

A study of the heliospheric modulation of cosmic rays in the past solar cycles

V. N. Otugo* and A. R. C. Amakiri

Department of Physics, Rivers State University, Port Harcourt, Nigeria.

*Corresponding author. Email: vivian.otugo@ust.edu.ng; Tel: +2347069924809.

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ABSTRACT: Cosmic rays are high-energy particles originating from outside the solar system, and their flux is modulated by the heliosphere, the region of space influenced by the sun. This study investigates the heliospheric modulation of cosmic rays over five consecutive solar cycles (20-24), spanning from 1964 to 2019, focusing on the variations in cosmic ray intensity with solar activity. A long-term correlative study has been done using the values of the monthly mean of sunspot number (SSN) and cosmic ray data from ground-based Neutron Monitor Stations (Kiel, Moscow and Oulu). By analysing the cosmic ray intensity during these cycles, a significant variation in the cosmic ray flux and its modulation by the heliosphere is shown. The statistical analysis of the data depicts a very high anti-correlation association between solar activity and cosmic rays' intensity for the period studied; which is consistent with earlier findings. The results in this study demonstrate distinct differences in the cosmic ray intensity between solar cycles and the level of statistical association between sunspot number and cosmic rays varies from cycle to cycle. Solar cycle 21 was observed to have a slightly weaker anti-correlation value as compared to other cycles; this displays a solar cycle-dependent modulation effect necessitating further research. The cut-off rigidity, which ranges from 0.80 to 8.28 GV, and the influence of cut-off rigidity on the energy spectrum of the cosmic ray was observed as the station with the lowest cut-off rigidity generated the strongest anti-correlation value. This research provides new insights into the long-term variability of cosmic rays and the heliospheric modulation processes, with important applications in space weather and radiation protection.

Keywords: Cosmic rays, cut-off rigidity, solar cycle, sunspot number.

INTRODUCTION

Cosmic rays are high, ultra-high and extremely high energy particles of extra-terrestrial origin, mostly protons that constantly impinge the Earth's atmosphere (Mishev, 2013). Cosmic rays come from various places including the sun, supernova explosions and extremely distant sources such as radio galaxies and quasars. Cosmic rays entering the Earth are controlled by the shielding effect of the outward-blowing solar wind and the frozen-in interplanetary magnetic field (Usoskin *et al.*, 2004). Studies have shown that Solar activity affects the strength of the Earth's magnetic field and the Geomagnetic field acts as a shield deflecting cosmic rays and modulating the flux that reaches the earth. During solar maximum, the geomagnetic field is weak; as such more cosmic rays penetrate the Earth's surface. Conversely, in the solar

minimum, the geomagnetic field is stronger deflecting more cosmic rays, resulting in the decrease of the total cosmic ray flux and the hardening of the cosmic ray spectrum at 1 AU. This decrease is referred to as Forbush decrease. Therefore, the intensity of cosmic rays on Earth has an anti-correlative relationship with the 11-year solar activity cycle (Forbush, 1987, Barouch and Burlaga, 1975; Usoskin *et al.*, 2001; Kane, 2005). Previously, a long-term cosmic ray modulation has been investigated by many researchers at different geomagnetic cut-off rigidities and different altitudes. Their findings show that cosmic ray intensity decreases with high latitude and vice versa. Consequently, since cut-off rigidities increase with latitude; Neutron monitor stations with low cut-off rigidities have higher cosmic ray intensity than those with high cut-off

rigidities.

Mishra (2005) conducted a correlative study on sunspot number (SSN), grouped solar flare (GSF), and cosmic ray intensity (CRI) using a running correlation method for three successive solar cycles 20 to 23. He observed that there is a negative and high correlation relationship between solar activity and cosmic rays. Similarly, Gupta *et al.* (2006) indicated a high correlation between tilt angle and cosmic ray intensity. Furthermore, Tiwari *et al.* (2011) conducted a study on the correlation of SSN and CR from 1976 to 2008; using Kiel's Neutron monitor data and ascertained that the correlation coefficient between SSN and CRI is negative and high for most of the years. However, they found a rather poor correlation during ascending and descending phases of the solar cycle.

Despite various works on solar modulation of cosmic rays for about half a century, it is still a subject of investigation to discover the constant varieties of occurrences in the sun and its effect on Earth. Therefore, in this study, a correlative study of the relationship between cosmic ray intensity and solar activity for five consecutive solar cycles (cycles 20, 21, 22, 23 and 24), from 1964 to 2019 was conducted. The aim is to ascertain the extent of solar modulation of cosmic ray intensity for each of the five solar cycles under study. Furthermore, a consideration of the effect of geomagnetic rigidity cut-off on the modulation was performed, by using data from stations with different geomagnetic rigidity cut-off.

DATA AND METHODS

Neutron monitors (NMs) are ground-based particle detectors, that detect secondary nucleons produced locally in the atmosphere, as a consequence of cascaded initiated by primary cosmic-ray particles (Belov, 2000; Simpson, 2000). The flux of cosmic rays varies as modulated by solar magnetic activity, and this variability is continuously monitored by NM count rates (Väisänen *et al.*, 2021). Consequently, in this study, cosmic ray count rate data from three Neutron monitor stations with different cut-off rigidities were used. The stations are Kiel, Moscow and Oulu Neutron Monitors. The stations were selected because of the availability of required data in these stations. Kiel and Moscow stations are mid-latitude stations while Oulu is a high-latitude station. Moreover, Moscow station is located at a very high altitude while Oulu and Kiel are located at a low altitude. The values of the cut-off rigidities, latitude, and altitudes of the Neutron monitor stations are presented in Table 1. All the cosmic ray data were obtained from the World Data Center of Geomagnetism (WDC), Kyoto.

Sunspot numbers are typically used as one of the most reliable and easily available solar parameters to measure solar activity (Mishra, 2005; Aslam and Badruddin, 2012). Therefore, data of the monthly averages of Sunspot Number (SSN) (1964-2015) obtained from the World Data Center- Sunspot Index and Long-term Solar Observations

(WDC-SILSO) Royal Observatory of Belgium Brussels were used as an index of solar activity.

To determine the extent of the correlation between solar activity and cosmic ray intensity for each of the cycles under study; the data was further divided into the five different solar cycles; **cycle 20** (1964-1976), **cycle 21** (1976-1986), **cycle 22** (1986 -1996), **cycle 23** (1996 – 2008) and **cycle 24** (2008 -2019). The monthly averages of cosmic rays count from ground-based neutron monitor stations were used.

The statistical analysis to obtain the correlation coefficient, r was done for each of the cycles under study using the Pearson Product moment correlation coefficient, r , as shown in equation (1):

$$r = \frac{\sum(x-x')(y-y')}{\sqrt{\sum(x-x')^2 \sum(y-y')^2}} \quad (1)$$

RESULTS AND DISCUSSION

Cut-off rigidity and correlation coefficient

The effect of the cut-off rigidity on the correlation coefficient is clearly seen in Table 2. The correlation coefficient obtained for Oulu station which has a very low cut-off rigidity of 0.8 Gv is noticeably high for the five solar cycles when compared to the other stations, especially Mosco stations with high cut-off rigidity of 8.26 Gv. This indicates that Oulu station detected a broader spectrum of cosmic rays, including lower energy particles leading to a strong anti-correlation; While Moscow station detected more energetic cosmic rays resulting in weaker anti-correlations.

Effect of solar activity on cosmic rays intensity

Figures 1, 2, and 3 illustrate an obvious anti-correlative relationship between solar activity and cosmic ray intensity. The correlation coefficient of SSN and CRI were found to be high and negative for each of the cycles studied. However, in solar cycle 21, the value of r is low (≈ -0.5) when compared with other solar cycles. In solar cycle 24, it was observed that the ascending phase of CRI did not overlap with the descending phase of SSN, as observed in the other solar cycles; and a very high value of r of ≈ -0.9 was noticed in solar cycle 22. The results presented in the Figures indicate that the peak of SSN does not necessarily correspond to the valley of the CRI variation. Additionally, an unusually high value of CRI was observed in 2010 in all the stations; this agrees with the findings of Stozhkov (2009). Gerasimova *et al.* (2011) suggest that this irregularity is due to the decreased turbulence of the interplanetary magnetic field.

For the five solar cycles studied, the results reveal a strong anti-correlation between cosmic rays' intensity and sunspot numbers, indicating a clear solar modulation effect on cosmic rays. A strong anti-correlation was

Table 1. Rigidities, latitude, and altitudes of the Neutron monitor stations.

Station	Rigidity cut-off (Gv)	Latitude	Altitude (meters)
Kiel	2.36	54.30N	54
Moscow	8.28	55.75N	2274
Oulu	0.8	65.05N	15

Table 2. Correlation coefficient r for each cycle from different stations.

Station	Cycle 20	Cycle 21	Cycle 22	Cycle 23	Cycle 24
Kiel	-0.731	-0.598	-0.911	-0.766	-0.85
Moscow	-0.795	-0.575	-0.896	-0.735	-0.765
Oulu	-0.881	-0.651	-0.906	-0.774	-0.851

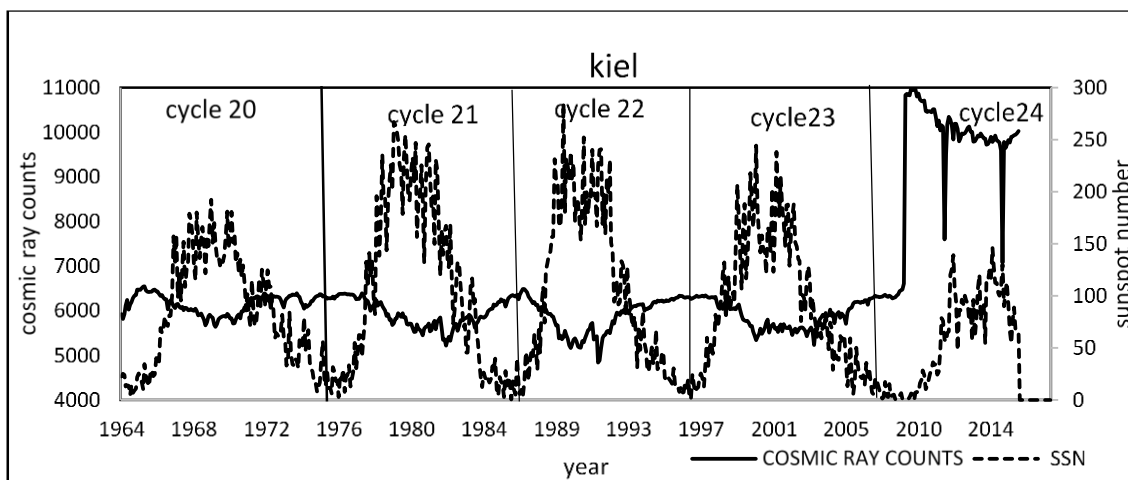


Figure 1. The relationship between SSN and CRI for solar cycles (20,21, 22, 23 and 24) (Kiel neutron monitor station).

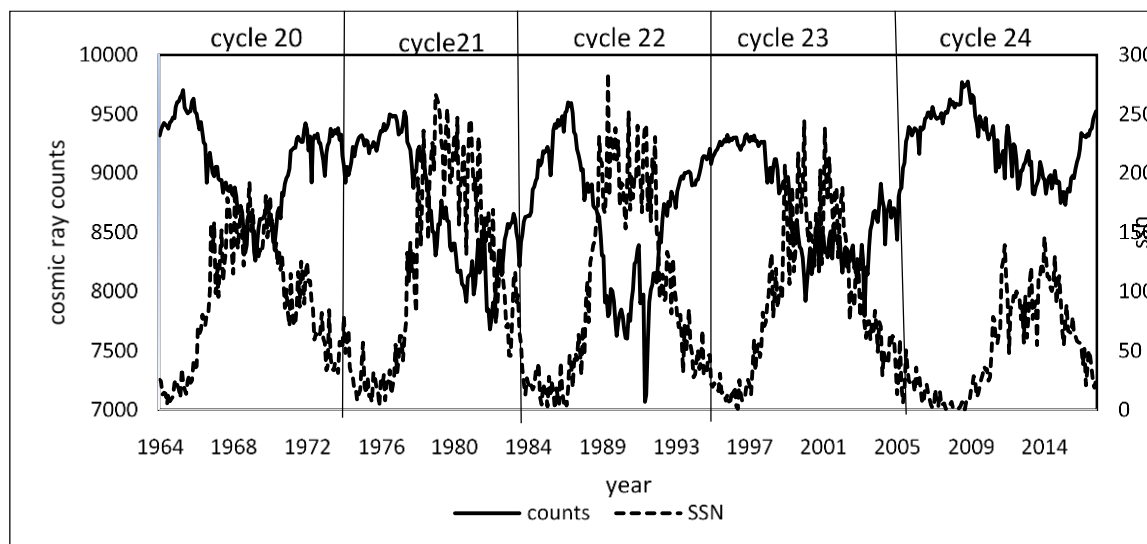


Figure 2. The relationship between SSN and CRI for solar cycles (20,21, 22, 23 and 24) (Moscow Neutron monitor station).

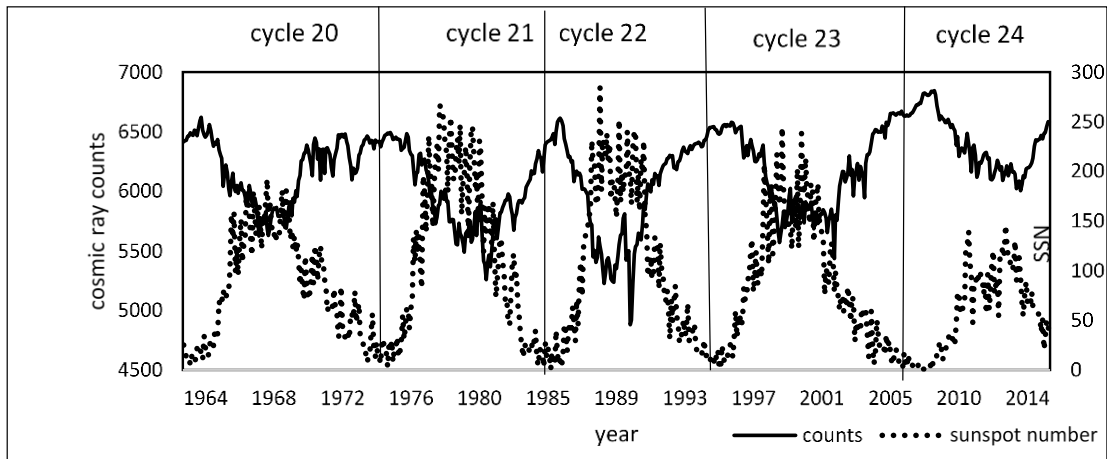


Figure 3. The relationship between SSN and CRI for solar cycles (20,21, 22, 23 and 24) (Oulu Neutron monitor station).

observed in solar cycles 20, 23 and 24 for the three stations analyzed. Similarly, an extremely strong anti-correlation was obtained during the solar cycle 22, however, a slightly weaker anti-correlation was observed during the solar cycle 21. The negative correlation coefficients indicate that as sunspot number increases cosmic ray intensity decreases, this is expected as stronger solar winds and magnetic fields which can deflect cosmic rays are generated during high solar activity periods. This outcome is consistent with the result of Potgieter (2013).

The results from this investigation confirm the solar modulation effect on cosmic rays, demonstrating that solar activity plays a crucial role in shaping the cosmic ray spectrum. The differing correlation coefficients between the three stations suggest that the solar modulation effect differs with latitude, altitude as well as cut-off rigidity. Furthermore, Bazilevskaya *et al.* (2014) have suggested that the level of the modulation is significantly dependent on the Cosmic rays' energy, which varies from a few per cent, for a Neutron monitor station in an equatorial region to approximately 20% for a Neutron monitor station in polar region.

The observed slightly weaker correlations in cycle 21 compared to the other four cycles studied indicate a solar cycle-dependent modulation effect. Ross and Chaplin (2019) suggested there is a conspicuous difference in the shape of the relationship between SSN and CRI in odd and even-numbered solar cycles, this discovery requires further investigation.

Finally, the analysis of five consecutive solar cycles suggests that the solar modulation effect may exhibit long-term variability which could impact the understanding of cosmic ray flux and radiation exposure in space.

Conclusions

The investigation on the heliospheric modulation of cosmic

ray intensity by solar activity for the past five solar cycles (1964-2015) using data from three neutron monitor stations has been studied. The results reveal a strong anti-correlation association between the cosmic ray intensity and sunspot number in solar cycles 20, 23 and 24 for the three stations analyzed. Correspondingly, an extremely strong anti-correlation was obtained during the solar cycle 22, however, a slightly weaker anti-correlation was observed during the solar cycle 21. The results from this investigation confirm the solar modulation effect on cosmic ray intensity, demonstrating that solar activity plays a crucial role in shaping the cosmic ray spectrum. The slightly weaker correlations in cycle 21 compared to other cycles show a solar cycle-dependent modulation effect necessitating further research. The differing correlation coefficients between the three stations suggest that the solar modulation effect differs with latitude, altitude and cut-off rigidity. Finally, the influence of cut-off rigidity on the energy spectrum of the cosmic ray was observed as the station with the lowest cut-off rigidity generated the strongest anti-correlation value.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in the execution of this study.

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