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Investigating Hysteresis Effects on Solar and Interplanetary Activity During Solar Cycles 23 and 24.

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Abstract: *The objective of this investigation was to analyse the hysteresis relationship between cosmic ray intensity (CRI) and solar parameters throughout solar cycles 23 and 24. Accordingly, we employed neutron monitor data from Oulu and Moscow neutron monitors in conjunction with data on sunspot number (SSN) and solar radio flux (SRF). Hysteresis curves were constructed to illustrate the relationship between cosmic ray intensity (CRI) and (SSN), as well as (CRI) and (SRF). We conducted a correlation analysis to determine time lags during the ascending and descending phases of solar cycles 23 and 24. By comparing the time lags between (CRI) and (SSN), as well as (CRI) and (SRF), during these phases, we identified variations in the observed time lag.*

Key Words: *Cosmic rays, sunspot number, Solar radio flux, hysteresis and time lag.*

1. INTRODUCTION:

The variation of (GCR) intensity within interplanetary space has been a subject of investigation since the 1950s, as evidenced by Forbush's work in 1954. The intensity of galactic cosmic rays (GCRs) shows an inverse relationship with the sunspot number (Mursulla, k., and Zieger, B. 2010). The orientation of the solar magnetic field's polarity undergoes a reversal during each solar cycle. Hence, polarity-dependent effects have been observed in GCR modulation. The GCR modulation on long terms basis has been studied significantly in terms of theoretical as well as observational aspects (Aslam and Badruddin, 2012, 2015; Belov, 2000; Chowdhry and Kudela, 2018). An inverse relationship exists between galactic cosmic ray (GCR) intensity and solar activity, accompanied by a time lag between them. This time lag has given rise to the observation of a hysteresis phenomenon in the GCR intensity and solar activity relationship over a solar cycle. Nevertheless, the duration of this time lag varies across different solar cycles (Bazilevskaya, 2014; Chowdhury, et al., 2011; Kane, 2014).

The modulation of cosmic rays (CR) initiates with a time lag following the appearance of sunspots. This time lag is more pronounced in odd solar cycles (e.g., 21, 23) compared to even cycles (e.g., 22, 24). The process behind CR modulation involves time-varying shifts in the heliosphere's position and the creation of diffusive barriers that propagate outward. These barriers arise by the convergence of coronal mass ejections (CMEs), shocks, and rapid streams of particles at a distance of approximately 10 to 15 (AU) from the Sun (Burlaga et al., 1985). The convection-diffusion process remains unaffected by the polarity of the solar magnetic field and behaves similarly during each cycle of sunspot activity (Dorman, 1959; Parker, 1963). Conversely, the drift - mechanism produces opposite effects as the direction of the solar magnetic field changes in alternating cycles (Jokipii and Davila, 1981; Jokipii and Thomas, 1981; Lee and Fisk, 1981; Potgieter and Moraal, 1985).

During the peak of sunspot activity in odd cycles, there is a reversal in the solar north-polar magnetic field orientation. This transition takes place within a span of a few months, shifting from an outward direction ($A > 0$) to an inward direction ($A < 0$). Similarly, several months later, the solar south-polar magnetic field also experiences a reversal, changing from an inward direction ($A < 0$) to an outward direction ($A > 0$). The scenario is different in even cycles. In cycles with $A > 0$, Cosmic rays (CR) enter the inner heliosphere more rapidly through the polar regions than through the heliospheric current. When $A < 0$, the situation is reversed as documented by Wibberenz et al. (2002). Cane et al. (1999) observed a strong inverse connection between alterations in cosmic rays (CR) and the overall interplanetary magnetic field strength (B) throughout successive cycles 21 and 22. Differences in time lag, varying between odd and even cycles, are evident in hysteresis diagrams by plotting cosmic rays against sunspot activity. These diagrams show broader hysteresis loops during odd cycles and narrower ones during even cycles (Dorman, 2001; Dorman et al.,2001a, b). In this current communication, hysteresis plots are presented, illustrating the relationship between cosmic rays (CR) and sunspot numbers, along with several other solar parameters.

2. DATA ANALYSIS:

We analysed the data from two neutron monitors positioned in Oulu and Moscow, along with two solar activity indicators - the sunspot number (SSN) and the 10.7 cm solar radio flux (SRF) - during the recent solar cycles 23 and 24. The sunspot number and solar radio flux data were sourced from http://omniweb.gsf..nasa.gov/form/dxl.html. We created graphical representations, called hysteresis curves, depicting the relationship between Galactic Cosmic Ray (GCR) intensity and solar activity parameters. Additionally, we conducted a lag correlation analysis to establish the time delay between GCR intensity and solar activity parameters throughout the entire cycle.

3. RESULTS AND DISCUSSION:

Figure 1 illustrates the monthly average plot of (GCR) intensity data, recorded by neutron monitors located in Oulu and Moscow. This data is accompanied by the concurrent changes in solar activity parameters, the sunspot number and the 10.7 cm solar radio flux, across two solar cycles 23 and 24. Solar cycle 23 is significant for being one of the lengthiest cycles, marked by a profound solar minimum and the maximum recorded cosmic ray flux during this minimum phase. On the other hand, cycle 24 represents the weakest solar activity cycle in terms of solar output. A number of investigations have been conducted to examine the influence of solar cycle variations on Galactic Cosmic Rays (GCRs) during solar cycle 23 and preceding cycles (Chowdhury et al., 2013; Inceoglu et al., 2014; Tomassetti et al., 2017). The graphs in Figure 1 depict an inverse relationship between GCR intensity and solar activity. Nevertheless, there is a noticeable time lag observed during the ascending and descending phases in these plots. Upon closer examination, it seems that during solar cycle 24, the time lag is possibly shorter compared to that observed during solar cycle 23.

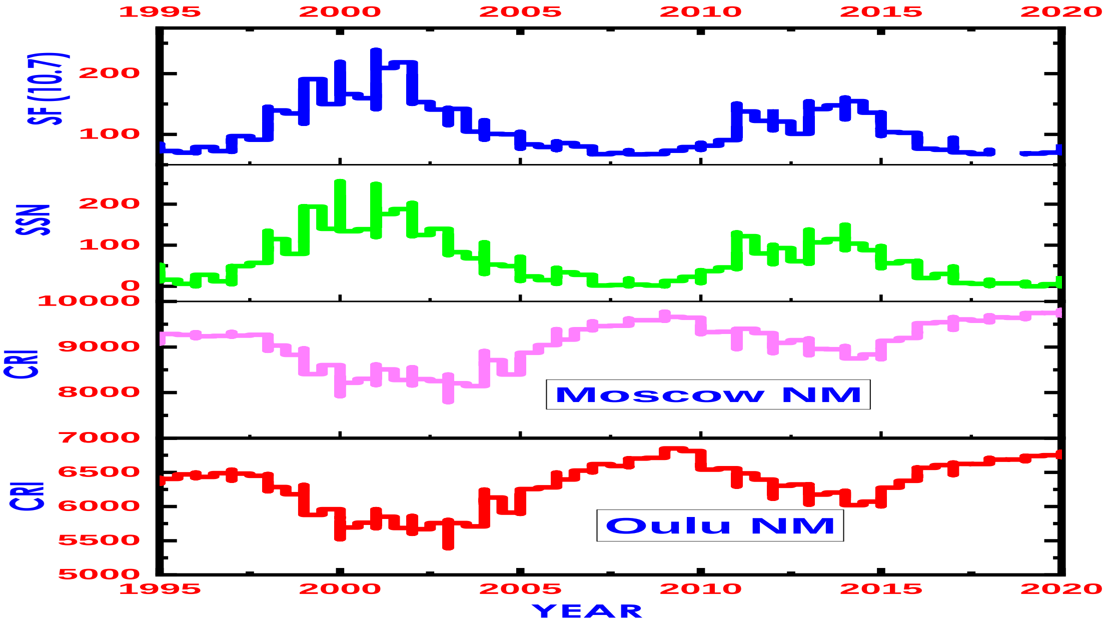

Fig.1 Time variation in the monthly average of CR data, as observed by neutron monitors in Oulu and Moscow, alongside solar activity indicators (SSN and SRF 10.7cm) for solar cycles 23 and 24.

The method to analyse the variations in the time lag between solar cycles involves generating hysteresis curves and then making comparisons. Figures 2 and 3 illustrate the hysteresis plots for solar cycles 23 and 24 respectively. These plots showcase the relationships between Oulu cosmic ray intensity and sunspot number (SSN), Moscow cosmic ray intensity and SSN, Oulu cosmic ray intensity and 10.7 cm solar radio flux (SRF), as well as Moscow cosmic ray intensity and SRF. To gain a broader perspective, the hysteresis plots of solar cycles 23 and 24 can be analysed alongside those of solar cycles 19, 20, 21, and 22 for comparison as presented in the study by Singh et al. (2008) with earlier research findings and related publications (kane, 2014; Ross and Chaplin, 2019). The hysteresis loop of solar cycle 24 shows a comparatively smaller area when compared to the broader hysteresis loop of the preceding odd-number solar cycle 23. Solar Cycle 23, which occurred between 1996 and 2008, exhibited a relatively broad hysteresis loop. This means that the increase in sunspot activity during the rising phase of the cycle (solar maximum) was slower and more gradual compared to the subsequent decrease in sunspot activity during the decreasing phase (solar minimum). In other words, it took a longer period for sunspot numbers to peak and then decline.

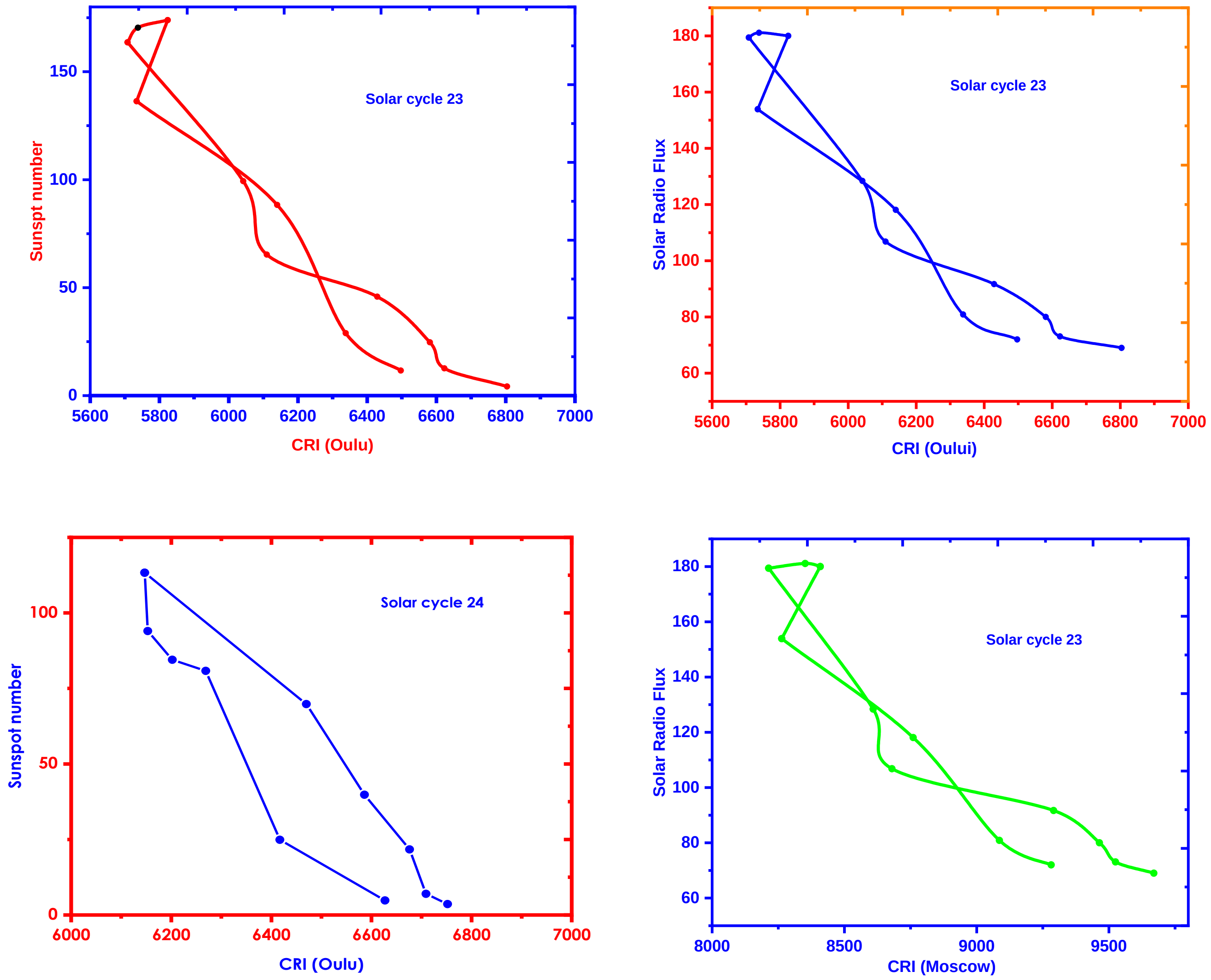

Fig.2 is a graphical representation illustrating the hysteresis plot for Solar Cycles 23 showcasing the relationship between CRI (measured in Oulu and Moscow) and two key solar parameters, sunspot number (SSN) and solar radio flux SRF (10.7).

During solar cycle 23, there was a period of positive polar magnetic characteristics observed in the hysteresis loop between 1996 and 2001. This was succeeded by a phase of negative polar magnetic field behaviour from 2002 to 2008. Figure 2 depicts the hysteresis loop relationship between CRI and Solar Radio Flux F(10.7cm) during the timeframe of solar cycle 23, spanning from 1996 to 2008. Within this context, solar cycle 23 displays two distinct and narrow loops. The study findings suggest that hysteresis loops connecting CRI and Solar Flux (F(10.7cm)) have a broader shape during even-numbered solar cycles (SC-24) and a more compact form during odd-numbered solar cycles (SC-23).

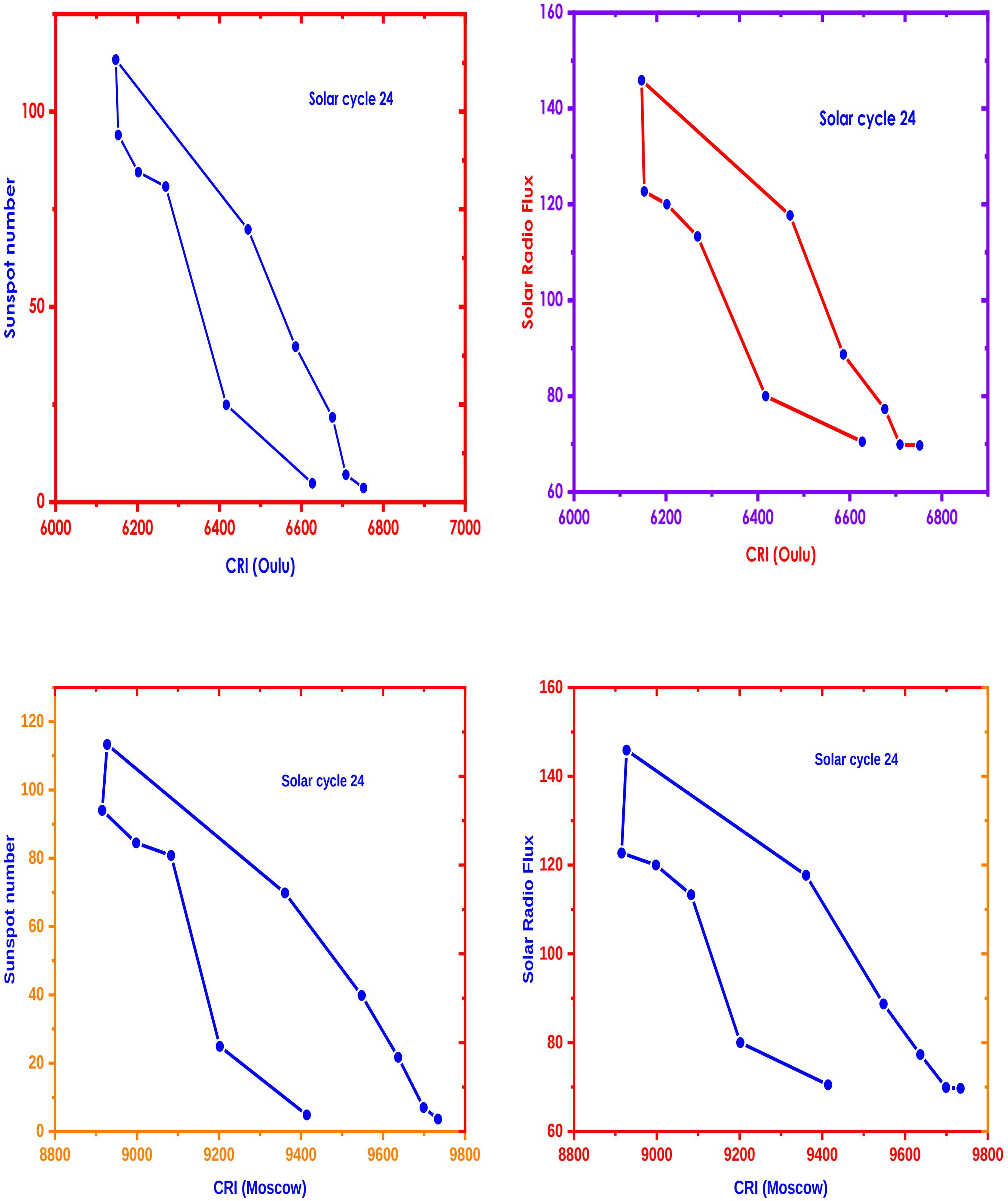

Fig.3 is a graphical representation illustrating the hysteresis plot for Solar Cycles 24 showcasing the relationship between CRI (measured in Oulu and Moscow) and two key solar parameters, sunspot number (SSN) and solar radio flux SRF (10.7).

The morphology of the hysteresis loop in cycle 24 implies that the time lag between CRI and SSN, as well as CRI and SRF, is relatively short. Nevertheless, a more meaningful approach involves quantifying this time lag. To achieve this objective, we conducted a correlation analysis that takes into account the time lag between monthly averaged solar activity indicators and CRI as shown in figure 4 and 5. This analysis involved utilizing two distinct solar activity parameters (SSN and SRF), alongside CRI data from two neutron monitoring stations (Oulu and Moscow).

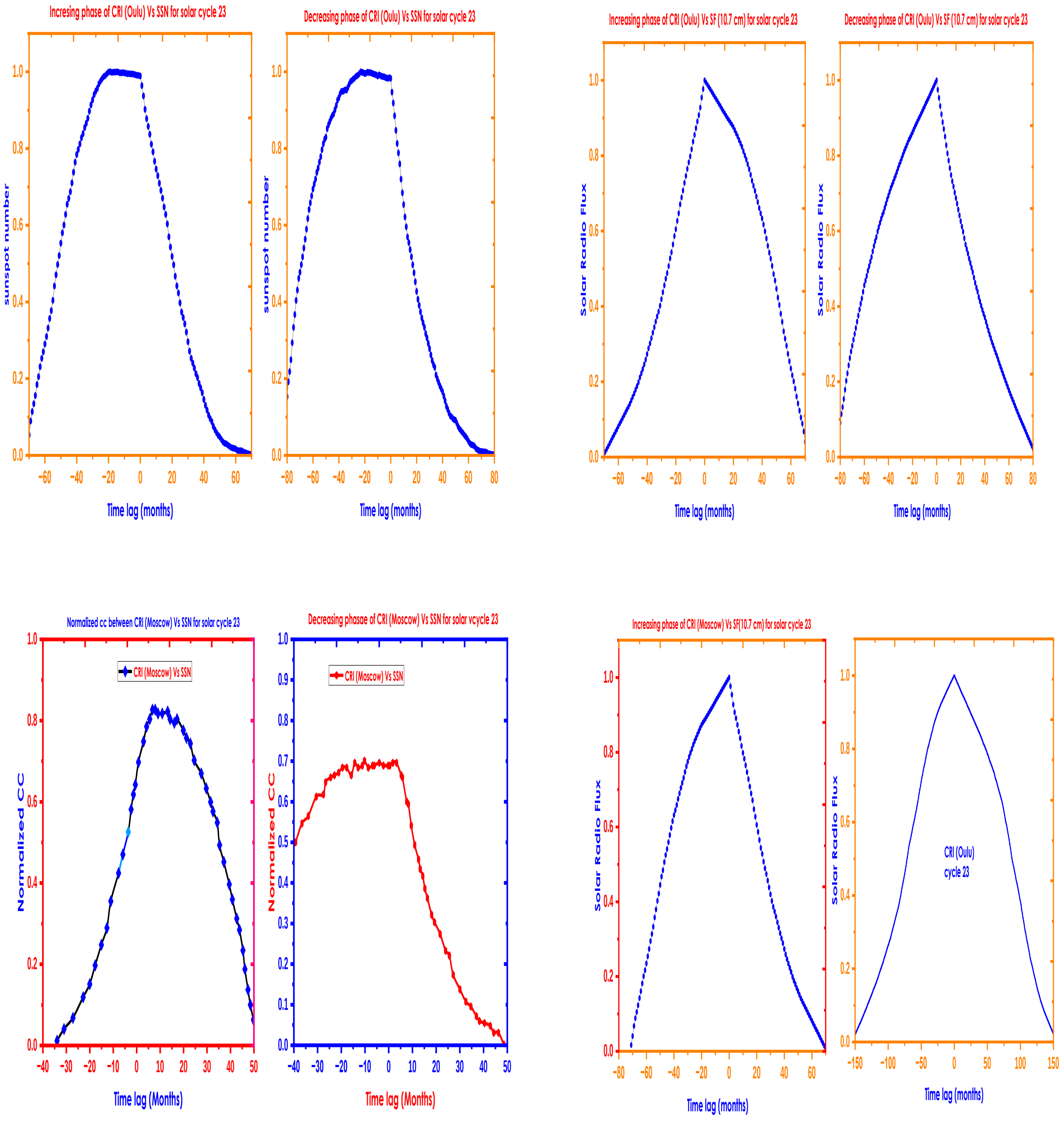

Fig.4 Correlation plots depicting time lags between Oulu NM and sunspot number, Oulu NM and solar radio flux, Moscow NM and sunspot number and Moscow neutron monitor and solar radio flux for solar cycle 23.

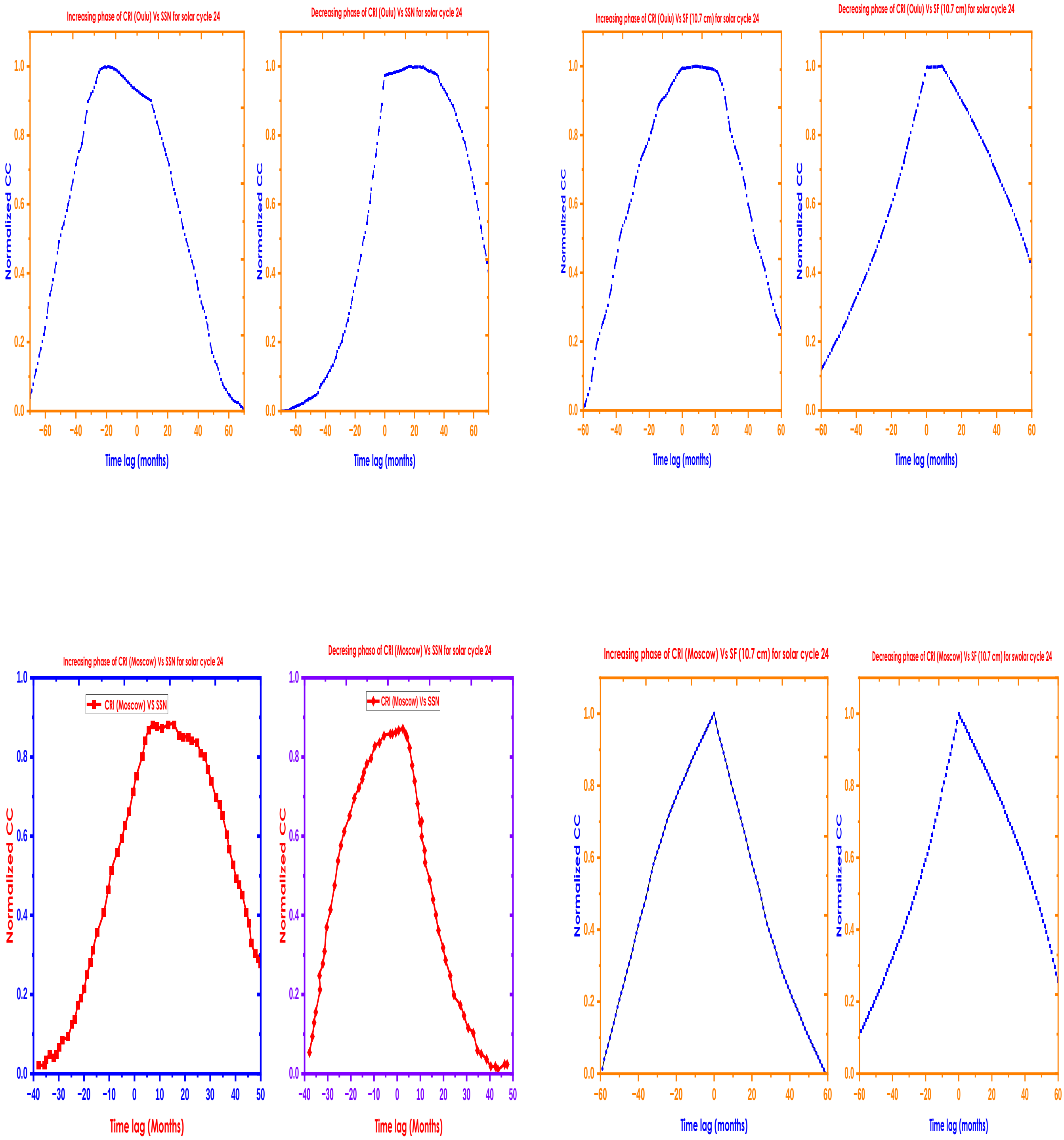

Fig.5 Correlation plots depicting time lags between Oulu NM and SSN, Oulu NM and SF (10.7 cm), Moscow NM and SSN and Moscow neutron monitor and SRF (10.7 cm) for solar cycle 24.

The combined duration of solar cycles 23 and 24 witnessed two distinct polarity conditions in the heliosphere: one with A<0 (negative A) polarity and the other with A>0 (positive A) polarity. This polarity shift occurred around the peak of solar activity. As solar cycles 23 and 24 progressed, the northern solar polar field exhibited an inward orientation while the southern polar field faced outward, defining the A<0 polarity phase. Conversely, as these cycles declined, there was a reversal in polarity during which the northern polar field directed outward and the southern polar field turned inward, characterizing the A>0 polarity phase. During the A<0 polarity period, the inner heliosphere experienced a greater influx of cosmic ray particles, with a significant portion entering through the equatorial region. However, following the polarity reversal, the trajectory of cosmic ray particles altered, causing them to preferentially enter the inner heliosphere through the polar region in the polarity phase A>0. Hence, there will likely be a greater lag in time. during epochs where A < 0, and a smaller delay during epochs where A > 0 (Cliver and Ling, 2001; Usoskin et al., 2001; Singh et al., 2008).

5. CONCLUSION:

We utilized data captured by the Oulu and Moscow neutron monitors to analyse hysteresis and time lag patterns of solar parameters, which encompassed solar parameters like sunspot number and solar radio flux for solar cycles 23 and 24. In solar cycle 23, Cosmic ray modulation commenced several months after the occurrence of sunspot minima. This outcome was anticipated, given that solar cycle 23 is an odd-numbered cycle. The cosmic rays experienced their most significant decrease during the years of elevated sunspot activity, specifically from 2000 to 2003. This overall inverse relationship between cosmic ray intensity and sunspot number aligns with expectations. The hysteresis diagrams depicting the relationship between cosmic rays and solar parameters exhibited narrow loops during even cycle 24, while wider loops were observed during odd cycles 23. A lag was observed between the initiation of cosmic ray modulation and the occurrence of sunspot minimum. The smaller time lag between solar activity indicators (such as SSN and SRF) and the recorded cosmic ray intensity (CRI) at neutron monitors (Oulu and Moscow) corresponds to the features observed in even solar cycles, as previously documented. In the ascending phase of solar activity cycle 24, when the heliosphere's polarity state is A<0, there is a comparatively extended time lag between solar activity indicators (SSN and SRF) and cosmic ray intensity (CRI). Conversely, during the descending phase of this solar cycle (with A>0), the time lag is observed to be comparatively shorter.

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