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Diurnal variations of Cosmic Ray Muons at Saudi Arabia Using KAAU muon detector

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The diurnal variation of cosmic rays (CR) is an important tool for understanding the fundamental physics of the Earth's heliosphere and magnetosphere. It depends on complex processes in the interplanetary magnetic field (IMF), magnetosphere and other regions, depending on the detector's location on Earth. Daily variations can be characterized by magnitude (maximum value) and phase (time of maximum magnitude). In this study, the first available data from the King Abdulaziz University (KAAU) muon detector was used to investigate the diurnal amplitude and phase of CR muons. KAAU is located in Jeddah (Rc = 14.8 GV) in western Saudi Arabia and has been operating since 2007. The magnitude and phase of daily fluctuations in CR muons were calculated and determined. Although the diurnal fluctuations of CR muons are more complex than those of neutron monitors, results comparable to those previously described were found.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

PoS(ICRC2023)436

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1. Introduction

Cosmic rays are high-energy particles that originate from outside the solar system and constantly bombard the Earth's atmosphere. The flux of cosmic rays can vary on different timescales, including diurnal variations over a 24-hour period. The diurnal variation of cosmic rays is a daily fluctuation in the intensity of cosmic rays that is observed by detectors on Earth[1-3]. The intensity of cosmic rays is influenced by a variety of factors, including the Earth's rotation, the interplanetary magnetic field, and the solar wind. The diurnal variation of the cosmic ray intensity is interpreted initially on the basis of an outward radial convection and an inward diffusion along the IMF. The balance between the convection and diffusion generates an energy independent anisotropic flow of cosmic ray particles from the 18-hour co-rotational direction[4-7].

The diurnal variation can be characterized by the magnitude (maximum value) and phase (time of maximum magnitude) of the fluctuations, which depend on the location of the detector with respect to the Earth's magnetic field [8-10].

Diurnal variations in cosmic rays can provide insights into physical processes in the Earth's environment, the behavior of cosmic rays in the Earth's magnetic field, and the interplay between the magnetic fields of the Earth and the Sun. The study of diurnal variations in cosmic rays detected by ground-based instruments is essential for understanding the underlying physical mechanisms responsible for these variations. This research has practical applications in space weather forecasting, radiation protection, and climate modeling.

There have been numerous studies on diurnal variations in cosmic rays over the years, using various types of detectors and measurement techniques. These studies have identified various factors that can influence diurnal variations in cosmic rays, including solar activity, atmospheric processes, and geomagnetic activity [1-10]. However, there is still much to be learned about the complex interactions between these factors and how they combine to produce diurnal variations in cosmic rays [4-8].

The primary objective of this research is to conduct a comprehensive analysis of the diurnal variations in cosmic rays detected by the King Abdulaziz University (KAAU) detector, located in Jeddah, Saudi Arabia. The study aims to investigate the distributions of the cosmic ray data collected by the detector over a six-year period, between 2007 and 2012. The research focuses on exploring the amplitude and phase of the diurnal variations in cosmic rays and comparing the results obtained with previous studies.

2. Data and methodology

In this study, cosmic ray data from the King Abdulaziz University (KAAU) muon detector were analyzed to investigate the diurnal variations of cosmic ray (CR) muons. The data used in this study covers the period between 2007 and 2012.

The detector used in this study is similar to the one previously installed at King Abdulaziz City for Science and Technology (KACST) and described in a previous publication [11]. The detector consists of four sheets of an NE10-type plastic scintillator, each measuring 100 cm ×100 cm ×5 cm, viewed by a 12 cm R877 Hamamatsu Photomultiplier Tube (PMT) housed in a light-tight container. Cosmic ray (CR) muons passing through the detector excite the scintillator material, which emits fluorescent light detected by the PMT and converted into an electrical signal. The

signals are then amplified and digitized for recording. Atmospheric pressure and laboratory temperatures are also recorded using pressure and temperature sensors.
To analyze the diurnal variation in the hourly pressure-corrected cosmic ray (CR) data were fitted with a single harmonic fit and a double harmonic fit.
The single harmonic fit involves fitting a cosine function with a period of 24 hours to the data using equation 1 [e.g., 9]:

$$f(t) = A + Bcos(\omega t + \emptyset) \quad (1)$$

where A represents the average value, B represents the amplitude, ω represents the angular frequency ($\omega = 2\pi/24$), t represents time, and ϕ represents the phase angle.
The double harmonic fit involves fitting two cosine functions with periods of 24 hours and 12 hours, respectively, to the data using the equation 2 [10]:

$$f(t) = B_0 \cos(\omega t + \varphi_0) + B_1 \cos(2\omega t + \varphi_1) \quad (2)$$

where A represents the average value, $B_\circ$ and B1 represent the amplitudes of the 24-hour and 12-hour period variations, respectively, ω represents the angular frequency ($\omega = 2\pi/24$), t represents time, $\phi_\circ$ and ϕ_1 represent the phases of the variations.
Previous authors, such as [10], have recommended using the double harmonic fit for analyzing the diurnal variation in CR muon data. The double harmonic fit captures both daily and sub-daily changes in atmospheric conditions and provides a more detailed representation of the diurnal variation in the muon data. In contrast, the single harmonic fit may be sufficient for analyzing the diurnal variation in CR neutron data, as the neutron component is less sensitive to changes in atmospheric conditions [10 and 13].
Figure 1 provides an example of the daily variations of CR muons during November 2011. The results show that the double harmonic fit (Figure 1.b) provided a better fit to the data compared to the single harmonic fit (Figure 1.a).

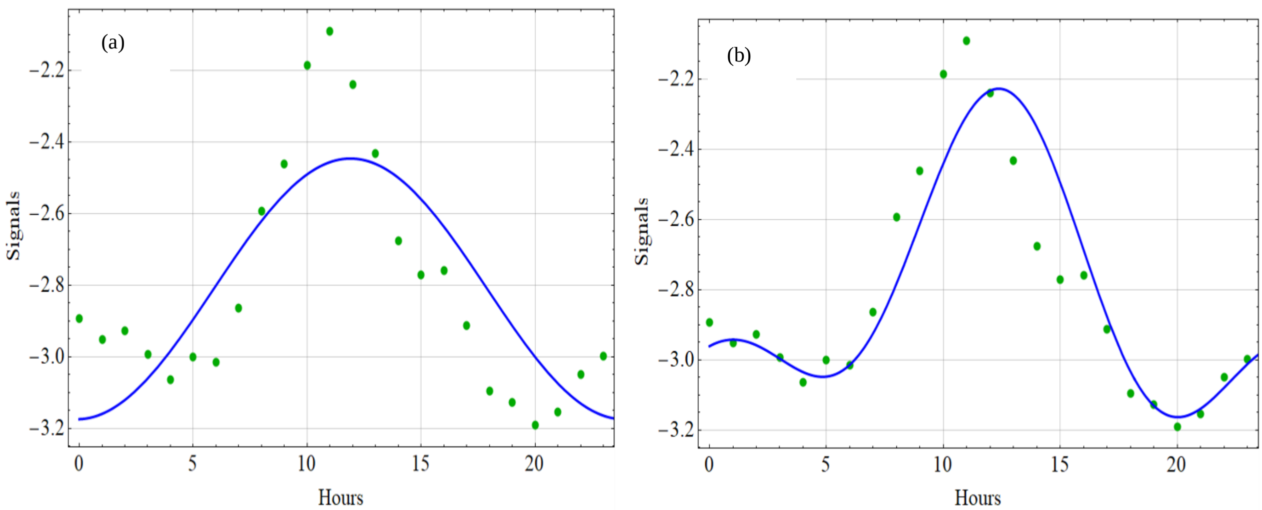

Figure 1. Displays the November 2011 recordings of CR muons by the KAAU detector, fitted by (a) Single harmonic Fit and (b) Double harmonics Fit models.

To evaluate the quality of the fits, the sum of squared differences between the observed and fitted values, denoted by d^2, was calculated for both the single and double harmonic fits. The equation used to calculate d^2 is defined as follows [9 and 12]:

$$D^2 = \sum_n \quad (Y_i - f(t_i))^2 \quad (3)$$

where n represents the number of data points, Y_i denotes the observed values, and $f(t_i)$ represents the corresponding fitted values. The smaller the value of D^2, the better the quality of the fit. In most cases, the values of D^2 were found to be extremely small, indicating good quality fits.

Once the coefficients of the fits for each month using epoch analyses were calculated, statistical assessments were conducted to analyze their values. The statistical assessments included conducting hypothesis tests to determine the statistical significance of the coefficients, examining the goodness of fit measures such as the coefficient of determination (R^2), and assessing the residuals to ensure that they were normally distributed and independent. The correlation coefficients were also calculated for each fit and found to be above 0.90 in all cases, and as high as 0.99 in some cases. In addition, descriptive statistics such as mean, maximum, quartiles, and standard deviation were used to provide information about the distribution of the data and to identify any outliers or unusual patterns in the data.

3. Results and Discussions

Figure (2) displays the distributions of the amplitudes and phases obtained using a single harmonic fit for each month during the six-year period. Panel (a) shows the distribution of amplitude values, while panel (b) shows the distribution of phase values.

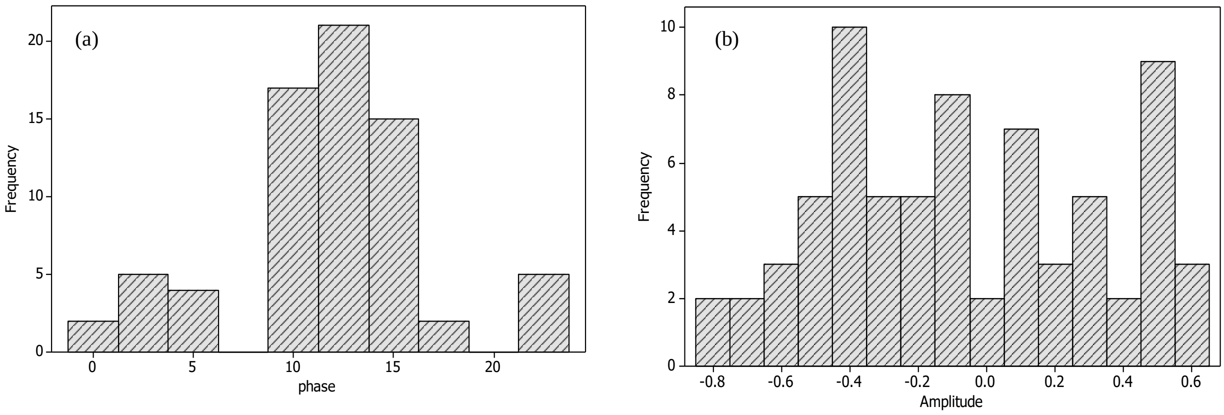

Figure 2. The monthly distributions of (a) phase ϕ (H in the figure) and (b) amplitude B for CRs detected by the KAAU muon detector between 2007 and 2013, using a single harmonic fit.

The figure showed that the mean phase (ϕ) value was 11:40 ± 4.803, with most values occurring between 09:00 and 15:00 UT (LT+3 h). The distribution was slightly left-skewed and leptokurtic. The mean amplitude (B) value was -0.0617 ± 0.3895 %, with a range of -0.83 to 0.57 %. The distribution was approximately symmetric and platykurtic. The mean phase value found, in this study, around 15:00 LT time was consistent with previous studies that reported the same time as the maximum intensity of CR muons [12].

However, the mean amplitude value obtained in this study was slightly smaller than those reported previously for CR neutrons. For instance, [7] reported mean amplitudes of 0.03% and 0.05% for underground muon detectors in Mawson and Hobart, respectively, while [12] study reported amplitude of variation values of 0.24% and phase values of about 14:00 and 14:30 local time for Aragats and Nor Amberd neutron monitors, respectively.

As we have disccused above the pattern of the daily variations of the muons requires more complicated function to consider the due to the existence of two minima and maxima between them needs additional analysis for relevant interpretation. The CR data were fitted by two cosines with 24- and 12-h periods (equation 2).

Figure 3 displays the distributions of the values of the monthly amplitudes and phases obtained using two harmonic fits over a six-year period.

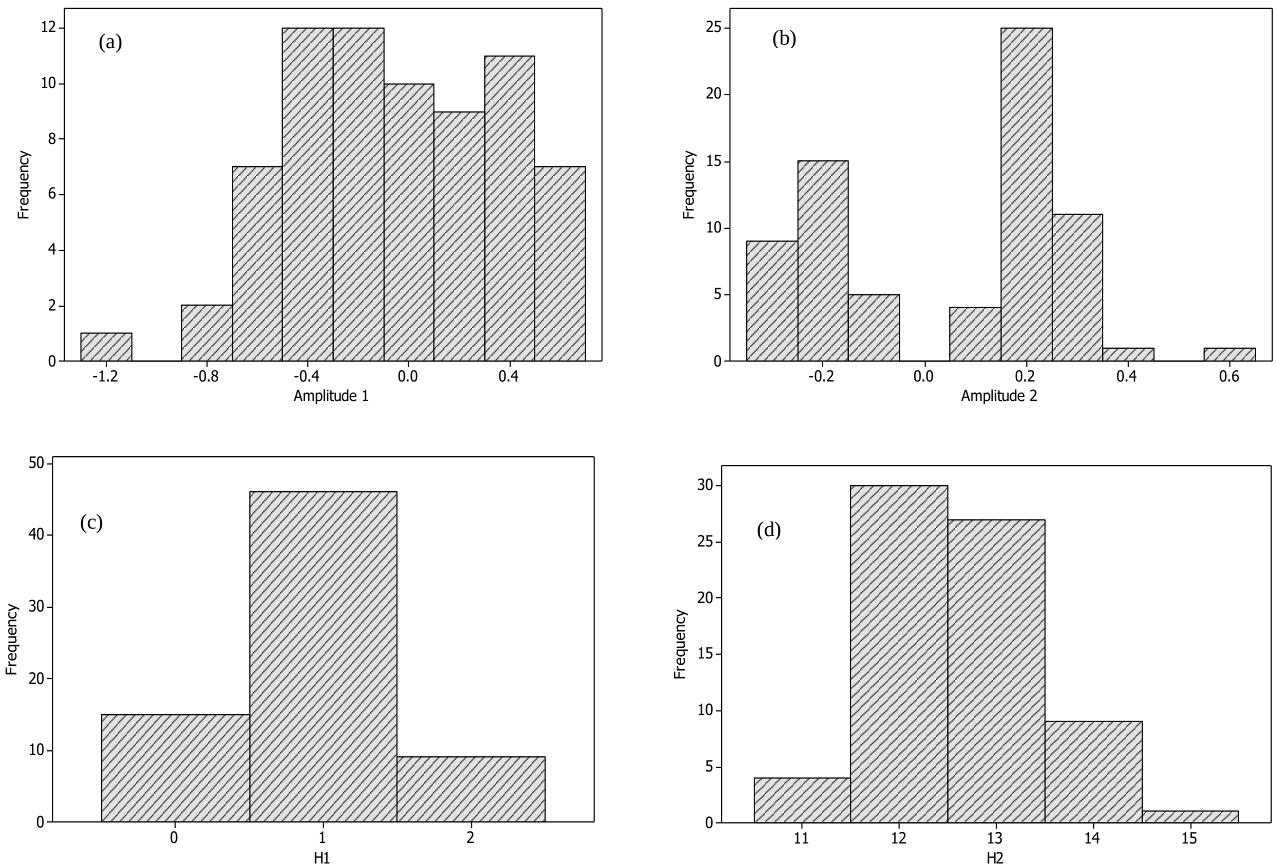

Figure 3. The monthly distribuations of (a) Amplitude 1 (B0), (b) Amplitude 2 (B), phase 1 (H1), and (d) phase 2 (H2) for CRs detected by the KAAU muon detector between 2007 and 2013, using two harmonic fit.

The mean value for B_0 was -0.05 ± 0.40 %, with a range of -1.11 to 0.57 %. The distribution was slightly left-skewed and platykurtic. The mean value for B_1 was 0.05 ± 0.23 %, ranging from -0.3322 to 0.5768 %. The distribution was slightly left-skewed and leptokurtic.
Phase 1 (ϕ_0 or H1 in the figure) had a nearly symmetric distribution with a mesokurtic shape, with the maximum CR intensity at 00:00 UT and the most highly concentrated intensity at 01:00 UT. Phase 2 (ϕ_1 or H2 in the figure) had a moderately variable distribution with a relatively narrow range of variation, with a mean value of 12:30 ± 0.83 UT and ranging between 11 and 15 UT. The distribution was slightly right-skewed and nearly mesokurtic.
The obtained results are consistent with those previously reported. For instance [13] by using the CR from the single chanel muon detector and MWC they found that the amplitude of the variation for the MWC is about 1.1 % and the first phase (corresponds to 01:24 UT). Similarly the single chanel muon detector has an amplitude of about 0.45 % and occurs at 11:33 UT. On the other hand, the minimum variations (ϕ_0) for both detectors (happens around 12:30 UT.
The amplitude and phase of cosmic ray (CR) muons are influenced by a wide range of factors, making it difficult to fully understand the observed variability in these parameters. Changes in atmospheric temperature, pressure, and electric field can affect the rate at which secondary cosmic rays reach the Earth's surface, with pressure having the greatest effect [6-7 and 13]. Other factors that can affect the amplitude and phase of CR muons include solar activity, which can modulate the flux of galactic cosmic rays and the solar wind, and geomagnetic activity, which can affect the propagation and direction of cosmic rays [6-10 and 14]. Latitude and altitude can also influence cosmic ray flux, with higher latitudes and altitudes generally leading to higher fluxes. The local time of observation can affect the observed diurnal variations in CR intensities, as the orientation of the Earth's magnetic field changes as the Earth rotates, affecting the direction of cosmic ray propagation and therefore the observed intensity [14-16].
Overall, understanding the complex interplay of these factors and their effects on the amplitude and phase of CR muons requires ongoing research and analysis of CR data.

Conclusions

This study utilized the first available data from the King Abdulaziz University (KAAU) muon detector in Jeddah, Saudi Arabia, to investigate the diurnal amplitude and phase of cosmic ray (CR) muons. The detector has been collecting data since 2007, and single and two harmonic fits were used to obtain the phase and amplitude of the daily variations of CR muons observed at this location.
Using single fit procedures, it was found that the maximum CR intensities occur at 11:40 ± 4.803 UT (14:40 LT) with a mean amplitude of -0.0617 ± 0.3895. Utilizing two harmonic fits, it was found that the CR muons exhibited two peaks, the first occurring around 00:00 UT with an amplitude of -0.05 ± 0.40, and the maximum found at 12:30 ± 0.83 UT with an amplitude of 0.05 ± 0.23%.
These results are consistent with previously reported findings and demonstrate the capability of the KAAU muon detector to provide valuable information about the diurnal variation of CR. The magnitude and phase of daily variations in CR depend on complex processes in the interplanetary magnetic field (IMF), magnetosphere, and other regions, which vary depending on the detector's location on Earth.
Overall, the diurnal fluctuations of CR muons are more complex than those of neutron monitors, but the results obtained in this study can help to improve our understanding of the underlying physical processes that contribute to the observed variations in CR data. This information can aid in the development of more accurate models of the Earth's heliosphere and magnetosphere.

Acknowledgments

The authors would like to thank King Abdulaziz University (KAAU) for supporting this work.

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