The Relationship Between Coronal Mass Ejection Intensity and Cosmic Ray Flux

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Abstract. This investigation examines the relationship between coronal mass ejection (CME) intensity and cosmic ray muon flux in North America using ground-level detectors. CMEs carry charged particles that interact with Earth's magnetic field, which deflects incoming galactic cosmic rays. As these cosmic rays reach the atmosphere, they generate showers of secondary particles, including muons, which can be measured by ground detectors. However, atmospheric pressure also influences muon flux. In this work, a method of correction was developed and tested that significantly reduced this barometric shielding effect. This correction enabled clearer characterization of muon flux changes due to the May 2024 CME. Analysis of corrected data using multiple detectors in the United States found an inverse relationship between CME intensity and cosmic ray muon flux consistent with a Forbush decrease pattern. Additionally, the impact of statistical error on the visibility of CME-induced effects was assessed.

INTRODUCTION

Coronal mass ejections (CMEs) are plasma from the Sun's corona that carry large magnetic fields which disrupt Earth's magnetic field.[1] These disturbances alter the total magnetic field surrounding Earth, affecting how incoming galactic cosmic rays are deflected. Cosmic rays are charged, high-energy particles likely originating from supernovae.[1,2] When cosmic rays collide with particles in our atmosphere, they produce showers of secondary particles. One such particle is the muon, which can penetrate deep into the atmosphere and be detected at ground levels.[3] As a result, the muon flux measured by ground-level QuarkNet detectors is used as a proxy for cosmic ray flux. CME intensity can be measured through changes to Earth's magnetic field using the K-index scale (Kp), which ranges from 1 to 9.[4] The CME of May 10, 2024, reached a Kp rating of 9, making it a highly significant disruption and the focus of this paper. Such events can disturb the usual path of cosmic rays. Typically, this results in a sharp decrease in cosmic ray flux with a gradual recovery back to normal levels, a phenomenon known as a Forbush decrease.[5] This study aims to refine a pressure correction method, assess how statistical error impacts the visibility of CME-induced effects, and provide additional evidence on the existence of the Forbush decrease and its reproducibility using multiple detectors in various locations. Studying CMEs and cosmic rays provides insight into two critical areas: the effects of cosmic rays on human health and the impact of CMEs on both space- and Earth-based technology.[6]

METHODOLOGY

This investigation utilized QuarkNet cosmic ray muon detectors consisting of scintillating plastic, photomultiplier tubes, and data acquisition cards.[7] Employing a twofold coincidence rate for each detector reduced background noise and improved signal reliability. The data were grouped in 3-h bins to balance sample size and statistical error with temporal resolution, allowing for clearer identification of onset and recovery patterns.[7]

First, data were corrected for barometric pressure fluctuations. Pressure variations affect muon flux because an increase in atmospheric density shields muons from detectors.[3] The muon rate changes by about 0.2% per millibar;

multiplied by typical daily pressure variations, this effect can be on the order of the size of the Forbush decrease. The resulting variation in muon rate can obscure data patterns, so barometric corrections were applied to each data point. A control month with no disruption in Earth's magnetic field was examined for each detector. A linear regression was fitted to the uncorrected flux versus pressure plot for the control month. From that graph, the slope m along with median flux F_{median} and pressure P_{median} were recorded. These values were then applied with Eq. (1) to each point on the uncorrected flux versus time graph (Fig. 1) to create a corrected graph (Fig. 2).

$$F_{corrected} = F_{original}\left(1 + \frac{m}{F_{median}}\left(P_{original} - P_{median}\right)\right) \tag{1}$$

The barometric correction revealed a clearer Forbush decrease and a more linear recovery (Fig. 2), demonstrating the method's effectiveness on real-world data.

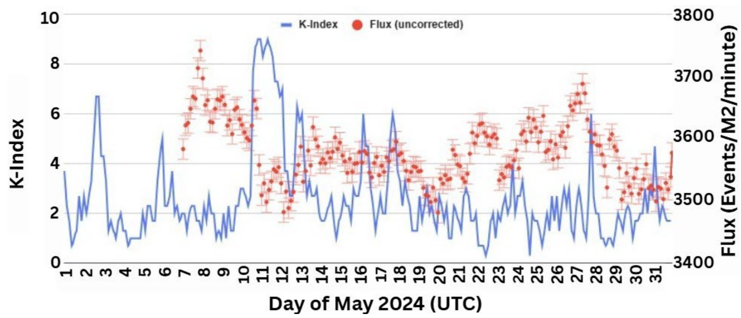

FIGURE 1. Uncorrected flux (red) and K-index (blue) versus time recorded in Skokie, Illinois, over the month of May 2024. Flux is in number of muons per m^2 per min. Data include short-term fluctuations obscuring the expected decrease and subsequent recovery, making the overall Forbush decrease pattern difficult to identify. The error bars represent $1/\sqrt{N}$, with N being the number of events.

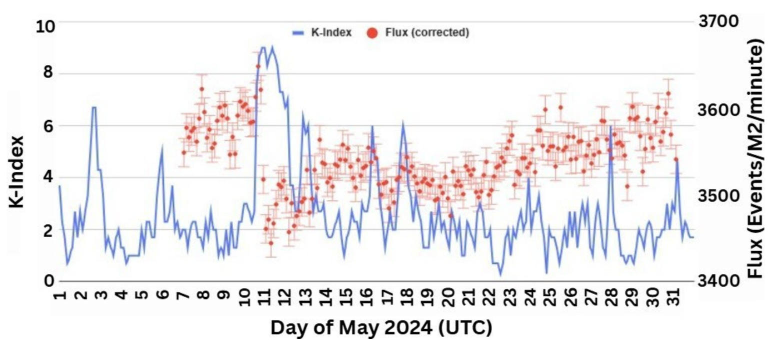

FIGURE 2. Corrected flux (red) and K-index (blue) versus time recorded in Skokie, Illinois, over the month of May 2024. Flux is in number of muons per m^2 per min. After pressure correction, the data reveal a clear Forbush decrease pattern with a gradual recovery toward baseline levels and minimal fluctuations that coincide with additional geomagnetic disturbances. The error bars represent $1/\sqrt{N}$, with N being the number of events.

RESULTS

In Table 1 the percent change in muon flux was calculated. First, we took the difference between the average flux of the period leading up to the CME event and the estimated flux value of the initial recovery phase (from the line of best fit), evaluated at the time of the initial flux drop caused by the CME. This difference was divided by the average and multiplied by 100 to find the percent change. The z-value was calculated by dividing the difference by the standard deviation of the calm period. This resulting z-value was used to calculate the p-value, the probability of randomly measuring this change from the mean. The recovery time measures how long after the initial flux drop the linear fit returned to the average flux value prior to the event.

TABLE 1. The percent change, percent error, *p*-value, average flux preceding the CME event, and recovery time in days for each cosmic ray detector during the May 10, 2024, CME event.

Location	% Change	% Error	Drop *p*-Value	Average Flux Prior to Event (counts/m^2/min)	Recovery Time (days)	Recovery *p*-Value
Batavia, IL	-1.43	1.12	0.22	579	7	<0.0001
Batavia, IL	-2.25	0.32	<0.0001	7614	7	<0.0001
Northfield, IL	-2.52	0.30	<0.0001	7904	8	<0.0001
Skokie, IL	-2.65	0.46	<0.0001	3586	9	<0.0001
Skokie, IL	-4.30	0.46	<0.0001	3491	6	<0.0001
Northbrook, IL	-2.68	1.15	0.023	544	9	<0.0001
Winnetka, IL	-2.96	0.30	<0.0001	8223	11	<0.0001
Honolulu, HI	-2.22	1.90	0.10	207	17	0.0002
Honolulu, HI	-1.27	1.31	0.39	422	7	0.0021

Measured flux depends on the unique configuration of each detector. All detectors with sufficient sensitivity recorded signal patterns like the ones seen in Fig. 2, with an initial drop followed by an average projected linear recovery of 7.3 days and a second and third CME event occurring on May 16 and 18, respectively, lengthening the overall average recovery to 13.6 days. However, this pattern was less visible in detectors with low flux, such as those in Hawaii (Fig. 3). A characterization of the flux recovery pattern is provided in Fig. 4.

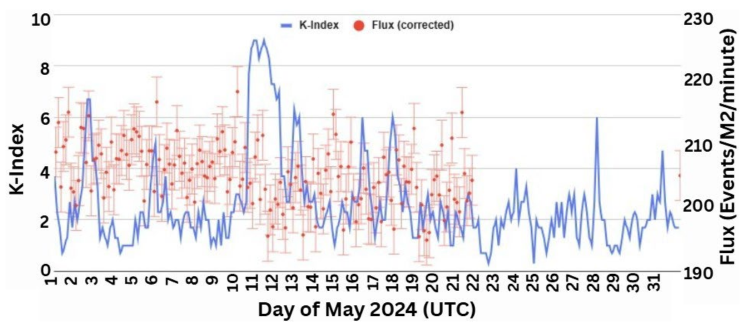

FIGURE 3. Pressure-corrected flux (red) and K-index (blue) versus time recorded in Honolulu, Hawaii, over the month of May 2024. Although a Forbush decrease is present, the pattern is less visually apparent than in higher-flux detectors because the lower count rate produces larger statistical fluctuations. The error bars represent $1/\sqrt{N}$ with N being the number of events.

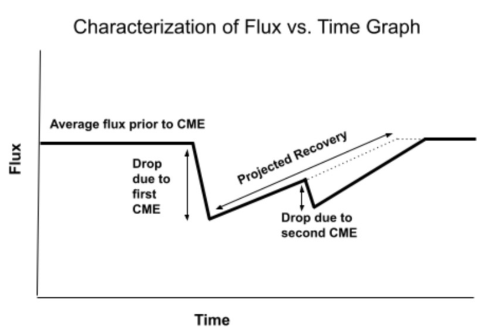

FIGURE 4. A schematic of the idealized pattern for CME onset and recovery. A rapid decline in muon flux coinciding with CME-driven geomagnetic disturbance is followed by a gradual recovery toward baseline levels as the interplanetary magnetic field stabilizes. A second sharp decrease corresponds to a subsequent CME event, demonstrating how multiple solar disturbances can produce repeated decreases that interrupt the recovery phase.

DISCUSSION

During May 10–12, 2024, a 9-Kp intensity CME, one of the strongest of the decade, occurred. Nine detectors recorded a decrease in muon flux on May 10, 2024. In all detectors with sufficient sensitivity, the drop was followed by a gradual recovery to baseline flux by May 30, 2024 (Fig. 2). This event demonstrated an inverse relationship between CME intensity and muon flux: as the K-index rose to 9, flux dropped; as the index returned to about 3, flux increased. This pattern, known as a Forbush decrease, has been supported by prior research.[8,9] The consistency of the decrease across all detectors with sufficient sensitivity, regardless of their location, strengthens the conclusion that the results were caused by a large-scale event. This multisite validation also supports the idea that CME events can encompass large areas while demonstrating the ability of ground-level detectors to measure space weather.

CONCLUSION

This study aimed to assess the impacts of CME events by measuring muon flux at locations across the United States. A pressure correction method was created and validated using real-world data. A Forbush decrease pattern was observed by all cosmic ray detectors with sufficient sensitivity, which demonstrates the pattern's reproducibility. Detectors with low flux measured a statistically insignificant decrease at CME onset due to the small sample size and large error. However, seven of the nine detectors recorded statistically significant decreases in muon flux consistent with a Forbush decrease, demonstrating reproducibility of the pattern across multiple locations.

ACKNOWLEDGMENTS

The authors thank Downers Grove South High School in Downers Grove, Illinois, and New Trier High School in Northfield, Illinois. This work was supported by QuarkNet National Science Foundation Grant No. PHY-2309272.

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