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Long-term Modulation of Cosmic Ray Intensity in relation to Sunspot Numbers and Tilt Angle

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Abstract. A detailed correlative analysis between sunspot numbers (SSN) and tilt angle (TA) with cosmic ray intensity (CRI) in the neutron monitor energy range has been performed for the solar cycles 21, 22 and 23. It is found that solar activity parameters (SSN and TA) are highly (positive) correlated with each other and have inverse correlation with cosmic ray intensity (CRI). The 'running cross correlation coefficient' between cosmic ray intensity and tilt angle has also been calculated and it is found that the correlation is positive during the maxima of odd cycles 21 and 23. Moreover, the time lag analysis between CRI and SSN, and between CRI and TA has also been performed and is supported by hysteresis curves, which are wide for odd cycles and narrow for even cycles.

Key words. Cosmic ray intensity—sunspot numbers—tilt angle.

1. Introduction

The long-term variations of galactic cosmic rays have been compared with the behaviour of different solar activity indices and heliospheric parameters several times (Belov *et al.* 2002 and references therein). The magnetic field on the source surface determines the structure and properties of the heliomagnetosphere. Therefore, it should be more closely connected with cosmic ray modulation than with other solar characteristics (sunspot numbers or coronal emission intensity). The intensity of galactic cosmic rays varies inversely with sunspot numbers, having their maximum intensity at the minimum of the 11-year sunspot cycle (Forbush 1954, 1958). The cosmic ray intensity curve also appears to follow a 22-year cycle with alternate maxima being flat-topped and peaked as predicted by models of cosmic ray modulation based on the observed reversal of the Sun's magnetic field polarity after every 11-year and curvature and gradient drifts in the large-scale magnetic field of the heliosphere (Jokipii *et al.* 1977; Jokipii & Thomas 1981; Smith 1990).

Recently, features of the interplanetary medium have been explained on the basis of heliospheric neutral current sheet, which separates the whole heliosphere into two regions of opposite polarity of magnetic field. In each hemisphere the field is well approximated by a Parker Archimedian spiral with the sense of the field being outward in one hemisphere and inward in the other. The field direction in each hemisphere altered in each 11-year sunspot cycle. At the solar minimum, the current sheet is nearly equatorial with the northern hemisphere solar magnetic field being in one direction and the southern magnetic field having the opposite sign. The solar magnetic field structure near the sunspot maxima is complex, where it corresponds roughly to increasing the inclination of the current sheet. The inclinations of the heliosphere neutral current sheet along the equatorial plane of heliosphere are often named as tilt angles. The waviness of neutral current sheet, i.e., tilt angle has been used as solar/interplanetary index by various investigators to explain the long-term modulation of cosmic rays (Webber & Lockwood 1988; Swinson & Yasue 1992; Ahluwalia 1992). The tilt angle is computed by averaging the maximum latitude through the neutral line in the north and south hemispheres in each Carrington rotation. The heliospheric neutral current sheet and its waviness provide us some basic physical mechanism to explain the long-term modulation of galactic cosmic rays.

Many researchers have studied that correlation between CRI and TA is better during qA < 0 than qA > 0 (Belov 2000; Iskra & Wybraniec 2001; Usoskin *et al.* 2003). In this paper we have made an attempt to correlate CRI with TA and SSN to explain the momentary behaviour of cross correlation function with respect to time (by running cross correlation method) during the whole investigation period. Moreover, the time-lag analysis between CRI and solar activity (SA) parameters has also been performed by the 'minimizing correlation coefficient method' and these results have been verified by the different shapes of hysteresis curves obtained by the cross plot of CRI and SA parameters.

2. Data and method of analysis

In the present work, SSN and TA (waviness of heliospheric neutral current sheet) have been considered as SA parameters to study the long-term modulation of CRI for the period of 1976 to 2005. To study the average behaviour of cosmic ray intensity, monthly mean values of neutron monitor stations of different cut-off rigidity (Oulu, Kiel and Huancayo) have been used, whereas the values of TA were obtained from the Wilcox Solar Observatory (WSO, classical model).

The correlation coefficient between cosmic ray intensity and different solar activity parameters with time lag has also been calculated for the said period using the method of 'minimizing correlation coefficient method'. Here we have selected both the series CRI and TA for the same period with zero time lag and then shifted one series by a step of one month and calculated the cross correlation coefficient between both the series. Similarly, the other series has also been shifted by one month and the new value of cross correlation coefficient is calculated. As such, the time (number of shifted months) is obtained, when the anti-correlation coefficient is maximum. This is the time lag between both the series CRI and TA. The probable error for each value of correlation coefficient has been calculated by the formula: P.E. $= 0.6745(1 - r^2)/\sqrt{N}$, where r is correlation coefficient and N is the number of samples.

In the present paper the 'Running cross correlation method' has been used to study the relationship between CRI and solar activity indices (Usoskin *et al.* 1998; Mishra & Tiwari 2003). In the said method we use a time window of width T centered at time t: $[t - T/2, t + T/2]$. The cross correlation coefficient $c(t)$ is calculated for data within this window. Then the window is shifted in time by a small time step $\Delta t < T$ and the new value of the cross correlation coefficient is calculated. Here we have used the time shifting of one month to calculate the correlation coefficient for each month between CRI and SSN and for CRI and TA for the period 1976 to 2005. The time window of 50 months has been taken. This value was chosen to match two contradictory requirements; (i) uncertainty of the calculated $c(t)$ is smaller for large T and (ii) T should be small in order to reveal the fine temporal structure of the cross correlation function.

Moreover, the hysteresis curve between CRI and SSN, and CRI and TA has been sketched by taking 30 months moving average of both the data series.

3. Results and discussion

The relationships of sunspot numbers and TA to cosmic ray intensity have been studied earlier (Cliver *et al.* 1996; Cliver and Ling 2001). The inverse correlation between TA and cosmic ray intensity along with 22-year patterns is observed in the evolution of TA. Here an attempt has been made to extend the study to the recent period in order to establish the relationship of sunspot numbers and TA to cosmic ray intensity considering low (Oulu, Rc ~ 1 GV), middle (Kiel, Rc ~ 3 GV) and high (Huancayo, Rc ~ 13 GV) cut-off rigidity neutron monitor stations for the period 1976 to 2005 (solar cycles 21, 22 and 23).

To see the associative behaviour of different cut-off rigidity stations with TA, we have used the % of monthly mean value of CRI for Oulu (Rc ~ 1 GV) Kiel (Rc ~ 3 GV) and Huancayo (Rc ~ 13 GV) from 1976 to 2005. Figure 1 shows overall inverse correlation between TA and % CRI (100% normalized at May 1965) of all the three stations during the whole period of investigation. Looking at the similar behaviour of low to high cut-off rigidity stations, we have chosen the monthly mean value of Kiel (Rc ~ 3 GV) a middle cut-off rigidity neutron monitor station. The variation of CRI (Kiel) and TA

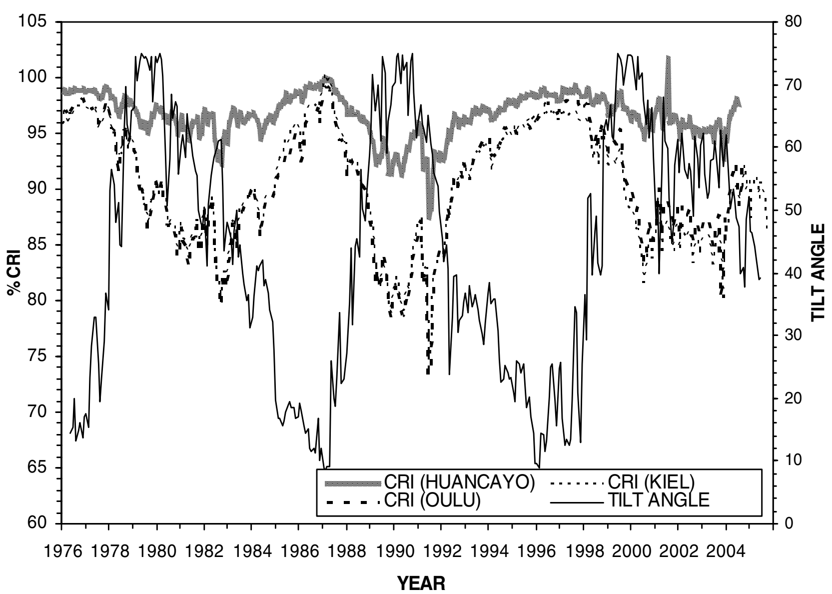

Figure 1. Shows the long-term variation of cosmic ray intensity observed by Oulu, Kiel and Huancayo neutron monitors along with tilt angle from 1976 to 2005.

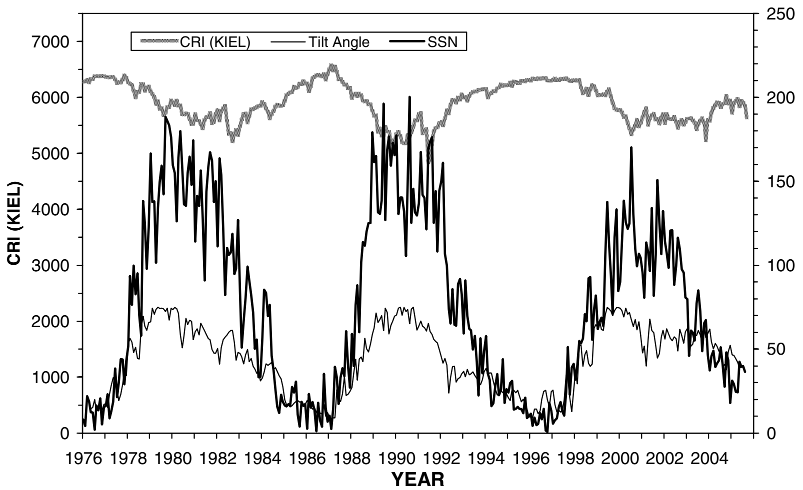

Figure 2. Shows the long-term variation of tilt angle and sunspot numbers with monthly count rates of cosmic ray intensity observed at Kiel neutron monitor for the period 1976 to 2005.

along with sunspot numbers from 1976 to 2005 is shown in Fig. 2. The sunspot number and TA shows a similar pattern and high degree of correlation (positive) with each other whereas cosmic ray intensity is inversely correlated with TA as well as with sunspot numbers with some period time lag during the whole period of investigation. Now we have calculated the cross correlation coefficient between CRI and TA and between CRI and SSN by shifting of both the series one by one by a step of one month. The cross correlation coefficient factor between CRI and TA and between CRI and SSN with different time lags and statistical error bars for solar cycles 21, 22 and 23 is shown in Figs. 3 and 4, respectively. It is observed that during odd cycles 21 and 23 the time lag between CRI and TA is $\sim$17 and 11 months at the time of maximum anti-correlation coefficient ($r \sim -0.8$) whereas for even cycle 22 the time lag has been found to be $\sim$ 2 months at the time of maximum anti-correlation coefficient ($r \sim -0.9$). It is $\sim$12 and 14 months for odd solar cycles 21 and 23 and $\sim$ 4 months for even solar cycle 22 in the case of CRI and SSN (Table 1). Now we have calculated the running cross correlation between CRI and TA and also for CRI and SSN. From Fig. 5, it is observed that running cross correlation function $c(t)$ is positive during the maxima of odd cycles 21 and 23 for both the cases, i.e., for CRI–SSN and CRI–TA. However, the value of cross correlation coefficient is almost similar in the case of CRI–TA relationship ($\sim$ 0.6) for both the cycles 21 and 23 and it is different in the case of CRI–SSN, which is $\sim$ 0.3 and $\sim$ 0.08 for cycles 21 and 23, respectively. This type of analysis is necessary to explain the momentary behaviour of cross correlation function with respect to time, the value of correlation coefficient is different for the different phases of the same solar cycle and it changes with time. The values obtained by this method if averaged over a cycle, will represent the correlation coefficient for a particular cycle. This shows the 22-year variational pattern of cosmic ray intensity and supports the odd–even hypothesis of the CRI cycles. The differences observed in the relationship between CRI and SSN and CRI and TA is perhaps attributable to the different sunspot activity in solar cycles 21 and 23, which is also clear from Fig. 2.

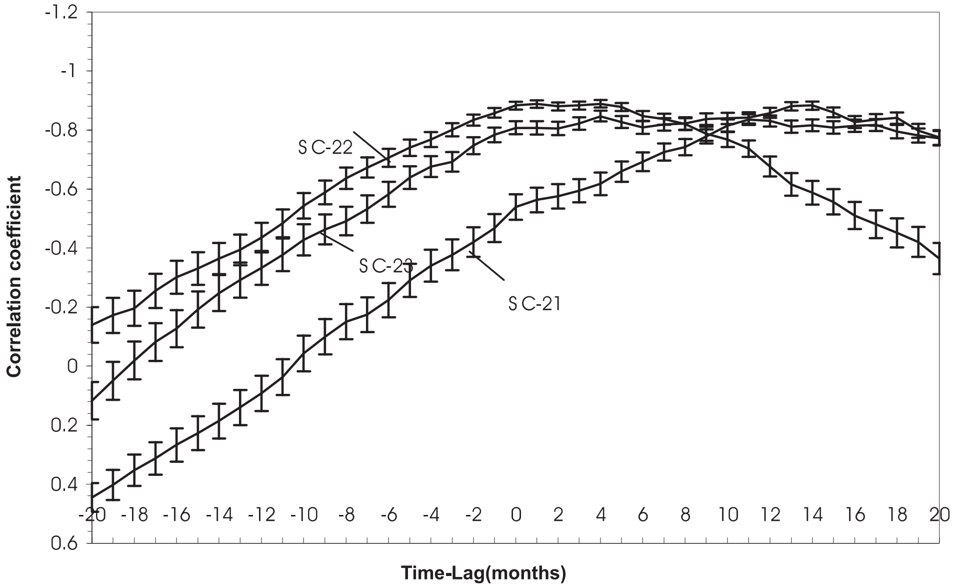

Figure 3. Shows the cross correlation coefficient factor between cosmic ray intensity (Kiel) and tilt angle with different time lags for solar cycles 21, 22 and 23. The statistical error bars are also shown for each value of the correlation coefficient.

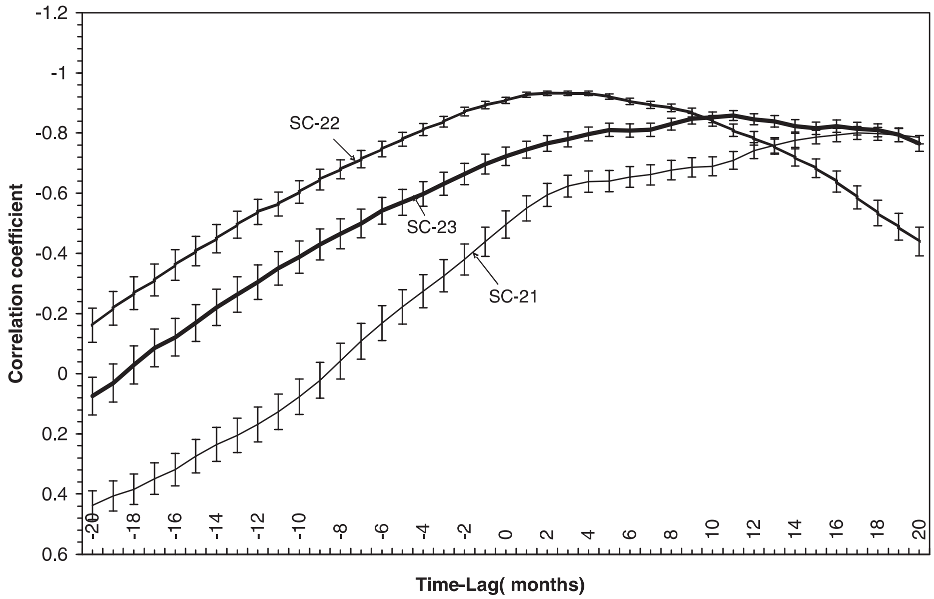

Figure 4. Shows the cross correlation coefficient factor between cosmic ray intensity (Kiel) and sunspot numbers with different time lags for solar cycles 21, 22 and 23. The statistical error bars are also shown for each value of the correlation coefficient.

Table 1. Correlation coefficient between CRI and SSN, and CRI and TA without time lag and with time lag for solar cycles 21, 22 and 23.

	CRI–SSN			CRI–TA		
	Correlation coefficient			Correlation coefficient		
Solar cycles	Without time lag	With time lag	Time lag (months)	Without time lag	With time lag	Time lag (months)
21	−0.539	−0.835	12	−0.495	−0.8002	17
22	−0.882	−0.888	4	−0.908	−0.932	2
23	−0.807	−0.882	14	−0.722	−0.858	11

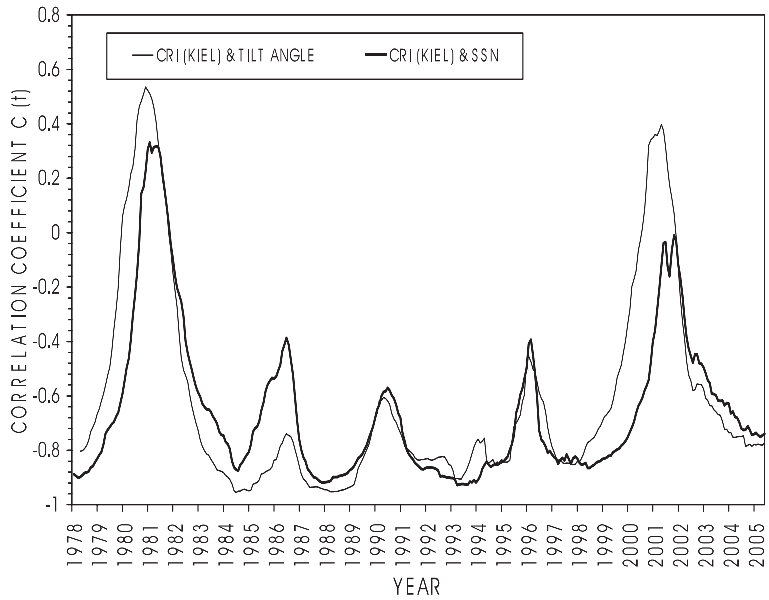

Figure 5. Shows the running cross correlation coefficient $c(t)$ between cosmic ray intensity (Kiel) and sunspot numbers as well as between cosmic ray intensity (Kiel) and tilt angle from 1976 to 2005.

From Fig. 5, it is also evident that there is a 5.5-year periodicity in the observed peaks occurred which is half of the (11-year) solar cycle period. The TA behaviour is similar during the rising phases of the solar cycles 21, 22 and 23 and different during the declining phase of the solar cycle 23 than the solar cycles 21 and 22 (Fig. 2). The similarities in the TA evolution during the rising of cycles 21 and 22 have also been reported (Suess *et al.* 1993; Cliver 1993; Cliver & Ling 2001).

To support the time lag findings, we have further plotted the hysteresis curves between CRI and TA as well as between CRI and SSN, which are shown in Figs. 6 (a, b and c) and 7 (a, b and c), respectively, for the solar cycles 21, 22 and 23. It has been observed that the hysteresis loops for CRI–TA and CRI–SSN are wider for odd cycles and narrow for even cycles, which supports the even–odd asymmetry of the cycles.

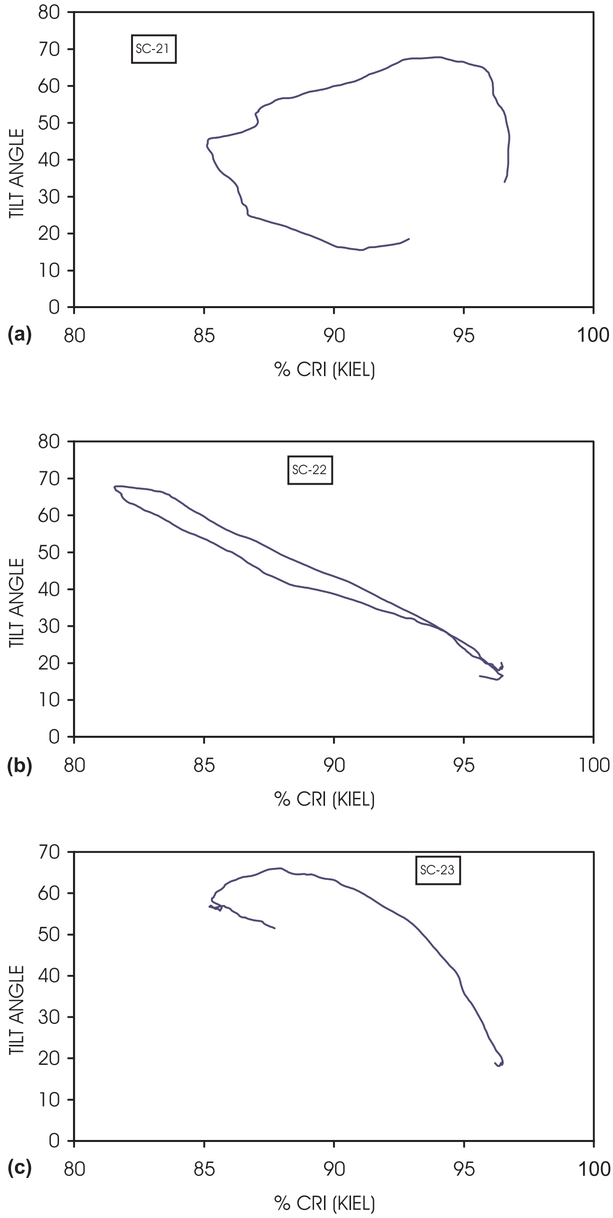

Figure 6 (a, b and c). Shows the hysteresis curves between CRI and tilt angle for the solar cycles 21, 22 and 23, respectively. The different shapes of curves for odd and even cycles are clearly apparent from the figure.

In the drift formulation of cosmic-ray modulation (Jokipii *et al.* 1977; Potgieter 1998), positively charged cosmic rays preferentially enter the heliosphere from the direction of the solar poles during $qA > 0$ cycles (corresponding to times when the polarity of the solar magnetic field is outward in the northern hemisphere) such as ∼1970–1980 and ∼1990–2000. During $qA < 0$ periods such as ∼1980–1990 when

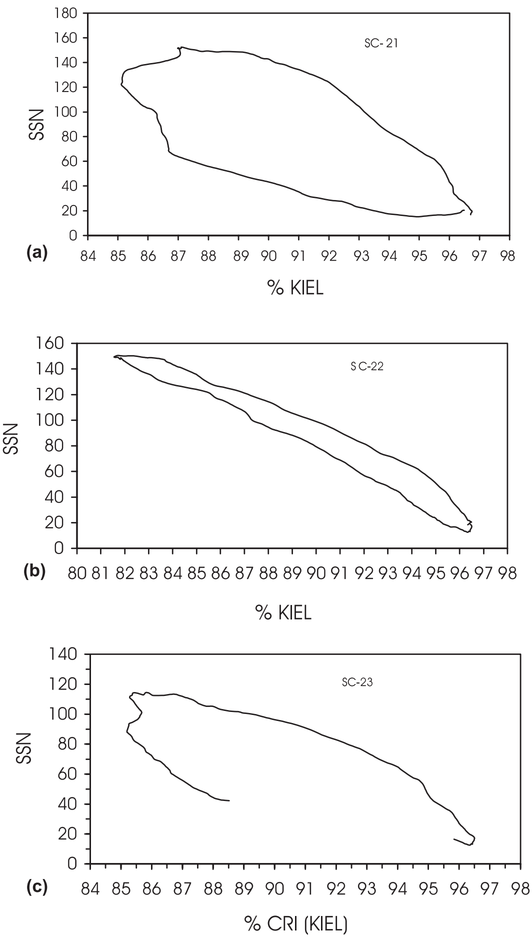

Figure 7 (a, b and c). Shows the hysteresis curves between CRI and SSN for the solar cycles 21, 22 and 23, respectively. The different shapes of curves for odd and even cycles are clearly apparent from the figure.

the solar field polarity is reversed, cosmic rays (positively charged) approach the Sun from along the HCS. During $qA > 0$ times, it might be expected that incoming cosmic rays will be less affected by drift effects associated with an increase in the TA at the beginning of a solar cycle (odd-numbered) or by diffusion associated with enhanced coronal mass ejection (CME) activity. CMEs, which are thought to be a key element in diffusion/convection-based pictures of modulation (Burlaga *et al.* 1984), are characteristically confined to the Sun's equatorial regions early in the solar cycle and appear at higher latitudes during the course of the cycle as the streamer belt at the base of the HCS moves poleward. At the beginning of even-numbered cycles ($qA < 0$), when cosmic rays approach the Sun along the HCS, they will be more readily affected by changes in the TA and low-latitude CMEs. Thus, the difference in the responsiveness to solar activity changes at the onset of even- and odd-numbered solar cycles is consistent with a drift effect (Smith 1990).

While the TA increase was remarkably similar during the rise phase of the last three cycles (Fig. 2), there is evidence that HCS evolution may differ on the decline of even and odd-numbered solar cycles. Specifically, the TA appears to collapse to low angles more rapidly during the decline of even-numbered cycles such as 22 (peak in $\sim$1990). We conclude that the differences observed in the relationship between CRI and SSN, and CRI and TA may be due to the low activity of the solar cycle 23.

The understanding of the solar modulation of galactic cosmic rays is still based on the standard model of diffusion, convection and adiabatic deceleration effect, where the interplanetary magnetic field lines including drift processes determine the path of individual particles through the heliosphere. This leads to characteristic differences between adjacent solar cycles due to the different polarity of the solar and large-scale interplanetary magnetic fields. The polarity of the solar magnetic field reverses the sign about every 11-year near the time of maximum solar activity. Thus successive activity maxima are characterized by different solar field polarity. However, for a better understanding of odd-even cycle's differences, the influences of curvature of interplanetary magnetic field on the transport of cosmic ray should also be considered.

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