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"Correlation of the cosmic ray intensity variations with sunspot numbers and tilt angle from solar cycle 21 to present solar cycle 24"

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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 cycle 21,22,23 and present solar cycle 24.It is an observed fact that sunspot numbers and tilt angle are highly correlated with each other and cosmic ray intensity shows inverse correlation with them during the entire period of investigation. The running cross correlation coefficient between CRI-SSN and CRI-TA have been obtained considering time lag factor and it is found that the correlation is unusually positive during maxima of odd solar cycles 21 and 23 and the time lag is larger for odd solar cycles in comparison to even solar cycles. It has been noticed that the behaviour of solar cycle 23 in declining phase is different than solar cycle 21 & 22 and tilt angle does not coincides with the sunspot activity during the minima of present solar cycle 24. Solar cycle 24 began after an unusually deep solar minimum that lasted from 2007 to 2009. In fact, during 2008 and 2009 there were almost negligible sunspots, causing a very unusual situation during solar minimum for almost a century. The maximum activity of solar cycle 24 and its unusual pattern are discussed with reference to earlier solar cycles.

Keywords: cosmic ray intensity; sunspot numbers; Tilt Angle

I. INTRODUCTION

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, Potgieter 1998).

Recently, features of the interplanetary medium have been explained on the basis of heliospheric neutral current sheet, which separates the whole heliosphere into the 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 Angle. 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 and Lockword 1988, Swinson&yasue, 1992, Ahluwalia 1992). The Tilt Angle (α) is computed by averaging the maximum latitude through the neutral line in the north and south hemisphere 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 Tilt Angle is better during qA<0 than qA>0 (Belov, 2000, Iskra&Wybraniec, 2001, Usoskin et al., 2003, Gupta et al, 2006). In this paper we have made an attempt to correlate CRI with Tilt Angle and SSN to explain the momentary behavior of cross correlation function with respect to time (by running cross correlation method) during the whole investigation period.

II. DATA AND METHOD OF ANALYSIS

In this work, we have taken waviness of heliospheric neutral current sheet (HCS) or Tilt Angle as a key parameter in drift model of modulation and the cosmic ray intensity for the period of 1976 to 2015. 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 Tilt Angle 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 Tilt Angle for the same period with zero time-lag and then shifted one series by a step of one months and calculated the cross correlation coefficient between both the series. Similarly, the other series has also been shifted by one months 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 Tilt Angle. The probable error for each value of correlation coefficient has been calculated by the formula: P.E. = $0.6745\ (1-r^2) / \sqrt{N}$.

In the present paper “Running cross correlation method” has been used to study the relationship between CRI and solar activity indices (Usoskin et al., 1998, Mishra &Tiwari, 2003, Gupta et al, 2006). 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 Tilt Angle for the period 1976 to 2015. The time window has been taken of 50-months. This value was chosen to match two contradictory requirements (i). uncertainty of the calculated c(t) are smaller for large T and (ii). T should be small in order to reveal fine temporal structure of the cross correlation function.

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

III. RESULTS AND DISCUSSION

The relationships of sunspot numbers and Tilt Angle to cosmic ray intensity have been studied earlier (Cliver et al., 1996, Cliver& Ling, 2001). The inverse correlation between Tilt Angle & cosmic ray intensity along with 22-year patterns is observed in evolution of Tilt Angle. Here an attempt has been made to extend the study for recent period to establish the relationship of sunspot numbers and Tilt Angle to cosmic ray intensity considering low (Oulu, Rc~1GV), middle (Kiel, Rc~3 GV) and high (Huancayo, Rc~13 GV) cut off rigidity neutron monitors stations for the period 1976 to 2015 (solar cycle 21, 22, 23&24).

To see the associative behaviour of different cut-off rigidity stations with Tilt Angle, we have used the % of monthly mean value of CRI for Oulu (Rc~1GV) Kiel (Rc~3GV) &Huancayo (Rc~13GV) from 1976 to 2015. Fig.1 shows overall inverse correlation between Tilt Angle and % CRI (100% normalized at May 1965) of all the three stations during the whole period of investigation. Looking the similar behaviour of low to high cut-off rigidity stations, we have chosen the monthly mean value of Oulu (Rc~1GV) a low cut-off rigidity neutron monitor station. The variation of CRI (Oulu) and Tilt Angle along with sunspot numbers from 1976 to 2015 is shown in fig.2. It is clearly apparent that more cosmic rays reach to the earth due to low solar activity of solar cycle 24 (fig.1,2). The sunspot number and Tilt Angle is showing similar pattern and high degree of correlation (positive) with each other whereas cosmic ray intensity is inversely correlated with Tilt Angle as well as with sunspot numbers with some period time lag during the whole period of investigation. The average correlation coefficient between CRI and SSN for the solar cycles 21, 22, 23 & 24 is ~ -0.514, -0.771,-0.591 & -0.639 respectively. The correlation between CRI and Tilt Angle is ~ -0.445, -0.796, -0.522 & -0.703 for the solar cycles 21, 22, 23 & 24 respectively. Now we have calculated the cross correlation coefficient between CRI and Tilt Angle by shifting of both the series one by one by a step of one month. The cross correlation coefficient factor with different time lag for solar cycles 21, 22,23& 24. It is observed that during odd cycles 21 and 23 the time lag between CRI and Tilt Angle is ~ 19 & 09-months at the time of maximum anti-correlation coefficient (c(t) ~ - 0.8) whereas for even cycle 22 and 24 the time-lag has been found to be ~01 & 09-months at the time of maximum anti-correlation coefficient (c(t) ~ - 0.9 & - 0.7). It is ~17 & 14-months for odd solar cycles 21 & 23 at the time of maximum anti-correlation coefficient (c(t) ~ - 0.8) and ~ 01 & 13-months for even solar cycle 22 and 24 at the time of maximum anti-correlation coefficient (c(t) ~ - 0.9) in the case of CRI and SSN. It is obvious from the above observational results that present solar cycle 24 does not follow the established hypothesis of small time-lag during the odd cycles. Now we have calculated the running cross correlation between CRI & Tilt Angle and also for CRI & SSN. From fig-3.it is observed that running cross correlation function c(t) is positive during the maxima of odd cycle 21 & 23 for both the cases i.e. for CRI-SSN and CRI-Tilt Angle.

However, the value of cross correlation coefficient is almost similar in the case of CRI-Tilt Angle relationship (~ 0.6) for both the cycles 21 & 23 and it is different in the case of CRI-SSN, which is ~ 0.3 and ~ 0.08 for cycles 21&23 respectively. Moreover, the running cross correlation coefficient is strong during ascending and descending phases of all the solar cycles and it is weak during extrema (maxima and minima) of the cycles. As for as solar cycle 24 is concerned, the maximum anti-correlation coefficient is observed to be strong (-0.8 to -0.9) during 20011 (ascending phase of cycle 24) and it becomes weak (-0.3) during 2008 (minima of the cycle).Though, the solar cycle 24 follows the previous solar cycles but the level of minimum anti-correlation has been maintained for along time (more than one year) perhaps due to the long lasting minimum solar activity during thestarting of solar cycle 24.This type of analysis is necessary to explain the momentary behavior of cross correlation function with respect to time, the value of correlation coefficient is different for the different phases of 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 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-SSN and CRI-Tilt Angle is perhaps attributable due to the different sunspot activity in solar cycles 21&23, which is also clear from fig-2. From which it is evident that there is 5.5-year periodicity in the observed peaks occurred which is half of the (11-year) solar cycle period. The Tilt Angle behaviour is similar during the rising phases of the solar cycles 21, 22, 23 & 24 and different during the declining phase of the solar cycle 23 than the solar cycles 21 and 22 (fig-2). The similarities in the Tilt Angle evolution during the rising of cycles 21 and 22 have also been reported (Suess et al., 1993, Cliver , 1993, Cliver& Ling, 2001, Gupta et al, 2006).

To support the time lag findings, we have further plotted the hysteresis curves between CRI and Tilt Angle as well as between CRI and SSN, which are shown in figures 4 (a, b, c & d) and 5 (a, b, c & d) for the solar cycles 21, 22, 23 & 24 respectively. It has been observed that the hysteresis loops for CRI-Tilt Angle and CRI-SSN are wider for odd cycles and narrow for even cycles, which supports the even-odd asymmetry of the cycles. The present solar cycle 24 has not been completed till now. But the hysteresis curves between SSN-CRI as well as between TA-CRI are not showing symmetry with the previous even cycles (cycle 22 and 24 in present case).

While the Tilt Angle 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 Tilt Angle appears to collapse to low angles more rapidly during the decline of even-numbered cycles such as 22 (peak in ~1990). We conclude that the differences observed in the relationship between CRI-SSN and CRI-TA may be due to the low activity of the solar cycles 23. The data available for the solar cycle 24 till now shows a strange behavior in respect to solar activity during minima and maxima of solar cycle.

The understanding of the solar modulation of galactic cosmic rays is still based on the standard model of diffusion, convection and adiabatic declaration 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 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. The continuous long duration and constant low sunspot activity of present solar cycle and very low solar activity during all over the cycle till now, could provide us an unique opportunity for the understanding of cosmic ray modulation in the low activity periods of the cycles.

A. Figures

Fig-1.Shows the long-term variation of cosmic ray intensity (Oulu, Kiel &Huancayo) with Tilt Angle from 1976 to 2015.

Fig-2.Shows the monthly variation of Tilt Angle and sunspot numbers with cosmic ray intensity (Oulu) from 1976 to 2015.

Fig-3. Shows the running cross correlation coefficient c(t) between cosmic ray intensity (Oulu) & sunspot numbers as well as between cosmic ray intensity (Oulu) & Tilt Angle from 1976 to 2015.

Fig-4 (a, b ,c& d). Shows the hysteresis curves between CRI (Oulu) and Tilt Angle for the solar cycles 21, 22, 23 &24 respectively.

Fig-5 (a, b, c & d). Shows the hysteresis curves between CRI (Oulu) and SSN for the solar cycles 21, 22, 23 &24 respectively.

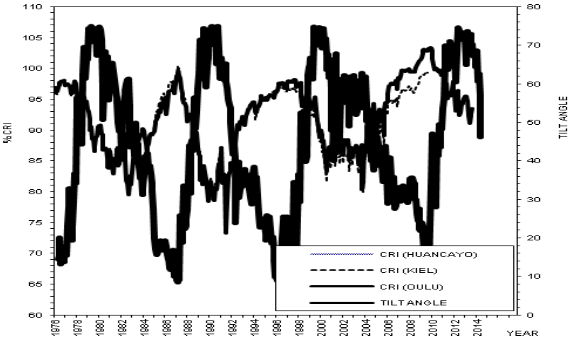

Figure-1.

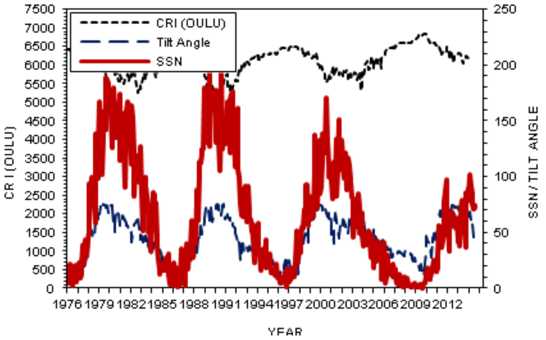

Figure-2.

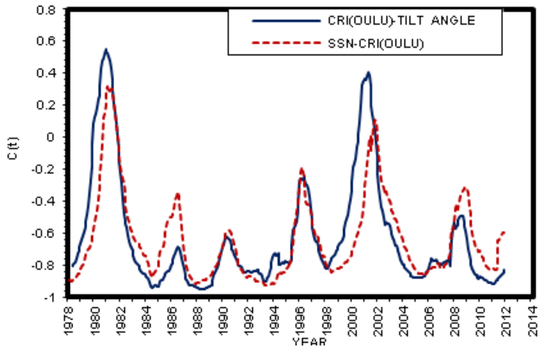

Figure-3

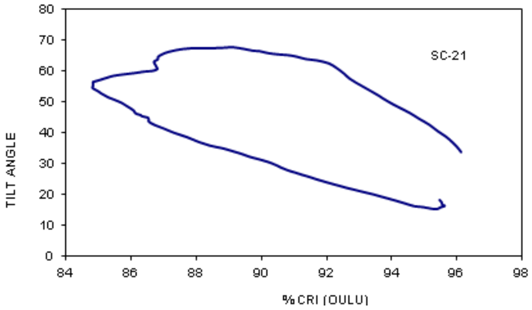

Figure-4(a).

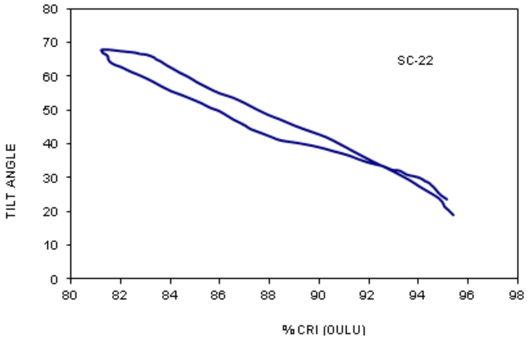

Figure-4(b).

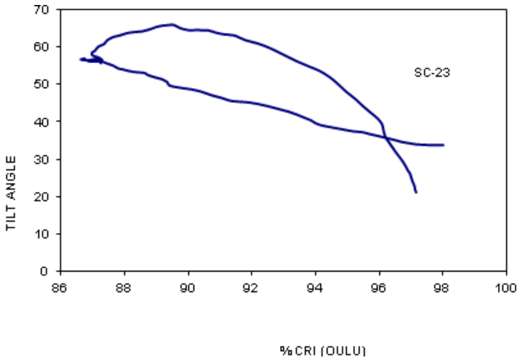

Figure -4(c).

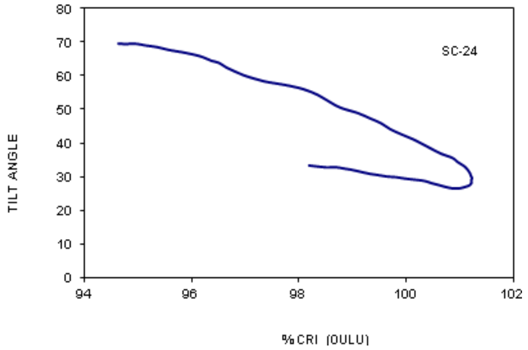

Figure- 4(d)

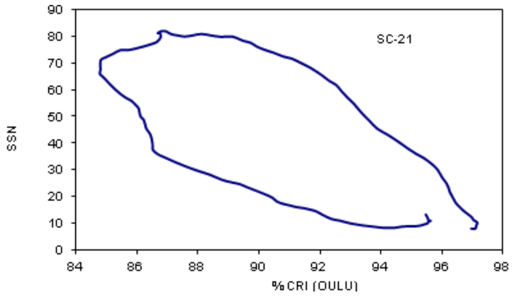

Figure -5(a).

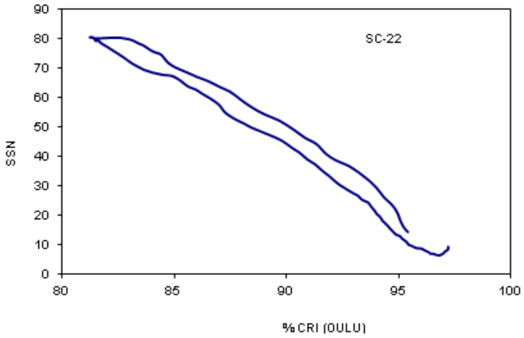

Figure -5(b).

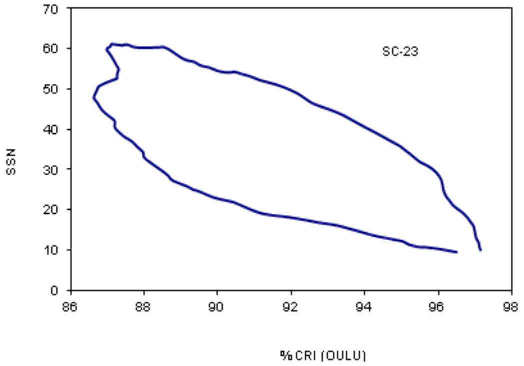

Figure -5©.

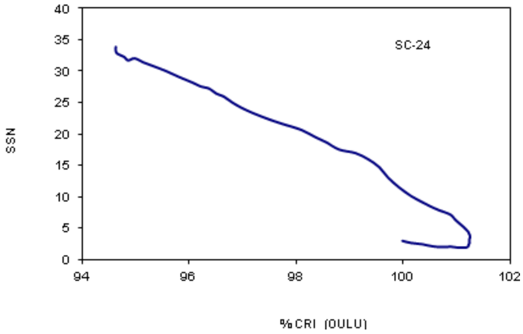

Figure -5(d).

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