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Influence of Magnetosphere Disturbances on particle fluxes measured by ground-based detectors.

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Abstract

This study examines how the Earth's surface particle fluxes are modulated by the Interplanetary Magnetic Field (IMF) carried by Coronal Mass Ejections (ICME). Our findings underscore the role of magnetic reconnection in allowing low-energy galactic cosmic rays (GCR) to penetrate the magnetosphere, leading to enhanced secondary particle fluxes through reduced cutoff rigidity—a phenomenon known as the magnetospheric effect (ME). In contrast, the Forbush decrease (FD) driven by the scalar magnetic field strength results in significant particle flux reductions. On May 10-11, 2024, the FD, directly linked to the enormous geomagnetic storm (GMS), was complicated by the simultaneous registration of secondary particles from the Solar Energetic Particle (SEP) event, which was energetic enough to generate secondary particles in space and on the ground, leading to increases in detector count rates, known as ground-level enhancements (GLEs). Using new experimental facilities, we reveal that secondary particles during ME events release up to 10 MeV energy (maximum energy of approximately 10 MeV), whereas, during FD and GLE events, the energy release extends to 100 MeV (maximum energy of approximately 100 MeV). These insights contribute to refining event classification schemes and predictive models of space weather.

1. Introduction

The solar-terrestrial relations involve variations in the intensity of neutral and charged particles measured on Earth's surface during geomagnetic storms (GMS) triggered by incoming Interplanetary Coronal Mass Ejections (ICME). The interaction between the ICME's magnetic field and Earth's geomagnetic field (GMF) disrupts the normally stable influx of GCRs, sometimes trapping low-energy particles in specific atmospheric regions or allowing their entry into otherwise restricted areas.

Cosmic rays are monitored on Earth by networks of particle detectors, which measure secondary cosmic rays produced when primary protons and stripped nuclei interact with atmospheric atoms. These networks include the largest Neutron Monitor network (NM [1]), the Solar Neutron Telescope (SNT) network [2], the SEVAN network [3], which additionally captures electron, gamma ray, and muon fluxes, Spaceship Earth [4], and the Global Muon Detector Network (GMDN [5]). The network of NMs covered almost the whole globe, from the Antarctic to the Arctic regions. SEVAN network detectors are located at mountain tops in Armenia, Germany, and Eastern Europe; other networks are located at different latitudes and longitudes. The detection of solar events is surprisingly coherent by Neutron monitors and SEVAN networks [6].

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The secondary particle fluxes can enhance for a few hours (magnetospheric effect, ME [7]) or deplete, with the following recovery (Forbush decrease, FD [8]). The ME is explained by the decrease of the cutoff rigidity (the minimal energy allowing galactic protons to enter the atmosphere above the detector), FD – by the emerging difficulties of entering galactic protons into the atmosphere due to magnetic traps that can deflect charged particles, impacting their entry into the atmosphere. Magnetospheric events, directly linked to GMS, can be complicated by the simultaneous registration of secondary particles from Solar Energetic Particle (SEP [9]) events accelerated during intense flares. SEPs sometimes contain protons energetic enough to generate secondary particles in space [10] and on the ground, leading to increases in detector count rates, known as ground-level enhancements (GLEs [11]). GLEs typically reach detectors in a few tens of minutes after a solar flare, while the arrival time of ICME after the solar burst is much longer, from 20 hours (shortest) to 5 days [12]. The same group of solar spots can result in multiple ICMEs before the SEP event, causing overlapping FD and GLE events.

Despite significant progress in understanding solar-terrestrial connections [13], there are no exhausting models of the solar wind—GMF interactions that can predict opposite effects in secondary particle flux intensity (FD or ME, [14]). Moreover, the existent ground-based particle detectors cannot measure the energy of the registered particles. The new type of measurements can help create more detailed models and better understand GCR modulation. Using a modernized SEVAN detector [15], we recently added to the CR variation research the energy release measurements of additional particles hitting the detectors during ME and GLE and the deficit of CR during FD. In this way, we access the energy of the GCR, affected by magnetosphere disturbances and energies of solar particles, that generated secondaries registered by ground-based detectors. Our analysis of the November 2023 and May 2024 events concentrated on implementing new experimental methods, underscoring the importance of advanced measurement techniques in studying solar-terrestrial relations.

2. Methods

The SEVAN (Space Environment Viewing and Analysis Network) consists of particle detectors strategically placed at middle to low latitudes, primarily on mountain peaks [3]. These detectors, operational for nearly 15 years, now include the SEVAN-light modules, which can measure particle energy release in the 5-100 MeV range, significantly improving over previous just count rate measurements.

The SEVAN modules contain three layers of particle detectors interlayered by lead absorbers to be compatible with neutron monitors. Upper and lower scintillators are 5 cm thick and 1 m^2 in area, and the middle detectors are 25 cm. thick and 0.25 m^2 in area (see details in [16]). SEVAN electronics counts all possible coincidences of scintillator pulses, selecting enriched by neutral and charged particle subsamples. However, after recognizing that charged fluxes are as sensible to solar modulation as neutrons, we commissioned new SEVAN-light detectors with two layers without lead (see Fig. 1). Also, SEVAN's electronics board was updated with a new capability to measure and store energy-release histograms of charged and neutral particles each minute. The logarithmic amplitude-to-digital converter (ADC) provides linearity in the energy range from 5 to 100 MeV (see Fig.4 of [17]). The upper scintillator's efficiency in registering charged particles

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is ≈99%, and neutral is less than 2%. Using the veto signal from the upper thin scintillator, the detector separates charged and neutral fluxes: “01” coincidence - the neutral particles, and “11” - charged particles. Correspondingly, the energy releases of charged and neutral particles are stored each minute.

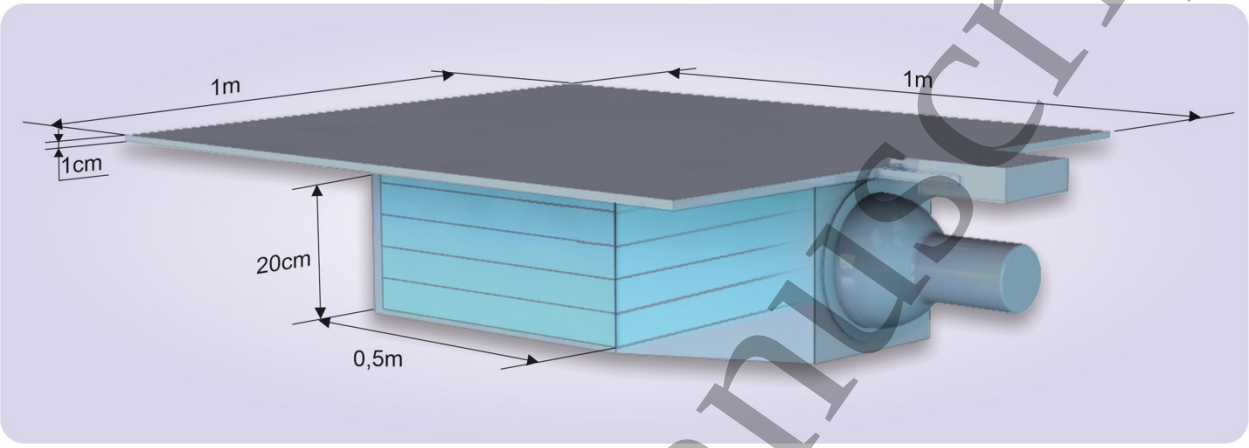

Figure 1. Detector SEVAN-light measuring charged and neutral species of cosmic rays and their energy releases.

The list of available information from SEVAN-light will be as follows:

- 1-minute count rates of stacked 1 and 20-cm thick scintillators.
- 1-minute count rates of the coincidences “01”, signal only in 20 cm scintillator; “10” – signal only in the upper 1-cm thick scintillator, and “11” – signal in both scintillators.
- Histograms of energy releases in the thick scintillator correspond to the abovementioned coincidences.

Table 1 shows the results of the SEVAN-light detector response calculation with the simulated cosmic ray flux on Aragats. As we can see in Table 1, the “01” coincidence (signal only in the bottom scintillator) comprises ≈32% of neutrons and ≈64% of gamma rays. The contamination of charged particles is negligible; thus, with the "01" coincidence, we achieve a large purity of selected neutral particles. The ”11” coincidence selects ≈63% of negative and positive muons and ≈23% of electrons and positrons; the share of neutral particles is ≈ 8%. Consequently, by the “11” coincidence, we select charged particles. Thus, using a SEVAN-light detector, we separate neutral and charged fluxes and measure the energy releases of each separately.

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Table 1. The share of cosmic ray species selected by different coincidences of the SEVAN-light detector in percent.

SEVAN-light	Neutron (%)	Proton (%)	mu+ (%)	mu- (%)	e- (%)	e+ (%)	gamma ray (%)
Coin. "01" neutral	32,1	0,3	1,0	0,9	1,0	0,9	63,8
Coin."11" charged	1,6	6,4	33,3	29,6	12,1	10,4	6,5

The next section will demonstrate how the newly introduced energy release histograms can be applied to characterize different solar events: Forbush decreases, magnetospheric effects, and ground-level enhancements. The FDs of the 25th cycle were described in detail in [6]. In this letter, we restrict ourselves by covering particle flux disturbances of 10-11 May (FD and GLE) and their comparison with the Magnetospheric effect of November 5, 2023 [18].

3. Geomagnetic disturbances on May 10-11

The 25th solar activity cycle, the maximum of which is expected in 2024, brings already a series of ICMEs, SEPs, and solar particle events registered in space and on the Earth's surface. On November 5, 2023, a significant geomagnetic storm driven by a cannibal ICME interacted with Earth's magnetic field, causing a rare magnetospheric effect [18]. The G5- geomagnetic storm that occurred on May 10-11, 2024, was one of the most intense in over two decades (see detailed analysis of the event in [19]). The event unleashed deep FD, accompanied by GLE #74 in its recovery phase. Ground-based neutron monitors [20] confirmed a GLE from 02 UT on 11 May 2024, following X.5.8 flare, which reached a maximum at 01:23 UT.

In Fig.2, we show the disturbances of the X-component of the GMF measured by the Aragats magnetometer (blue), along with the SEVAN-light count rate (red) and disturbances of the near-surface electric field (black). Electric field during solar events was quit: no thunderstorms and lightning flashes were detected. Aragats magnetometer observed storm sudden commencement (SSC) at 17:05, which triggered the extreme geomagnetic storm with a Dst index of −412 nT at 2 UT on 11 May 2024, marking the sixth-largest storm since 1957 [19]. The magnetometer also shows a large compression upon the shock arrival, confirmed by THEMIS-E's and Kakioka's measurements on the magnetic field and plasma data [19].

The atmospheric electric field was calm during major geomagnetic disturbances. However, it is interesting to mention that 3 hours before SSC, at 14:00, the count rate experienced an abrupt burst, so-called thunderstorm ground enhancement (TGE, [21]) due to the strong atmospheric electric field (see the peak in the black curve at the left bottom corner).

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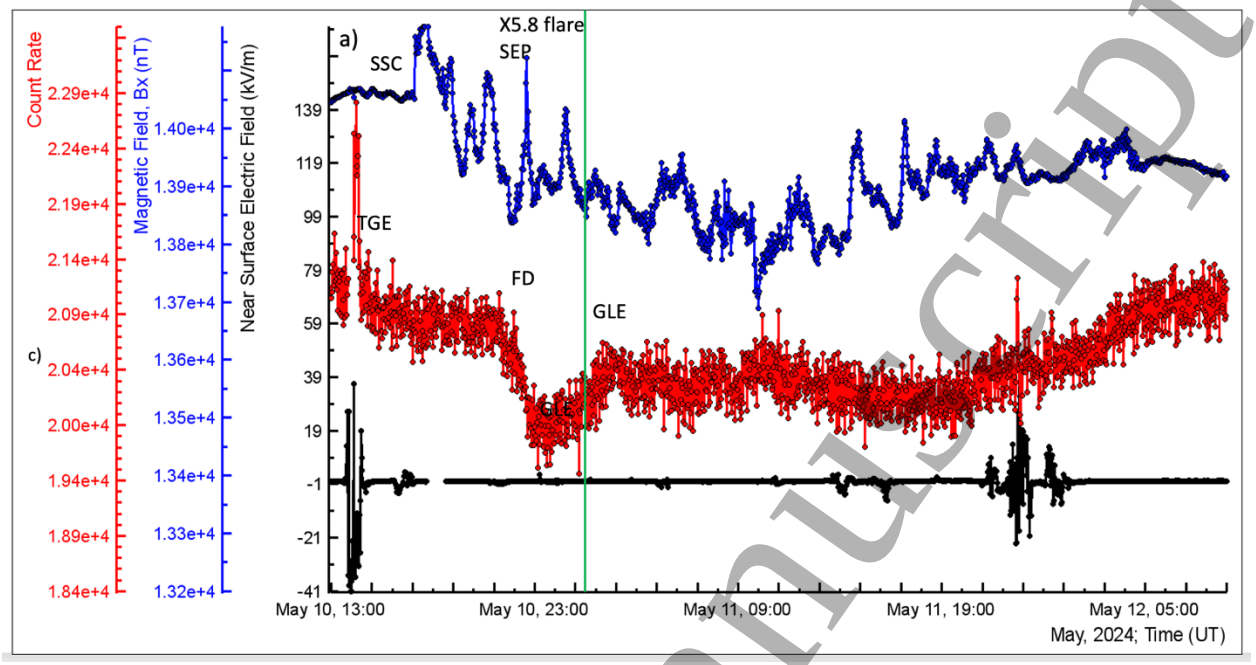

Figure 2. The X-component of the GMF measured by the Aragats magnetometer (blue), along with disturbances of the near-surface electric field (black) and the count rate of the SEVAN-light detector (red).

4. Observation of the May events by the SEVAN network and SEVAN-light detector

In Figure 3, we present a 10-minute time series of count rates of the Nor Amberd neutron monitor (NANM) and neutral and charged fluxes selected by the coincidences of the SEVAN-light detector. Depletion of fluxes was calculated according to the mean values measured at 19:00-20:00 on May 10 (shown by the dashed lines). The FD started at ≈18:30, ≈1.5 hours after SSC. As was mentioned in [22], "when ICME with depleted cosmic ray flux inside passes over the Earth, ground-based monitors generally show a decrease in their flux". Maximum depletion was ≈8% for the NANM and ≈5% for SEVAN-light, reached around midnight. Afterward, at the recovery phase, FD was interrupted by GLE after the X5.8 flare unleashed the SEP. The GLE amplitude was calculated relative to means measured at 23:00 – 24:00 on May 10.

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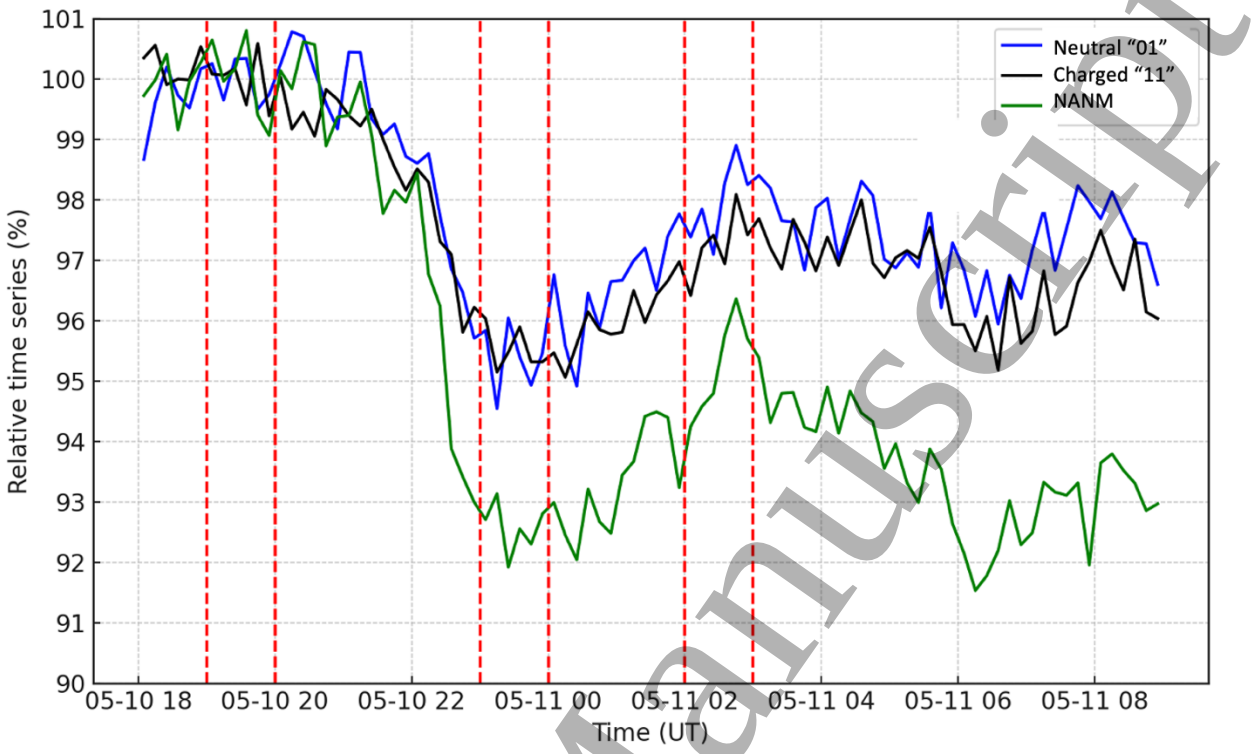

Figure 3. Time series of count rates of Nor Amberd Neutron Monitor (NANM, green) and SEVAN-light neutral and charged particles (blue and black).

Figure 4 demonstrates a minute time series of precise correlated counts of the 5 cm thick, 1 m^2 area SEVAN upper scintillators on Mts. Aragats (40.25N, 44.15E, altitude3200 m), Musala (42.1N, 23.35E, altitude 2930 m) and Lomnicky Stit (49.2N, 20.22E, altitude 2634 m).

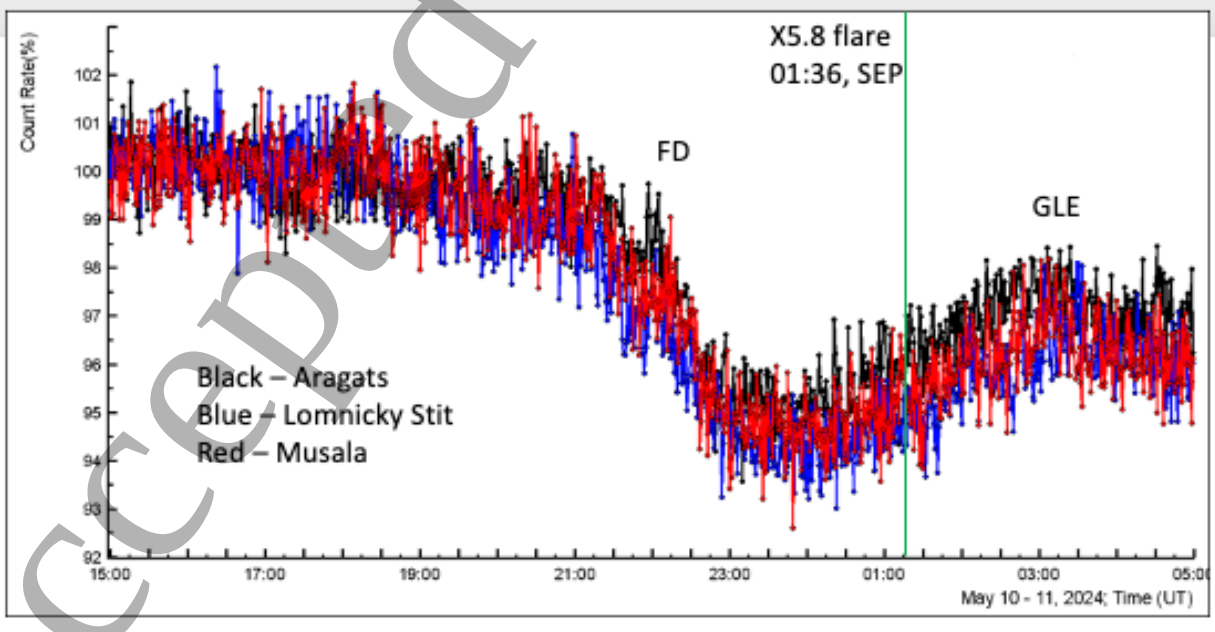

Figure 4. Observation of FD and GLE by SEVAN network's Aragats, Lomnicky Stit, and Musala detectors

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Figure 5 shows the energy release histograms collected during 1 hour of maximum depletion of FD (5a, 5b) and maximum flux of GLE and ME (Figs. 5c, 5d and 5e, 5f). Histograms are obtained with the SEVAN-light detector for charged and neutral particles separately. For GLE and ME, we subtract the fair-weather histogram from the maximum flux histogram; for FD, visa verse, we subtract the maximum depletion histogram from the fair-weather histogram. The exact times are shown in Fig. 3 by dashed lines. The smooth bump in muon energy spectra is explained by electrons' and muons' most probable energy release in a 20 cm thick plastic scintillator. Assuming that the energy release in each cm of scintillator is ≈ 2 MeV [23], ≈40 MeV will be the most probable energy release. Charged particles can produce bremsstrahlung gamma photons, creating electron-positron pairs, thus enhancing energy release. Neutrons in the scintillator can undergo nuclear reactions, producing charged particles along their path.

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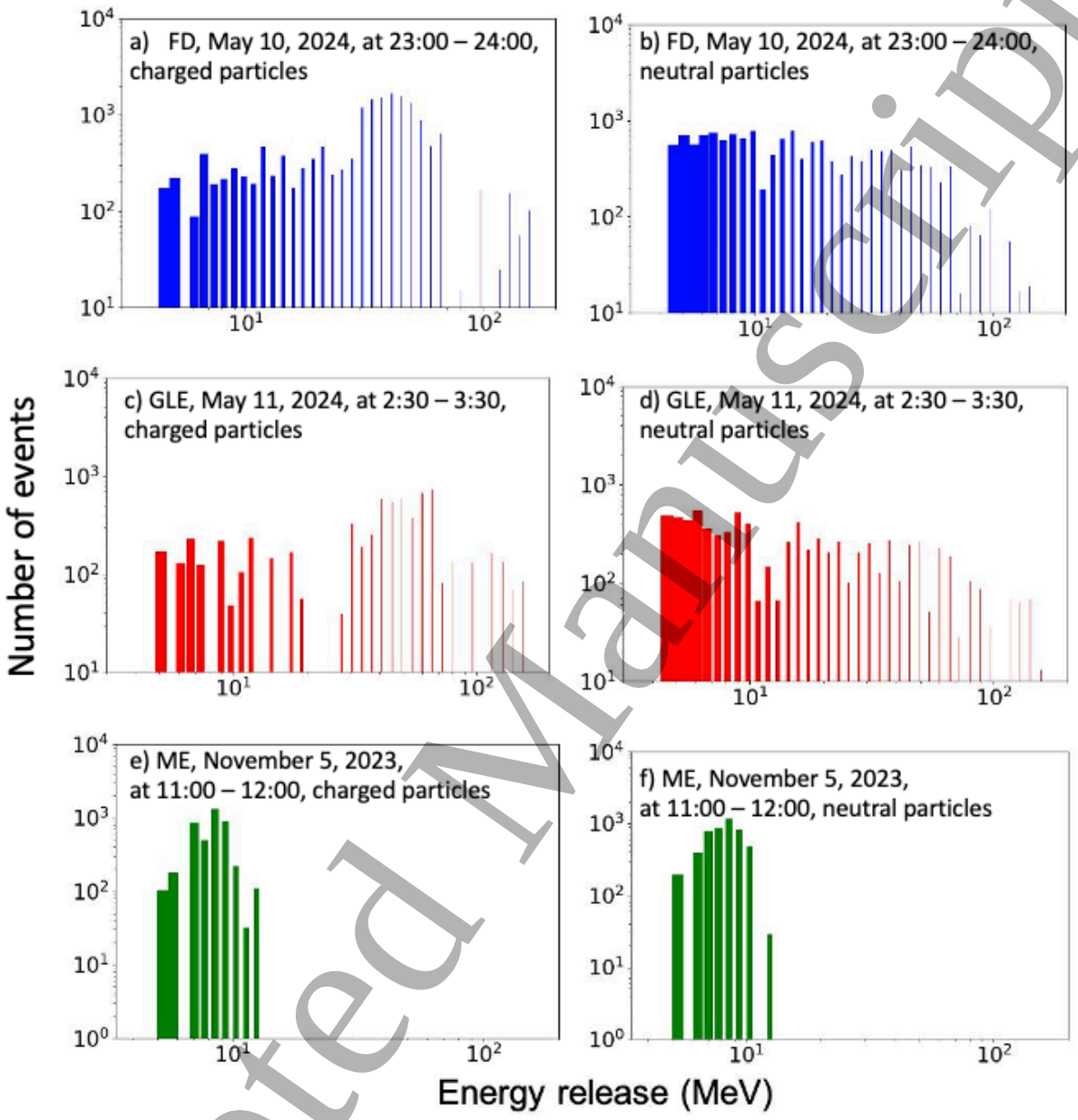

Figure 5. The energy release histograms measured by SEVAN-light detector during three types of solar events: FD a, b), GLE c, d), and ME e, f).

As Fig. 5 shows, the energy release histogram for the magnetospheric effect strictly differed from the ones from the FD and GLE. The energies of additional particles comprising ME (Fig 5e, 5f) are mostly lower than 10 MeV. As shown in [18], lowering the geomagnetic cutoff below 7 GeV allows low-energy GCRs to enter the atmosphere and produce showers reaching mountain altitudes. There was no flux enhancement in Arctic/Antarctic regions and on sea level. The low-energy primary protons consequently originate low-energy secondaries, which do not reach sea level and were registered by mountain-based detectors. The energy releases of secondary particles related to FD and GLE (Figs 5a, 5b and 5c, 5d) are extended to 100 MeV. Thus, galactic

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and solar protons with energies higher than those that originated the ME are responsible for these events.

5. Discussion and Conclusions

On May 10-11, strong, coherent structures in the disturbed magnetosphere act as a barrier, reducing the influx of galactic cosmic rays causing a deep FD. Intensification of the solar wind speed and pressure compressed the magnetosphere and reduced the horizontal component of the geomagnetic field measured by ground magnetometers (upper blue curve in Fig. 2 and [19]). After dissipating these structures at the recovering phase of FD, solar protons accelerated during the X5.8 flare reach the atmosphere and initiate secondaries that reach particle detectors on the Earth's surface. The energies of GLE protons and galactic cosmic rays responsible for the Forbush decrease were above the cutoff rigidity, as we can infer by comparing energy releases of FD and GLE with ME.

When the Bz component of the ICME is southward (negative Bz), it is opposite to the northward direction of Earth's magnetic field. This opposition facilitates magnetic reconnection on the dayside of Earth's magnetosphere, allowing solar wind energy to enter the magnetospheres. This is linked to suppressing the magnetosphere, lowering the cutoff rigidity, and allowing low-energy GCRs to enter the magnetosphere. The enhancement of the count rate of surface particle detectors at middle altitudes, and not at arctic and antarctic regions, characterized the ME. The energy releases histogram (Figs.5e, f) is a convincing confirmation of the ME, strictly differentiated from other solar-induced events.

Using the SEVAN-light detector, we measure the energy releases of neutral and charged particle fluxes. These newly established options contribute to our understanding of space weather and its potential hazards, particularly in improving the classification of solar events and refining predictive models.

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