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The impact of several solar activity and geophysical parameters on the CR muons observed at high cut-off rigidity station

Maghrabi Abdullrahman [a] Almasoudi Aisha*[b], and Alruhaili Aied[b]

[a] *National Centre for Climate change, King Abdulaziz City for Science and Technology, Riyadh 11442, Saudi Arabia.*

[b] *Astronomy and Space Science Department, King Abdulaziz University, Jeddah 21589, Saudi Arabia*

E-mail: amaghrabi@kacst.edu.sa, aioshalhothali@gmail.com,, aalruhaili@kau.edu.sa

The cosmic ray (CR) particles are modulated by solar activity with varying magnitudes and time scales. To better understand the modulation processes and their impact on the observed CR flux, it is important to investigate data from locations with different cut-off rigidities. In this study, we investigated the impact of interplanetary magnetic field (IMF B), sunspot number (SSN), solar radio emission flux at 10.7 cm (F10.7), and Dst index on the cosmic rays measured by the King Abdulaziz University (KAAU) muon detector located in Jeddah, western Saudi Arabia (Rc =14.8 GV) since 2007. We also used data from the King Abdulaziz City for Science and Technology (KACST) muon detector located in Riydah, central Saudi Arabia (Rc 14.4 GV) for comparison purposes. Our results revealed that the CR intensities were significantly anti-correlated with all variables except for the Dst index, which showed a positive correlation. The magnitude and strength of the correlations between the considered variables and CRs were determined and discussed. These findings are consistent with previous studies conducted by several investigators.

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*Speaker

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1. Introduction

The modulation of cosmic rays (CR) is a complex process that is influenced by various physical phenomena occurring in the heliosphere. As CRs travel through interstellar space towards Earth, they are impacted by interplanetary parameters such as the solar activity cycle, interplanetary magnetic field, solar wind speed, and the heliospheric current sheet [1-3]. Changes in these parameters can alter the flux, energy spectrum, and composition of cosmic rays that reach the Earth, resulting in what is known as CR modulation. Several activity parameters have been utilized to quantify CR modulation processes.

Sunspot number (SSN) is considered to be one of the most useful and representative solar activity indicators due to its long-term availability [4]. Solar radio flux arises at the active regions at heights where magnetic fields could take values from a few hundred to about 1500 gauss [e.g., 5-6]. This variable has been observed for several decades and has shown to be a good tracer of the activity of the solar cycle. The solar wind is magnetized plasma that flows continuously from the sun. Due to the frozen-in magnetic field, solar wind modulates the incoming CR charged particles through the convection, diffusion, adiabatic cooling, and drifts processes. The Dst index is a geomagnetic index that provides a measurement of the ring current enhancement encircling the Earth [7]. While these variables differ from one another in their physical representation, scale, threshold, and range of applicability, they all follow the 11-yr solar cycle [8]. The relationships between the CR variations and solar activity parameters have been investigated using CR data from locations with different, mainly low, cutoff rigidities.

Understanding the variations in these parameters is crucial in comprehending the modulation processes under different activity levels [8-12]. However, limited research has been conducted on CR muon measurements from sites with high rigidities.

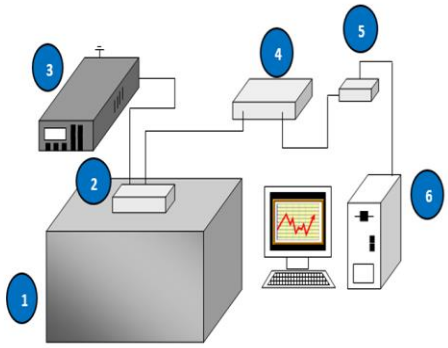
In this study, the impact of some solar activity parameters on the CR data is studied quantitatively. This is achieved by conducting correlative analysis between interplanetary magnetic field (B), solar radio flux at 10.7 cm (f10.7), Dst index, and smoothed sunspot number (SSN) and the CR data from the KAAU and King Abdulaziz City for Science and Technology (KACST) muon detectors for the period between 2007 and 2012. In the following sections, the observational data and methodology will be briefly described, followed by a discussion of the obtained results and associated interpretations.

2. Datasets and methodology

This study utilized pressure-corrected cosmic ray (CR) data obtained from the KAAU muon detector located in Jeddah, western Saudi Arabia, with a rigidity cut-off of 14.8 GV. Addationally, for comparsion purposes the CR data from King Abdulaziz city for Science and Technology (KACST) located at Riydah, central Saudi Arabia (cutoff rigidity 14.4 GV). Both detectors are the same and have been discussed in details in [13-15]. The detector (Figure 1) comprises a 1 m^2 plastic scintillator viewed by a photomultiplier tube contained within a light-tight box, and the associated electronics and data acquisition system were locally built and tested [15]. The detector has been in operation from January 2007 until 2021, with some periods of downtime due to upgrading processes, calibration procedures, and relocation. Data from the period between 2013 and 2021, with the most missing data, were excluded from considerations.

Solar, interplanetary, and geophysical data for the four variables (SSN, B, Dst index, and F10.7 cm) for the considered period were obtained from the OMNI NASA database.

Regression analysis was employed to investigate the relationship between CR data and solar activity parameters. This involved examining the correlation between CR data and each independent variable. The correlation coefficient, standrd deviations, and regression equation were obtained for each correlation. The Pearson correlation method was used to test the significance of the correlation coefficients with a probability of $p < 0.05$ and a confidence level of 95%.



1	Muon Box	4	Amplifier
2	PMT Base and Preamp	5	ADC
3	HV Power Supplier	6	Data Acquisition Board

Figure 1. Schematic diagram of the KAAU and KACST muon detectors.

3. Results and Discussions

Figure 2 displays a long-term plot of the mean daily values of cosmic ray muons detected by the KAAU and KACST detectors for the period between January 2007 and July 2012. Both detectors exhibit similar general variations over time, with some minor differences observed over the considered period. The number of CRs detected by both detectors decreases to a minimum in 2012, which corresponds to the maximum of the solar cycle 24. Additionally, monthly variations are observed in both detectors, with a peak in the summer and a minimum in the winter. The KACST detector exhibits slightly higher values of CRs than the KAAU detector, likely due to its location at a slightly higher latitude.

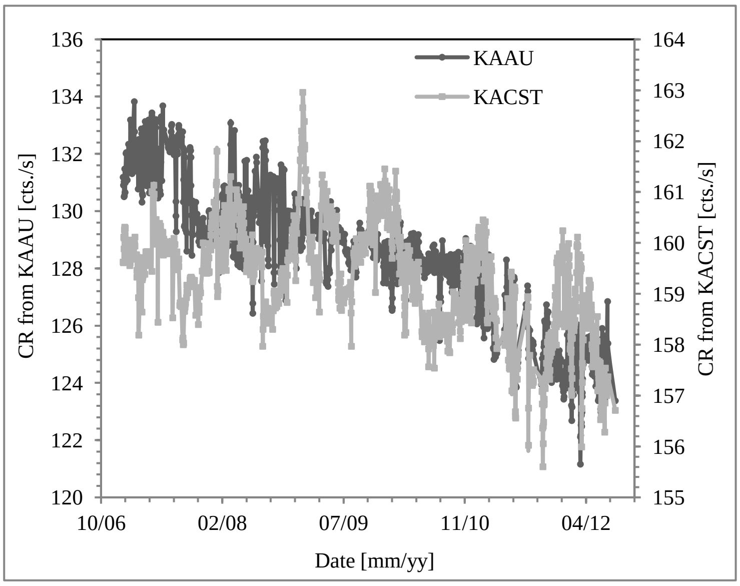


Figure 2. Time series of the mean daily values of the cosmic ray (CR) muons from the KACST detector and the KAAU detector for the period between 2007-2012.

Figure 3 is , an example, shows scatter plots of the mean monthly secondary CR count rate from the KAAU muon detector and two variables, the radio flux f10.7 and the Dst index, for the considered period. The scatter plot between CRs and radio flux f10.7 shows a generally weak negative correlation. Conversely, a weak positive correlation is observed between Dst index and cosmic ray muons.

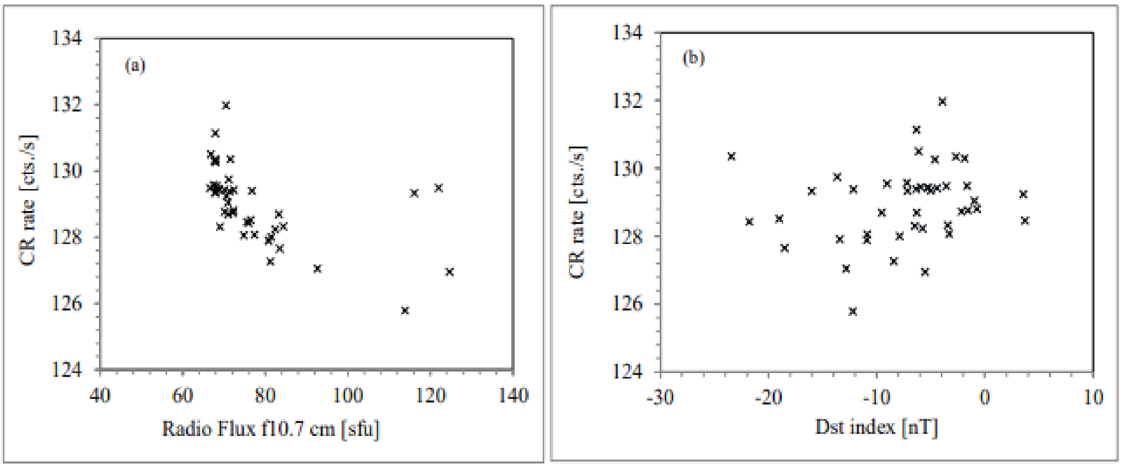


Figure 3. Scatter plots show the relationship between the monthly means of the secondary cosmic ray muons from KAAU detectors (a) radio flux f10.7 cm and (b) Dst index. For the period between 2007-2012.

Attempts were made to fit non-linear models, such as logarithmic, power law, and exponential, between the cosmic ray muons and the four parameters considered in this study. However, these models did not show better results than the linear fit. The slopes of the regression equations, correlation coefficients, and standard deviations were calculated between the monthly means of the CRs data from both detectors and the considered variables, and are presented in Table (1).

Table 1. Statistical results for the regression analyses (regression equations; correlation coefficient R; standard deviations (StDev) between the monthly mean values of the secondary CR muons from KACST and KAAU detectors and solar activity variables during the study period.

	KAAU			KACST muon detector		
	slope	R	StDev	slope	R	StDev.
IMF(B)	-0.33	0.15	1.27	-0.61	0.30	0.78
Sunspot number (SSN)	-0.05	0.71	0.92	-0.02	0.32	0.77
Dst index	0.04	0.27	0.2	0.04	0.22	0.80
F10.7 cm	-0.05	0.57	1.01	-0.01	0.1	0.82

The correlation analyses revealed statistically significant but weak to moderate correlations between the solar activity parameters and CRs measured by both detectors. Specifically, for interplanetary magnetic field (B), the KAAU detector showed a slope of -0.33 and a correlation coefficient of 0.15, while the KACST detector showed a steeper slope of -0.61 and a correlation coefficient of 0.3. For sunspot number (SSN), both detectors showed a slope of -0.05, with KAAU having a higher correlation coefficient of 0.71 and KACST having a coefficient of 0.32. For Dst index, both detectors showed a slope of 0.04, with KAAU having a higher correlation coefficient of 0.27 and KACST having a coefficient of 0.22. For radio flux F10.7 cm, the KAAU showed a slope of -0.05 and KACST showed a slope of -0.01, with KAAU having a higher correlation coefficient of 0.57 and KACST having a coefficient of 0.1.

The differences observed in the correlation coefficients and slopes between the two detectors may be attributed to local geophysical conditions, although it is important to note that other factors such as local atmospheric conditions may also play a significant role in CR measurements. However, the correlation results presented in this study align with and reinforce previously established relationships, as documented in other studies [7-12 and 16]. For instance, Singh et al. [11] found that CR intensity from the Beijing neutron monitor (9.56 GV) decreased as the sunspot number for solar cycle 22 to 24. Additionally, Maghrabi et al. [10] reported negative correlations between CR muons recorded by the KACST muon detector and the interplanetary magnetic field, sunspot numbers, and F10.7 cm radio flux.

The variations observed in the correlation coefficients and magnitudes of variation between CR intensity and the solar activity variables used by different investigators may be attributed to several factors, including the time period analyzed, the detector type, and the cutoff rigidity. For instance, different detector types may be sensitive to different aspects of CR intensity, such as neutron monitors being more sensitive to low-energy CRs than muon detectors. Moreover, the time period analyzed may have an impact on the correlations observed, as the solar activity parameters and CR intensity may vary over different time scales. Additionally, the cutoff rigidity of the detector may affect the correlation coefficients, as it determines the minimum energy of the CR particles that can be detected. Overall, the results of this study contribute to the growing body of knowledge on the relationship between solar activity parameters and CRs, and highlight the need for further studies to explore the underlying factors that affect these correlations.

Conclusion

This study aimed to investigate the relationship between four solar activity parameters and secondary CR particles using monthly mean values. The KAAU and KACST muon detectors in Jeddah and Riyadh were used to collect CR data for the period between 2007 and 2012. The findings showed that the CR muons from both detectors were anti-correlated with all the parameters, except for the Dst index, which showed a positive correlation. These results are consistent with previous studies that have established similar relationships between CRs and solar activity parameters. However, the strengths of the correlations observed in this study were slightly weaker, which could be attributed to several factors.

Firstly, the study period may have played a role in the weaker correlations observed in this study. Previous studies have used longer time periods, and the shorter study period used in this study might have contributed to the weaker correlations observed. Secondly, the type of detection systems used in this study could have influenced the results. The KAAU and KACST muon detectors used in this study have different detection efficiencies and energy thresholds than those used in previous studies, which might have affected the strength of the correlations observed. Additionally, the cutoff rigidities used in this study might be different from those used in previous studies, which could have contributed to the weaker correlations observed.

Lastly, seasonal variations could have affected the strength of the correlations observed in this study. Cosmic ray muons were used in this study, which are more affected by seasonal variations compared to cosmic ray neutrons, which were used in most previous studies. Therefore, the seasonal variations could have contributed to the weaker correlations observed in this study.

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Further studies using longer time periods and different detection systems are needed to confirm these findings and improve our understanding of the relationship between solar activity and cosmic rays.

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