 4
Decrease in cosmic ray intensity with solar flux ($-\mathrm{d}C/\mathrm{d}I$) during initial (increasing) phase of different solar activity cycles

Cycle	Period	Solar polarity	$-\mathrm{d}C/\mathrm{d}I$	
			Climax NM	Oulu NM
19	1954–56	$A>0$	19.8	
20	1965–68	$A<0$	61.0	88.5
21	1976–79	$A>0$	34.5	46.4
22	1987–89	$A<0$	62.2	80.1
23	1997–99	$A>0$	38.6	48.8
Combined		$A>0$	29.6	47.3
Combined		$A<0$	62.1	83.2

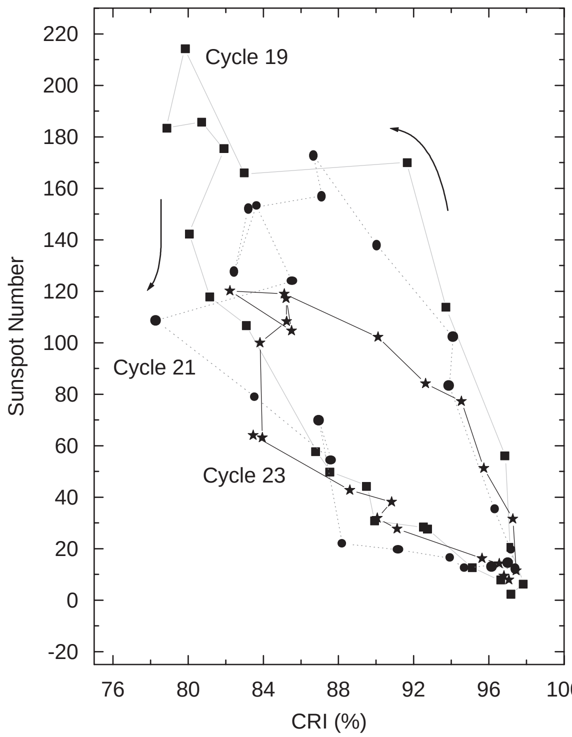

Fig. 11. Comparison of SSN–CRI (Climax NM) hysteresis loops of three odd solar cycles 19, 21 and 23 shown by squares, circles and stars, respectively.

To clarify this controversy, from the CRI modulation point of view, we have plotted hysteresis loops for cycle 23 (up to 2006) with two other odd cycles 19 and 21 (Figs. 11–14) and with even cycles 20 and 22 (Figs. 15–18). We observe that the shape, the rate of change of CRI with solar activity and the area of the cycle 23 loop resemble those of the other odd cycles 19 and 21 (see Tables 3 and 4).

4. Discussion

According to the drift picture of charged particle propagation in the heliosphere, during the initial (increasing) phase of the odd solar activity cycles (e.g. 19, 21, 23) solar polarity is positive ($A>0$) and in this situation positively charged particles enter the heliosphere through the polar regions (see reviews by Venkatesan and Badruddin, 1990; Potgieter et al., 2001). We have found that both the areas of the hysteresis loops and the time lags between solar activity indices (SSN, SRF, SFI) and CRI are larger during odd solar cycles than during the even cycles; this result concurs with earlier studies (e.g. Van Allen, 2000; Kane, 2006a,b). Contributions of certain periodicities seen in neutron monitor data are reported to be different in odd and even cycles (e.g. see Kudela et al., 1991, 2002). It has also been found that the time lags are larger during the $A<0$ epoch when positively charged cosmic ray particles enter the inner heliosphere through the equatorial region (heliospheric current sheet). Under such conditions these particles will be more readily affected by heliospheric current sheet and propagating diffusion barriers associated with solar activity, mainly confined to near equatorial regions. It is known that the solar activity is mostly confined to low-latitude regions on the solar surface (e.g. see Badruddin et al., 1983). Thus, it is likely that larger loop areas and larger time lags observed during odd solar cycles are mainly due to the delayed recovery of cosmic ray intensity as

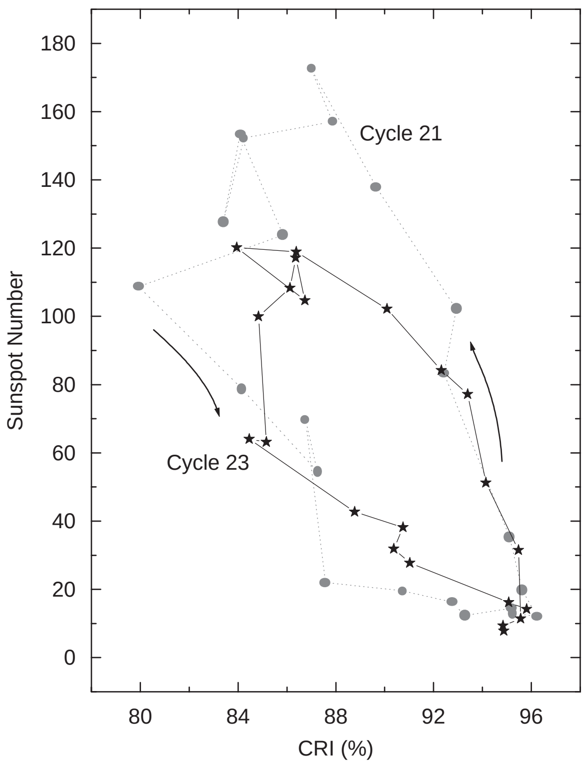

Fig. 12. Comparison of SSN–CRI (Oulu NM) hysteresis loops of two odd solar cycles 21 and 23 shown by circles and stars, respectively.

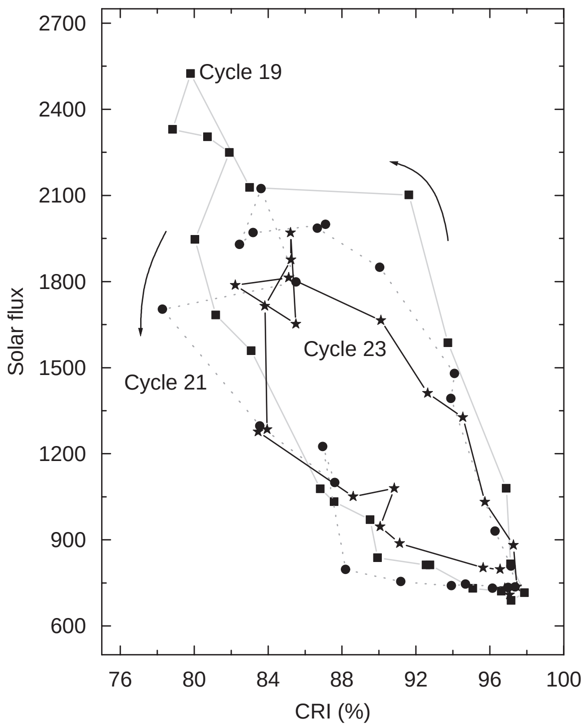

Fig. 13. Comparison of SRF–CRI (Climax NM) hysteresis loops of three odd solar cycles 19, 21 and 23 shown by squares, circles and stars, respectively.

positively charged particles enter the heliosphere through the equatorial region during the recovery phase of the ~11-year modulation.

During even solar cycles, the areas of the loops and the time lag between solar indices and CRI are relatively small. During initial (increasing) phase of the even solar cycles the heliospheric polarity is negative ($A<0$) and positively charged particles enter the heliosphere through the equatorial region. After the polarity reversal near solar maximum, the path of the cosmic ray particles changes and they enter the heliosphere through the polar regions in the $A>0$ polarity condition. After the initial modulation during the increasing solar activity, the recovery is not much delayed due to solar variability because the particles are mainly coming through the polar regions of the heliosphere. Under such conditions these particles will be less sensitive to the heliospheric current sheet and the near equatorial solar activity (also see Cliver and Ling, 2001; Usoskin et al., 2001). Consequently, the recovery is expected to be fast, time lag short and loop area small during even cycles.

The initial slower (faster) rate of decrease in cosmic ray intensity with solar activity during odd (even) cycles can also be explained on the basis of the motion of the charged particles in the heliosphere as the rate of intensity decrement with solar activity is expected to be faster when the particles enter through the equatorial region of the sun.

Similarly, during the declining phases of the odd (even) solar activity cycles, the faster (slower) rate of decrease in intensity can also be understood due to different access routes of the charged particles through equatorial or polar regions. However, the appearance of secondary loops and sometimes even reverse modulation (increasing solar activity resulting in increased CRI) around the solar maximum/polarity reversal may be better explained by considering that near solar maximum/polarity reversal, the route of the cosmic ray particles access may not be well defined. Moreover, the presence of global merged interaction regions (GMIRs) may also be complicating the drift effect during this phase of the solar cycle. Thus, we may expect such

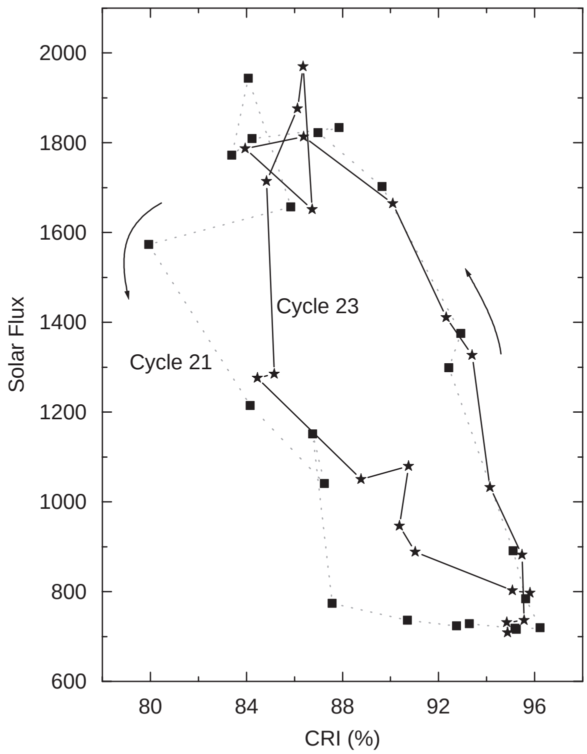

Fig. 14. Comparison of SRF–CRI (Oulu NM) hysteresis loops of two odd solar cycles 21 and 23 shown by squares and stars, respectively.

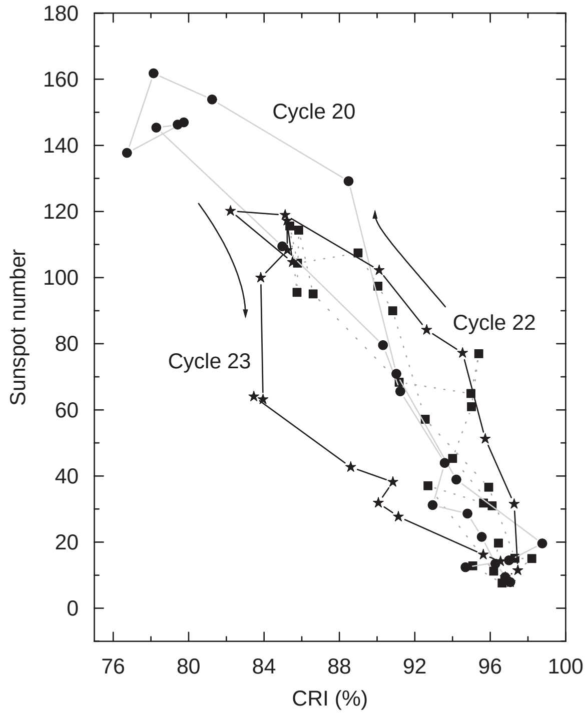

Fig. 15. Comparison of SSN–CRI (Climax NM) hysteresis loop of odd solar cycle 23 with those of two even solar cycles 20 and 22, shown by stars, circles and squares, respectively.

unorganized behavior during and around the solar maximum/polarity reversal periods.

5. Conclusions

In agreement with previous workers, we have found that evolution of cosmic ray intensity is different for odd and even solar activity cycles. The hysteresis loops obtained for different cycles show differences between even and odd cycles. We furnish here further quantitative details about these features.

The average time lags between solar activity and cosmic ray intensity for cycles 19–23 are calculated and found to be 6 months. However, the time lags between cosmic ray intensity and the solar indices are 9–14 and 1–3 months for odd and even cycles, respectively. We found differences in time lags for the periods of $A<0$ and $A>0$ polarity states. It is also observed that the time lag is larger when the recovery phase of long-term (~11-year) modulation of CRI lies in the $A<0$ epoch. The difference in time lags during odd and even cycles does not appear to be related to the level of the solar activity but is due to the motion of cosmic ray particles in the large-scale heliospheric magnetic field influenced by the polarity state of the heliosphere.

Small cyclic changes are superposed at/around solar maximum (polarity reversal) in the modulation loops of almost every cycle (both odd and even). It may be due to Gnevyshev gap effect—double peak structure in the maximum phase of the solar activity cycles (Gnevyshev, 1967) or due to peculiar particle drift effect at solar maximum. At solar maximum (when the tilt of the current sheet is close to 90°), the particles encounter the magnetic fields in the polar regions of both positive and negative polarity and they drift sometimes inward and sometimes outwards (Zhang, 2003). However, the second possibility has a more plausible explanation (see also Kane, 2005).

The areas of odd cycle loops are much larger than even cycle loops. This difference appears mainly due to slow (fast) recovery of cosmic ray intensity during odd (even) solar cycles.

Rates of decrement in intensity of cosmic rays with solar activity during the increasing phase of each solar cycle have been calculated. It is larger for even cycles than for odd cycles. This difference

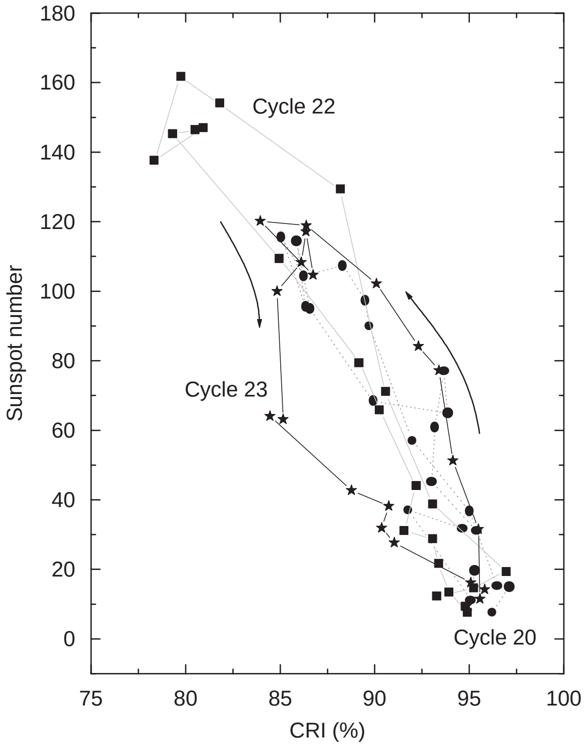

Fig. 16. Comparison of SSN–CRI (Oulu NM) hysteresis loop of odd solar cycles 23 with those of two even solar cycles 20 and 22, shown by stars, circles and squares, respectively.

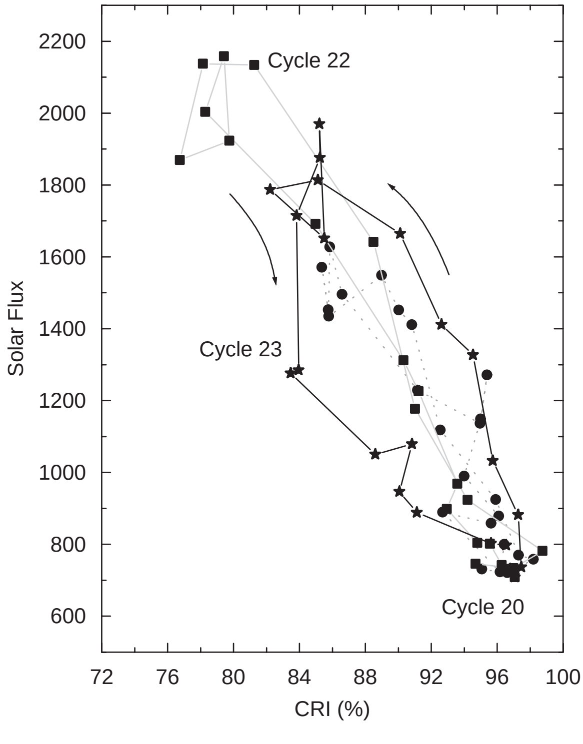

Fig. 17. Comparison of SRF–CRI (Climax NM) hysteresis loop of odd solar cycle 23 with those of two even solar cycles 20 and 22, shown by stars, circles and squares, respectively.

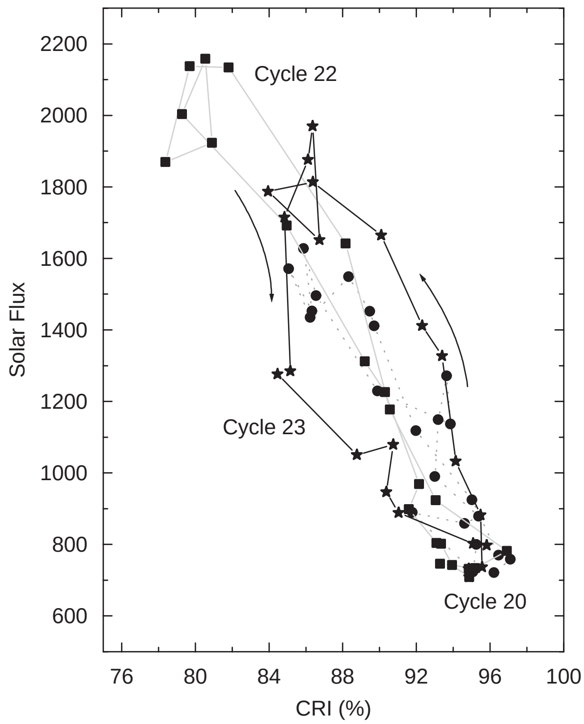

Fig. 18. Comparison of SRF–CRI (Oulu NM) hysteresis loop of odd solar cycle 23 with those of two even solar cycles 20 and 22, shown by stars, circles and squares, respectively.

appears to be related to polarity state of the heliosphere and drift effects in the heliosphere.

The overall structure of cycle 23 loop (shape, area, etc.) resembles with other odd cycles 19 and 21.

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