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Study of solar activity and cosmic ray modulation during solar cycle 24 in comparison to previous solar cycle

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Abstract: Based on the monthly data of sunspot numbers (SSN), sunspot area of full disc (SSA) and cosmic ray intensity (CRI) observed by neutron monitors (NM) located at Oulu (Cut off Rigidity = 0.8 GV) and Moscow (Cut off Rigidity = 2.3 GV), the trend of solar activity variation and cosmic ray modulation has been studied during the cycles 23 & 24. The SSN have maintained its minimum level exceptionally for a long period (July 2008–Aug. 2009) of time. The intensity of galactic cosmic rays measured by ground based detectors is the highest ever recorded by Oulu NM since April 1964 during the recent solar minimum. Furthermore, the maximum value of SSN is found to be very low in the present cycle in comparison to previous solar cycles (19–23). The correlation coefficient between SSN and CRI without and with time-lag as well as regression analysis during the solar cycle 24 (Jan. 2008–Dec. 2015) has been estimated and compared with previous solar cycle. Based on the maximum value of correlation coefficient, the time-lag during present solar cycle is found to be 4 and 10 months for both the stations, while it is 13–14 months during cycle 23. The behaviour of running cross correlation function has also been examined during present solar cycle and it is found that it attains its maximum value ~ -0.8 to ~ -0.9 for a long duration in comparison to previous cycles. The variation of SSN and SSA has also been compared and found that they are highly correlated to each other ($r > .92$) for both the cycles. In the light of exceptional behaviour of solar cycle 24, the trend of cosmic ray modulation has been discussed and compared with earlier cycles.

Keywords: Sunspot numbers; Cosmic rays; Neutron monitors; Solar cycles

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1. Introduction

It is established long back that the intensity of galactic cosmic rays (GCR) varies inversely with sunspot numbers (SSN) having their maximum intensity at the minimum of the 11-year sunspot cycle [1, 2]. The cosmic ray intensity (CRI) curve also appears to follow a 22-year cycle with alternate maxima being flat-topped and peaked. The models of cosmic ray modulation based on the observed reversal of the solar magnetic field polarity after every 11-year alongwith curvature and gradient drifts in the large-scale magnetic field of the heliosphere have been discussed in the literature from time to time [3–6].

Long-term cosmic ray modulation can be studied by analysing the monthly data of global network of neutron monitoring stations having different cut-off rigidities. Neutron monitors (NMs) are most sensitive to cosmic rays in the energy range from 0.5 to 20 GeV, which coincides with maximum energy response for effective solar modulation. Earlier results have indicated that the time-lag exists in the correlation between the long-term variation of solar activity and its effect on cosmic rays, which varies from one cycle to other and even during different phases of the same solar cycles [7 and the references therein]. A statistical technique, namely, "running cross correlation" has been used to study the correlation between SSN and CRI during different phases of the solar activity cycle [7–10]. Generally, the sunspot numbers (SSN) are used as an indicator of solar activity to study the long-term relationship between solar activity and cosmic rays. On the monthly average basis, the SSNs, are highly correlated with other solar parameters and hence, SSNs are safely used as a solar activity parameter for correlative studies, until and unless there are some specific reasons to use other

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available solar parameters (or indices) [11]. Though, the SSN and sunspot area (SSA) are highly correlated to each other, however, SSA are reported to be better parameter for physical measures of the solar activity [12]. The long-term modulation of CRI using different solar parameters for previous solar cycles has been studied in detail by various investigators [7, 8, 10, 13].

In the present paper, we have tried to investigate the trend of cosmic ray modulation associated with solar activity variation during the present solar cycle 24, in relation to previous solar cycle, based on the monthly data of solar activity parameters (SSN and SSA) and CRI recorded by Oulu and Moscow Neutron Monitors (Cut off Rigidity = 0.8 and 2.3 GV respectively).

2. Data and method of analysis

In this study, we have taken the CRI monthly mean data of Oulu NM (Cut off Rigidity = 0.8 GV) and Moscow NM (Cut off Rigidity = 2.3 GV) along with SSN and SSA as solar parameter. The cosmic ray data for Oulu NM is available through the website (https://cosmicrays.oulu.fi) since April, 1964, Moscow NM data have been taken from website http://cr0.izmiran.rssi.ru/mosc/main.htm, while SSN data are available at the website (http://www.sidc.be/silso/datafiles). WDC-SILSO, Royal Observatory of Belgium, Brussels, has recently (June 2015) adjusted their original observed sunspot numbers (Version 1.0) to a Version 2.0 series. The series of new (Version 2.0) sunspot numbers are unweighted sunspot number counts. More information about the various diagnostics and corrections applied to the sunspot number series in version 2.0 is available in the literature [14]. The monthly mean sunspot area data of full disc has been taken from the Royal Observatory, Greenwich (http://solarscience.msfc.nasa.gov/greenwch/sunspot_area.txt).

In the present paper "Running cross correlation method" has been used to study the relationship between CRI and solar activity indices [7, 13, 15]. In the said method we use a time window of width T cantered 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 1 month to calculate the correlation coefficient for each month between CRI and SSN for the period 1996–2015. The time window has been taken of 50-month. This value is 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 fine temporal structure of the cross correlation function. Further, since the time span in

the present study is one and half solar cycle, the several valuable informations regarding cross correlation and time-lag between SSN and CRI may be filtered out for large time-window, the time window of 24-month has also been used to calculate C (t) and compared with the results that obtained from 50-month time window.

The correlation coefficient between SSN and CRI has also been calculated without time-lag to show the cycle wise average behaviour of CRI modulation. The same has been calculated with time lag for the solar cycles 23 & 24 using the "minimizing correlation coefficient method". Here we have selected both the series CRI and SSN for the same period with zero time-lag and then shifted CRI series forward by a step of 1 month and calculated the cross correlation coefficient between both the series. As such, the time (number of shifted months) is obtained, when the correlation coefficient is maximum, which represents the time lag between CRI and SSN.

3. Results and discussion

The long-term reliability of the CRI data has been verified by a cross plot between the monthly average count rates of Oulu and Moscow NMs (Fig. 1). In fact, the comparison of data of these two stations shows a high degree of correlation (r ∼ .98) for solar cycle 24 and hence can be used for the study of long-term cosmic ray modulation.

Qualitative behaviour of normalized (100 % in Dec. 2009) count rates of CRI (Oulu and Moscow), SSN and SSA is illustrated in Fig. 2 for solar cycles 23 & 24 (1996–2015). The general trend of inverse relationship of solar activity parameters (SSN and SSA) with CRI is clearly apparent from the Fig. 2, with a time-lag between solar activity parameters and CRI of both the stations. Moreover, the level of correlation is also seems to be qualitatively change with time. The difference in variational pattern of CRI and SSN/SSA is clearly apparent during cycles 23 & 24. The maximum value
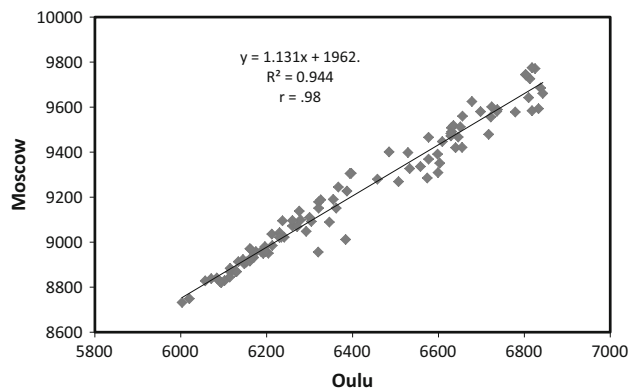

Fig. 1 Shows the cross correlation between the count rates of Oulu and Moscow Neutron Monitors
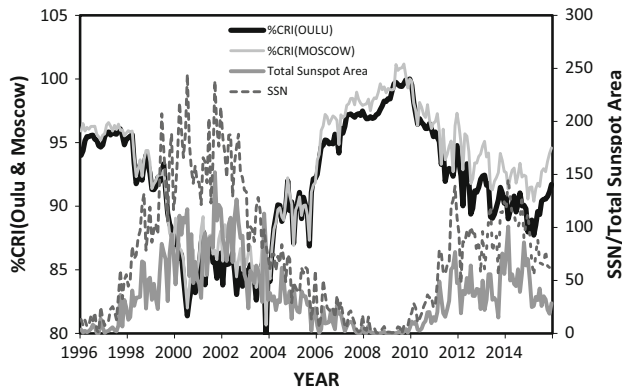
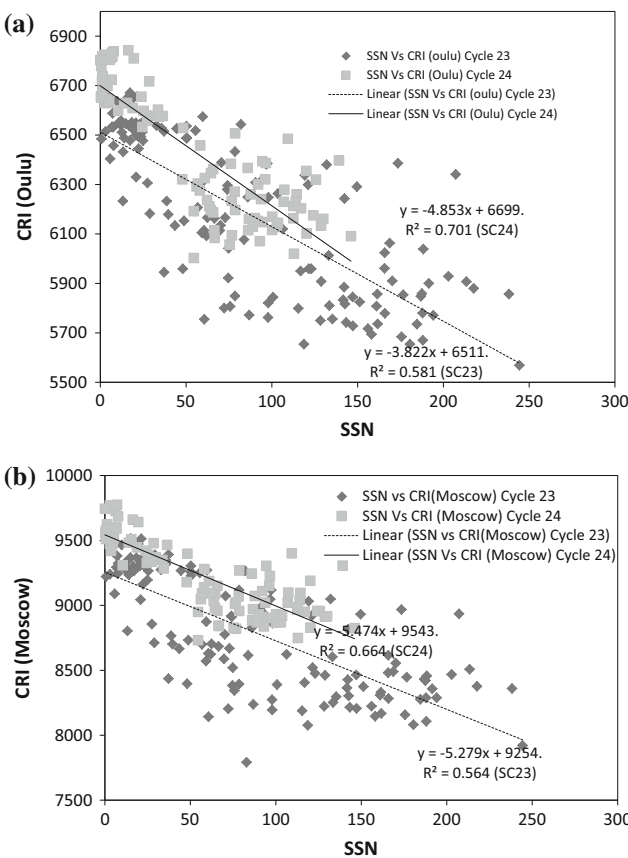**Fig. 2** Shows the long term variation of SSN and %CRI (Oulu and Moscow) for the solar cycles 23 & 24

Fig. 3 Scatter plot between SSN and CRI for cycles 23 & 24 (**a**) for Oulu NM and (**b**) for Moscow NM

Fig. 4 Scatter plot between SSA and CRI for cycles 23 & 24 (**a**) for Oulu NM and (**b**) for Moscow NM

of SSN was 244.3 (July 2000) during cycle 23, while it has been found to be only 146.1 (Feb. 2014) in the present cycle. The intensity of GCR measured at Earth is the highest ever recorded by Oulu and Moscow NMs during the recent minimum of solar cycle 24.

To observe the quantitative relationship (average) between SSN and CRI, we have shown the cross plot
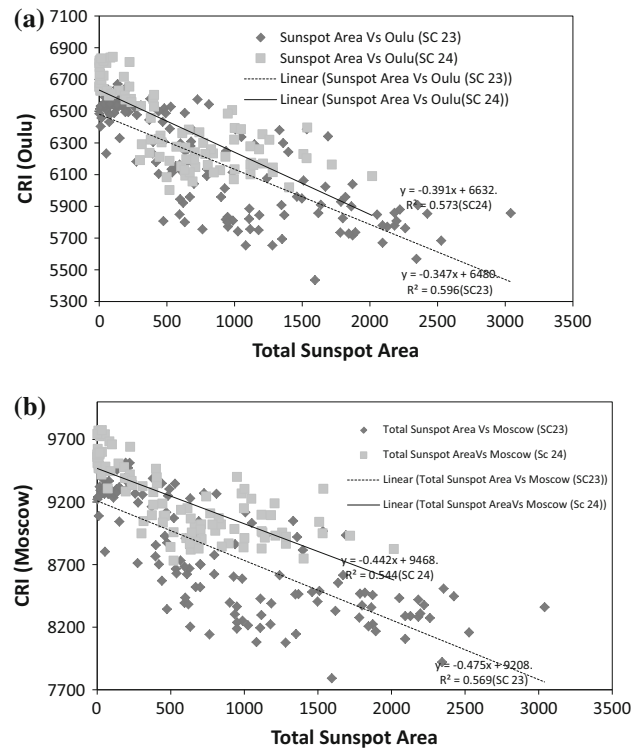
between these two parameters for both the stations Oulu and Moscow (Figs. 3(a) and 3(b)). Clearly distinct relationships between SSN and CRI (linear trend lines) are observed for cycles 23 & 24. It is observed that the best fit line for cycle 24 lie above the line of cycle 23, indicating that for the same SSN, CRI is higher during cycle 24. Similarly from the cross plots between SSA and CRI (Oulu and Moscow) it is found that the behaviour of linear trend lines are almost identical to those observed in the case of SSN-CRI relationship (Figs. 4(a) and 4(b)). We have also calculated the correlation coefficient between SSN and SSA which is >0.92 for both the solar cycles 23 & 24. Therefore, one can consider either of the parameters for such a study and hence we have considered only SSN for further analysis.

The cross correlation coefficient between SSN and CRI (Oulu and Moscow) without and with time-lag has been calculated for solar cycles 23 & 24 (Table 1). It is found that the cross correlation coefficient (without time-lag) between these two parameters is higher (-0.840 ± 0.059 and -0.820 ± 0.067) during cycle 24 as compared to cycle 23 (-0.762 ± 0.068 and -0.751 ± 0.071) for both the cosmic ray stations. It is noticed from the above observational results that the average correlation coefficient is slightly higher during cycle 24 than in cycle 23 for both cosmic ray stations. Further, time-lag between SSN and
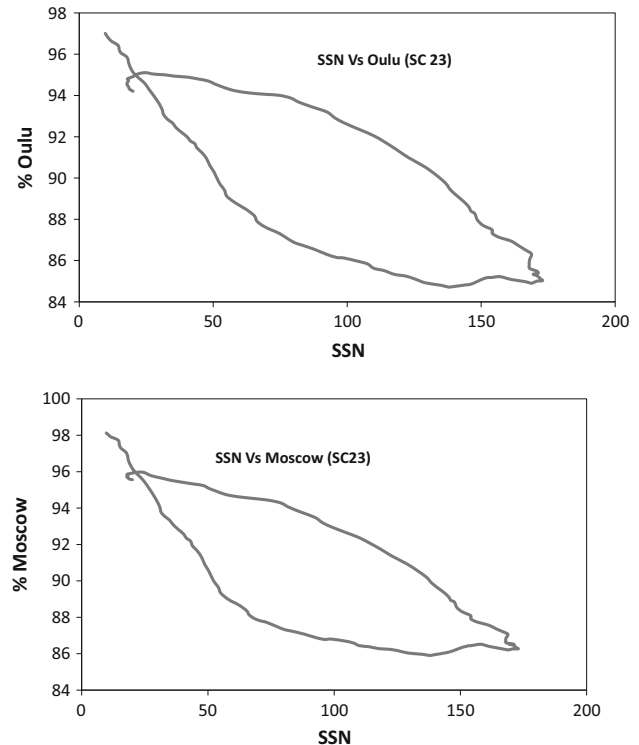
Table 1 Shows the value of cross correlation coefficient between SSN and CRI (without and with time-lag) for solar cycles 23 & 24

Solar cycles	SSN-CRI (Oulu)			SSN-CRI (Moscow)		
	Correlation coefficient			Correlation coefficient		
	Without time-lag	With time-lag (Maximum)	Time-lag (in months)	Without time-lag	With time-lag (Maximum)	Time-lag (in months)
23	−0.762 ± 0.068	−0.883 ± 0.036	14	−0.751 ± 0.071	−0.858 ± 0.043	13
24	−0.840 ± 0.059	−0.885 ± 0.043, −0.892 ± 0.040	4–10	−0.820 ± 0.067	−0.845 ± 0.057, −0.854 ± 0.054	4–10
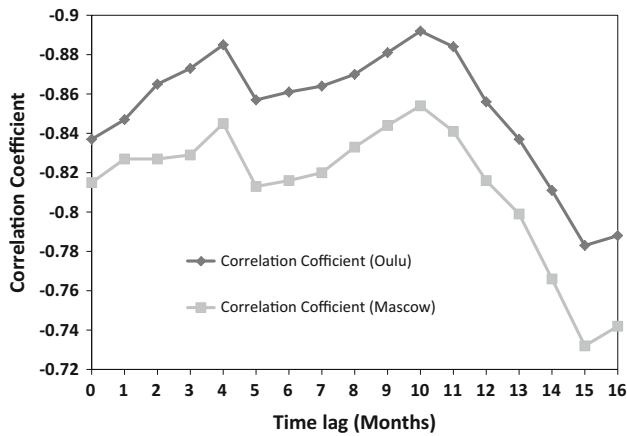
Fig. 5 Shows the variation of correlation coefficient with time-lag during cycle 24. Correlation coefficient is calculated between SSN and CRI (Oulu and Moscow) by considering time-lag of 0–13 months

Fig. 6 Shows the hysteresis curves between SSN and CRI for solar cycle 23 for the cosmic ray stations Oulu (*upper panel*) and Moscow (*lower panel*)

CRI has been calculated for both the stations (Oulu and Moscow). The maximum correlation coefficient is achieved with time-lag of 4 and 10 months during cycle 24 for both the stations. A variation of correlation coefficient with time-lag is shown in Fig. 5. Fig. 5 clearly shows that the first peak of correlation coefficient appears corresponding to the time-lag of 4 months while second peak corresponds to 10 months time-lag for both the stations.

It has been observed that cosmic rays lag-behind the sunspot activity but the magnitude of lag is different for both the cycles. It is well known that the cross-plot between SSN and CRI shows hysteresis loop but the width of loops are different for even and odd solar cycles [8, 16, 17]. In the present study, we have plotted the hysteresis curves for the solar cycles 23 & 24 between SSN and CRI. For this purpose, we have taken the 30-month moving average of both the series to filter out the short term fluctuations and then plotted the SSN and CRI as a cross plot. The hysteresis curve for solar cycle 23 between SSN and CRI (Oulu and Moscow)) is shown in Fig. 6. Similarly the hysteresis loops for even solar cycle 24 are illustrated in Fig. 7. It is evident that the hysteresis loops are broader during the odd cycle 23 and appears to be narrow during the even cycle 24 as usual

for both the cosmic ray stations. It is also observed that the shapes of hysteresis loops are almost identical for the Oulu and Moscow neutron monitor stations. The observation of thick and thin cycles seems to be related with the change in magnetic field polarity. The observation of broad loops corresponds to (±) reversal and narrow ones to (∓) reversal of the solar magnetic field [17]. It has also been recognized that if the CRI near the earth is higher under negative polarity and the relationship between solar indices and CRI is similar for different polarities, then the (±) transition would broaden the hysteresis and the (∓) transition would make it narrow [18].

The running cross correlation functions between SSN and CRI (Oulu and Moscow) for 50-month time window is
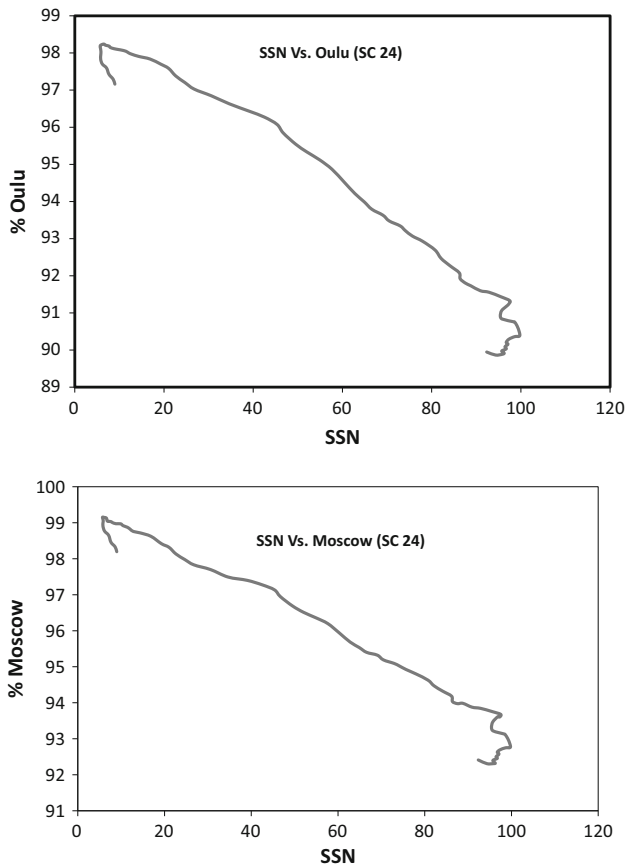
Fig. 7 Shows the hysteresis curves between SSN and CRI for solar cycle 24 for the cosmic ray stations Oulu (*upper panel*) and Moscow (*lower panel*)

Fig. 8 Shows the running cross correlation coefficient C (t) between SSN and CRI (Oulu and Moscow) alongwith sunspot numbers for the cycles 23 & 24. C (t) has been calculated by taking 50-month window (*upper panel*) and 24-month window (*lower panel*). The 95 % confidence limit for C (t) is also shown as *dashed line* in the *upper panel*

shown in Fig. 8 (upper panel). The 95 % confidence interval for running cross correlation function is also depicted in the figure. This type of analysis is useful to explain the momentary behaviour of cross correlation function with respect to time. The value of correlation coefficient is different for different phases of a particular solar cycle and it varies with time. The value obtained by this method (if averaged over a cycle) represents the correlation coefficient for a particular cycle. It is seen that the general behaviour of cross correlation coefficient is similar for both the neutron monitor stations except the initial ascending phase of both the cycles and descending phase of cycle 23. These differences are probably attributable due to the difference in the variational pattern of Oulu and Moscow NMs which depicts slight rigidity dependence of cosmic rays. Actually, it is expected that solar modulation is more pronounced for high latitude stations with low cut off rigidity [19]. It is also observed that the NM count rates are much higher during the current solar maximum than previous solar maximum which is evident from the count rates of both the low and middle cut off rigidity stations (Fig. 2). A slight difference (not significant) in the cross
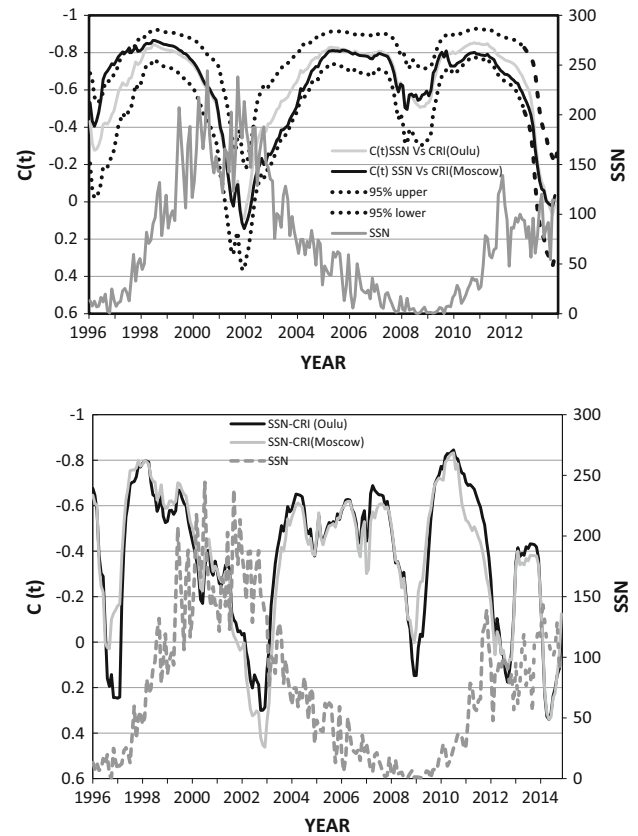
correlation coefficient between SSN and CRI for Oulu and Moscow NMs (both in the case of average as well as in running cross correlation) confirms the findings regarding rigidity dependent cosmic ray modulation during previous and present solar cycles. Furthermore, the differences in the cross correlation coefficients between these two stations are well within the 95 % confidence interval, except for the particular period of 1996-97 (minimum of cycle 23). During this particular period, Moscow count rates have followed SSN much better than Oulu, resulting in a better correlation for Moscow NM in comparison to Oulu. This overall coincidence means that the general behaviour of long-term cosmic ray modulation is similar for particles with different energy, even if the depth of modulation changes with particle energy, which is in good agreement with earlier finding [15]. It is found that correlation coefficient is strong (~-0.8 to ~-0.9) for ascending and descending phases of solar cycles, while it is weak during the maxima and minima (~-0.1 to ~-0.5). The correlation coefficient has been observed to be unusually little bit positive during 2001–2002. It is well known that the

variation of either of the indices (SSN and CRI) is small during the extrema (maxima and minima) and it is large during the ascending and descending phases of any solar cycle. Hence, the poor correlation during extrema and better during ascending and descending phases is expected. Similar analysis has been performed by taking a time window of 24-month. It is observed from the Fig. 8 (lower panel) that overall behaviour of cross correlation function is similar to that observed in 50-month time window, except some short-term changes in correlation coefficient during the entire period of investigation. It is also evident from the figure that the running cross correlation coefficient becomes little bit positive two times (1996–1997 and 2002–2003) during cycle 23 while the similar situation has been observed three times (2009, 2013 and end of 2014) during cycle 24. It is also found that the sharp increases or decreases in SSN results to a high correlation coefficient between SSN and CRI. As such, for long-term studies the 50-month time window is more appropriate to filter out the short term fluctuation with more statistical accuracy than 24-month time window.

A clear difference in the behaviour of cross correlation function is observed during the solar cycles 23 & 24. It is noticed from the figure that the cross correlation coefficient has maintained its maximum level (-0.8 to -0.9) in 50-month window curve for a long time (2005-2008) i.e. during the descending phase of solar cycle 23 and onset of cycle 24 contrary to previous solar cycles. This finding confirms the fact that cycle 23 has a long lasting descending phase which causes the late onset of cycle 24.

The mechanism of the solar modulation of galactic cosmic rays is explained on the basis of standard model of diffusion, convection and adiabatic deceleration effects, where the path of individual particles through the heliosphere is determined by the interplanetary magnetic field lines, including drift processes. This leads to the characteristic difference between adjacent solar cycles due to the different solar polarity and large scale magnetic fields. The polarity of the solar magnetic field reverses sign about every 11-year near the time of maximum solar activity. Thus successive minima of activity are characterized by different solar field polarity [8]. In view of various theories, the influences of curvature of interplanetary magnetic field on the transport of cosmic ray particles should also be taken into account for a better understanding of odd–even cycle's differences [10].

An unusual pattern of cosmic ray modulation during solar cycles 23 & 24 has been reported in the literature [19]. It has been found that, after 2009, CR modulation during solar activity (SA) growth phase is much weaker over 3 years (2010–2012) than during the corresponding SA growth periods in the previous cycles [20]. The results obtained in the present analysis indicate the peculiarly low solar activity and higher level of CRI during the onset of present solar cycle, which are in agreement with the earlier findings [19, 20]. It is also reported that, the slow decline of solar cycle 23 and slow rise of cycle 24 resulted in a very low solar activity for a long period from about 2006 to end of 2009, with 2008 and 2009 being particularly quiet years [21]. Our findings regarding the time-lag during odd cycle 23 is in good agreement with earlier findings, where the time lag between SSN and CRI has been found to be 13–14 months [21–23]. The time-lag during the ascending phase of cycle 24 has also been reported earlier by various investigators. A time-lag of 2 months has been reported by Mavromichalaki and Paouris [21], while it has been reported to be 6–7 months by Kane [24]. A remarkably large time-lag (10–17 months) between solar activity parameters and CRI has also been reported for the ascending phase of present solar cycle [25].The present study covers comparatively long duration including the ascending phase as well as the maxima and initial descending phase of cycle 24, resulted into different time-lag during cycle 24. However, the clear picture will be emerged out after the completion of cycle 24. The onset characteristics of the cycle 24 has also been analysed and it has been found that there is a lag of 3 months between large, sharp increase in the tilt-angle of the heliospheric neutral current sheet and the onset of modulation [26].

It has been recognised that hysteresis effect of cosmic ray intensity due to solar activity as measured by sunspot numbers exhibits a different behaviour during even and odd solar cycles. The characteristic difference between even and odd solar cycles can be explained in terms of different processes influencing cosmic ray transport in the heliosphere. During even cycles convection play the most important role while diffusion becomes dominant during odd cycles. The effect of drift only determines how the particles gain access to the observation points [27]. The heliospheric current sheet (HCS) divides the heliosphere into two hemispheres of oppositely charged magnetic fields. The waviness of HCS plays an important role in the cosmic ray modulation [23]. Actually, the effect of drift should also be included in the modulation mechanism of cosmic rays to understand the odd–even asymmetry. According to drift phenomena, during the sunspot maxima of any odd cycle, the solar north-polar magnetic field reverses from the outward direction (A > 0) to the inward direction (A < 0) after an interval of few months. A few months later the Sun's south-polar magnetic field also reverses from the inward direction to the outward direction. The opposite changes occur in the even cycles. During the A > 0 state, positively charge particles enter the heliosphere through the polar regions. After the reversal of polarity around solar maximum, the state of heliosphere becomes A < 0 and the cosmic ray particles enter the

heliosphere through the equatorial region. Under this condition, these particles are more affected by propagating through diffusive barriers associated with solar activity and the waviness of HCS, resulting in a large time-lag [28].

The behaviour of time-lag (4 and 10 months) during present cycle needs further extensive analysis considering other solar and interplanetary parameters (solar flare index, grouped solar flares, tilt angle of heliospheric current sheet, solar wind velocity, interplanetary magnetic field etc.). The long lasting higher correlation coefficient during the descending phase of cycle 23 and minima of present solar cycle is perhaps attributable due to the constant low solar activity for a long time in the beginning of cycle 24. The continuous long duration and constant low sunspot activity (ascending phase) of present cycle and very low solar activity during the cycle 24 till now, has given us a unique opportunity to assess the mechanism of cosmic ray modulation during the low activity periods.

4. Conclusions

Based on the observational results, it is concluded that sunspot activity level during the end of solar cycle 23 and beginning of solar cycle 24 continued to be at minimum level for longer duration in comparison to earlier cycles and the cosmic ray intensity has got highest level recorded so far during this broad solar minimum. The level of cosmic ray modulation has also been found different as the correlation coefficient between SSN and CRI (without time-lag) during cycle 24 is -0.840 ± 0.059 and -0.820 ± 0.067 while it is -0.762 ± 0.068 and -0.751 ± 0.071 during cycle 23 for Oulu and Moscow NMs, respectively. Likewise correlation coefficient, regression lines between SSN and CRI also behaves differently during cycles 23 & 24. The time-lag analysis between SSN and CRI has also shown two time-lags (4 and 10 months) during cycle 24, whereas there is single time-lag 14 months (Oulu) and 13 months (Moscow) during solar cycle 23. Furthermore, the behaviour of running cross-correlation function shows maximum value of anti-correlation (~ -0.8 to ~ -0.9) for a longer duration in comparison to previous solar cycle. The results indicate that the cosmic ray modulation mechanism during present solar cycle (till Dec. 2015) is significantly different in comparison to previous solar cycle in the light of peculiar solar activity conditions.

References

[1] S E Forbush *J. Geophys. Res.* **59** 525 (1954)

[2] S E Forbush *J. Geophys. Res.* **63** 651 (1958)

[3] J R Jokipii, E H Levy and W B Hubbard *Astrophys. J.* **213** 861 (1977)

[4] J R Jokipii and B T Thomas *Astrophys. J.* **243** 1115 (1981)

[5] E J Smith *J. Geophys. Res.* **95** 731 (1990)

[6] M S Potgieter *Space Sci. Rev.* **83** 147 (1998)

[7] V K Mishra and D P Tiwari *Ind. J. Radio Space Phys.* **32** 65 (2003)

[8] M Gupta, V K Mishra and A P Mishra *Ind. J. Radio Space Phys.* **35** 167 (2006)

[9] M Gupta, V K Mishra and A P Mishra *Ind. J. Phys.* **80** 697 (2006)

[10] M Gupta, S R Narang, V K Mishra and A P Mishra *Int. J. Eng. Technol. Manag. Appl. Sci.* **2** 104 (2014)

[11] V K Mishra, D P Tiwari, C M Tiwari and S P Agrawal *Ind. J. Radio Space Phys.* **34** 13 (2005)

[12] D H Hathaway, *Living Rev. Solar Phys.* **7** 1 (2010)

[13] A P Mishra, M Gupta and V K Mishra *Solar Phys.* **239** 475 (2006)

[14] F Clette, L Svalgaard, J M Vaquero and E W Cliver *Space Sci. Rev.* **186** 35 (2014)

[15] I G Usoskin, H Kanane, K Mursula, P Tankanen and G A Kavaltsov *J. Geophys. Res.* **103**(A5) 9567 (1998)

[16] M Gupta, V K Mishra and A P Mishra *J. Astrophys. Astron.* **27** 455 (2006)

[17] M Gupta, V K Mishra and A P Mishra *Ind. J. Radio Space Phys.* **35** 387 (2006)

[18] K Nagashima and I Morishita *Planet Space Sci.* **28** 195 (1980)

[19] A A Pacini and I G Usoskin *Solar Phys.* **290** 943 (2015)

[20] O P M Aslam and Badruddin *Solar Phys.* **290** 2333 (2015)

[21] H Mavromichalaki and E Paouris *Adv. Astron.* doi 10.1155/2012/607172 (2012)

[22] E Paouris, H Mavromichalaki, A Belov, R Gushchina and V Yanke *Solar Phys.* **280** 255 (2012)

[23] P Chowdhury, K Kudela and B N Dwivedi *Solar Phys.* **286** 577 (2013)

[24] R P Kane *Solar Phys.* **269** 451 (2011)

[25] P Chowdhury, K Kudela and Y J Moon *Solar Phys.* **291** 581 (2016)

[26] H Ahluwalia and R Ygbuhay *Adv. Space Res.* **48** 61 (2011)

[27] H Mavromichalaki, E Marmatsouri and A Vassilaki *Earth Moon Planets* **42** 233 (1988)

[28] M S Potgieter, R A Berger and S E S Ferreira *Space Sci. Rev.* **97** 295 (2001)