PROCEEDINGS OF SCIENCE

Study of modulation cycles of cosmic ray diurnal anisotropy variation using 22 years of GRAPES-3 muon data

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The diurnal variations of the galactic cosmic rays (GCRs) measured by ground-based detectors represent an anisotropic flow of GCR at 1 AU, also known as solar diurnal anisotropy (SDA). The GRAPES-3 muon telescope (G3MT) has been recording high statistics of muons at a rate of ∼50000 per second for the past two decades allowing us to probe the tiny variations in the muon flux caused by solar phenomena. We have examined the 22 years (2000-2021) of G3MT data using the Fourier series technique to obtain the daily SDA amplitude and phase. We observe that the yearly averages of SDA amplitudes have a period of one sunspot cycle (11 years), which strongly correlates with the interplanetary magnetic field. The annual phase variation suggests the presence of 22-year periodicity and shows a clear shift towards earlier hours with a decrease in solar activity.

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1. Introduction

The small amplitude of diurnal variation poses a challenging investigation of the various solar-induced effects on cosmic ray modulation. Accurately determining this diurnal anisotropy's long-term and daily characteristics is crucial for developing theoretical models explaining the fundamental mechanism of diurnal amplitudes (DA). The diurnal variation refers to a nearly sinusoidal fluctuation in galactic cosmic rays (GCR) intensity resulting from local anisotropy in the GCR flux. This anisotropy is influenced by both the convection caused by the solar wind and the diffusion along the interplanetary magnetic fields (IMF). The modulation of GCR flux occurs through anti-sunward convection and sunward diffusion along the spiral magnetic fields, resulting in a minimum during post-midnight and a maximum during early afternoon local time (LT) sectors [1–3]. The idealized phase and amplitude of a diurnal variation can be altered due to factors such as drifts, local latitudinal gradients in cosmic ray intensity, fluctuations in diffusion levels, or varying conditions of the solar wind. These factors may cause deviations from the expected diurnal pattern.

Many ground-based detectors have observed the diurnal variations primarily using neutron and muon [4–6]. According to Oh et al. (2006), the maximum phase of diurnal variation is influenced by changes in the interplanetary magnetic field due to solar activity and the cutoff rigidity associated with geomagnetic latitude [7]. Another study, Oh et al. analyzed diurnal variation using the "pile-up method" with neutron monitors located at high latitudes (Oulu) covering the period from 1964 to 2006, middle latitudes (Rome) covering the period from 1967 to 2006, and equator-located (Haleakala) covering the period from 1953 to 2006. The study found that at high latitudes, the maximum phase is modulated by a 22-year cycle, while at the equator, both 11-year and 22-year cycles influence the maximum phase [8]. It is important to note that the present study focuses solely on diurnal amplitudes and does not examine variations in phase.

2. The GRAPES-3 Muon Telescope

The GRAPES-3 experiment in Ooty, India, consists of a large-area (560 m^2) muon telescope (G3MT) designed to study the muonic components of extensive air showers. The G3MT comprises proportional counters (PRCs), six-meter-long iron tubes with a cross-section of $10\times10\,\mathrm{cm}^2$. There are 3712 PRCs arranged in four super-modules, each containing four modules with four layers of 58 PRCs. The orthogonal arrangement of consecutive layers allows for 2D directional reconstruction of incident muons, providing 225 independent directions. To achieve an energy threshold of 1 GeV for vertical muons, a total thickness of 550 $\mathrm{gm\,cm^{-2}}$ in the form of concrete blocks is employed as an absorber by placing 15 layers of concrete blocks. The concrete blocks have been arranged in an inverted pyramid to achieve an energy threshold 1 (secθ) GeV for muons incident on the detector with zenith angle (with coverage up to 45°) as shown in Fig. 1 [9]. The impressive high rate of the G3MT, reaching 50,000 Hz, allows us to explore even the subtlest fluctuations in the muon flux.

Additionally, the unique capability of precise directional reconstruction of G3MT opens up numerous possibilities for scientific investigations. Beyond its primary purpose of studying extensive air showers, the G3MT can also be utilized to explore transient phenomena. For example, it can be employed to monitor geomagnetic storms [10] and investigate the acceleration of particles during

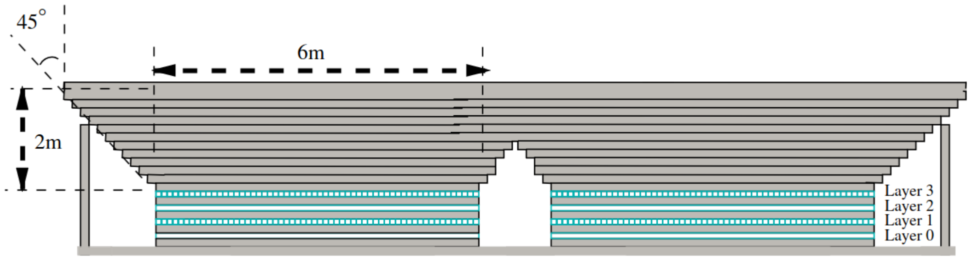

Figure 1: Schematic of muon detector module with four layers of proportional counters integrated into concrete blocks.

thunderstorms [11]. These additional capabilities make the G3MT an incredibly versatile tool for the scientific community, enabling researchers to delve into various fascinating phenomena.

3. Data Preparation and Results

The G3MT dataset spanning 22 years (2000-2021) has undergone initial correction to account for atmospheric pressure effects [12]. Subsequently, the Fourier series technique has been applied to extract the daily DA from the dataset. These amplitudes were further utilized to construct yearly distributions, allowing us to calculate the yearly means. Fig. 2 shows the overlapped distributions of a high (2002) and a low (2009) solar activity year during the analysis period. During the high solar activity year, the mean DA and the distribution spread are found to be higher (mean = 0.24% and RMS = 0.13%) as compared to the low solar activity year(mean = 0.08% and RMS = 0.04%).

Simultaneously, we acquired solar plasma parameters (IMF and V_{SW}) and sunspot numbers for the same duration from the OMNI-Web database (https://omniweb.gsfc.nasa.gov/) and computed their yearly averages. Fig. 3 presents the findings, with panel (a) presenting the yearly variations of observed DA, panel (b) depicting the yearly values of IMF, panel (c) illustrating the yearly variations of V_{SW}, and panel (d) showcasing the yearly trends of sunspot numbers, serving as indicators of solar activity throughout the analyzed period. The yearly diurnal amplitude (DA) data exhibits an 11-year periodicity, with two prominent maxima observed in 2002 and 2015 and two corresponding minima in 2009 and 2020. Remarkably, this pattern closely mirrors the variations observed in the yearly interplanetary magnetic field (IMF), as depicted in panels (a) and (b) of Fig. 3. We calculated the Pearson correlation coefficient (r) using the available 22 years of data to quantify the correlation between the DA amplitude and the IMF. The analysis reveals a highly robust positive correlation (r(20)=0.96) with an extremely low p-value (p=1.6x10^{-}12). Additionally, when examining the relationship between the DA amplitude and solar wind velocity (V_{SW}), a moderate positive correlation is observed (r(20)=0.58) with a statistically significant p-value (p=0.004).

To further quantify the relationship between the daily diurnal amplitude (DA) and interplanetary magnetic field (IMF), a linear fit was applied as depicted in Fig. 4. The analysis yielded a slope value of (0.047,±,0.001)%,/,nT. Notably, data points with larger error bars correspond to years of high solar activity. In contrast, the error bars for low solar activity years are minimal and hardly noticeable.

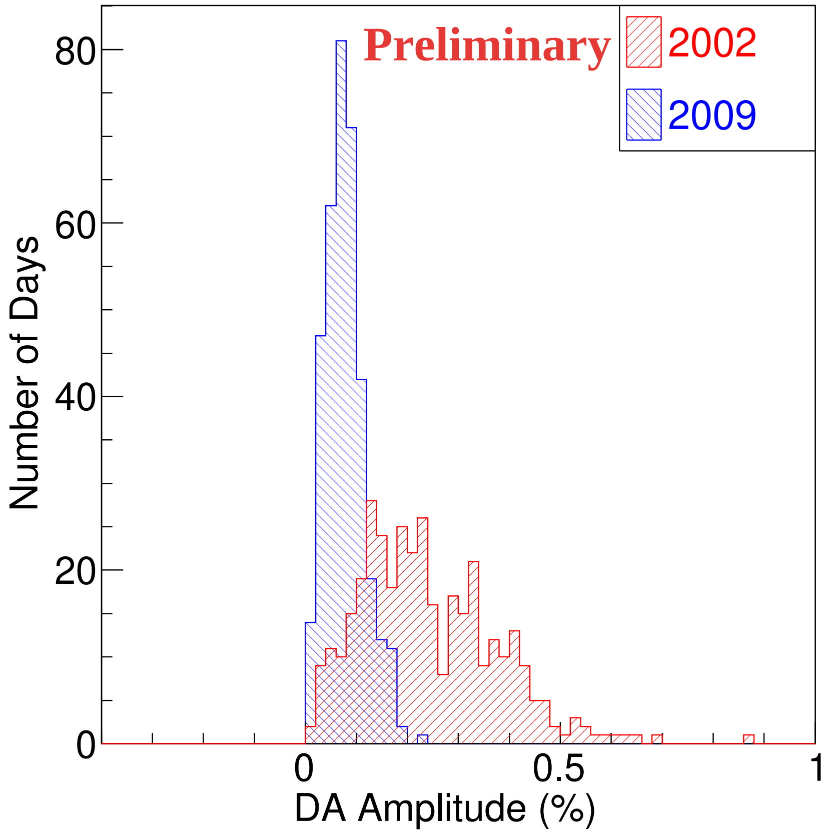

Figure 2: Distribution of daily values of diurnal amplitudes of DA for the year 2002 (mean = 0.24% and RMS = 0.13%), and for year 2009 (mean = 0.08% and RMS = 0.04%).

4. Discussion

Atmospheric conditions can influence the muon flux detected by ground-based detectors. Similarly, the data from the G3MT also experiences modulations due to changes in atmospheric pressure. Before further investigations, corrections were made to account for these atmospheric pressure effects. With the advantage of a large statistical dataset from 2000 to 2021, the G3MT allows one to study even the smallest variations in the daily DA. The Fourier series technique was employed to extract the daily DA values to achieve this. These amplitudes were then used to construct yearly distributions and calculate the mean values from these distributions. Compared to years with lower solar activity, higher solar activity years display a larger DA and wider distributions, which may be attributed to significant disruptions occurring in the heliosphere. Subsequently, the mean yearly DA values were plotted alongside the mean yearly IMF values, revealing a strikingly similar variation pattern (r(20)=0.96) and indicating an 11-year periodicity. A comparable pattern of variation was also observed in the mean yearly V_{SW} values. However, the correlation between DA and V_{SW} was found to be weaker (r(20) = 0.58) than the correlation between DA and IMF. This weaker correlation suggests that IMF diffusion plays a more significant role in causing DA than the effects of V_{SW} convection. A linear regression analysis was conducted using a linear fit to quantify the relationship between DA and IMF further, resulting in a slope value of (0.047 ± 0.001)% nT.

5. Summary

This study focused on the role of solar plasma parameters in producing the DA detected by the G3MT data. Corrections were applied to account for atmospheric pressure effects. Utilizing a large dataset from 2000 to 2021, the daily DA variations were extracted using the Fourier series technique. Higher solar activity years exhibited larger DA values and wider distributions, possibly due to heliosphere disruptions. The mean yearly DA values showed a strong correlation (r(20) = 0.96) with IMF, indicating an 11-year periodicity, while the correlation with V_{SW} was weaker (r(20) = 0.58). IMF diffusion was found to have a more significant role in causing DA. Linear regression yielded a slope value of (0.047 ± 0.001)% nT. This work offers the advantage of utilizing a large dataset and employing advanced analysis techniques to uncover correlations between solar activity and muon flux variations. It provides valuable insights into the role of solar activity and heliosphere disturbances in influencing ground-based muon detectors, enhancing our understanding of these phenomena.

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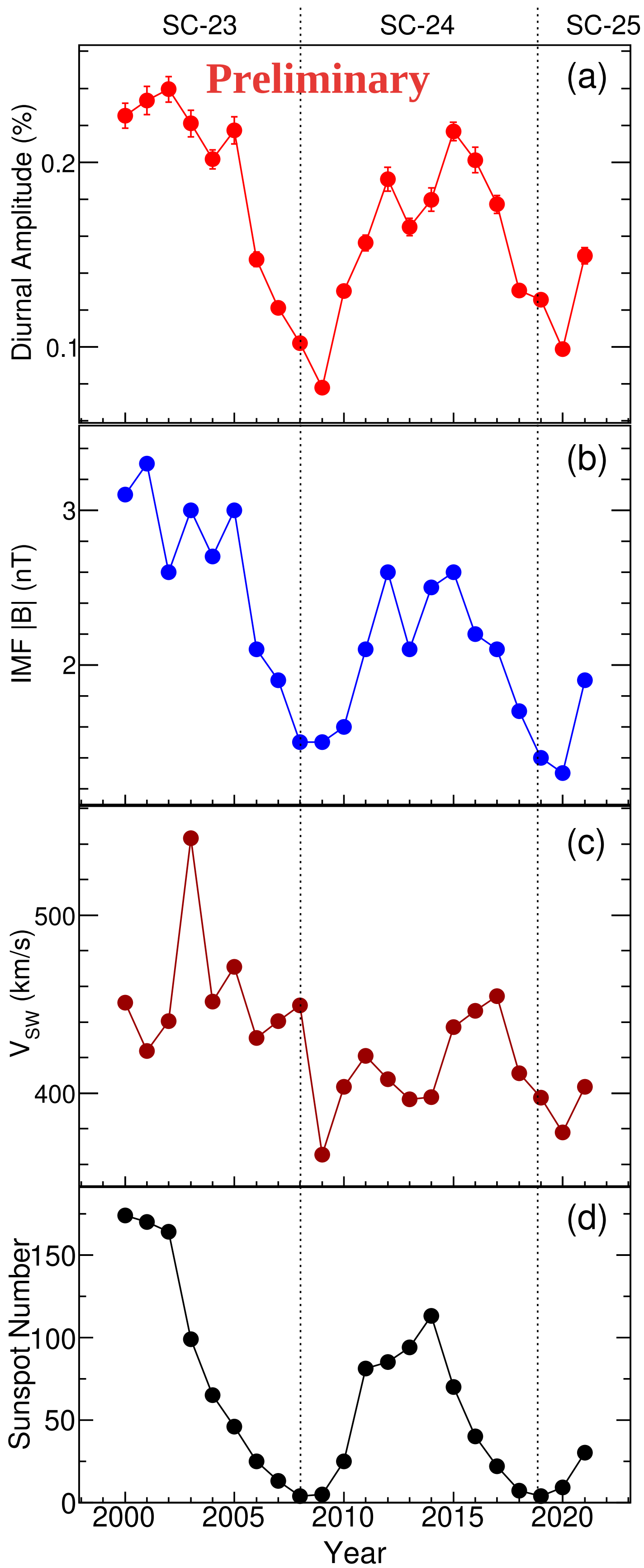

Figure 3: Annual variation of the DA amplitude in panel (a), IMF |B| in panel (b), V_{SW} in panel (c), and sunspot numbers in panel (d), from 2000 to 2021.

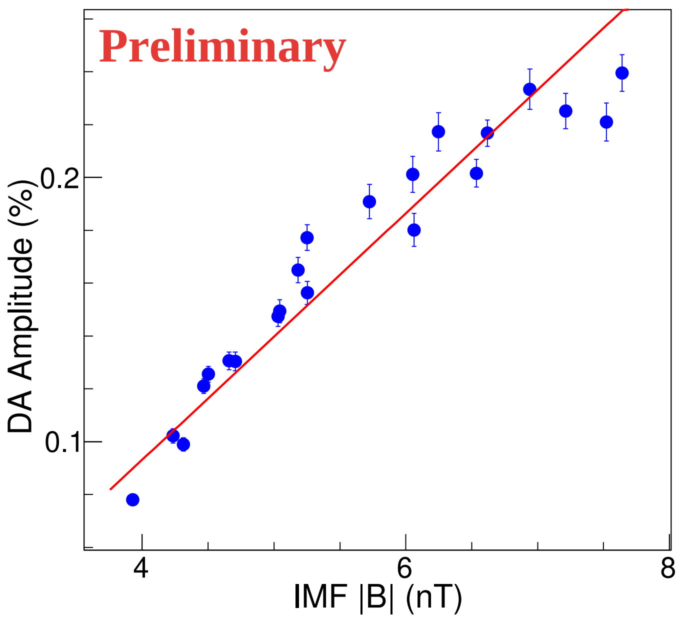

Figure 4: Dependence of the DA on IMF |B| for 2000 to 2021. The linear fit yields the coefficient of $(0.047 \pm 0.001)\% / \mathrm{nT}$