Kingdom of Saudi Arabia
Imam Mohammad Ibn Saud Islamic University (IMSIU)
Faculty of Sciences – Department of Physics

Identifying Solar Event Signatures in Cosmic Ray Data

A graduation project submitted to the Department of Physics in partial fulfillment of the requirements for the degree of Bachelor of Science in Applied Physics

By

Ashwaq Saleh Alrasheedi

Mariam Ibrahim Bani salamah

Supervised by

Dr. Ghada Khouqeer (IMSIU)

Dr. Mokhtar Fal (KACST)

IMSIU-Riyadh-KSA

May, 2025

Table of Contents

Table of Figures

Table of Tables

ACKNOWLEDGEMENTS

الحمد لله الذي بنعمته تتم الصالحات، وبتوفيقه تُختتم الجهود وتُكلل المساعي بالنجاح.

نهدي هذا الإنجاز إلى والدينا العزيزين، اللذين كانا بعد الله السند الحقيقي والدافع الأكبر في مسيرتنا. لقد شكّلا في حياتنا مصدر الإلهام الأول، وبنيا مستقبلهما بعزيمة وإصرار، ليمنحانا من خلاله دروسًا في الطموح والالتزام. لم يكن عطاؤهما يومًا محدودًا، بل كان غامرًا، ممتدًا، لا يُقاس. وإن كنا لا نبلغ مقامهما، فإننا نحمل مسؤولية تمثيلهما بكل فخر، ونمضي على خطاهما بمحبة وامتنان، ساعين لأن نكون امتدادًا لما زرعاه فينا من قيمٍ وأحلام.

كما نتوجه بخالص الشكر والتقدير إلى أعضاء هيئة التدريس في القسم، وخاصة من كان لهنّ دورٌ مباشر في تعليمنا وتوجيهنا. لقد كنا بحق محظوظين بأن نتعلم على أيدي نخبة من الأكاديميات المتميزات، اللاتي قدّمن لنا العلم بأسلوب راقٍ، وحرصن على إيصال المعرفة بأفضل صورة ممكنة، فكنّ مثالًا في العطاء والإخلاص.

ونخص بالشكر والعرفان سعادة **الدكتورة غادة خوقير**، التي كانت لنا قدوةً ومُلهمة، وركيزة أساسية في هذا المشروع. لقد منحتنا من وقتها وجهدها وعلمها بسخاء، وكانت حريصة على أن نصل إلى أفضل ما يمكن. حضورها في هذه الرحلة لم يكن مجرد إشراف أكاديمي، بل كان تجربة إنسانية وعلمية نعتز بها ونفخر. إن ما قدمته لنا يفوق حدود الشكر، وسيظل أثره ممتدًا في مسيرتنا القادمة.

كما نتقدم بجزيل الشكر **للدكتور مختار فال**، الذي كان داعمًا ومساندًا في كل مرحلة من مراحل هذا المشروع، وحرص دائمًا على أن نُقدّم أفضل ما لدينا، فكان لتوجيهاته وملاحظاته دورٌ كبير في تطوير العمل وتحقيق أهدافه.

ولا يفوتنا أن نُعبر عن امتناننا العميق **للبروفيسور عبدالرحمن مغربي**، الذي أتاح لنا فرصة ثمينة للاستفادة من علمه وخبرته الواسعة. لقد كان لتوجيهاته العلمية الدقيقة أثرٌ بالغ في توسيع مداركنا وتعميق فهمنا، وأسهمت مساهماته في بناء هذا البحث على أسس علمية متينة.

كما نُثمن عاليًا جهود **المهندس محمد المطيري**، الذي لم يتوانَ عن تقديم الدعم العلمي والعملي في كل مرحلة من مراحل المشروع. لقد كان مثالًا في التعاون والحرص، وكان لعطائه دورٌ جوهري في إنجاز هذا العمل.

ونُعبر عن شكرنا وتقديرنا **للمهندس عبدالله الدوسري**، الذي كان حاضرًا بدعمه وتعاونه، وأسهم بلباقته وعلمه في تسهيل العديد من جوانب هذا المشروع. لقد كان لعطائه أثرٌ ملموس في مسيرتنا، ونُثمن له كل ما قدمه من وقت وجهد.

وأخيرًا، نتوجه بجزيل الشكر إلى مدينة الملك عبدالعزيز للعلوم والتقنية (**KACST**)، على إتاحة هذه الفرصة البحثية القيّمة، التي كان لها بالغ الأثر في إثراء تجربتنا الأكاديمية، وتوسيع آفاقنا العلمية.

ABBREVIATIONS

CR: Cosmic Rays

GPS: Global Positioning System

GICs: Geomagnetically Induced Currents

CMEs: Coronal Mass Ejections

HSS: High-Speed Streams

SIRs: Stream Interaction Regions

SC: Sudden Commencements

SNN: Sunspot Number

F10.7: 10.7 cm Radio Flux

PMT: Photomultiplier Tube

NMDB: Neutron Monitor Database

Abstract

Cosmic rays (CR) are high-energy particles originating from various astrophysical sources that constantly bombard Earth from all directions. Variations in space weather, defined by dynamic solar activity, significantly influence the flux of cosmic rays. When CR interact with atmospheric molecules, they produce secondary particles detectable by ground-based instruments. This research aims to identify distinct patterns in CR flux variations associated with specific space weather events. Identifying time lags between solar events and CR responses is a starting point for developing advanced statistical methods to understand the relationship between solar activity, CR flux, and ground-based detection methods, paving the way for improved space weather forecasting. The study conducted shows that the Forbush decrease is greater when the Earth's magnetic rigidity cutoff is lower — that is, in regions where lower-energy particles can penetrate more easily. Additionally, we observed that an increase in solar wind speed leads to a stronger Forbush decrease. Furthermore, the impact on cosmic rays is more pronounced when solar activity occurs on the side of the Sun directly opposite Earth, meaning that solar events such as flares or coronal mass ejections originate from regions facing the planet.

الملخص

الأشعة الكونية (CR) هي جسيمات عالية الطاقة تنشأ من مصادر فلكية متعددة وتقوم بقصف الأرض باستمرار من جميع الاتجاهات. تؤثر التغيرات في الطقس الفضائي، والذي يُعرّف بالنشاط الشمسي الديناميكي، بشكل كبير على تدفق الأشعة الكونية. عندما تتفاعل الأشعة الكونية مع جزيئات الغلاف الجوي، فإنها تنتج جسيمات ثانوية يمكن اكتشافها بواسطة أجهزة موجودة على سطح الأرض. يهدف هذا البحث إلى تحديد أنماط مميزة في تغيرات تدفق الأشعة الكونية المرتبطة بأحداث معينة في الطقس الفضائي. إن تحديد الفترات الزمنية الفاصلة بين الأحداث الشمسية واستجابة الأشعة الكونية يُعد نقطة انطلاق لتطوير أساليب إحصائية متقدمة لفهم العلاقة بين النشاط الشمسي، وتدفق الأشعة الكونية، وطرق الكشف الأرضية، مما يمهد الطريق لتحسين التنبؤ بالطقس الفضائي. أظهرت الدراسة التي أُجريت أن انخفاض فوربوش يكون أكبر عندما يكون حد الصلابة المغناطيسية للأرض أقل أي في المناطق التي يمكن للجسيمات ذات الطاقة المنخفضة أن تخترقها بسهولة أكبر. بالإضافة إلى ذلك، لاحظنا أن زيادة سرعة الرياح الشمسية تؤدي إلى انخفاض فوربوش أقوى. علاوة على ذلك، فإن التأثير على الأشعة الكونية يكون أكثر وضوحًا عندما تحدث النشاطات الشمسية على الجانب المقابل مباشرةً للأرض من الشمس، مما يعني أن الأحداث الشمسية مثل التوهجات أو الانبعاثات الكتلية الإكليلية تنشأ من مناطق تواجه الكوكب.

Chapter 1: Theoretical Background

1.1 Introduction

Cosmic rays (CR) are high-energy particles originating from various astrophysical sources that continuously bombard Earth from all directions. Variations in space weather, defined by the dynamic conditions in space influenced by solar activity, play a significant role in affecting the flux of CRs. When CRs interact with atmospheric molecules, they generate secondary particles that are detectable using ground-based detectors.

This research investigates CR flux variations linked to specific space weather events. It lays the groundwork for advanced statistical methods to understand these phenomena by identifying time lags between solar events and CR responses. Through this project, we aim to clarify the relationship between solar activity, CR flux, and ground-based detection methods, to enable improved space weather forecasting.

1.2 Cosmic Rays

Cosmic Rays (CR) were discovered by Victor Hess and Kohlhorster in 1912, through their ionizing effect on airtight gas-filled vessels containing two electrodes with a high voltage applied between them. This ionizing effect increased with altitude during balloon flights, indicating that the source must be extraterrestrial. [1]

CRs are high-energy particles or photons that originate from sources outside the Earth. Primary CR particles having energies ranging from 1 GeV up to 10^{22}eV, arriving at the top of Earth's atmosphere from galactic, extragalactic, and solar sources. Before entering Earth's atmosphere, they mainly consist of protons, alpha particles, and heavy nuclei. Based on their sources, CRs are classified into three types: solar, galactic, and extragalactic.

These rays interact with magnetic fields from the Earth, the Sun, and galaxies, causing their paths to become complex and their directions to change. As a result, some CRs arrive at Earth in an approximately isotopic manner. Additionally, CRs have played an important role in the discovery of fundamental particles like the positron and muon [2, 3].

Origin and Composition

CRs originate from various astrophysical sources both within and beyond the Milky Way galaxy. Primary CRs consist of protons (90%), alpha particles (9%), and electrons (1%). Upon reaching Earth, primary CRs first interact with the planet's magnetic field before colliding with atmospheric particles, as shown in Figure 1.1. Low-energy particles are deflected by the Earth's magnetic field near the geomagnetic equator due to the perpendicular orientation of the magnetic field relative to their trajectories. Only very High-energy particles with energies above 10^{15} Mev can penetrate this barrier.Additionally, CRs can reach the Earth near the geomagnetic poles where the field lines are nearly vertical and more aligned with their incoming paths [4,5].

Interaction with Earth's Atmosphere

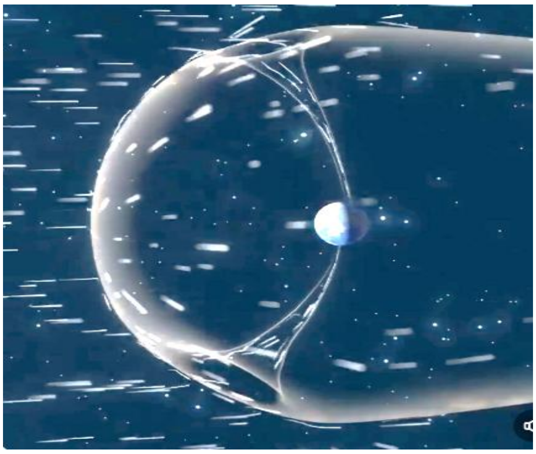


Figure 1.1: A visualization of the Earth's magnetic field

When CRs enter Earth's atmosphere, they undergo interactions with atmospheric particles, resulting in the production of secondary particles initiating several key physical processes, Such as:

Ionization: CRs, primarily composed of charged particles such as protons and alpha particles, collide with atmospheric molecules, stripping electrons from atoms and ionizing the surrounding air. This process creates ionized particles and free electrons, leading to the formation of ionization trails along the CR trajectory.

Nuclear Spallation: High-energy CRs can collide with atmospheric nuclei, triggering nuclear reactions known as spallation. In these collisions, the CR breaks the nucleus into smaller particles, such as protons, neutrons, and alpha particles, which contribute to the production of secondary CRs and particle cascades [5].

These interactions produce a phenomenon known as cosmic ray ***air showers***, which generate secondary particles, including muons, neutrons, and electromagnetic components, as shown in Figure 1.2. When these particles reach the Earth's surface, they are detected using specialized instruments: Muons via muon detectors, and Neutrons via neutron detectors.

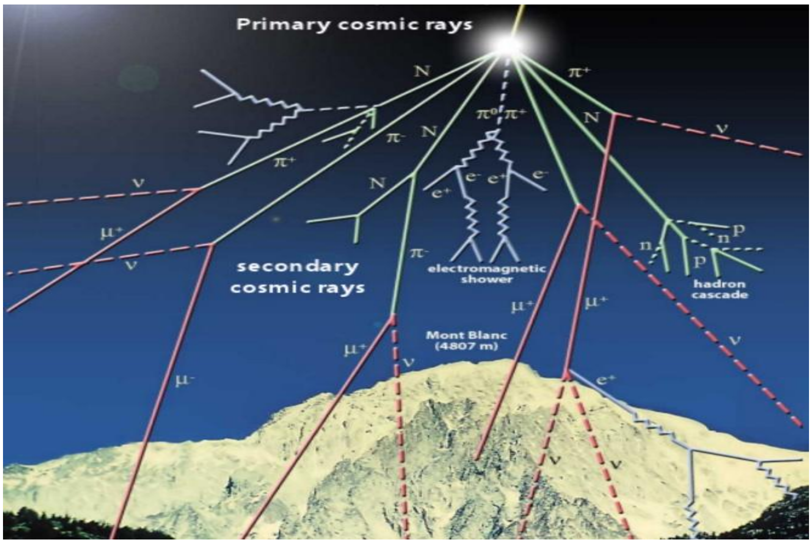


Figure 1.2: Air showers from CR interaction with the atmosphere

1.3 Space Weather

Definition and Impact

Space weather refers to the physical conditions in near-Earth space, encompassing electric and magnetic fields, plasma, and particle fluxes. The term first appeared in scientific literature in 1968, evolving over time to include the study of solar-terrestrial interactions and their effects on the environment and technology. Space weather encompasses various phenomena such as solar flares, coronal mass ejections, and high-speed plasma streams originating from solar coronal holes. These phenomena trigger disruptions like geomagnetic storms and geomagnetically induced currents (GICs).

The primary effects of space weather manifest as disruptions in technological systems, both in space, such as satellites, and on Earth, like power grids and energy transmission lines. Common impacts include GPS signal disruption, radio communications interference, and accelerated pipeline corrosion due to induced currents. As technological dependence grows, the consequences of these disturbances become increasingly severe, underscoring the importance of understanding and forecasting space weather to develop more sustainable and resilient systems [6, 7].

Primary Solar Phenomena

The key drivers of space weather involve three primary solar phenomena that interact significantly with the space environment and directly impact Earth as shown in Figure 1.3. These drivers are:

Solar Flares: Solar flares are powerful and sudden bursts of electromagnetic energy spanning multiple wavelengths, from radio waves to gamma rays. These flares result from magnetic reconnection in the Sun's active regions, releasing high-energy charged particles. Their effects include disruptions to Earth's ionosphere, which can interfere with radio communications and navigation systems.

Coronal Mass Ejections (CMEs): CMEs are massive plasma and magnetic field eruptions originating from the Sun's closed magnetic field regions. They release significant amounts of energy and particles into space, often causing geomagnetic storms when they collide with Earth's magnetosphere. These storms can impact satellites, power grids, and other critical infrastructure.

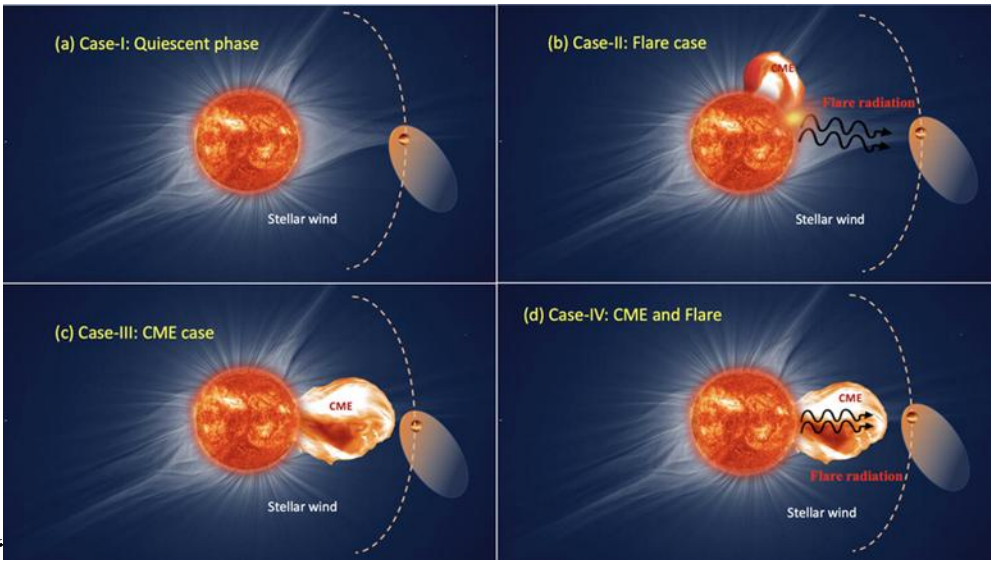
"

Figure 1.3: CME and Flare [8].

Solar Wind and High-Speed Streams (HSS): Solar wind consists of charged particles continuously emitted by the Sun in all directions. When coronal holes appear on the Sun's surface, particles escape at high velocities, forming high-speed streams (HSS). These streams interact with regular solar wind, producing stream interaction regions (SIRs) that can disturb Earth's magnetosphere and impact both space-based and ground-based systems.

Each of these phenomena contributes uniquely to the formation of space weather and impacts Earth in distinctive ways, emphasizing the importance of understanding and predicting these drivers to mitigate their effects [9].

Earth's Geospace Response

Earth's geospace response encapsulates the intricate and dynamic interactions within its magnetosphere, driven by solar phenomena such as interplanetary shocks and intensified solar wind conditions. These phenomena cause significant disturbances in Earth's magnetic field, one of the most notable being Sudden Commencements (SCs). SCs occur when interplanetary shocks exert compression on the Earth's magnetosphere, triggering shifts in electric currents across both the magnetosphere and ionosphere. Such shifts propagate waves of disturbance across Earth's geospace environment.

Beyond the magnetosphere, the ionosphere also bears the brunt of these phenomena. These disruptions can significantly affect critical systems such as satellite communications and GPS navigation, underscoring the necessity of comprehending these responses for technological and safety reasons. Araki's 1994 model plays a pivotal role in elucidating the mechanisms behind these geomagnetic phenomena, offering a detailed framework for understanding the Earth's geospace dynamics [10].

1.4 Objectives

In this project, the objectives are to investigate the impact of solar events on CR flux using data from multiple stations with varying cut-off rigidities of CRs. Then compare the impact of strong versus moderate solar events. Additionally, calculate the Forbush decrease percentage for CRs. Finally, analyze differences in wind speed and humidity between observation stations.

1.5 Historical Overview of Cosmic Ray Modulation

The heliosphere modulates the fluxes of CRs observed at Earth through a combination of processes, including solar magnetic activity, solar wind dynamics, and the structure of the heliospheric magnetic field. Variations in the solar activity cycle, such as the 11-year solar cycle, lead to changes in the heliospheric modulation of CRs, with higher fluxes observed during solar minimum and lower fluxes during solar maximum. During periods of low solar activity (solar minimum), the heliospheric magnetic field weakens, allowing more galactic CRs to penetrate the inner solar system. Conversely, during periods of high solar activity (solar maximum), the heliospheric magnetic field strengthens, thereby deflecting and confining CRs away from the inner solar system.

Forbush Decreases and Short-Term

Forbush decreases are short-term depressions in the CR flux reaching Earth. They were first reported by Forbush 1937 and Hess and Demmelmair (1937) using ionization chamber data [11] With the later development of space coronagraphs and neutron monitors, CMEs were identified as a primary cause of Forbush decreases in the interplanetary medium. These events demonstrated that the variation of the cosmic-ray intensity inversely correlates with the 11-year variation of the solar activity, with a few months' time lag. Forbush decreases depend on the different phases of the solar cycles and are not observed simultaneously at all monitoring stations on Earth. Observations using neutron monitor detectors are more intense at the geomagnetic poles, independent of atmospheric variability. Moreover, the magnitude of the Forbush decrease also depends on solar wind parameters, including its velocity and magnetic field intensity [12].

Solar Cycle Effects and Long-Term Variations

Solar activity exerts a significant influence on the modulation of CRs, impacting their fluxes, energy spectra, and arrival patterns at Earth. The effects of solar activity on CR modulation are primarily driven by changes in the solar magnetic field, solar wind dynamics, and heliospheric conditions. Solar magnetic activity, characterized by the presence of sunspots, solar flares, and coronal mass ejections (CMEs), affects the modulation of CRs through its influence on the heliospheric magnetic field. During periods of high solar activity, when sunspot numbers and solar flare frequencies are elevated, the heliospheric magnetic field strengthens, deflecting and confining CRs away from the inner solar system. This leads to decreased CR fluxes observed on Earth. Variations in solar wind properties, such as speed, density, and magnetic field strength, play a crucial role in modulating CRs in the heliosphere. During periods of high solar activity, when the solar wind is more intense, CRs experience enhanced scattering and diffusion, resulting in decreased fluxes observed at Earth. Conversely, during periods of low solar activity, weaker solar wind conditions allow CRs to penetrate deeper into the heliosphere, resulting in increased CR fluxes at Earth [12,13].

1.6 Solar Activity Indices and Their Relationship to Cosmic Rays

Sunspot Number

Sunspots appear as dark areas on the surface of the Sun. The evolution of the solar cycle can be recorded by the sunspot number (SNN), which is the count of individual sunspots and sunspot groups on the surface of the Sun. This number plays a role in tracking the long-term evolution of the solar cycle and the Sun’s potential long-term influence on Earth’s environment. The number of sunspots recorded over the centuries serves as a proxy for the solar activity level. Furthermore, monthly data of sunspot numbers is used [15].

F10.7 cm Radio flux

F10.7 is one of the most commonly used parameters to measure solar activity. The applications of solar radio flux are used as a simple solar activity level indicator, serving as a simpler proxy for solar activity compared to other solar emissions that are more complex to measure. It comprises a time-varying combination of up to three main emission techniques, that may be differently distributed across the solar disk and may change independently over time. These include thermal bremsstrahlung (free-free emission) from the chromosphere and corona, and emission from plasma trapped in active region magnetic fields. F10.7 is observed as a flux density and commonly referred to as "the flux." It represents the total solar flux emitted from all sources on the solar disk over a 1-hour period at a 10.7 cm wavelength [15].

Solar Wind and Magnetic Field Indices:

Solar magnetic activity, characterized by the presence of sunspots, solar flares, and coronal mass ejections (CMEs), affects the modulation of CRs through its influence on the heliospheric magnetic field. During periods of high solar activity, when sunspot numbers and solar flare frequencies are elevated, the heliospheric magnetic field strengthens, deflecting and confining CRs away from the inner solar system. This leads to decreased CR fluxes observed at Earth.

Variations in solar wind properties, such as speed, density, and magnetic field strength, play a crucial role in modulating CRs in the heliosphere. During periods of high solar activity, when the solar wind is more intense, CRs experience enhanced scattering and diffusion, resulting in decreased fluxes reaching Earth. Conversely, during periods of low solar activity, weaker solar wind conditions allow CRs to penetrate deeper into the heliosphere, leading to increased fluxes detected on Earth [5].

Chapter 2: Detection and Data Acquisition

2.1 Ground-Based Cosmic Ray Detectors

Ground-based detectors are essential tools for studying CRs and the secondary particles resulting from their interactions with the atmosphere. The main types of these detectors include:

Plastic Scintillators:

These detectors rely on the property of scintillation, where light is emitted when charged particles interact with the scintillator material. The light signals are amplified by a photomultiplier tube (PMT) and converted into electrical signals for analysis [16].

Water Cherenkov Detectors:

These detectors measure light emitted when charged particles travel through water at speeds exceeding the speed of light in the medium. This allows for the analysis of high-energy particles [17].

Fluorescence Telescopes:

These detect fluorescence light generated by nitrogen molecules in the air when excited by charged particles [17].

Air Cherenkov Detectors:

These detectors measure Cherenkov light produced by particles in the air, enabling the study of extremely high-energy CR s.

Neutron Monitors

Neutron monitors are critical tools for detecting secondary neutrons produced by CRs interacting with the atmosphere.

Mechanism of Action:

Moderating materials, such as polyethylene, are used to slow down neutrons for detection. Neutrons are measured using sensitive sensors, and their signals are recorded and analyzed [17].

Significance:

- Neutron monitors help analyze long- and short-term changes in CR flux.
- They provide valuable insights into solar activity and its effects on CRs .

Muon Detectors

Muon detectors are highly sensitive devices designed to detect secondary particles such as muons, which are produced by CRs.

Mechanism of Action:

- These detectors measure muon flux using systems like scintillator materials and photomultiplier tubes.
- The signals generated are amplified and analyzed to determine the intensity and trajectory of the particles [18].

Significance:

- Muon detectors aid in understanding temporal and spatial changes in CR intensity.
- They are also used to observe the effects of space weather and geomagnetic disruptions [18].

Plastic Scintillator Detector

In this project, the **Plastic Scintillator Detector** was used. It is a specialized device developed at **King Abdulaziz City for Science and Technology (KACST)** in Riyadh, Saudi Arabia. This detector is designed to study CRs and analyze charged particles such as muons. It enables detailed tracking of particle movement and intensity, helping to understand the impact of solar activity and monitor rare phenomena.

Device Components

The detector includes several interrelated components that work together efficiently, as shown in Figure 2.1 and detailed below:

1. Upper and Lower Detectors:

The system has **two separate detectors**: an upper detector and a lower detector, placed one above the other.

These detectors operate in unison to measure the intensity and direction of charged particles as they pass through the system.

Each detector contains **scintillating crystals** that emit light when interacting with the particles.

2. Scintillating Crystals:

The crystals are the main component of the detectors, responsible for producing light upon interaction with charged particles. This light is later amplified for analysis.

3. Photomultiplier Tubes (PMTs):

PMTs are used to amplify the optical signals from the crystals and convert them into precise electrical signals for further processing.

4. Electronic Units:

These units further process PMT signals, converting them into digital data used to study particle properties.

Figure 2.1: (a) The upper and lower detectors stacked on top of each other, (b) scintillating crystals used within the detectors, (c) the photomultiplier tubes.

5. Muon and Neutron Detectors:

Muon detectors are used to measure the intensity and direction of muons, providing insights into CR interactions.

Neutron detectors measure the environmental effects of CRs on neutrons, assisting in understanding particle behavior under cosmic influences. Figure 2.2 illustrates that both devices are integrated with the scintillator system to deliver comprehensive data

Figure 2.2: The mini neutron and muon monitor installed at the KACST station.

6. Display Screen:

The screen shows real-time results in graphs and tables, aiding the analysis of particle density and direction.

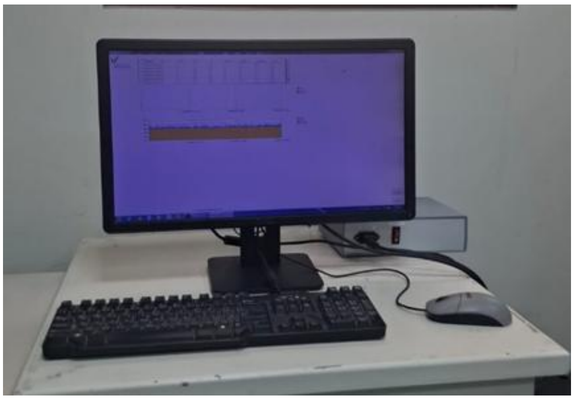


Figure 2.3: Translation, which shows the screen during live data display.

System Diagram of the Plastic Scintillator Detector

Figure 2.4 illustrates the interconnection between the various components of the device. It includes the upper and lower detectors, scintillating crystals, photomultiplier tubes, electronic units, and the muon and neutron detectors. The diagram provides a comprehensive visualization of the distribution of parts within the system and how they work together to analyze CRs and charged particles.

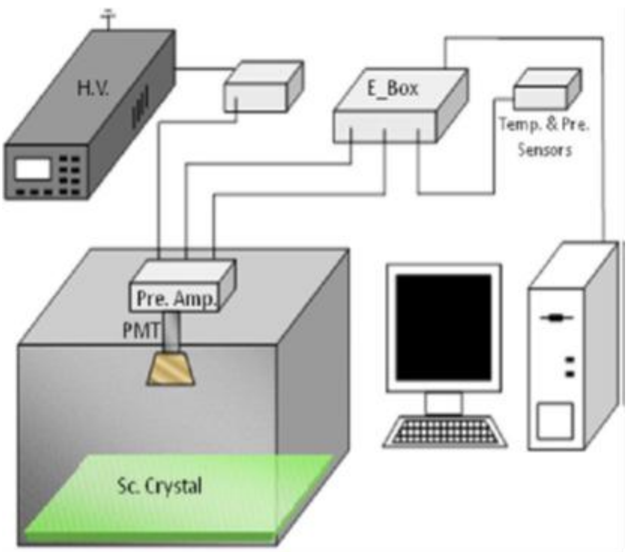


Figure 2.4: Schematic diagram of the muon detector and its components.

Usage of the Detector

The detector monitors and analyzes charged particles generated by CRs, such as muons. By utilizing both upper and lower detectors, the system can precisely track particle pathways and measure density. Scintillating crystals produce light during interaction, which is amplified by PMTs and processed by electronic units to deliver clear, interpretable results through the display screen.

Importance of the Detector

The **Plastic Scintillator Detector** is critical for understanding the impact of solar activity on CRs and analyzing rare phenomena such as Forbush decreases. It also serves as an educational tool to demonstrate particle physics concepts to students and researchers [18].

2.2 Detector Networks and Databases

Detector Networks:

Detector networks collect data from multiple locations, enabling comprehensive analysis of CR activity. Networks such as the Neutron Monitor Database (NMDB) allow for global data interpretation and tracking solar and cosmic ray-related phenomena [16].

Databases:

These databases store long-term CR data, making them essential for studying temporal variations in CRs. Researchers use these records to analyze environmental and geographical impacts on CR intensity [18].

2.3 Data Correction and Preprocessing Methods

Atmospheric Corrections

Atmospheric corrections are crucial for improving the accuracy of muon readings by minimizing the effects of atmospheric pressure and temperature.

To account for atmospheric influences, mathematical formulas are applied to adjust detection rates based on pressure variations. One such equation is:

$$cor.Rate = (Rate)(1 - \propto dp) \qquad (2\text{-}1)$$

where, $cor.Rate$ is the corrected rate. (Rate) represents the recorded detection rate or the measured variable influenced by atmospheric pressure. ($\propto$) is the correction coefficient that represents sensitivity to pressure changes.

$$\frac{I - I^\circ}{I^\circ} = \alpha(P - P^\circ) \qquad (2\text{-}2)$$

$$\propto = 0.000742$$

where , I is the CRs Intensity. $I°$ is the Mean CRs Intensity. dp is the pressure difference, calculated

$$dp = P - P_{avg} \qquad (2\text{-}3)$$

where, P is the Atmospheric pressure at the time of measurement. P_{avg} is the average pressure (reference atmospheric pressure for Riyadh, 942.1 pascals).

This equation ensures accurate corrections for atmospheric pressure effects and is essential for maintaining data precision in CR analysis [18].

Pressure and Temperature Effects

Atmospheric Pressure: Causes variations in particle detection rates, necessitating precise corrections.

The Impact of Pressure on Detection Rates:

Atmospheric pressure plays a significant role in altering muon detection rates. As pressure increases, the number of muons detected decreases due to the scattering effect caused by denser air. To visualize this relationship, Figure 2.5 below illustrates the inverse correlation between atmospheric pressure in hectopascals (*hPa*) and muon detection rates (in particles/second). This relationship reinforces the importance of applying precise pressure corrections in the data analysis process.

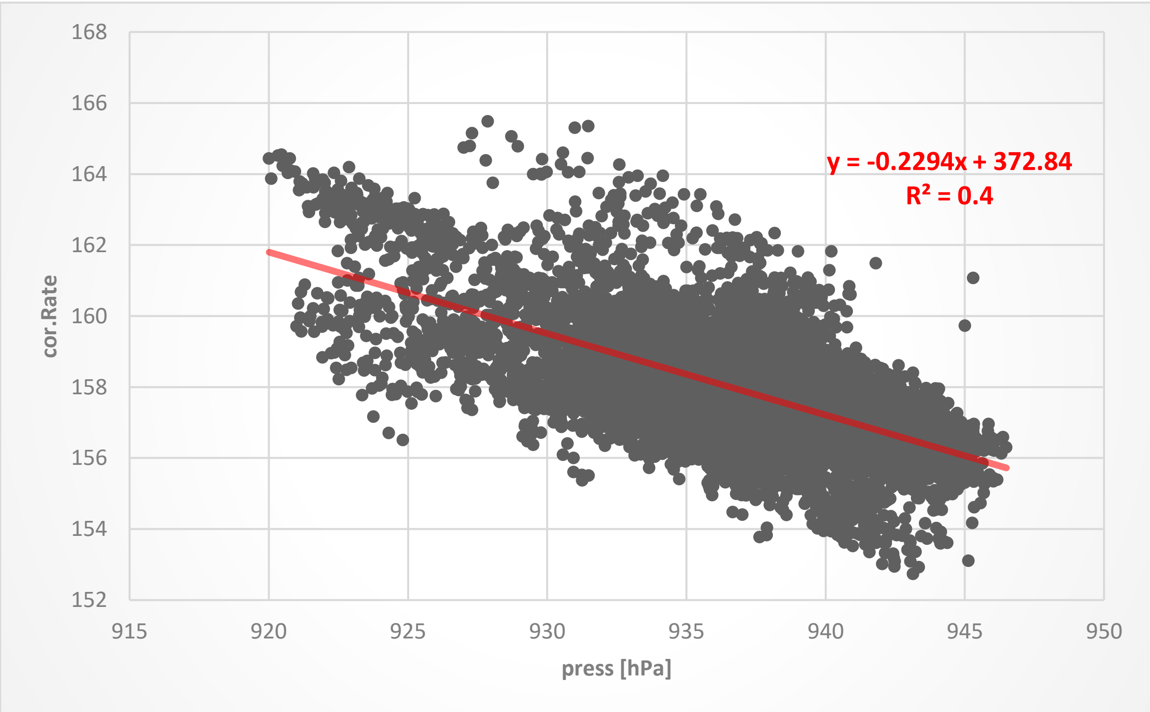


Figure 2.5: The inverse relationship between atmospheric pressure and muon detection rates.

We analyzed the CRs data and plotted it against atmospheric pressure to determine the correlation between them. We found a strong correlation, as the correlation coefficient (r) was close to one, indicating a strong positive relationship. The resulting linear equation reflects how changes in pressure correspond to increases or decreases in detection rates. Since the points are not all on the straight line, this line is the line of best fit, which averages the data, with some points falling above or below it.

This observation highlights the necessity of pressure correction equations to normalize detection rates under varying atmospheric conditions. The corrections ensure the accuracy of muon flux measurements across diverse environments.

***Temperature*:** Alters the density of secondary particles, requiring thermal adjustments to improve measurements *[18]*.

Chapter 3: Results and Discussion

3.1 Daily Cycle of Cosmic Rays

The daily cycle is monitored on the devices in the lab. Previously, we mentioned the correlation coefficient with pressure, but there are climatic and weather factors that have a positive or negative impact on CRs, such as clouds, dust, and temperature. Several random days are taken, the readings are recorded, and the solar cycle is plotted for the day dated 5/2/2023. Figure 3.1 shows peaks and troughs of the day. The peak was at noon, which is expected as the Sun is at its highest point, making the CR flux reach its maximum, because the sun is perpendicular to the Earth's surface, making the Cosmic Rays flux at its highest, and the lowest when the sun sets. However, there is still a flux of CRs in the absence of the sun because other cosmic sources continue to emit particles, and even when the Sun is not visible from a specific location, it still contributes to the CR environment globally.

Figure 3.1: Diurnal Variations of CR Muons Intensity (CR Muons) Measured on 5/2/2023, influenced by weather conditions.

Data was also taken on 25/2/2023 as shown in Figure 3.2, and on 18/10/2023 as shown in Figure 3.3, and it was found that the daily cycle was different due to effects such as dust and clouds.

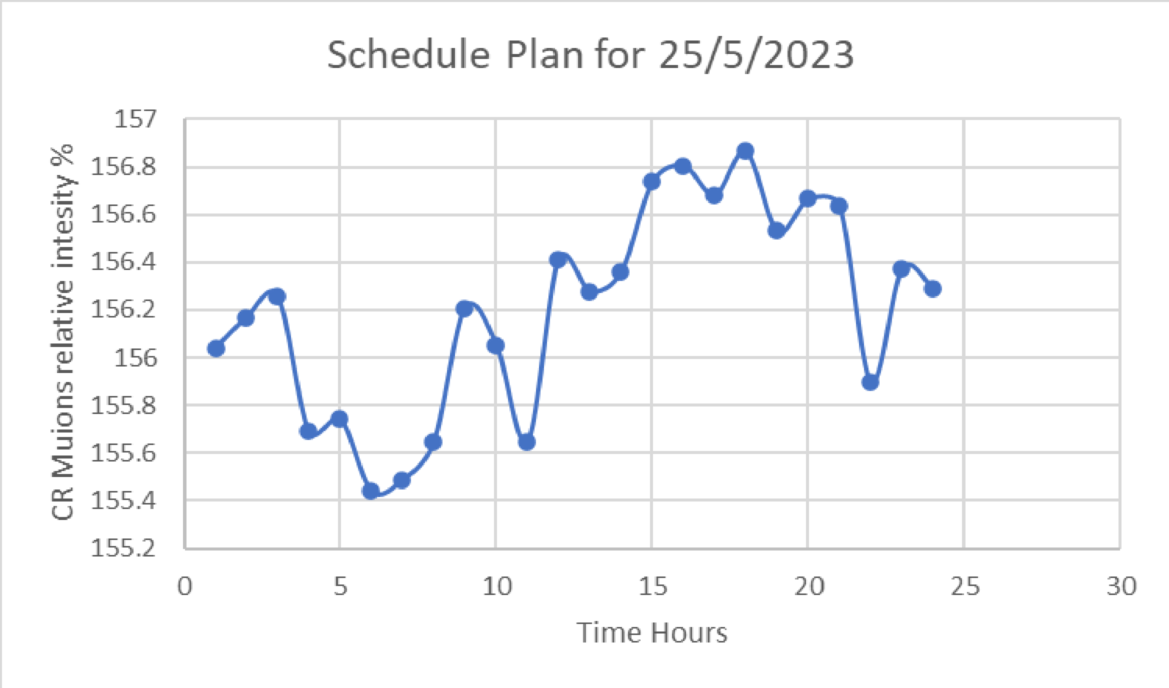


Figure 3.2: Diurnal Variations of CR Muon Intensity (CR Muons) Measured on 25/5/2023, influenced by weather conditions.

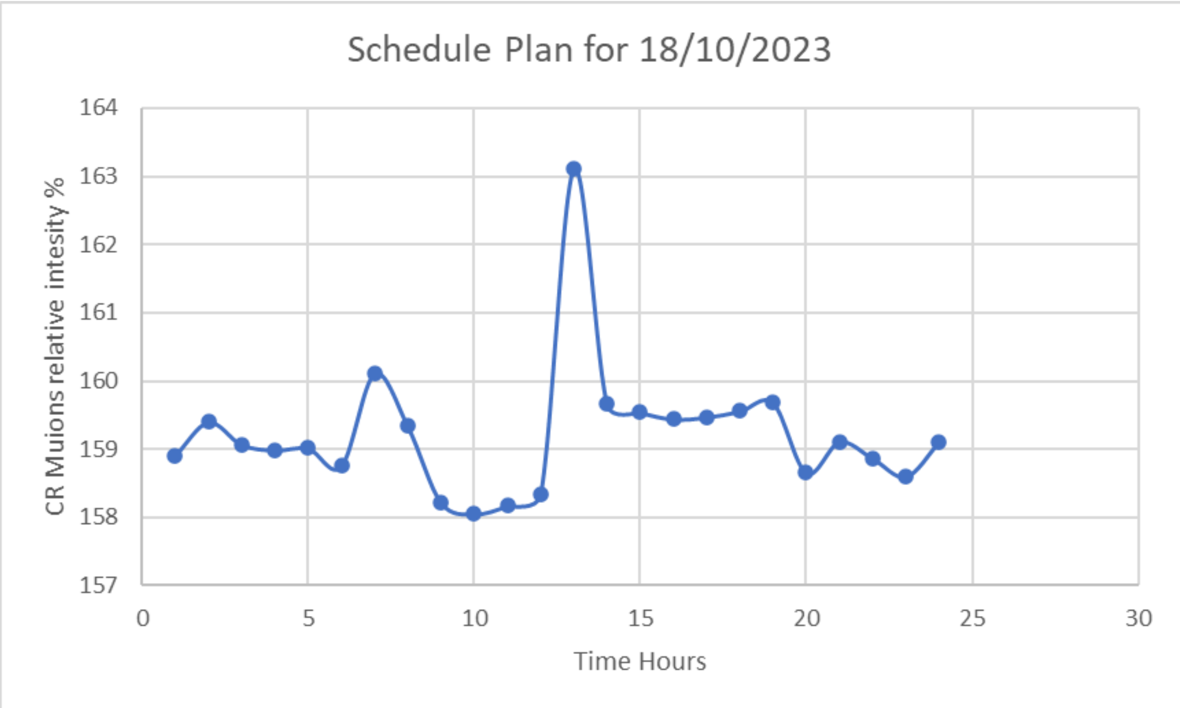


Figure 3.3: Diurnal Variations of CR Muons Intensity (CR Muons) Measured on 18/10/2023, influenced by weather conditions.

To obtain a daily cycle without any effects except pressure and temperature, because other effects come and go, but pressure and temperature are constant, we took the average for each hour and each day over the entire year. Thus, eliminating the complete effect of weather and climate and taking the solar cycle without the instantaneous factors, which is the true solar cycle in all parts of the world with varying quantities due to different altitudes as shown in Figure 3.4.

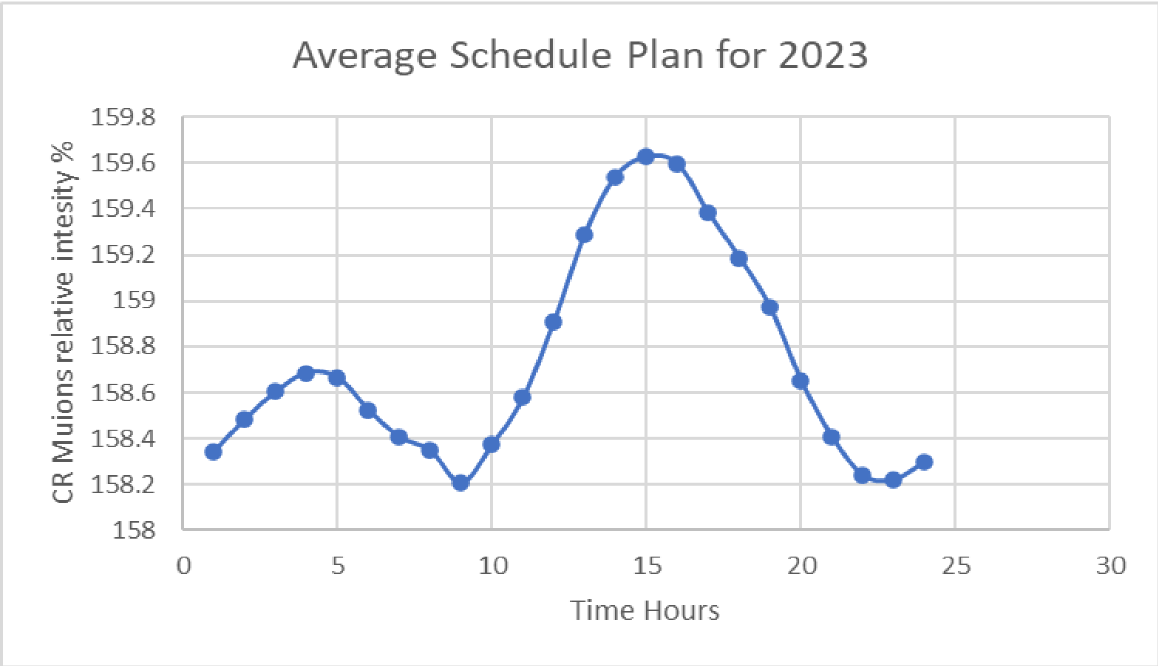


Figure 3.4: CR Muons Intensity (CR Muons) During the year 2023 Based on the Average Daily Schedule.

3.2 Study of Forbush Decrease Events

After studying CRs and understanding their behavior, observation of transient effects is taken in consideration, that persist over a long period, unlike the daily variations of CRs. Sometimes, there are daily solar flares accompanied by disturbances in CRs, including what is known as the Forbush Decrease. Forbush Decrease was discovered by the scientist Scott Forbush, who found that CRs experience periods of decrease lasting from one to five days before returning to normal levels. He conducted studies on this phenomenon in the 1930s and 1940s, and it was named after him. He concluded that these decreases are caused by CMEs from the sun.

In this project, satellite data from NASA were used to determine the speed of solar winds. These solar flares are transported from the sun to the Earth by solar winds in space. Sometimes, the solar winds are strong, causing a significant shock and a higher decrease in CR when they collide with the Earth. Another factor is the location of the solar flare whether it is facing the Earth or not. The year 2003 were chosen because it recorded the largest event since 1900. There was another significant event in 1859, but it was not recorded by instruments, so we cannot determine the extent of the decrease. However, it is believed to have caused major disruptions. Since radio and aviation systems did not exist at that time, the full extent of the impact could not be documented. Only the telegraph system existed, and it was severely disrupted by the event. If such an event were to occur now, it could disrupt all navigation and satellite systems. The 2003 event was the largest recorded event after the existence of detectors, and we studied this event in several stations. The goal was to collect data and readings from these locations, considering the Earth's geomagnetic strength.

Figure 3.5: Locations of CR observation stations around the world **..**

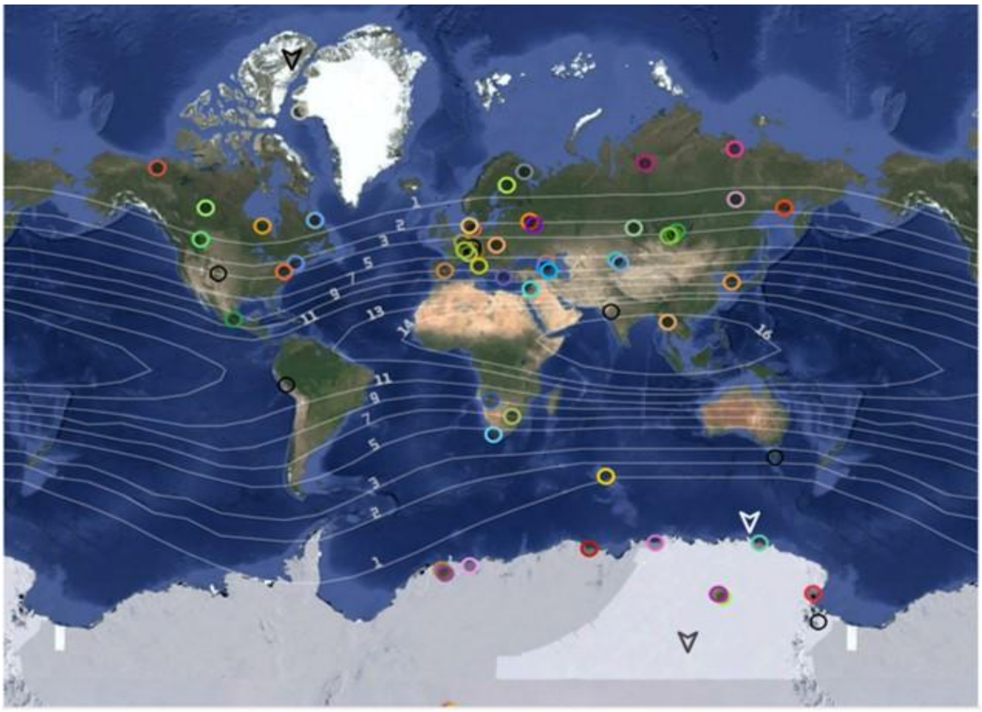


Figure 3.5 shows the locations of CR observation stations around the world, which vary in their proximity to the poles and altitude above sea level. These stations play a crucial role in collecting data related to CRs, helping to understand the effects of solar flares and solar winds on the CRs reaching the Earth. By studying data from these stations, we can determine how different factors such as geographic location and altitude affect the intensity of CR.

Forbush Decrease Calculation

The Forbush decrease for each station can be calculated using the following formula:

$$\text{Forbush Decrease (\%)} = \left[\frac{(\text{Value Before Event} - \text{Value During Event})}{\text{Value Before Event}}\right] \times 100 \qquad (3\text{-}1)$$

Event 2003: Largest Recorded Forbush Decrease

In 2003, a significant solar explosion was observed, leading to noticeable changes in Earth's environment. This study focuses on analyzing data collected from multiple observation stations. To assess the impact of the explosion on CR flux and associated magnetic phenomena, we selected ground-based observation stations from various regions, specifically Oulu, Moscow, Athens, and Riyadh. Forbush decrease is used as a key indicator to evaluate these variations. The data was collected and corrected for atmospheric pressure to ensure accuracy.

Illustrations:

Figure 3.6 below illustrates the changes in pressure corrected CR values during the event. This visual representation highlights a notable decrease in CR flux during the period of the solar explosion, indicating the presence of a Forbush decrease.

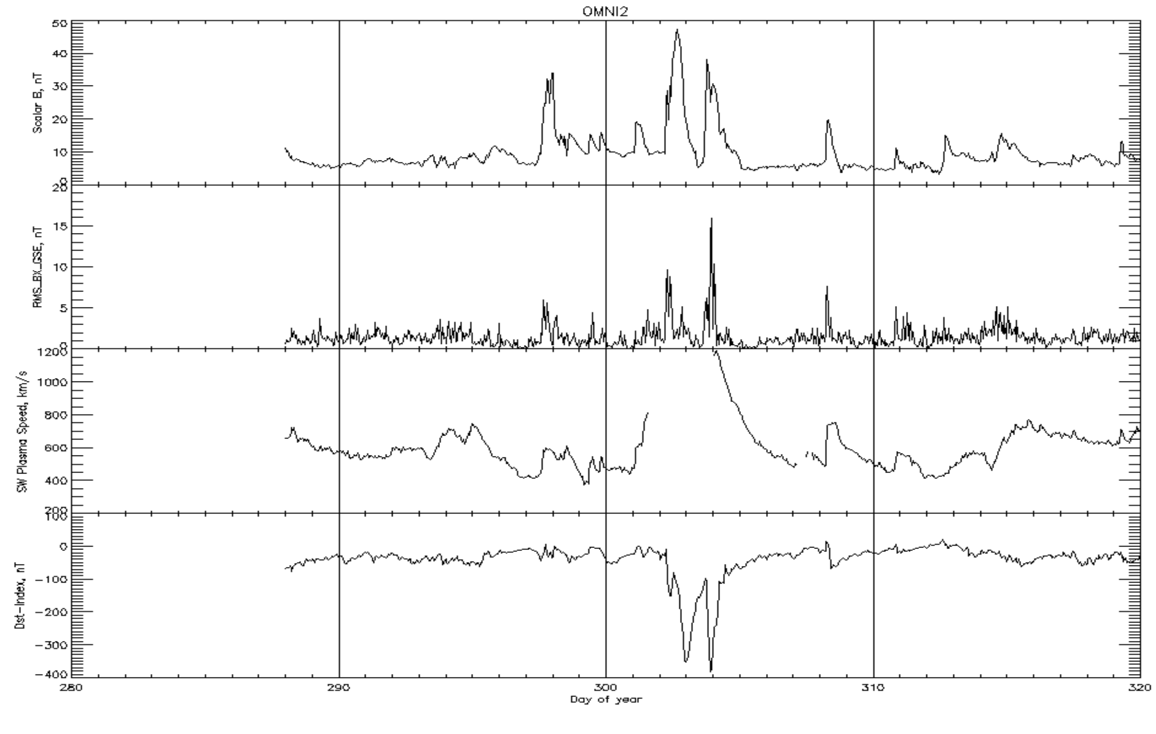


Figure 3.6: Multiple satellite data for the event period from October 25 to November 10, 2003, including source altitude, radiation flux, solar wind plasma speed, and interplanetary magnetic field index."

Four different locations were studied here as shown in the following Figures [3.7, 3.8, 3.9. 3.10]. They showed the corrected CR measurements recorded by the O*g*lu, oulo, Athn, and %zz

Figure 3.7: Corrected CR measurements recorded by the Oglu station, illustrating the impact of the 2003 solar event and the resulting Forbush decrease.

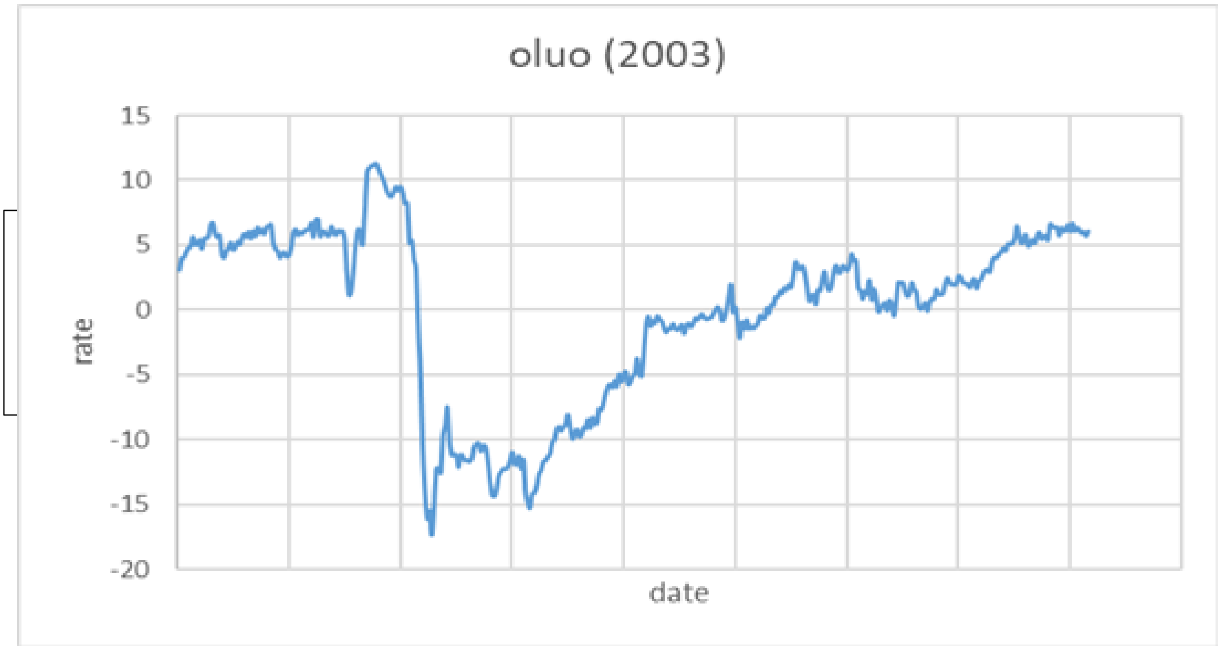


Figure 3.8: Corrected cosmic ray measurements recorded by the oulo ,station, illustrating the impact of the 25/10/ 2003 to 10/11/2003 solar event and the resulting Forbush decrease.

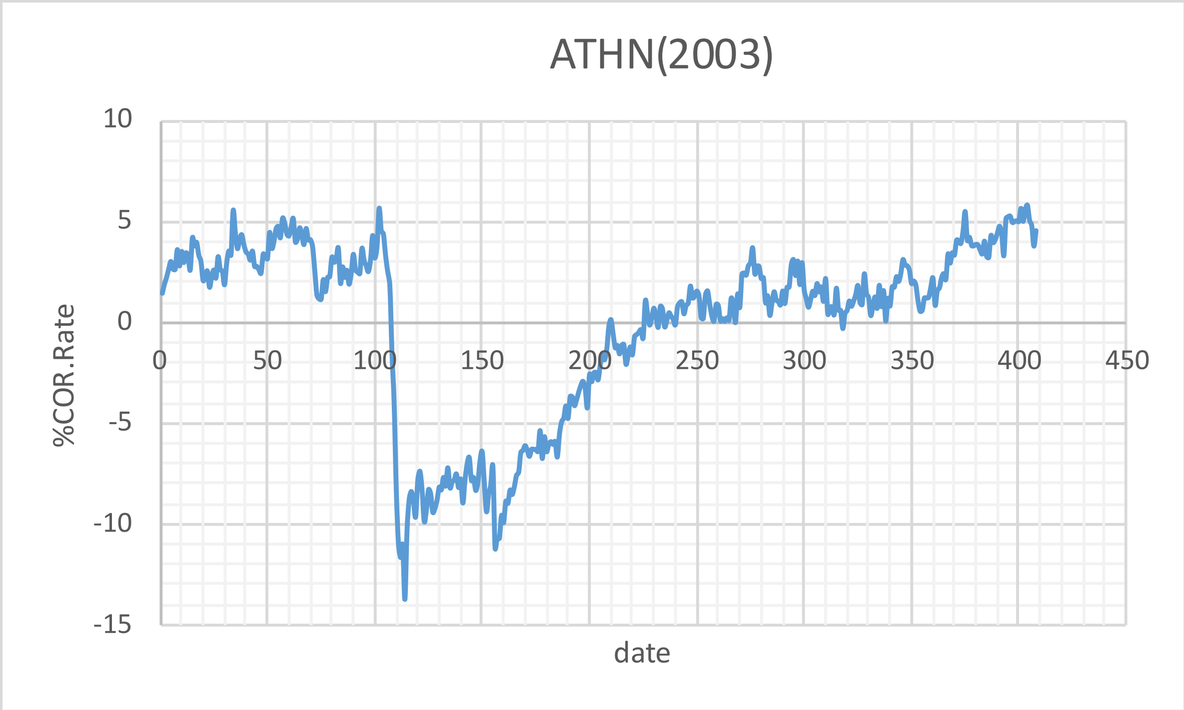


Figure 3.9: Corrected CR data as measured by the Athn station, highlighting the Forbush decrease observed during the 2003 solar event.

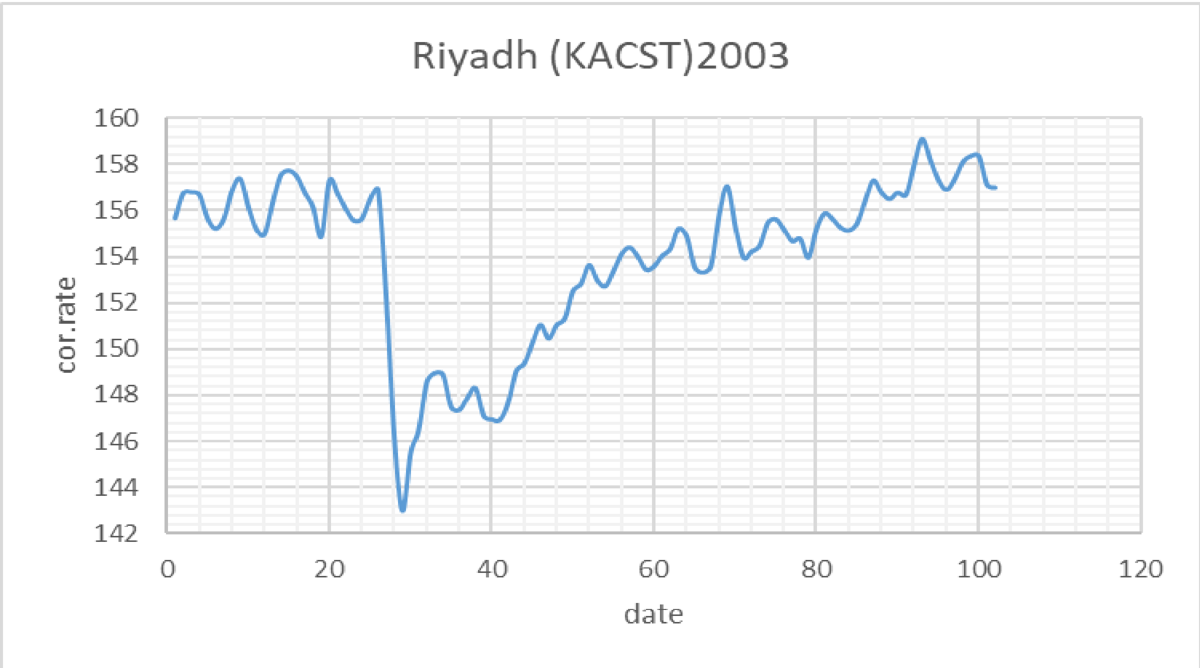


Figure 3.10: Corrected CR data as measured by the Riyadh (KACST) station, highlighting the Forbush decrease observed during the 2003 solar event.

Detailed information for each observation station is recorded in Table 3.1, including geographical coordinates, altitude above sea level, pressure-corrected CR values, and the calculated Forbush decrease percentage. Relationship between rigidity and forbush decrease (2003) is givin by the graph in Figure 3.11. It showes that the Forbush effect decreases with increasing the rigidity.

Table 3.1 Detailed data from the stations studied during the 2003 event.

Stations	Let	Long	Alt	RC	Forbush %
Riyadh	24 43	46 40	613m	14.4GV	9%
Athens	37 59	23 43	260m	8.53GV	20%
Moscow	55 45	37 37	200m	2.43GV	25%
Oulu	65 1	25 28	260m	0.81GV	28%

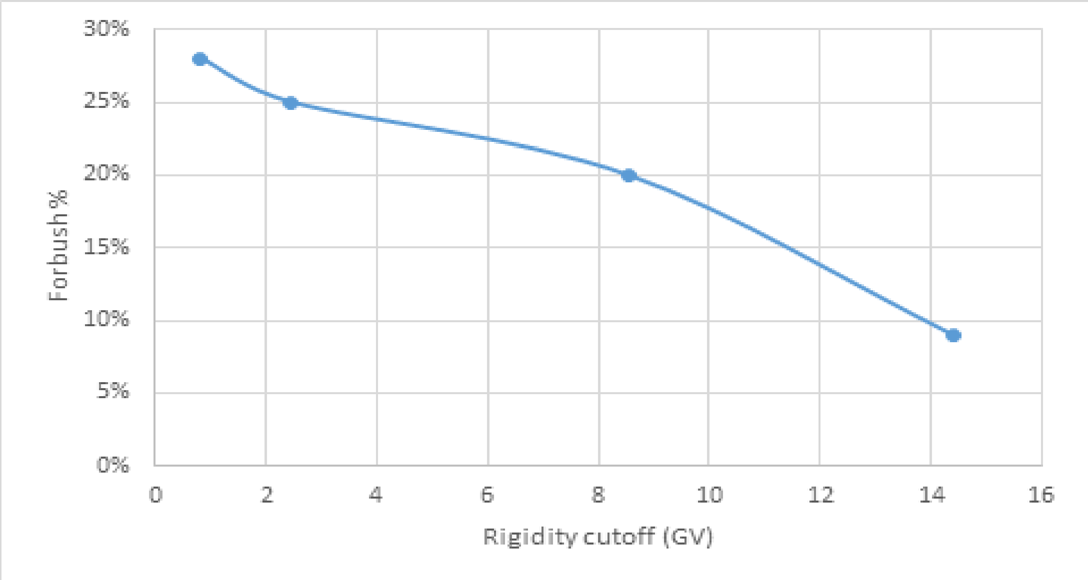


Figure 3.11: Relationship between rigidity and forbush decrease(2003).

From the resultes above it can be concluded that data revealed a substantial drop in values related to CR flux during the event. The observed Forbush decrease values varied between stations, indicating a dependence on geographical location and altitude. The atmospheric pressure correction enhanced the accuracy of the results, highlighting the importance of such adjustments.

Event 2024: Forbush decrease during October 8-17

A solar event occurred in 2024 with lower intensity than the major solar event of 2003as observed from Figure 3.12.

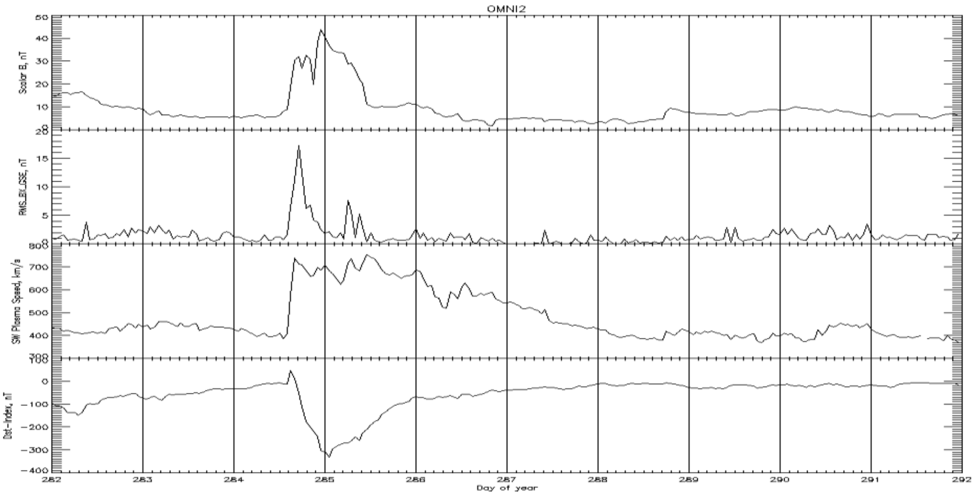


Figure 3.12: Multiple satellite data for the event period from October 8 to October 17, 2024, including source altitude, radiation flux, solar wind plasma speed, and interplanetary magnetic field index.

Figure 3.13: Corrected CR data as measured by the Riyadh (KACST), Athin, Mexico, Rome, and Oulu stations, highlighting the Forbush decrease observed during normal solar event in 2024.

In Figure 3.13, the corrected CR measurements record by the Riyadh (KACST), Athin, Mexico, Rome, and Oulu stations respecively, highlighting the Forbush decrease observed during normal solar event in 2024. Detailed information for each observation station is recorded in Table 3.2, including geographical coordinates, altitude above sea level, pressure-corrected CR values, and the calculated Forbush decrease percentage. Figure 3.14 demonstrate the relationship between rigidity and forbush decrease (2024).

Table 3.2: Detailed data from the stations studied during the 2024 event.

Stations	Let	Long	Alt	RC	Forbush %
Riyadh	24 43	46 40	613m	14.4GV	3%
Athens	37 59	23 43	260m	8.53GV	6%
Mexico	23 63	102 55	2274 m	8.28 GV	6%
Rome	41 53	12 30	0 m	6.27GV	7%
Oulu	65 1	25 28	260m	0.81GV	10%

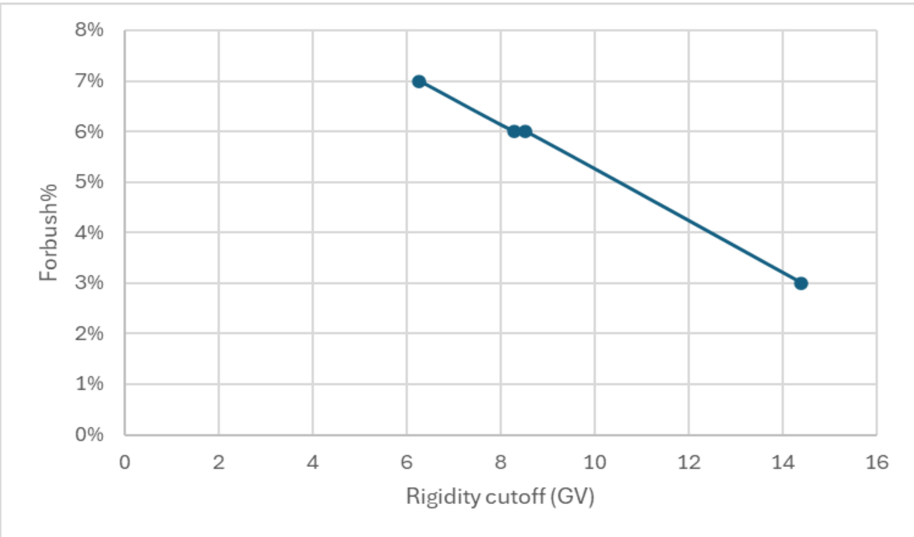


Figure 3.14: Relationship between rigidity and forbush decrease (2024).

Event 2025: Forbush Decrease During Our Research

During the research period, a solar flare occurred between April 15 and April 16, 2025. Data was collected from several observation stations to measure the flux of cosmic particles entering Earth's atmosphere at various locations: Oulu, Mexico, Riyadh (KACST), and Thule as shown in Figure 3.15. Figure 3.16 and 3.17 shows corrected CR data as measured by the Mexico, Oulu, Thule, and Riyadh station, highlighting the Forbush decrease observed during solar event in 2025.

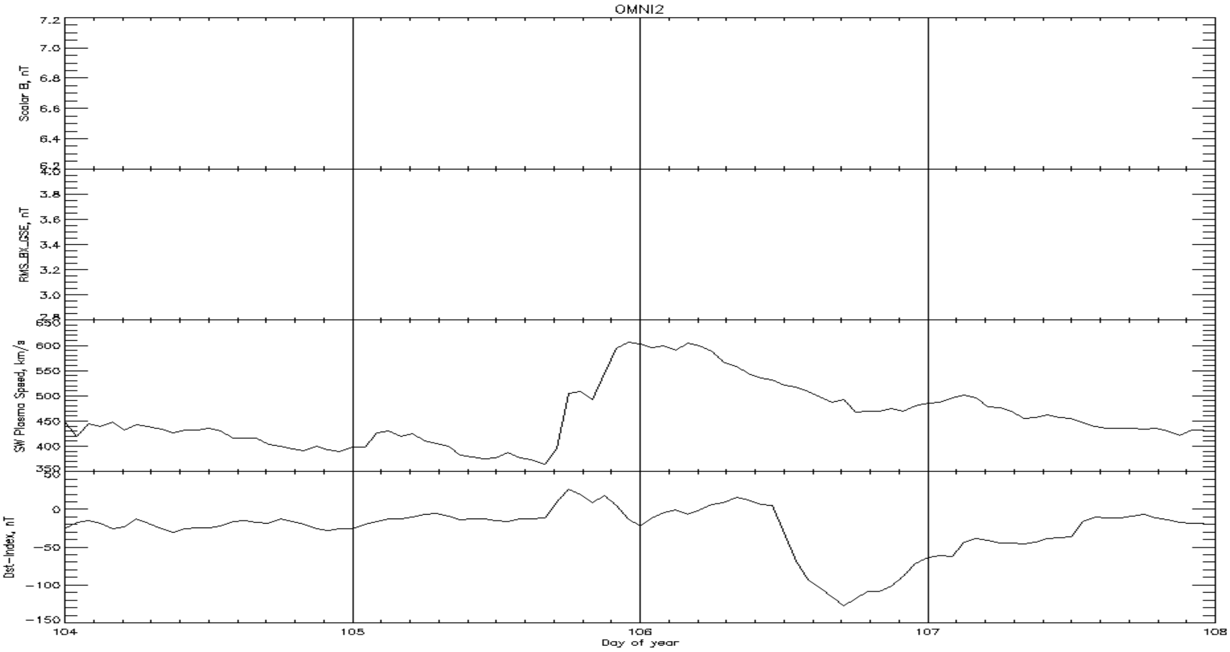


Figure 3.15 Multiple satellite data for the event period from April 14 to April 17, 2025, including source altitude, radiation flux, solar wind plasma speed, and interplanetary magnetic field index.

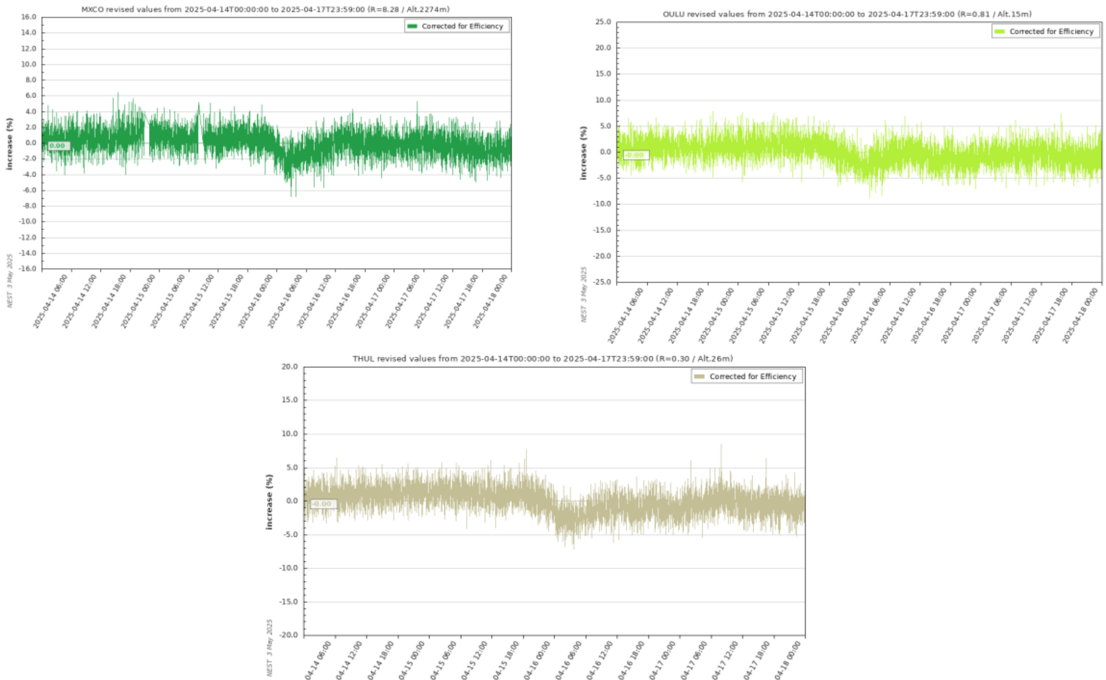


Figure 3.16: Corrected CR data as measured by the Mexico, Oulu, and Thule station, highlighting the Forbush decrease observed during solar event in 2025

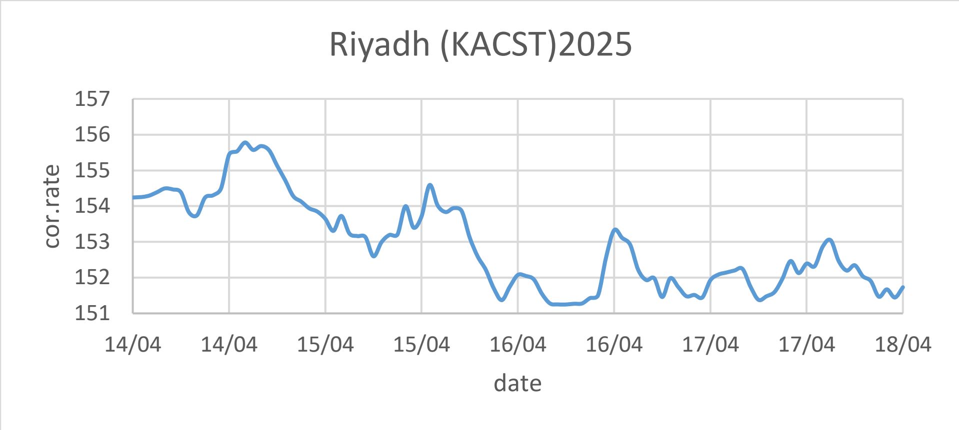


Figure 3.17: Corrected cosmic ray data as measured by the Riyadh (KACST) station, highlighting
Detailed information for four observation station are recorded in Table 3.3, including geographical coordinates, altitude above sea level, pressure-corrected CR values, and the calculated Forbush decrease percentage. Figure 3.18 demonstrates the relationship between rigidity and Forbush decrease (2025).

Table 3.3: Detailed data from the stations studied during the 2025 event

Stations	Let	Long	Alt	RC	Forbush%
Riyadh	24 43	46 40	613m	14.4GV	2.20%
Mexico	23 63	102 55	2274m	8.28GV	7%
Oulu	65 1	25 28	260m	0.81GV	9%
Thule	76 30	68 42	26m	0.30GV	11%

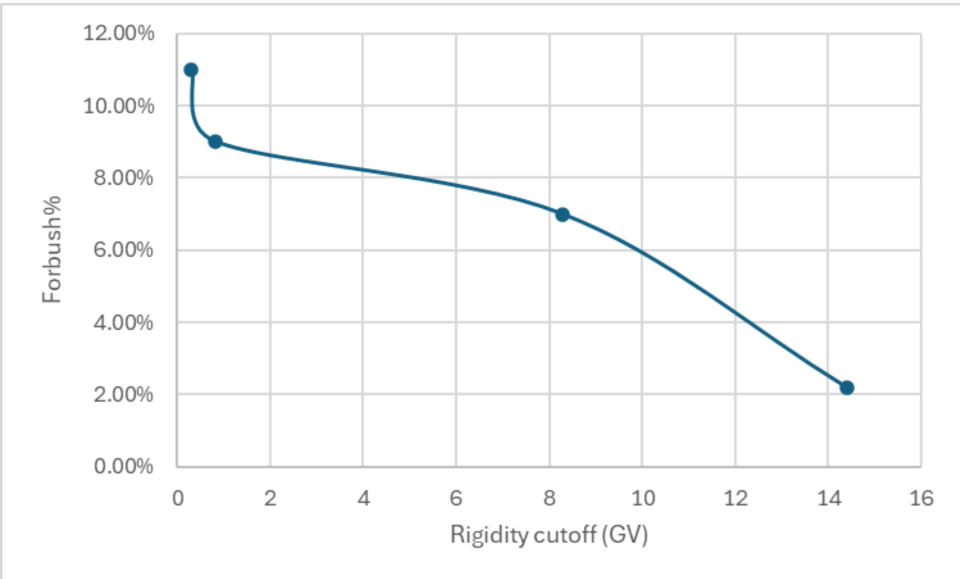


Figure 3.18: Relationship between rigidity and Forbush decrease (2025).

Conclusion

In this study, data from two stations Riyadh and Oulu were analyzed, focusing on three major events as shown in Table 3.4. The strongest event was in 2003, which was extremely powerful. This event was compared to a natural event in 2024, and finally, the 2025 event that occurred during the project work, which is considered a normal event. The differences in wind speed and humidity between the two stations were calculated, as well as the Forbush decrease percentage for CRs. The results showed that the abnormal event in 2003 had a significant impact on CR flux compared to the other events.

Table 3.4 Data from two stations Riyadh and Oulu for three major events.

Event	Wind Speed	Stations	RC	Forbush%
2003	≈1500	Riyadh	14.4GV	9%
_	_	Oulu	0.81GV	28%
2024	750	Riyadh	14.4GV	3%
_	_	Oulu	0.81GV	10%
2025	600	Riyadh	14.4GV	2.20%
_	_	Oulu	0.81GV	9%

Implications for Space Weather Forecasting

The findings highlight the potential for using CR data to improve space weather forecasting. By understanding the relationship between solar activity and CR flux, more accurate predictions of space weather events can be made, which is crucial for protecting technological systems both in space and on Earth. These forecasts can help mitigate the negative impacts on satellites, power grids, and communication systems.

Future Work

Future research should focus on refining the statistical methods used to analyze CR data and exploring additional factors that may influence CR flux. Expanding the network of ground-based detectors and incorporating more comprehensive data sets will also be essential for advancing the field of space weather forecasting. Additionally, future studies could include investigating the impacts of space weather on various technological systems and developing strategies to mitigate these effects.

References

[1] B. H. Reader, T. W., Flin, R., Mearns, K., & Cuthbertson, “Scholar (17),” 2009.

[2] J. Kirkby, “Cosmic rays and climate,” *Surv Geophys*, vol. 28, pp. 333–375, 2007.

[3] H.-M. Mok, *Cosmic Rays: Climate, Weather, and Applications*. New York: Nova Science Publishers, Inc, 2012.

[4] J. Leckenby, Jd Li, H, Negus, K, Pickering, Mj, Adorno, T, Horkheimer, M , Dolnicar, Sara, Chapple, Alexander, Horkheimer, M “Scholar (18),” 2014.

[5] R. K. Mishra, D. Mishra, and R. Agarwal, “Cosmic Rays and Space Weather Predictions: Exploring the Dynamic Universe,” 2024.

[6] R. Miteva, S. W. Samwel, and S. Tkatchova, “Space weather effects on satellites,” *Astronomy*, vol. 2, no. 3, pp. 165–179, 2023.

[7] V. A. Pilipenko, “Space weather impact on ground-based technological systems,” *Solar-Terrestrial Physics*, vol. 7, no. 3, pp. 68–104, 2021.

[8] G. Hazra, A. A. Vidotto, S. Carolan, C. Villarreal D’Angelo, and W. Manchester, “The impact of coronal mass ejections and flares on the atmosphere of the hot Jupiter HD189733b,” *Mon Not R Astron Soc*, vol. 509, no. 4, pp. 5858–5871, Feb. 2022 .

[9] N. Gopalswamy, “The Sun and space weather,” *Atmosphere (Basel)*, vol. 13, no. 11, p. 1781, 2022.

[10] X. Shi, Lin, Dong, Wang, Wenbin, Baker, Joseph B H, Weygand, James M, Hartinger, Michael D, Merkin, Viacheslav G, Ruohoniemi, J Michael, Pham, Kevin, Wu, Haonan., “Geospace concussion: Global reversal of ionospheric vertical plasma drift in response to a sudden commencement,” *Geophys Res Lett*, vol. 49, no. 19, p. e2022GL100014, 2022.

[11] S. ~A. Flannery, B.~P.Teukolsk , Vetterling W, Leckenby J, Li H, Bruns A, Danowski J, Choi J, Zill, D GPress W, Wright W, Optiz G, Team R, Payerle G, Chapra S, Canale R, Analysis N, Floudas C, Pardalos P, Negus K, Pickering M, Leckenby J, Li H, Danowski J , “Scholar (8),” 2004.

[12] S. Lee, S. Oh, Y. Yi, P. Evenson, G. Jee, and H. Choi, “Long-term statistical analysis of the simultaneity of Forbush decrease events at middle latitudes,” *Journal of Astronomy and Space Sciences*, vol. 32, no. 1, pp. 33–38, 2015.

[13] C. Oscier, N. Bosley, and Q. Milner, “Scholar (13),” 2008.

[14] B. Neilson and N. Rossiter, “Scholar (16),” 2005.

[15] Z. F. Hussein, “A study of the correlation between sunspot number and solar flux during solar cycle 24.,” *Iraqi Journal of Physics*, vol. 17, no. 42, pp. 56–64, Jul. 2019.

[16] M. Abdullrahman, A. Abdulah, and A. Mohammed, “First Observations of Cosmic Ray Neutrons by a Mini Neutron Monitor at Riyadh, Saudi Arabia,” *International Journal of Astronomy and Astrophysics*, vol. 10, no. 04, pp. 319–333, 2020.

[17] P. K. Mohanty, “Cosmic ray sources and detectors,” 2025, *Springer Science and Business Media Deutschland GmbH*.

[18] A. H. Maghrabi, H. H. Alharbi, A. S. Alghamdi, A. A. Alwuhayb, and M. M. Almuteri, “Cosmic Ray Detectors for Variation Studies and Outreach Programs in Saudi Arabia,” 2013.