PROCEEDINGS OF SCIENCE

Akeno Muon Observations: Japan-India Collaborative Research on Near-Earth Space in 2024

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Ground-based observations of cosmic rays provide one of the most effective methods for investigating the effects of solar activity in near-Earth space. The Akeno muon telescope, which employs a detection technique and energy threshold similar to those of the GRAPES-3 muon telescope, serves as a complementary observation system. The field of view of the Akeno telescope overlaps by approximately 20 % with that of GRAPES-3 at a distance of 25 Earth radii. By utilizing the multidirectional observation capabilities of both muon telescopes—located in Japan and India—it becomes possible to resolve the global anisotropy of cosmic rays and its precise temporal and spatial evolution. Such observations not only advance our understanding of the fundamental mechanisms governing cosmic ray propagation in the interplanetary magnetic field (IMF) but also contribute to the early detection of solar activity-induced phenomena.

From June 2024 to June 2025, a large number of solar flares, coronal mass ejections, and geomagnetic storms were recorded. During this period, both the Akeno and GRAPES-3 telescopes successfully captured multiple variations in cosmic ray intensity associated with these solar events, including several clear Forbush Decreases. This report presents an overview of these observations without interpretation, demonstrating the effectiveness of the joint observation system for space weather monitoring.

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1. Introduction

Ground-based cosmic ray detectors have long served as effective tools for monitoring the influence of solar activity on near-Earth space. Among these, muon telescopes are particularly sensitive to anisotropic changes in cosmic ray intensity caused by disturbances in the interplanetary magnetic field (IMF), such as those induced by coronal mass ejections (CMEs).

In our previous report at ICRC2023, we described the setup and operational status of the Akeno muon telescope in Japan and its collaboration with the GRAPES-3 muon telescope in Ooty, India. These two facilities, separated by about 6,000 km in longitude, offer a unique opportunity to observe cosmic ray anisotropies and Forbush Decrease (FD) events from multiple geographical distant points. Notably, the Akeno telescope's field of view overlaps with that of GRAPES-3 by approximately 20 % at a radial distance of 25 Earth radii. Such joint observations contribute to improved understanding of cosmic ray propagation and the detection of solar-induced space weather phenomena [1,2].

This paper presents new observational results from the period June 2024 to June 2025, which was marked by heightened solar activity, including numerous M- and X-class solar flares and CMEs. These events triggered a number of FDs that were simultaneously detected by both the Akeno and GRAPES-3 muon telescopes. While physical modeling and interpretation are beyond the scope of this report, we aim to document the observed variations in muon intensity and demonstrate the effectiveness of joint monitoring for space weather diagnostics.

Figure 1 shows the geographic locations of the Akeno and GRAPES-3 muon observatories used in this study.

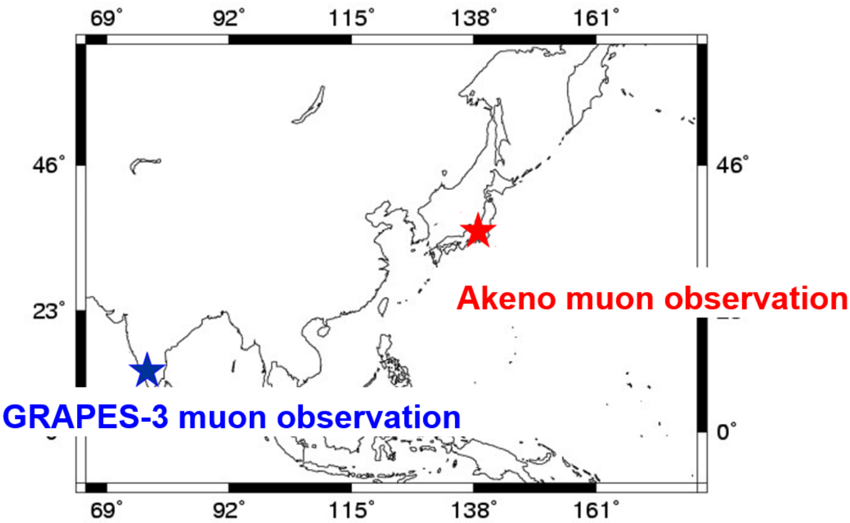

Figure 1: Geographical locations of the Akeno (Japan) and GRAPES-3 (India), separated by approximately 6,000 km in longitude. The overlapping field of view enables joint observation of near-Earth cosmic ray variations.

2. Muon Detectors and Observation System

2.1 Overview of the Joint Observation

The collaborative muon observation system consists of two large-scale ground-based detectors: the Akeno Muon Telescope in Japan and the GRAPES-3 Muon Telescope in India. These observatories are separated by approximately 6,000 km in longitude, providing significant spatial coverage of near-Earth cosmic ray anisotropy. Both detectors employ similar detection techniques using proportional counter tubes, enabling consistent comparison of cosmic ray intensity variations. The observational capability is further enhanced by the overlapping fields of view, which allow for cross-validation of directional responses to space weather events such as Forbush Decreases.

2.2 Detector Configuration

2.2.1 Akeno Muon Telescope

The Akeno Muon Telescope operates with three independent detector stations (M1, M5, and M8), each housed in reinforced concrete enclosures providing an energy threshold of 1 GeV for vertical muons. Each station is equipped with a four-layer array of orthogonally arranged proportional counters filled with P10 gas. The GRAPES-3 muon telescope has been described in detail in previous studies [2]. The proportional counters are constructed from 10 cm × 10 cm square steel tubes, 5 m in length, with tungsten wire at the center and a high voltage of 2,800 V applied. The total detection area is 75 m^2, approximately 1/7th that of the GRAPES-3 system.

2.2.2 GRAPES-3 Muon Telescope

The GRAPES-3 telescope, located in Ooty, India, consists of a larger detector array with a total area of 560 m^2. It uses a similar four-layer proportional counter configuration and achieves an angular resolution of about 10°. Its high statistical precision (0.1%/hour) allows for the detection of small variations in cosmic ray intensity.

Despite the difference in scale, both telescopes share comparable detection geometries, enabling synchronized analysis of directional cosmic ray variations.

Figure 2: Photographs of the Akeno Muon Telescope (left) and the GRAPES-3 Muon Telescope in Ooty, India (right). Both use layered proportional counters with similar angular resolution.

2.3 Multi Directional Observation

Each detector divides its observational sky into 169 angular bins based on the azimuth and zenith angle of the incoming muons. These bins are used for high-resolution anisotropy studies. For practical purposes, these 169 directions are often grouped into 9 major sectors: NW, N, NE, W, V (vertical), E, SW, S, and SE.

The directional cells are defined by angular acceptance, and are fixed for each detector system. This common mapping approach facilitates direct comparison of directional muon intensity between the two observation sites.

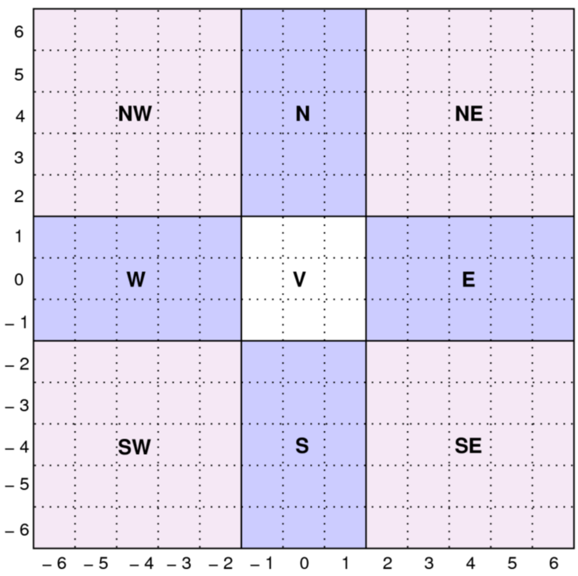

Figure 3: Field of view configuration of the Akeno and GRAPES-3 muon telescopes. Each detector divides the sky into 169 fine angular bins based on the direction of incoming atmospheric muons. For analytical purposes, these 169 bins are commonly grouped into 9 sectors: NW, N, NE, W, V (vertical), E, SW, S, and SE. The angular coverage and directional sensitivity of both detectors are comparable, enabling meaningful directional comparison of cosmic ray intensity variations.

3. Summary of Solar Activity in 2024–2025

The period from beginning 2024 through mid-2025 coincided with a high level of solar activity during the peak phase of Solar Cycle 25. This interval was marked by the frequent occurrence of medium to strong solar flares, Earth-directed coronal mass ejections (CMEs), and geomagnetic disturbances.

Between October and December 2024, clusters of M- and X-class solar flares were recorded by the GOES satellite system, many of which were accompanied by high-speed CMEs. These eruptions often triggered interplanetary shocks and disturbances in the magnetic field, subsequently causing geomagnetic storms and associated modulations in the galactic cosmic ray flux reaching Earth.

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Another period of enhanced solar activity occurred in late May to early June 2025, highlighted by an M8.1-class solar flare on May 31. This event, along with several smaller flares and CMEs during the same period, led to notable space weather effects, including variations in cosmic ray intensity observed at ground level.

These periods of solar activity provided ideal conditions for detecting cosmic ray modulation effects, such as Forbush Decreases (FDs), using the Akeno and GRAPES-3 muon telescopes. In the next section, we present the observational results focusing on FD events detected during these two periods.

4. Forbush Decrease Events

During the observation period, we focused on two time intervals as interesting space weather phenomena: October to December 2024 and late May to June 2025. In both periods, the Akeno and GRAPES-3 muon telescopes detected significant variations in cosmic ray intensity that are characteristic of Forbush Decrease (FD) events.

4.1 Overview of Muon Intensity Variations (Oct–Dec 2024)

Figure 4 shows the directional hourly muon count rates in percentage recorded at Akeno and 4-min rates in percentage GRAPES-3 during October to December 2024. Multiple depressions in muon intensity are visible and are associated with solar eruptions and Earth-directed CMEs observed in the same period. The temporal correlation and similar patterns across both sites suggest that these are manifestations of global FD events.

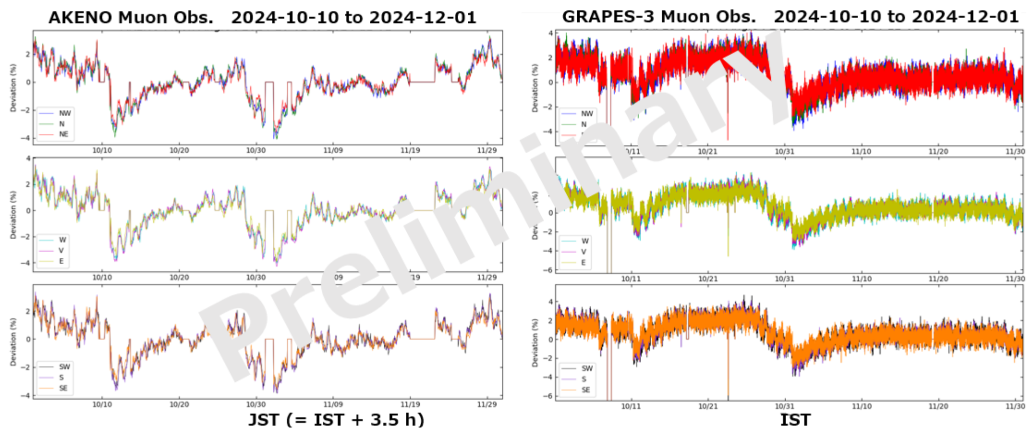

Figure 4: Directional muon intensity variation at Akeno (left) and GRAPES-3 (right) from October to December 2024. Each panel contains 9 directional subplots, arranged in three vertical tiers corresponding to NE/N/NW (top), E/V/W (middle), and SE/S/SW (bottom). This layout facilitates comparison of anisotropic variations across both observatories.

4.2 FD Event: October 10 – November 20, 2024

One of the most pronounced and structured FD events during this period occurred from October 10 to November 20, 2024. As shown in Figure 5, the muon intensity decreased significantly across multiple directional channels and recovered gradually over a period of nearly 10 days. This extended duration and directional coherence make it a clear case of interplanetary magnetic disturbance associated with CME activity.

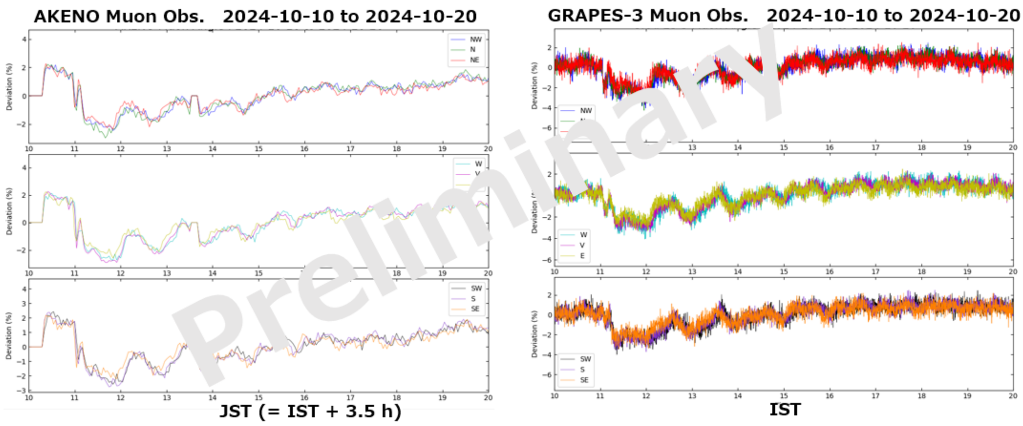

Figure 5: Time profile of the Forbush Decrease observed from October 10 to November 20, 2024. Separate plots are shown for Akeno (left) and GRAPES-3 (right), each consisting of 9 directional subplots grouped as NE/N/NW, E/V/W, and SE/S/SW.

4.3 FD Event: May 25 – June 15, 2025

Another clear FD was observed following solar activity in late May 2025. This event, shown in Figure 6, coincided with an M8.1-class flare on May 31 and the subsequent arrival of a CME at Earth. Both Akeno and GRAPES-3 recorded a coordinated decrease in muon intensity beginning around June 1, with a gradual recovery continuing through mid-June.

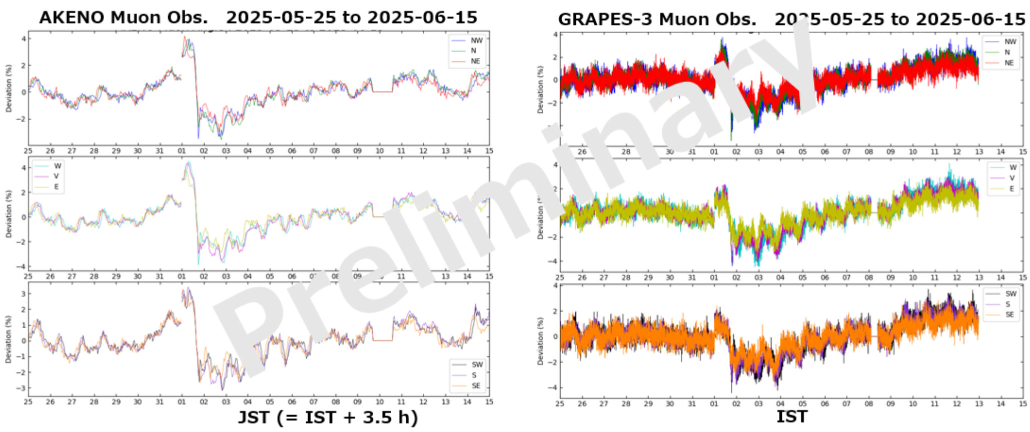

Figure 6: Muon intensity variation during the Forbush Decrease from Jun 1 to June 13, 2025. The 9-direction format and side-by-side layout enable visual comparison of directional response patterns at both observation sites.

These two Forbush Decrease events illustrate the capability of the joint observation system to capture cosmic ray intensity variations associated with solar transients. The high directional resolution and wide longitudinal separation of the two detectors enhance the reliability and spatial coverage of the measurements.

5. Discussion

The joint muon observations conducted at Akeno (Japan) and GRAPES-3 (India) during the active period of beginning 2024 through mid-2025 demonstrate the utility of geographically separated, directionally resolved cosmic ray monitoring. The two Forbush Decrease (FD) events presented in this paper—one extended event from October to November 2024, and one shorter but distinct event in June 2025—showed consistent variations in cosmic ray intensity at both observation sites. The use of a 9-directional format, with subplots grouped into NE/N/NW, E/V/W, and SE/S/SW, enabled detailed comparison of directional anisotropies in the observed muon intensity. By arranging Akeno and GRAPES-3 data side-by-side in Figures 4–6, it was possible to visually examine both temporal and directional coherence across the two systems. In several cases, suppression patterns were more prominent in specific directional groups, likely reflecting the geometry of the interplanetary disturbance.

It is important to note that, for the GRAPES-3 data, only one of the sixteen muon telescope modules was used in this analysis. Similarly, the data from Akeno were derived solely from Module M5. Furthermore, no corrections were applied to either dataset—neither for instrumental sensitivity nor for environmental effects such as pressure and temperature. Anomalous values were not removed, and all results were obtained directly from raw, unprocessed data. Despite these limitations, the consistency observed between the two sites underscores the robustness of the detection system and the potential of comparative muon monitoring. These results strongly suggest that multi-site muon observations are effective for tracking transient cosmic ray events such as FDs. While the GRAPES-3 system benefits from high statistical precision due to its large detection area, the Akeno observatory contributes valuable longitudinal separation and directional resolution. The overlapping field of view at approximately 25 Earth radii further enhances the joint observational coverage.

Based on the success of these simultaneous detections, future efforts will aim to enhance the muon observation capabilities in Japan to reach a level of statistical precision comparable to GRAPES-3. In addition, it would be beneficial to identify new candidate sites for muon detection systems that can overlap with GRAPES-3's field of view at intermediate or distant altitudes, potentially increasing the spatial and directional sensitivity of the global muon monitoring network.

6. Summary

This paper presented joint observations of cosmic ray variations using muon telescopes located at Akeno, Japan, and at the GRAPES-3 site in Ooty, India, over the period from June 2024 to June 2025. The analysis focused on two intervals of enhanced solar activity—October to December 2024 and late May to June 2025—during which multiple Forbush Decrease (FD) events were recorded.

Directional muon intensity data from both observatories, displayed across 9 angular sectors, revealed consistent and simultaneous decreases corresponding to interplanetary disturbances caused by solar eruptions. Two representative FD events were analyzed in detail, illustrating the capability of multi-site muon monitoring to track the temporal and spatial dynamics of cosmic ray modulation. It is noteworthy that the analysis was based on unprocessed data: only one module from the GRAPES-3 telescope and the M5 module from Akeno were used, without any corrections for pressure, temperature, or detector sensitivity. Despite this, clear and consistent FD signals were observed, emphasizing the robustness of the detection systems.

These results highlight the effectiveness of Japan–India collaborative observations in capturing global features of cosmic ray disturbances. Looking forward, plans are underway to enhance the muon observation capacity in Japan toward achieving statistical precision comparable to GRAPES-3. Furthermore, expanding the global coverage by establishing new observation sites that overlap with the GRAPES-3 field of view at approximately 25 Earth radii will be considered. Such developments would strengthen the role of ground-based muon detectors in space weather research.

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