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# Increase in the count rates of ground-based cosmic-ray detectors caused by the heliomagnetic disturbance on 5 November 2023

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**Abstract:** This letter presents a rare physical phenomenon associated with solar activity, manifesting in anomalies within neutron, electron, and gamma-ray fluxes in the atmosphere. Conventionally, Earth's magnetic field disturbances reduce cosmic ray intensity reaching the surface. However, a temporary surge in cosmic ray flux occurs intermittently known as the Magnetospheric Effect (ME). Our observations reveal that this effect predominantly induces a count rate increase in particle detectors positioned at middle latitudes on mountaintops. On November 5, 2023, a 2-3% increase in neutron monitors at mountain altitudes and up to 5% increase in thin plastic scintillators registering electrons and gamma rays was observed. This flux escalation coincided with a southward orientation of the interplanetary magnetic field. Importantly, we present, for the first time, the energy spectrum of the Magnetospheric Effect observed at two mountaintops: Aragats and Zugspitze. Simulations of low-energy proton interactions in the terrestrial atmosphere affirm the augmentation of low-energy cosmic rays. Protons, typically restricted by the geomagnetic cutoff, reached the Earth's atmosphere, generating detectable particle showers on the Earth's surface.

**Plain Language Summary:** The unexpected surge in solar activity in fall 2023 following a period of the calm sun during the previous relatively small 24th solar activity cycle indicates the approach of the solar maximum of the 25th cycle expected in 2024. The nonlinear interplay between disturbed interplanetary magnetic and geomagnetic fields yields diverse effects, from damage to satellite electronics to fascinating Auroras. In these circumstances, it is increasingly important to understand the effects of large magnetized clouds ejected from the Sun on near-Earth environments. Cosmic rays are direct messengers, conveying crucial information about these intricate processes. Networks of particle detectors continuously monitoring cosmic ray flux on the Earth's surface provide valuable insights complementary to spaceborne detectors operated by NOAA, NASA, and ESA. Our report unveils a rare Magnetospheric Effect observed by particle detector networks at middle latitudes on mountaintops. Additionally, we present, for the first time, the energy spectrum of the particles causing the observed count rate enhancement, shedding light on the solar-magnetospheric interaction.

**Highlights:**

1. We measure an increase in the count rate of magnetospheric origin using particle detectors located at mountain altitudes and middle latitudes.

2. For the first time, we measured the energy spectra of the particle fluxes during the magnetospheric effect with spectrometers located on Mount Aragats and Zugspitze.
3. Particle flux enhancement coincides with the depletion of the horizontal component of the geomagnetic field.
4. We explain why the magnetospheric effect was observed at mountain altitudes and not at sea level.

**Keywords:**
Cosmic rays, Magnetospheric effect, Interplanetary Coronal Mass Ejections (ICME), Interplanetary Magnetic Field (IMF), Geomagnetic Field (GM)

## 1. Introduction

The Earth's interaction with the solar wind, including geomagnetic field disturbances, profoundly impacts planetary environments [1]. This interaction influences the flux of secondary cosmic rays (SCR) reaching the Earth's surface, providing valuable insights into the distribution of magnetic structures in the heliosphere and the solar wind's interaction with the magnetosphere. Short-term fluctuations in galactic cosmic ray (GCR) flux are observed due to the passage of the "fast" solar wind, associated with corotating high-speed solar wind streams, shock waves, and interplanetary coronal mass ejections (ICMEs) [2]. The magnetic field of ICME is resolved into three components: Bx along the sun-earth line, By perpendicular to Bx in the earth's orbital plane, and the Bz component perpendicular to both. The southward orientation of Bz plays a crucial role in modulating cosmic rays (CR), allowing solar wind and cosmic rays an easier path into the near-Earth environment. Changes in the Bz can alter the energy spectrum of cosmic rays that reach Earth, affecting their count rate.
The arrival of a magnetized plasma cloud to the magnetosphere triggers a major geomagnetic storm (GMS), measured, in particular, by Dst and Kp indices. Various factors, such as the interplanetary magnetic field (IMF) structure and the speed and density of solar wind streams, can influence cosmic ray intensity variations.
Earth's magnetic field becomes compressed and more tangled during GMS. This leads to an enhanced shielding effect, causing more cosmic rays to deflect from the Earth's surface. Thus, disturbances of Earth's magnetosphere structure can create less conducive conditions for cosmic rays to penetrate and reach the surface. Disturbed heliospheric conditions generally reduce cosmic ray intensity reaching the surface, exhibiting Forbush decreases (FDs).
FDs, observed through neutron monitors and muon/electron detectors, show asymmetrical structures characterized by a rapid flux decrease over a few hours, followed by a gradual recovery over several days. Usually, solar bursts follow each other, with multiple fast waves of magnetized plasma traveling simultaneously, sometimes overtaking each other in interplanetary space. Thus, FDs can have rather complex structures demonstrating consequent depletions without a recovery stage. Cosmic ray flux typically shows pre-increases of 1 – 2% due to cosmic rays reflected on the approaching solar wind shock. The abrupt change in the geomagnetic field,

known as sudden storm commencement (SSC), occurs when the shock wave from fast solar wind reaches Earth's magnetosphere, leading to the main decrease phase caused by the southward magnetic field.

The relationship between coronal mass ejections' plasma and magnetic field characteristics and GMS activity is an increasingly interesting topic in space weather. Statistical studies indicate that the deepest FDs and largest GLEs are associated with ICMEs accompanied by a magnetic cloud [3]. However, while the fundamental physics of how solar ejecta and magnetic fields influence geomagnetic storms is well established, the exact prediction and understanding of these phenomena under varied solar and interplanetary conditions remain active and necessary research areas.

The disturbed geomagnetic field can also lower the cutoff rigidity below which solar protons cannot penetrate the Earth's magnetic shield, allowing lower-energy-than-usual solar protons to access the atmosphere. The entrance of low-energy protons in the terrestrial atmosphere results in the 2-5% enhancement of secondary cosmic rays reaching the Earth's surface and generating the so-called magnetospheric effect (ME). The ME is more prominent in regions at middle latitudes and high cutoff rigidities, especially at high altitudes.

An analysis of ME events registered on Aragats during the 23rd solar activity cycle identified 24 events of count rate enhancements during GMSs [4]. The correlation analysis of particle fluxes and ICME parameters indicates that if the Bz is southward at the ICME's arrival, the CR flux peaks coincide with the abrupt change in solar wind speed and Bz. Reducing the geomagnetic field for several hours changes the effective cutoff rigidity, allowing secondary cosmic rays to be detected on Earth's surface. After the ICME passage, the disturbed geomagnetic field recovers, preventing low-energy particles from entering the atmosphere. The ME of the 23rd cycle was reported by Kudela and Storini [5] on November 20, 2023.  A rather strong enhancement of the magnetospheric transparency in the time of minimum Dst (-471 nT) strongly affected the transmissivity of the magnetosphere. It yielded huge increases at all three middle and high cutoff stations: Haleakala, Mexico, and Rome. During the 24th solar activity cycle, Karel Kudela et al. [6] monitored enhanced cosmic ray fluxes on Lomnicky Stit by the SEVAN detector [7] installed there in 2014. Impulsive flux enhancements were attributed to the thunderstorm ground enhancements (TGEs [8]), correlated with thunderstorms and emergences of strong atmospheric electric fields.

Despite advances in modeling techniques, the accurate prediction of geomagnetic storms' exact timing, duration, and intensity continues to pose a significant challenge. The interactions between solar wind and Earth's magnetosphere are complex, leading to inherent uncertainties in predictive models. The highly complex and non-linear nature of plasma interactions in space necessitates simplifications in current models, which may not fully encapsulate all the variables present in actual space weather scenarios. Furthermore, the intricate coupling between Earth's magnetosphere and ionosphere adds another layer of complexity, with ongoing research to refine models to understand better and anticipate these processes. Measurements of particle fluxes at

various latitudes, both at sea level and on mountaintops, are essential for this purpose [9]. Specifically, analyzing the energy spectra of the enhanced particle fluxes provides valuable data for our ability to classify and understand geomagnetic storm-induced events.
This study contributes to the field by examining the influence of the disturbed magnetosphere on the count rates observed by the SEVAN and Neutron monitor networks across different latitudes and altitudes. It presents, for the first time, the energy spectra of ME particles, providing new insights into the influence of GMS on cosmic ray fluxes.

## 1. Instrumentation

Several particle detector networks operate continuously, offering uninterrupted monitoring of cosmic ray fluxes incident on the Earth's surface. The time series data obtained from these networks play a crucial role in studying the influence of solar activity on the Earth's environment, providing valuable insights into the interactions between the interplanetary magnetic field and the magnetosphere through patterns of changing intensities of different cosmic ray species.
The neutron monitor database (NMDB) plays a significant role by providing neutron measurements from stations worldwide [10]. This collaborative project involves numerous countries and institutions, integrating data from neutron monitors to offer a comprehensive and continuous view of cosmic ray activity. The NMDB is a platform for scientists and researchers to access real-time and historical data on cosmic ray intensities.
SEVAN (space environment viewing and analysis network) represents an essential network of particle detectors strategically located at middle to low latitudes, primarily on mountain peaks [8]. Initiated during the International Heliophysical Year (IHY - 2007), SEVAN is currently operational as part of the International Space Weather Initiative (ISWI). Over nearly 15 years, SEVAN detectors have measured time series data of charged and neutral particle count rates. SEVAN detectors cover various latitudes and altitudes, operating in various locations, including Armenia, Croatia, Bulgaria, Slovakia, the Czech Republic, and Germany. Notable sites include Mt. Aragats in Armenia, Mt. Musala in Bulgaria, and Zugspitze Schneefernerhaus in Germany.
The Aragats Space Environment Center (ASEC, [11]) 24/7 monitors cosmic rays and their interactions with the Earth's atmosphere and magnetosphere. Located on Mount Aragats, ASEC contributes to solar, atmospheric physics, and space weather research. The network includes 12 scintillators arranged in 3 detector sites, allowing for detailed measurements across an area of 50,000 $m^2$. Connected to a fast data synchronization system [12], the time series of the count rates of the STAND1 network ([13], sampling time 50 ms) provides valuable insights into the dynamics of cosmic ray interactions in the Earth's environment.
LEMI-417M digital magnetotelluric station, produced by Lviv Space Research Institute, has been operating on Aragats since September 2010 [14]. It provides the 1-minute time series of the 3 components of the geomagnetic field. The magnetometer is produced on the base of the flux-gate sensor, and all three components are implemented in the same thermostable housing.

## 2. The Magnetospheric Effect Observed During the Geomagnetic Storm on 5 November 2023

The Space Weather Prediction Center (SWPC) of NOAA has updated its solar activity prediction for Solar Cycle 25, indicating a faster and higher peak level than initially forecasted in December 2019. The revised prediction suggests a peak for Solar Cycle 25 between January and October 2024, with a maximum sunspot number ranging from 137 to 173. Geomagnetic disturbances from the Sun manifested at the beginning of November, confirming the revised forecasts. Numerous coronal mass ejections (CMEs) left the Sun on 2 November, leading to disturbances in the heliomagnetic field. At 08:10 UT, the interplanetary magnetic field's (IMF) total strength (Bt) reached 34nT, with a southward Bz component of -27nT, see Fig. 1. A second strong shock in the solar wind was observed at 11:46 UT, with Bt reaching 45nT. While the Bz component initially turned northward, it rotated southward for 4 hours, causing global geomagnetic activity and auroras at middle-latitude locations. The geomagnetic storm reached G3 strength at 17:40 UT, with no presence of solar energetic particles.

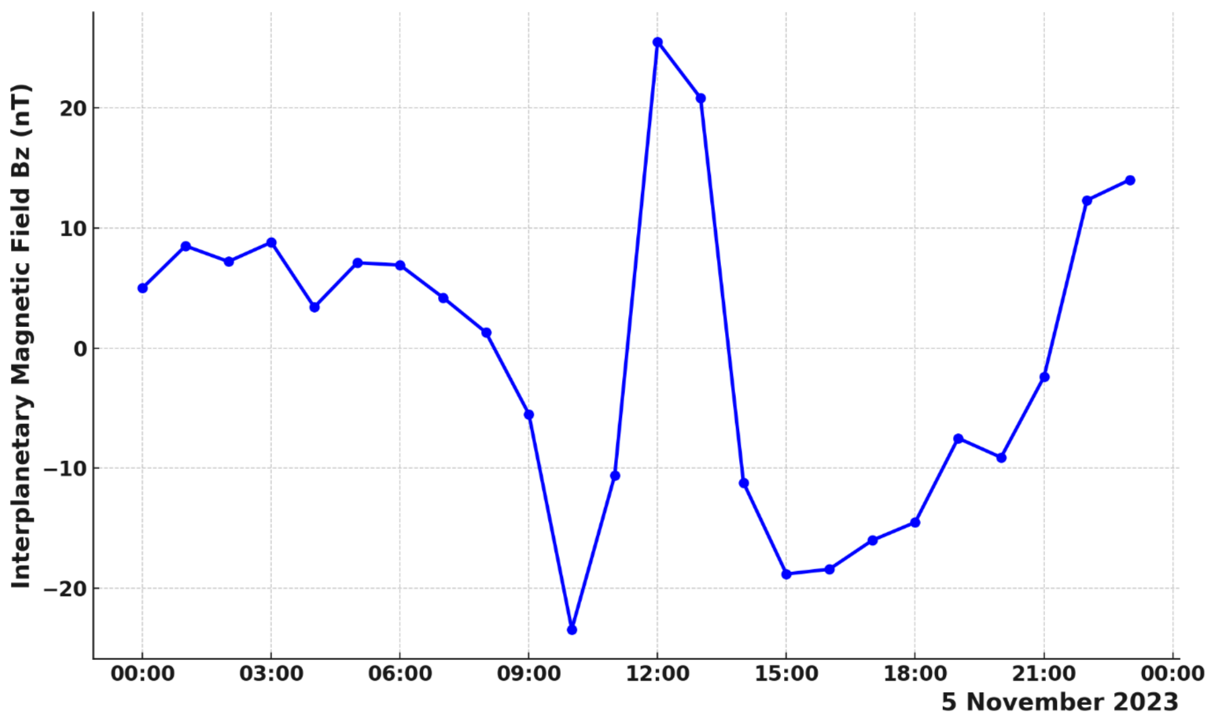


**Figure 1** Interplanetary Magnetic Field Bz component on 5 November 2023 (data from OMNI Web).

The data from the NMDB [10], Fig.2, reveals a magnetospheric effect observed by middle-altitude mountain neutron monitors from 10:00 to 13:30 UT on 5 November 2023. The count rate enhancement for Nor Amberd and Lomnicky Stit neutron monitors at 2000 m and 2634 m altitudes reached approximately 3%. The sea-level monitor Oulu, cutoff rigidity R = 0.81GV, altitude H= 15 m, shows no enhancement. The high-altitude South Pole (R=0.1 GV, H=2820 m) and low-altitude Terre Adele (R=0.01 GV, H=32 m) Antarctic neutron monitors also showed no count rate increase due to the low cutoff rigidities.

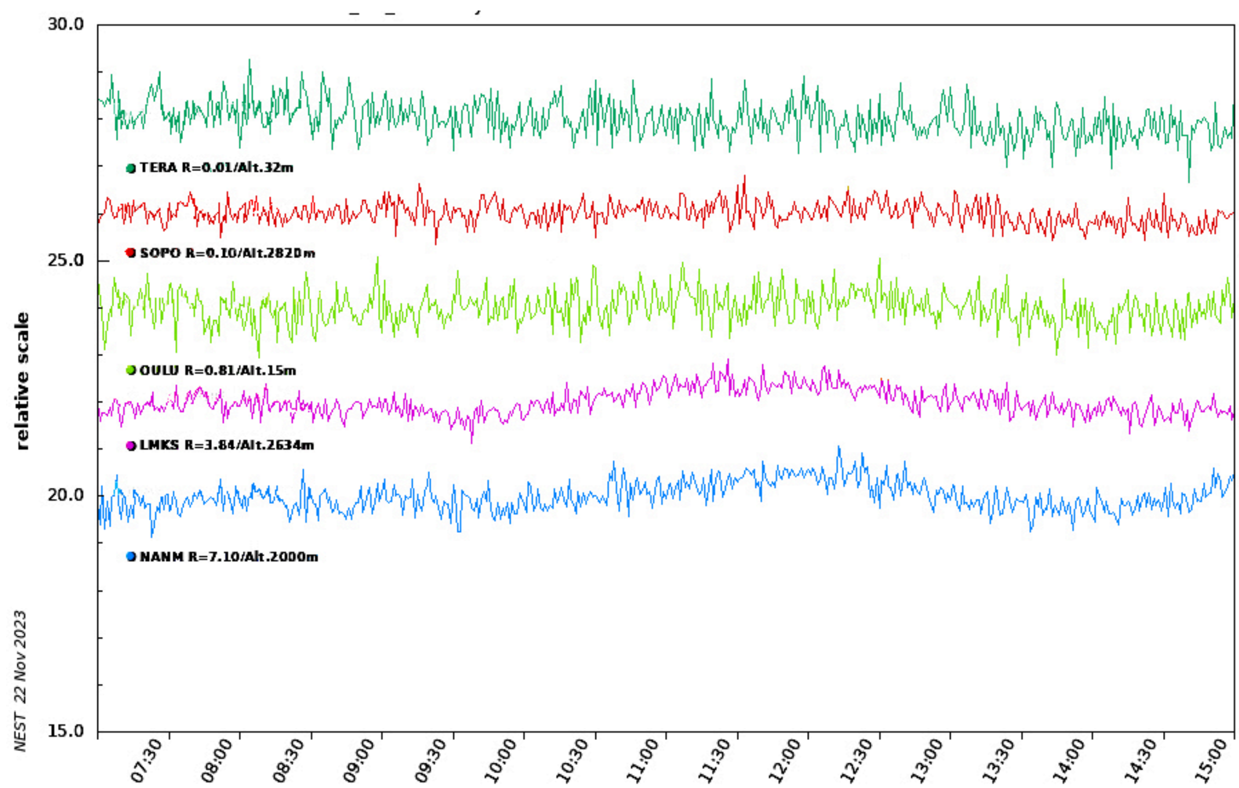


**Figure 2.Time series of count rates of Neutron Monitors on 5 November 2023, located at high, low, and middle latitudes, mountain tops, and sea levels.**

Simultaneously, the SEVAN particle detector network, spanning Eastern Europe, Germany, and Armenia, detected the magnetospheric effect with consistent amplitude. Figure 3 illustrates the time series of Aragats (3200 m) and Zugspitze (2600 m) SEVAN light detectors, which were recently modernized to measure the energy spectra of incident neutral particle flux [15].

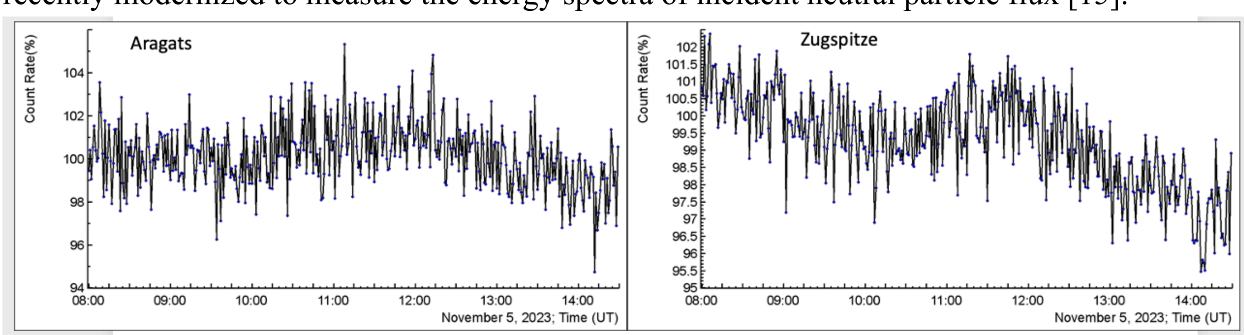


**Figure 3.Time series of Aragats and Zugspitze SEVAN 20 and 25 cm thick, 0.25 m$^2$ area plastic scintillators during ME time**

All particle detectors with low thresholds at Aragats registered the magnetospheric effect. Figure 4 displays the 1-minute count rates of 1 cm thick and 1 m² plastic scintillators from the STAND1 array, indicating a 5% enhancement starting around 10:20 UT. Magnetic reconnection on the sunward side of Earth's magnetosphere, a key driver of geomagnetic activity, becomes more likely when the horizontal component of Earth's magnetic field is reduced. The magnetic reconnection allows solar wind to enter the magnetosphere, enhancing geomagnetic disturbances and increasing particle counts of ground-based particle detectors on 6 November 2023, i.e., neutron monitors (Fig. 3) and scintillator detectors (Fig.4).

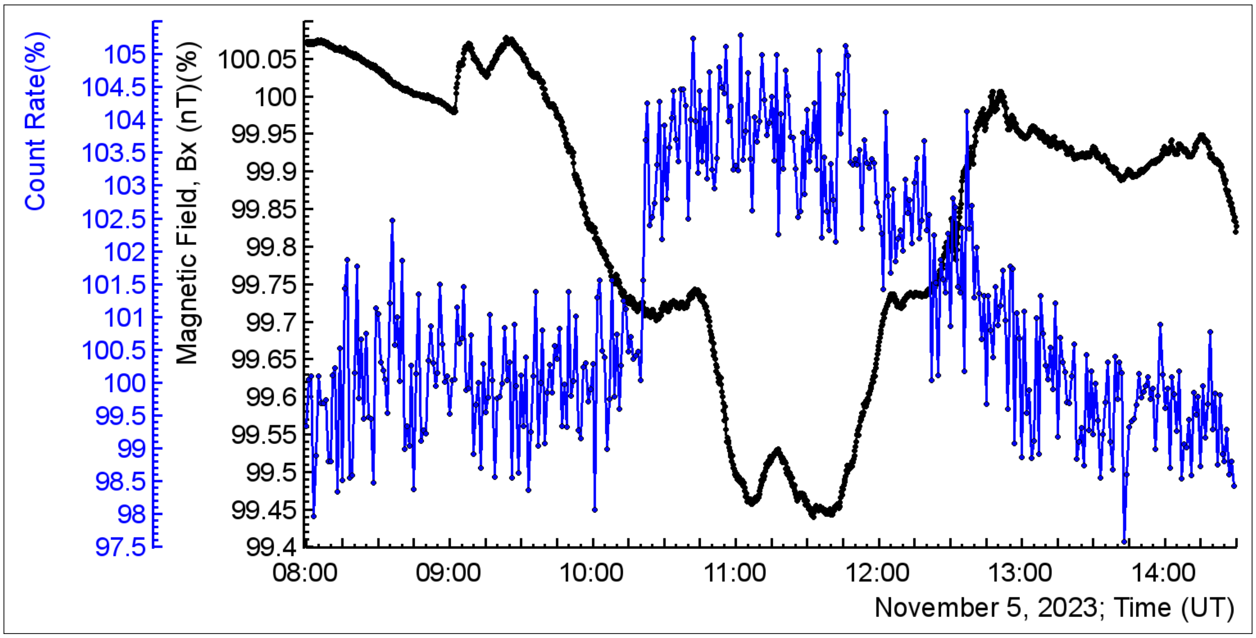


**Figure 4. 1-minute count rates of 1 cm thick and 1 m$^2$ area plastic scintillator of STAND1 array and the geomagnetic field's horizontal component.**

Energy release histograms in Figure 5, measured by 20 cm (Aragats) and 25 cm (Zugspitze) thick plastic scintillators, show a decline at 8 MeV. The secondary neutron energies of 6.5-8 MeV correspond to low-energy primary protons with energies below cutoff rigidity, reaching Earth's surface at mountain altitudes during ME. These “surplus neutrons” are additional to the ones reaching the detectors at fixed energy cutoff.

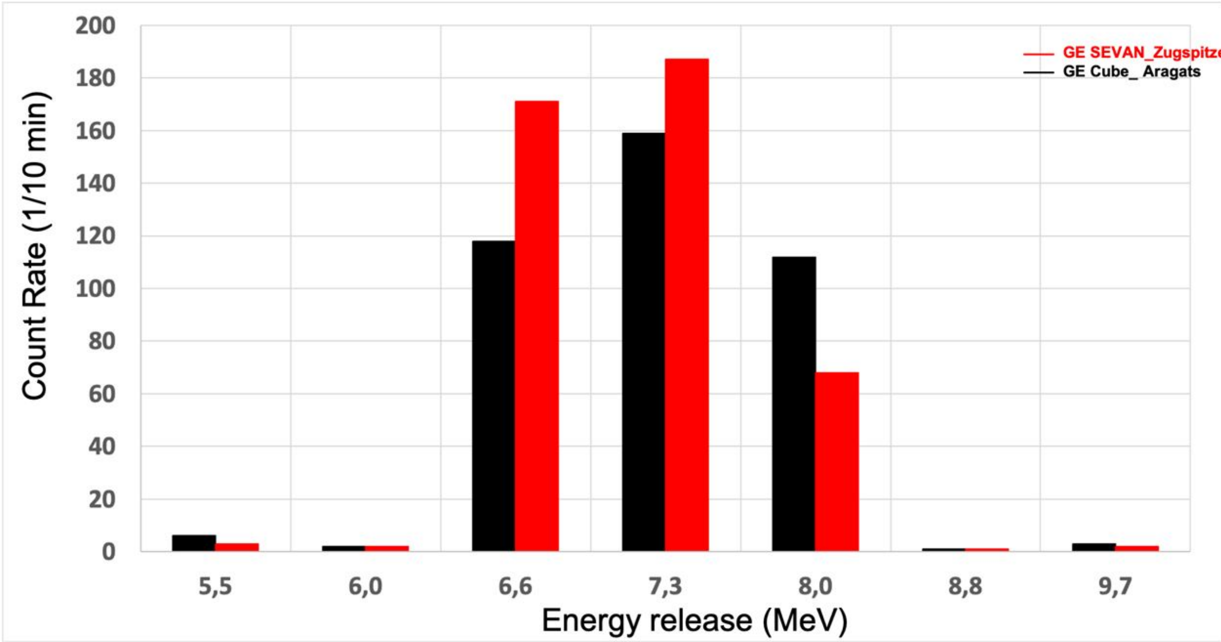


**Figure 5. Energy release histograms measured by 20 cm (Aragats, red) and 25 cm (Zugspitze, black) thick and 0.25 m$^2$ area plastic scintillators during ME's 10 minutes from 11:57 to 12:06.**

In [16], we presented fluxes of secondary particles influenced by the largest Geomagnetic Storm of the 23rd solar activity cycle, which occurred on 20 November 2003 (Dst = -455, Bz = -49nT). To model the secondary fluxes, we utilized the CORSIKA code [17] version 7.75, simulating extensive air showers with the hadronic interaction models QGSII_UrQMD [18] and GHEISHA7.56 [19], along with the electromagnetic interaction model EGS4 [20]. The flux increases were assessed relative to the pre-event count rate, calculated from one-hour data collected before the shock's arrival. Neutrons exhibited an increase of approximately 6%, charged particles (>7 MeV) approximately 0.8%, and high-energy muons (>200 MeV) around 0.5%. The comparison between simulated and experimental increases in count rates suggested that the November 20, 2003 event could be associated with a cutoff rigidity decrease of ~1 GV (refer to Tabs 4 and 5 of [21]). Thus, a substantial flux enhancement corresponds to a 1 GV reduction in the cutoff.

For the smaller increase observed on 5 November 2023 (2-3% in neutron flux), we anticipate a cutoff reduction smaller than 1 GV. To assess the expected flux enhancement on 5 November 2023, we conducted simulations using the same CORSIKA code, focusing on particle fluxes resulting from 6 GeV protons incident on the terrestrial atmosphere (see Fig. 6). In this presentation, we showcase fluxes of gamma rays and electrons above 1 MeV, which were not included in [16]. We tracked shower particles until they reached an energy of 1 MeV, executing 10,000 simulations. Most surviving shower particles were low-energy gamma rays, aligning well with the energy release histograms measured on Aragats and Zugspitze. The enhanced fluxes reach mountain altitudes (Fig. 6a, compare with Fig. 4); however, they attenuate in dense air on the way to sea level (Fig. 6b). The particles responsible for the observed flux enhancement during ME are generated through the interactions of solar protons with energies below the cutoff rigidity. As a result, these particles possess relatively low energy and cannot reach sea level, rendering them undetectable by sea-level neutron monitors and scintillators. Conversely, GLE), the secondary particles are produced by solar protons with energies exceeding the cutoff rigidity. These higher-energy protons give rise to secondary particles that reach sea level, which can be registered by ground-based detection equipment

.We have shown that decreasing the cutoff value impacts the fluxes of secondary electrons and gamma rays. Neutron simulation with energies below 10 MeV is not feasible using codes that simulate the propagation of extensive air showers in the Earth's atmosphere computational constraints. The minimum neutron energy threshold used in the CORSIKA code is 50 MeV.

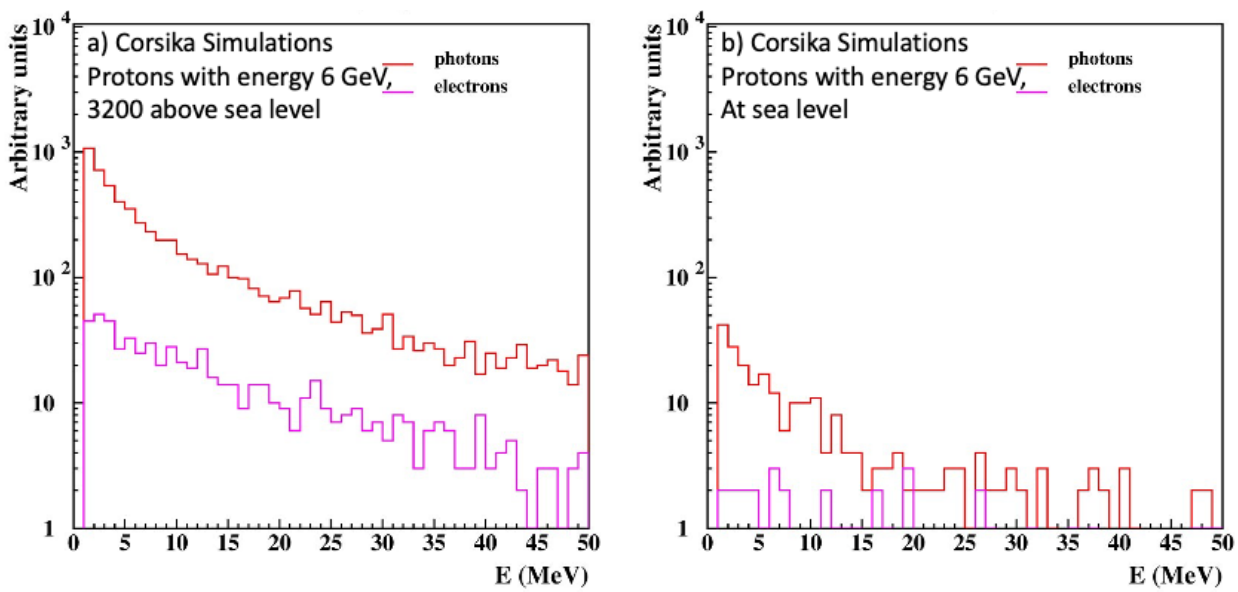


**Figure 6. Gamma-ray and electron energy spectra from EASs caused by 6 GeV protons reaching the Aragats station and sea level.**

### 3. Discussion and conclusions

On November 5, 2023, the Neutron Monitor and SEVAN particle detector networks detected a synchronized increase in intensity lasting 3.5 hours from 10:00 to 13:30 UT. This enhancement is attributed to a Magnetospheric effect, indicating a global reduction in cutoff rigidity, and coincided with a sudden southward excursion of the horizontal component of the geomagnetic field. The maximum amplitude observed in the 1-minute time series in the neutron flux was approximately 3% (refer to Fig. 2 and Fig. 3). Outdoor plastic scintillators at the Aragats station, with a lower energy threshold, recorded a ME amplitude of around 5% (see Fig. 4). The energy release spectra of the ME particles were measured for the first time at both Aragats and Zugspitze, revealing a precise coincidence confirming global nature of ME and confirming the reduction in cutoff rigidity at both locations (see Fig. 5). Modeling of the low-energy proton flux

entering the terrestrial atmosphere due to cutoff reduction (see Fig. 6). aligns with the 5% count rate increase measured on Aragats by STAND1 detector (Fig. 4).
The ongoing deployment of new particle detectors on mountain altitudes, particularly spectrometers measuring energy spectra of charged and neutral particles, is crucial for comprehending the cause of global count rate enhancement and the intricate interactions between ICME and the magnetosphere.

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The data utilized in this study is accessible through [22] in numerical and graphical forms. We also acknowledge the NMDB database (www.nmdb.eu), established under the European Union's FP7 program (contract no. 213007), for providing access to neutron monitor data.

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