

JGR Space Physics

RESEARCH ARTICLE

10.1029/2026JA035375

Special Collection:

Space Weather Events of 2024
May 9–15

Key Points:

- GLE #74 was characterized by moderately hard proton rigidity spectra with a pronounced spectral roll-off that gradually weakened
- A notable anti-Sunward component was present in the solar energetic particle (SEP) flux, suggesting complex interplanetary transport
- The reconstructed SEP spectra and anisotropy provide constraints on the acceleration and transport of SEPs

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Citation:

Mishev, A., Larsen, N., Koldobskiy, S., Hayakawa, H., Ebihara, Y., & Usoskin, I. (2026). Features of ground level enhancement (GLE #74) event on 11 May 2024. *Journal of Geophysical Research: Space Physics*, 131, e2026JA035375. <https://doi.org/10.1029/2026JA035375>

Received 20 MAR 2026

Accepted 10 OCT 2026

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Features of Ground Level Enhancement (GLE #74) Event on 11 May 2024

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Abstract Ground Level Enhancement (GLE #74) occurred on 11 May 2024 following an X5.8 solar flare from active region AR 13668 and the associated halo coronal mass ejection. The event was observed by both ground-based neutron monitors (NMs) and space-borne instruments and occurred during a deep Forbush decrease and one of the strongest geomagnetic storms of the current solar cycle, making its analysis particularly challenging. Using de-trended NM observations and explicitly accounting for storm-time variations in geomagnetic cutoff rigidity, we reconstructed the temporal evolution of the rigidity spectra and pitch-angle distributions of solar energetic particles (SEPs). The SEP rigidity spectra were moderately hard during the onset phase and exhibited a pronounced roll-off that gradually weakened as the event evolved, resulting in progressively softer spectra. The particle angular distribution revealed a significant anti-Sunward component and was best represented by a double-Gaussian pitch-angle distribution, suggesting complex interplanetary transport associated with disturbed magnetic field structures. The reconstructed SEP characteristics were in good overall agreement with GOES observations. These results provide new constraints on the acceleration and transport of high-energy SEPs during extreme space-weather events and demonstrate the robustness of NM-based SEP reconstructions under highly disturbed geomagnetic conditions.

Plain Language Summary On 11 May 2024, a powerful X5.8 solar flare and its associated coronal mass ejection accelerated charged particles to extremely high energies, producing Ground Level Enhancement (GLE #74). These particles were energetic enough to be detected by neutron monitors on the ground, providing a valuable opportunity to study the most energetic population of solar particle radiation. Such events are relatively rare and can pose radiation hazards to spacecraft, astronauts, and high-altitude aviation. The event occurred during a strong geomagnetic storm and a deep Forbush decrease, making it particularly difficult to determine the properties of the incoming solar particles. Using observations from the global neutron monitor network, we reconstructed how the energies and arrival directions of the particles evolved throughout the event. We found that the particle energy spectrum gradually softened with time, and that a significant fraction of the particles arrived from anti-Sun direction, suggesting complex transport through disturbed interplanetary magnetic fields. These results provide new insight into how high-energy solar particles are accelerated and transported through interplanetary space. They also improve our ability to characterize extreme solar radiation events and assess their potential space-weather impacts.

1. Introduction

Eruptive processes on the Sun, namely solar flares and CMEs, in some cases can accelerate charged particles, for example, ions and electrons, to relativistic energies. These accelerated particles are commonly known as solar energetic particles (SEPs) (e.g., Cliver et al., 2022; Desai & Giacalone, 2016; Klein & Dalla, 2017; Reames, 1999, and references therein). The SEP flux can be greater than that of the background galactic cosmic ray (GCR) flux and last from several hours to days (e.g., Papaioannou et al., 2016; Waterfall et al., 2023). In the majority of these events, the energy of the SEPs is in the deka-MeV/n range, in some cases up to 100 MeV/n. Rarely, about several times per solar cycle, SEPs can be accelerated to the GeV/n range (e.g., Aschwanden, 2012; Gopalswamy et al., 2016; Reames, 2017, and references therein).

SEPs with energies less than 500 MeV/n can be registered by the fleet of space-probes (e.g., Kühl et al., 2017; Kouloumvakos et al., 2024), yet some instruments are sensitive up to the relativistic energies (Bruno et al., 2018; Kress et al., 2021). In the latter case, the energy of SEPs is sufficient to induce a complicated hadron-electromagnetic-muon particle shower in the Earth's atmosphere (for details see Dorman, 2004;

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Grieder, 2011; A. Mishev & Poluianov, 2021, and references therein). The secondaries of this particle shower can reach the Earth's surface, and can eventually be registered by convenient detectors such as neutron monitors (NMs) (for details see Simpson, 2000, and references therein). Such events, observed as an increase of count rate in ground-based particle detectors, are called GLEs (see e.g., Poluianov et al., 2017; Shea & Smart, 1982; Stoker, 1995). We note, that NMs have important advantages compared to space probes at low orbits, that is, inside the magnetosphere: NM network is sensitive to the 300 MeV–GeV/n energy range (A. Mishev & Poluianov, 2021; Poluianov & Batalla, 2022) over the whole event and allows to reconstruct the anisotropy of incoming fluxes, in contrast to space probes that are constrained by their orbit over high rigidity cutoff regions (e.g., Miroshnichenko, 2015, and references therein).

GLE events occur only a few times per solar cycle, with greater probability in periods of solar maximum and its declining phase (Papaioannou et al., 2016; Shea & Smart, 2012). When occurring, they have a significant impact on space weather, particularly on the electronics of space probes and the radiation field in space and at aviation flight altitudes (e.g., Duzellier, 2005; Kudela et al., 2000; Lewis et al., 2002; Miroshnichenko, 2018; A. Mishev & Jiggins, 2019; Pulkkinen, 2007, and references therein). Another important question is the origin of SEPs, specifically the high-energy population, that is, the relativistic part (for details see the discussion in Anastasiadis et al., 2019; Cliver et al., 2022). GLEs are usually studied on a case-by-case basis, because they differ in features such as the spectral and angular distribution, as well as the interplanetary and geomagnetic conditions during their occurrence (Kocharov et al., 2023; Miroshnichenko, 2018; Papaioannou et al., 2016), the former is important for their interpretation, and the latter for their analysis. In addition, the employment of different methods and models for GLE analysis could lead to considerably different results obtained by different teams (e.g., see Bütikofer & Flückiger, 2013, and the discussion therein). Thus, applying the same reconstruction method, including the response function, geomagnetic modeling, and unfolding procedure to as many GLEs as possible, is crucial for scientific consistency.

Systematic study of GLEs is particularly important to provide the necessary basis for determining whether they represent a distinct class or a subset of a continuous distribution of SEP events and to clarify their acceleration mechanism(s) (Desai & Giacalone, 2016; Vainio et al., 2009). Herein, we present a methodological study of a particularly notable event GLE #74 on 11 May 2024, which occurred during a deep Forbush decrease (FD) and one of the strongest geomagnetic storms (for details see, Hayakawa et al., 2025, and the discussion therein).

The present paper generalizes and develops the works by Hayakawa et al. (2025) and Papaioannou et al. (2025), where a plethora of observations were collected, while only a preliminary analysis has been performed. Herein, we significantly improve the time resolution of the GLE-causing SEP spectra reported by Papaioannou et al. (2025), reduce the uncertainties in the derived SEP characteristics, and constrain the shapes of their spectral and angular distributions, which is specifically important to study the related origin and propagation of accelerated solar ions (Waterfall et al., 2022, 2023). We reveal the different populations of SEPs, and most importantly, we perform a comparison with direct space-borne records. In addition, we realistically determine the contribution of SEPs to NM count rate variation by employing a thorough geomagnetospheric and FD modeling.

The paper is organized as follows. In Section 2 we report the observations. In Section 3, we present the modeling of the global NM response, including the Geomagnetosphere, and describe the geomagnetic disturbance, specifically its relation to the challenges associated with the analysis of this event. In Section 4 we present the derived SEP spectra and angular distributions and their temporal evolution throughout the event. Finally, in Section 5 we discuss the obtained results and compare the results of NM-based analysis with direct space-based measurements.

2. GLE #74 on 11 May 2024

GLE #74 was observed on 11 May 2024, following a period of enhanced solar activity. Most of the active processes were due to NOAA Active Region 13,664 (Dikpati et al., 2025; Hayakawa et al., 2025; Razquin et al., 2025), which appeared on the south-eastern limb of the solar disk on 1 May 2024. GLE # 74 emerged in association with an X flare in AR 13668, which was magnetically linked to nearby AR 13664 (Papaioannou et al., 2025). This implied a complex eruption (Kwak et al., 2024; Papaioannou et al., 2025; Shen et al., 2012; Török et al., 2011; Wang et al., 2016), see the top panel of Figure 1 and the discussion below.

Among the said eruptions, two were responsible for the acceleration of SEPs: a major X5.8 flare on 11 May 2024, produced by active region AR 13668 with coordinates S15W55, and the related halo CME (see the bottom panels

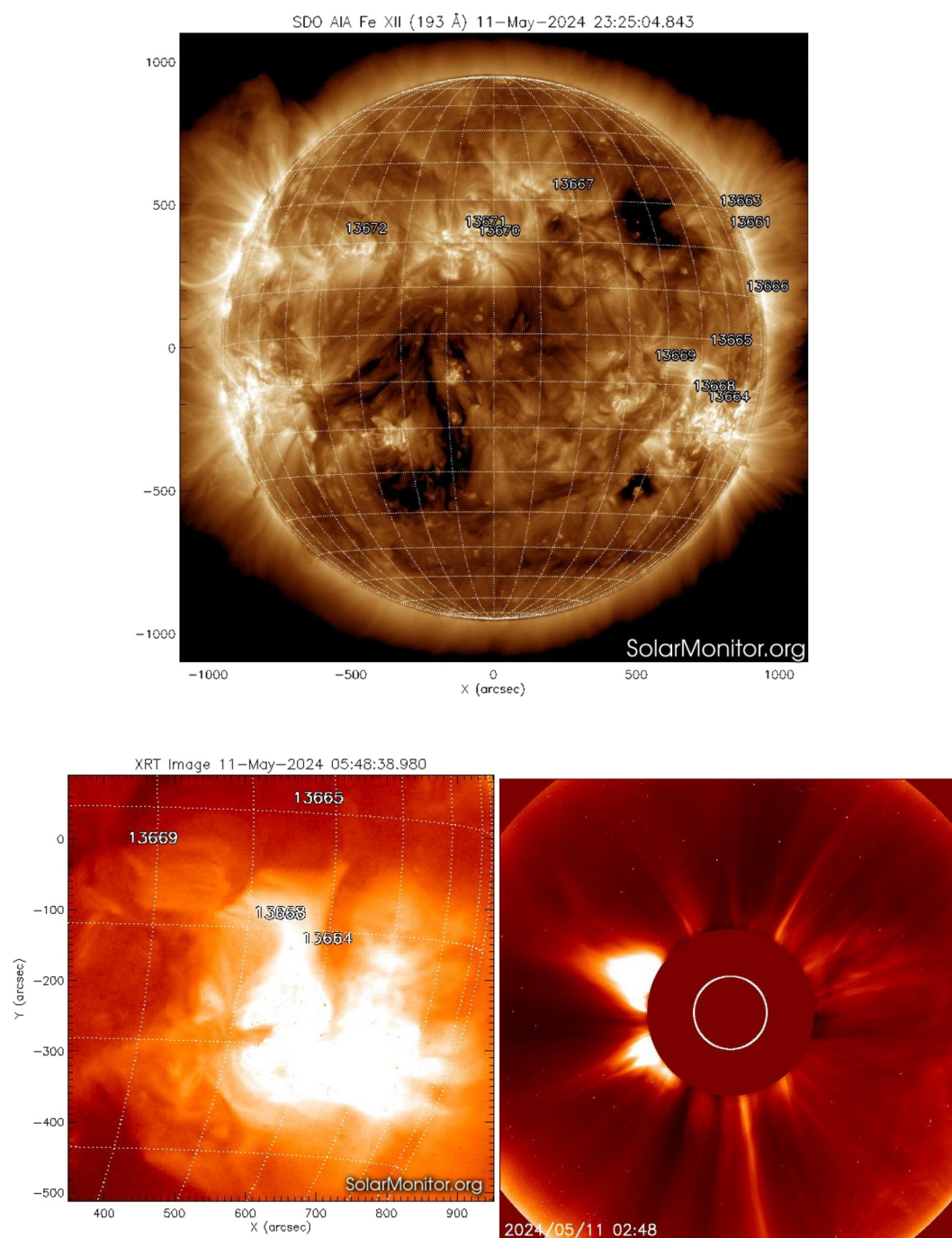


Figure 1. Top panel: The Sun as observed on 11 May 2024, by the AIA instrument onboard the Solar Dynamics Observatory (SDO). Active region AR 13664 is visible in the southwestern part of the solar disk. Left bottom panel: X5.8 solar flare from AR 13668. Right bottom panel: Halo CME as observed by L2 coronagraph of LASCO. Images retrieved from <https://solarmonitor.org/index.php?date=20240511&region=13668> and <https://soho.nascom.nasa.gov/data/Theater/>.

of Figure 1). The flare started at 01:12 UT and peaked at 01:23 UT. The halo CME had a speed of about 1,614 km/s, observed by LASCO at 01:36 UT. Accelerated SEPs have been observed by the global NM network and several space instruments, such as GOES (see the top panel of their Figure 6 in Hayakawa et al., 2025), details are given in Papaioannou et al. (2025). Therefore, the event satisfies the formal criteria for registration of a GLE (Poluianov et al., 2017), that is, particles of solar origin simultaneously registered by both ground-based and space-borne detectors, for example, NMs and space probes.

Table 1

Selected Solar Eruptions During the Period Preceding the GLE #74

Flare, UT	Class	Coordinates	CME, time [UT]	Linear speed [km/s]	Type
8 May, 04:37	X1.0	S18W17	8 May, 05:36	530	Halo
8 May, 11:26	M8.7	S20W11	8 May, 12:24	677	Halo
8 May, 21:08	X1.0	S20W17	8 May, 22:24	952	Halo
9 May, 08:45	X2.2	S20W26	9 May, 09:24	1,280	Halo
9 May, 17:23	X1.1	S14W28	9 May, 18:52	1,024	Halo
10 May, 06:27	X3.9	S17W34	10 May, 07:12	953	Halo
11 May, 01:10	X5.8	S15W45	11 May, 01:36	1,614	Halo

Note. The table includes the flare onset time, GOES soft X-ray class, coordinates, the corresponding CME launch time, its speed, and type.

Initially, we focus on the period preceding the GLE, as it determines the heliospheric conditions in which SEP propagate, and accordingly, their properties in the vicinity of the Earth and ground observations (Engelbrecht et al., 2022; Laitinen & Dalla, 2025; Mitthumsiri et al., 2025). On 8 May 2024, among the other flares, NOAA AR 13664 produced an X1.0 at 4:37 UT, M8.7 at 11:26, and X1.0 at 21:08 flares accompanied by CMEs (Hayakawa et al., 2025; Khuntia et al., 2025), details given in Table 1 (see also their Table 2 in Kwak et al., 2024). These active processes shaped the heliospheric and geomagnetospheric conditions, the former determining the propagation of accelerated solar ions (Waterfall et al., 2022), whilst the latter is particularly important for the propagation of SEPs in the geomagnetosphere and the proper modeling of the NM response (Bütikofer, 2018a).

At Earth's surface, the GLE onset was observed by the bulk of NM stations. Time profiles of count rates of selected NMs are shown in Figure 2. Herein, we present five-minute NM data stored in the International GLE Database (IGLED; <https://gle oulu.fi/>; Usoskin et al., 2020). The event revealed a typical gradual increase and notable anisotropy (see details in Section 4). For instance, during the onset and initial phase of the event, a moderate count-rate increase was recorded by sunward-looking NMs (e.g., Fort Smith and South Pole), see their Figure 2 in Papaioannou et al. (2025) and Figure 2 in Thakur and Vichare (2025). A careful study of the available NM records implies the presence of SEPs with the rigidities up to at least ~ 2 GV. We emphasize that the determination of arrival times and amplitudes of count rate increases at different NMs was rather difficult, because SEPs propagated under disturbed conditions due to the sequence of preceding CMEs, the mentioned above FD, and the severe geomagnetic storm (for details see Hayakawa et al., 2025), the latter leading to a

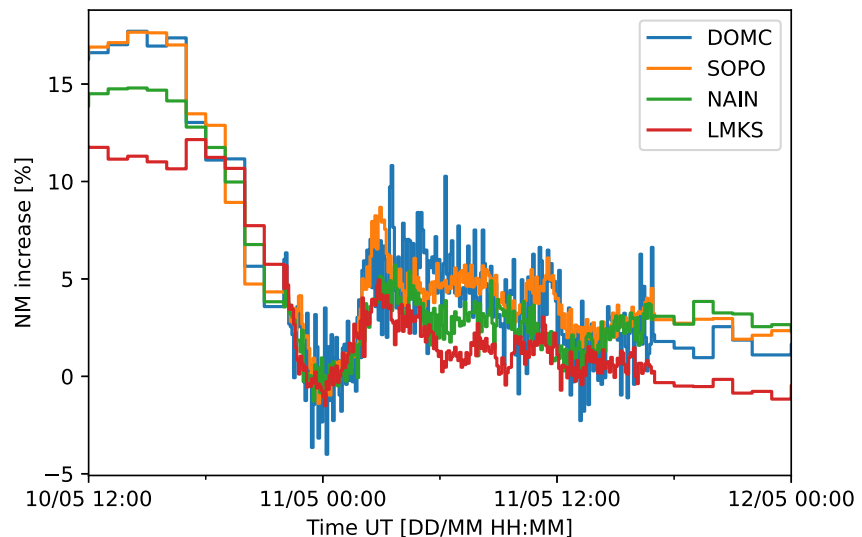


Figure 2. Relative count rate increases on May 10–11, 2024 (with respect to period 23.00–01.00 UT for DOMC, 23.30–01.30 UT for SOPO, NAIN, and LMKS). The full list of stations used for the analysis is given in Table 2, the records are available in the international GLE database <https://gle oulu.fi/>.

reduction in cutoff rigidity, specifically on mid-latitude NMs, contributing to the increase of station's count rates on top of the SEP signal, as well as challenges of NM acceptance modeling, particularly the asymptotic directions computation, see below Subsection 3.1.

Most of the stations revealed count rate increases at around 01:45 UT; however, a statistically significant (for details see Poluianov et al., 2025, and the discussion in Appendix A) and a great enough signal, which allowed us to study the SEP spectra and angular characteristics, was observed at 02:00 UT and thereafter. The strongest count rate increase was detected by high-altitude Antarctic stations, namely Dome C $\approx 10.0\%$ and South Pole $\approx 7.7\%$. We note that lead-free (bare) NMs recorded greater count rate increases, namely Dome C bare $\approx 16.0\%$ and South Pole bare $\approx 8.9\%$, because they are more sensitive to the low-energy range of the primary cosmic rays (CRs) (Vashenyuk et al., 2007). We point out that the bare NMs are not included in the analyses, because of their unknown yield function (response) (for details see A. L. Mishev et al., 2020, and the discussion therein).

3. Analysis

To reveal the characteristics of SEPs that led to the GLE on 11 May 2024, we collected available records from the global NM network and GOES satellite. Since the registered NM count rate variations are shaped by the recovery of the large FD and the reduction of the rigidity cutoff of the stations, as a first step, we deduced the actual signal due to SEPs. For this purpose, we parameterized the recovery of the FD similarly to Usoskin et al. (2020), details given in Appendix A, see Figure A1, and also accounted for the increase in the NM count rate due to the reduction in cutoff rigidity by employing the magnetospheric modeling results (Larsen & Mishev, 2025); details are given below. Hence, we can proceed further with de-trended NM count rates, that is, the count rate increase is supposed to be due only to the SEPs contribution.

The unfolding of the SEP spectra and angular distribution using ground-based records involves realistic modeling of the magnetospheric conditions and solar protons propagation, as well as the response of the NM network (Bütikofer, 2018a, 2018b). Most importantly, the magnetospheric modeling would allow us to examine the reduction of the rigidity cutoff, specifically for mid-latitude stations, where the effect is more pronounced. From this, we can properly derive the contribution of SEPs from the NM count rates.

3.1. Modeling of the Magnetospheric Conditions

GLE #74 occurred during disturbed interplanetary and geomagnetospheric conditions (De Michelis & Consonini, 2025; Hayakawa et al., 2025; Piersanti et al., 2025; Tulasi Ram et al., 2024). A CME arrival at 17:05 UT on May, 10 compressed the magnetosphere. Several satellites recorded their traverse of the magnetopause: THEMIS A and THEMIS E satellites crossed the boundary of the magnetopause at a distance of 5.37 Earth radii (hereafter R_E) and 5.08 R_E , respectively (Hayakawa et al., 2025). GOES 16 and GOES 18 crossed the boundary of the magnetopause at 6.6 R_E (6.3, 0.1, 2 R_E in the XYZ coordinates) and 6.6 R_E (3.7, 5.3, 1.4), respectively (Fu et al., 2025). ARASE satellite crossed the magnetopause at $\approx 4.96 R_E$, considered as the innermost spacecraft observation of the magnetopause ever available in the literature (Yamamoto et al., 2025). Employing global magnetohydrodynamics simulation, Tulasi Ram et al. (2024) modeled the magnetopause standoff position as 3.3 R_E , which goes beyond what the satellites measured and somewhat compares to the extreme case ($\approx 3.4 R_E$) estimated for the magnetospheric compression upon the March 1940 storm (Hayakawa et al., 2022). These results are broadly consistent with the initial estimates of Hayakawa et al. (2025) and confirm the magnetopause compression significantly beyond the geosynchronous orbit of $\approx 6.6 R_E$. This magnetospheric compression led to the sudden commencement with a magnitude up to 130 nT (Hayakawa et al., 2025; Piersanti et al., 2025).

The peak value of the provisional Dst value was initially calculated as -412 nT at the World Data Center for Geomagnetism at Kyoto (for details see Figure 12 in Hayakawa et al., 2025). For this estimate, they used solar quiet variations based on GFZ's international 5 quietest days in April instead of May, as the calculation of the provisional Dst was made exceptionally earlier than their normal routine. On 28 January 2025, the World Data Center modified the peak value of the provisional Dst index to -406 nT (Nose et al., 2015; Weiler et al., 2025), using their list of the international 5 quietest days in May, which was released later. We emphasize that, until the final Dst index is released, the Dst index is subject to change, which may slightly affect the magnetospheric modeling necessary for the analysis of the NM records. However, a considerable change in the final results is not expected (Desorgher et al., 2005; Larsen et al., 2023; Tsyganenko, 2002a) as discussed below.

The magnetospheric conditions were modeled using the recently developed OTSO (Open-source geo-magneToSphere prOpagation, <https://zenodo.org/records/19580673>) tool for the computation of CR trajectories in the geomagnetosphere (details given in Larsen et al., 2023). OTSO is based on previously developed models and formalism, namely, it employs a combination of internal magnetic field and external magnetic field. For the internal field herein, we consider the International Geomagnetic Reference Field (IGRF, Alken et al., 2021). For the external field, related to the system of magnetospheric currents, we used the storm-time variant of the Tsyganenko 01 (TSY01S) model (Tsyganenko et al., 2003), which is similar to Tsyganenko 01 (TSY01) model (Tsyganenko, 2002a, 2002b), but is parameterized using data specifically collected during geomagnetic storms. Therefore, TSY01S provides a better description of the geomagnetosphere during stormy magnetospheric conditions (Kudela & Usoskin, 2004), which was the case during GLE #74. There are several inputs for the TSY01S model: solar wind speed (v), y and z components of the interplanetary magnetic field (IMF_y and IMF_z), solar wind dynamic pressure (P_{dyn}), Dst index, G2 and G3, the latter are variables unique to TSY01S computed using geomagnetic conditions during the hour preceding the event. The data used as input parameters were taken from the OMNI database (spdf.gsfc.nasa.gov/pub/data/omni/).

The difference between pre-storm (10/05/2024 17:00 UT) and event (11/05/2024 02:00 UT) global rigidity cutoffs, computed using OTSO with the previously described input parameters, is shown in the top panel of Figure 3. The corresponding solar wind and geomagnetic input parameters are listed in Table 4, while cutoff rigidities for the NM stations analyzed in this work are compared in Table 3. At the onset of GLE #74, geomagnetic shielding was strongly suppressed, particularly at mid latitudes, where cutoff rigidity might have been decreased by 1–2 GV. In contrast, high-latitude stations exhibited only minor changes, and in a few cases, a slight increase in cutoff rigidity is seen (e.g., SOPO and MWSN). Although such increases have a negligible impact on the present analysis, as the resulting cutoff values remain well below typical atmospheric cutoff rigidities at mountain and sea level altitudes (≈ 0.65 –1 GV for protons; see for example, (Poluianov & Batalla, 2022)), these changes are nevertheless noteworthy, as they may reflect the complex magnetospheric configuration during the event, as well as potential limitations of the TSY01S model under extreme storm conditions.

The bottom panel of Figure 3 depicts the evolution of the cutoff rigidity throughout the event for three NM stations: Oulu, Kiel, and Lomnický Štít. A very significant and dynamic reduction in cutoff rigidity after the CME arrival is clearly seen. The cutoff rigidity did not recover at the time of GLE onset. Similar temporal behavior was observed for other NMs.

We emphasize that this creates notable uncertainty in the exact GLE count rate increase of mid-latitude NMs since their count rate is a superposition of many factors, namely, the changing GCR flux due to the recovery phase of the FD, possible registration of SEPs, and increased sensitivity to both GCRs and SEPs due to cutoff rigidity reduction. Accordingly, due to the complexity of estimating their SEP response, we are neglecting mid-latitude stations in the analysis as described below.

The count rate of an NM is determined not only by the rigidity cutoff, but also by its asymptotic cone, that is, the region in space from which primary charged particles must arrive in order to be detected at a given location, for example, NM station (Bütikofer, 2018a; Cooke et al., 1991; Shea & Smart, 2000). Because polar NMs usually possess narrow asymptotic cones, they provide greater angular resolution compared to mid-latitude stations (Bieber & Evenson, 1995).

Using OTSO with IGRF and TSY01s models, and the parameters from Table 4, we computed the asymptotic directions and rigidity cutoffs for all NM stations used in the analysis of the event, see Table 2. An illustration for selected NMs during the event onset (02:00 UT) and the late phase (04:00 UT) is given in Figure 4. One can see that considerably distorted cones are pronounced, for example, twists in Inuvik NM (left panel of Figure 4), which notably differ from quiet conditions (e.g., see their Figure 2 in Plainaki et al., 2009). Moreover, notable fluctuations are also present, including in the high rigidity range, for example, see Jang Bogo and South Pole cones on the left panel of Figure 4 for the event onset and Tixie Bay on the right panel of Figure 4 for the late phase, respectively. The mentioned effects play a role in NM response modeling and make the analysis rather challenging. We point out that the values in Table 4 differ from (Papaioannou et al., 2025), which was based on analysis performed soon after the event's occurrence, whilst herein we benefit from high-resolution (5-min)

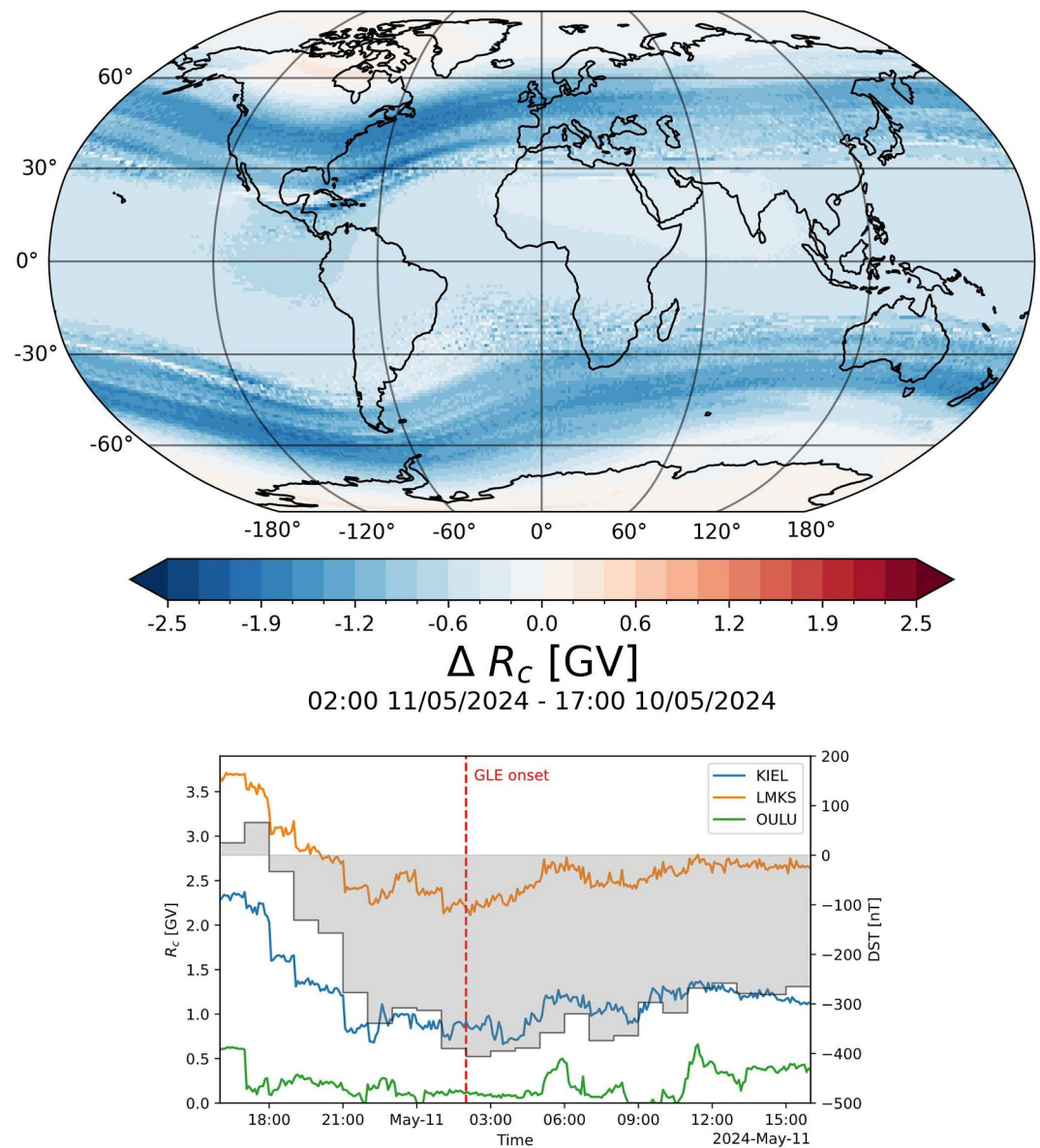


Figure 3. Top panel: Global map of the difference between pre-storm geomagnetospheric conditions before the storm commencement, and the computed rigidity cutoff during the event onset. The pre-storm and storm-time computations were done for 10/05/2024 17:00 UT and 11/05/2024 02:00 UT, respectively, using the IGRF14 and TSY01S models. Bottom panel: evolution of cutoff rigidity for three NM locations: OULU, KIEL, LMKS, before and during the GLE #74 event. The shadow area represents the variation of the Dst index.

updated OMNI data. However, according to our computations, the difference in asymptotic cones is minor (of about a degree), and does not impact the analysis.

3.2. Modeling the Global NM Response

The analysis of NM records includes modeling of the global NM response, and subsequent optimization, that is, solution of a non-linear least squares problem of modeled over the observed data points. Herein, we rely on the method by Cramp et al. (1997), further developed by Bombardieri et al. (2006) and Vashenyuk et al. (2006). The detailed description is given elsewhere (A. Mishev et al., 2024). The method allows one to derive the spectral and angular characteristics of GLE-causing SEPs, as well as the anisotropy axis direction, in total seven free parameters for this specific case, as presented in Table 5.

Table 2

List of NM Stations Used for the Analysis in This Work

Name	Acronym	NM type	Altitude (m asl)	Min. cutoff R_l (GV)	Max. Increase (%)
Alma Aty	AATY	18NM64	3,340	4.01	4.0
Apatity	APTY	18NM64	177	0.1	6.9
Baksan	BKSN	6NM64	1,700	3.7	5.3
Barentsburg	BRBG	18NM64	70	0.0	4.3
Calgary	CALG	12NM64	1,128	0.39	4.7
Castilla-La Mancha	CALM	12NM64	708	5.1	4.0
Dome C	DOMC	mini-NM	3,233	0.0	10.04
Dourbes	DRBS	9NM64	225	1.56	5.2
Fort Smith	FSMT	18NM64	180	0.16	5.2
Inuvik	INVK	18NM64	21	0.0	5.0
Irkutsk3	IRK3	6NM64	3,000	1.69	5.6
Jang Bogo	JBGO	6NM64	30	0.0	2.5
Jungfraujoeh	JUNG1	3NM64	3,475	2.77	4.5
Kiel	KIEL	18NM64	54	0.56	8.5
Lomnický Štít	LMKS	8SNM15 ^a	2,634	1.91	4.95
Moscow	MOSC	24NM64	200	0.54	5.7
Mirny	MRNY	12SNM15 ^a	30	0.0	5.2
Mawson	MWSN	18NM64	30	0.1	6.4
Mexico City	MXCO	6NM64	2,274	6.32	3.5
Nain	NAIN	18NM64	46	0.22	5.2
Newark	NEWK	9NM64	50	0.81	3.5
Norilsk	NRLK	18NM64	0	0.01	3.6
Novosibirsk	NVBK	24NM64	163	0.78	5.9
Oulu	OULU	9NM64	15	0.01	5.8
Princess Sirindhorn	PSNM	18NM64	2,560	16.25	1.8
Peawanuck	PWNK	18NM64	53	0.28	5.1
Rome	ROME	17NM64	60	4.38	4.6
SANAE IV	SNAE	6NM64	856	0.2	5.5
South Pole	SOPO	3NM64	2,820	0.0	7.7
Terre Adelie	TERA	9NM64	30	0.0	2.6
Thule	THUL	18NM64	26	0.0	6.3
Tixie Bay	TXBY	18NM64	0	0.0	5.5
Yakutsk	YKTS	18NM64	105	0.35	4.3

Note. The NM64 is the standard supermonitor described by Carmichael (1968). The recently introduced mini-NM was described in Strauss et al. (2020). The NM records are taken from the International GLE database. The station elevation is given in meters above sea level (m asl). The lower geomagnetic rigidity cutoff R_l is computed specifically for the GLE occurrence period with the OTSO tool (Larsen et al., 2023), employing a combination of IGRF (Alken et al., 2021) and Tsyganenko 01S models (Tsyganenko et al., 2003). Maximal count rate increase for 5-min intervals is given in the last column. ^aSNM 15 is the Russian counterpart of B-28 detector used in NM64 design.

The method involves computing the magnetic cutoff rigidities and asymptotic directions of the NM stations used in the analysis and optimizing the difference between the modeled and experimental NM records. We emphasize that during the analysis, it is necessary to replicate the count rate increases of all stations with statistically significant responses, as well as stations with marginal or zero responses (Cramp et al., 1997; A. Mishev et al., 2024).

Table 3
Computed Effective Geomagnetic Cutoffs (GV)

Station	17:00 10/05/2024	02:00 11/05/2024
AATA	5.93	4.98
APTY	0.34	0.12
BKSN	5.49	4.47
BRBG	0.12	0.06
CALG	1.17	0.46
CALM	7.07	5.82
DOMC	0.00	0.00
DRBS	3.39	1.86
FSMT	0.33	0.43
INVK	0.11	0.00
JRKT	3.03	1.79
JBGO	0.00	0.00
JUNG	4.47	3.38
KIEL	2.33	0.95
LMKS	3.70	2.19
MOSC	2.18	0.91
MRNY	0.14	0.02
MWSN	0.00	0.12
MXCO	7.46	6.80
NAIN	0.58	0.27
NEWK	2.79	1.05
NRLK	0.22	0.10
NVBK	2.35	1.17
OULU	0.60	0.12
PSNM	16.69	16.27
PTFM	7.08	6.07
PWNK	0.51	0.34
ROME	6.14	5.08
SNAE	0.69	0.22
SOPO	0.00	0.17
TERA	0.07	0.00
THUL	0.00	0.00
TXBY	0.12	0.00
YKTK	1.35	0.80

The NMs with null or marginal responses are used to constrain the SEP flux, specifically the hardness of the spectra, and are also important to determine the boundary conditions of the angular distribution of incoming SEPs.

Using the results from the magnetospheric modeling, see for details Figure 3 and fifth column of Table 2, we computed the expected count rate variation of NMs during the GLE #74 due to the reduction of the rigidity cutoff. Herein, we employed the parametrization of the GCR spectrum by Vos and Potgieter (2015) within the force-field model (Usoskin et al., 2017).

Additionally, we parameterized the recovery of the FD. In general, the recovery can be expressed as an exponent in time. The recovery is modeled using the recovery time (τ) and peak magnitude (M) (Lockwood et al., 1986; Webber, 1962) as parameters. The method employed here is described by Usoskin et al. (2008) (see also their

Table 4
Solar Wind and Geomagnetic Parameters

Parameter	17:00 10/05/2024	02:00 11/05/2024	04:00 11/05/2024
V [km/s]	447.4	738	692.9
B_y [nT]	2.25	−0.8	−22.59
B_z [nT]	−0.22	−20.5	−30.4
P_{dyn} [nPa]	5.96	48.76	6.03
Dst [nT]	25	−390	−395.0
G2	0.04	75.64	99.56
G3	0.73	290.48	1,494.7

Section 6 in Larsen & Mishev, (2025), details are given in Appendix A. Thus, we de-trended NM count rates from the FD and magnetospheric effects, which would be fitted with modeled NM count rate increases. Therefore, we can model the NM count rate increase using only the SEP contribution.

The modeled relative count rate increase of a specified NM during a GLE is given by:

$$\frac{\Delta N}{N}(R_{\text{cut}}, t) = \frac{\int_{R_{\text{cut}}}^{R_{\text{max}}} J_{\text{SEP}}(R, t) \cdot S(R) \cdot G(\alpha(R, t)) \cdot A(R) dR}{\sum_i \int_{R_{\text{cut}}}^{\infty} J_{\text{GCR}_i}(R, t) \cdot S_i(R) dR} \quad (1)$$

where $\Delta N(t)$ is the count rate increase produced by the incoming SEPs with spectra J_{SEP} over the background $N(t)$ due to GCRs. Accordingly, $J_{\text{GCR}_i}(R, t)$ is the rigidity spectrum of the i component (proton or α -particle, etc...) of GCRs at time t , herein modeled employing the force-field model (Usoskin et al., 2005), considering the local interstellar spectrum by Vos and Potgieter (2015) and modulation potentials by Usoskin et al. (2011), estimated as 812 MV for May 2024 (https://cosmicrays.oulu.fi/phi/Phi_Table_2017.txt). $G(\alpha(R, t))$ accounts for the pitch angle distribution (PAD) of incoming SEPs, while GCRs are assumed to be isotropic outside of the geomagnetosphere. Study of possible anisotropy of GCRs during the FD is out of the scope of this work, however, its possible impact on the global fitting procedure would not be crucial, see the discussion below of the specifics of the unfolding procedure. $A(R)$ is a step-function with $A(R) = 1$ for allowed trajectories and $A(R) = 0$ for forbidden

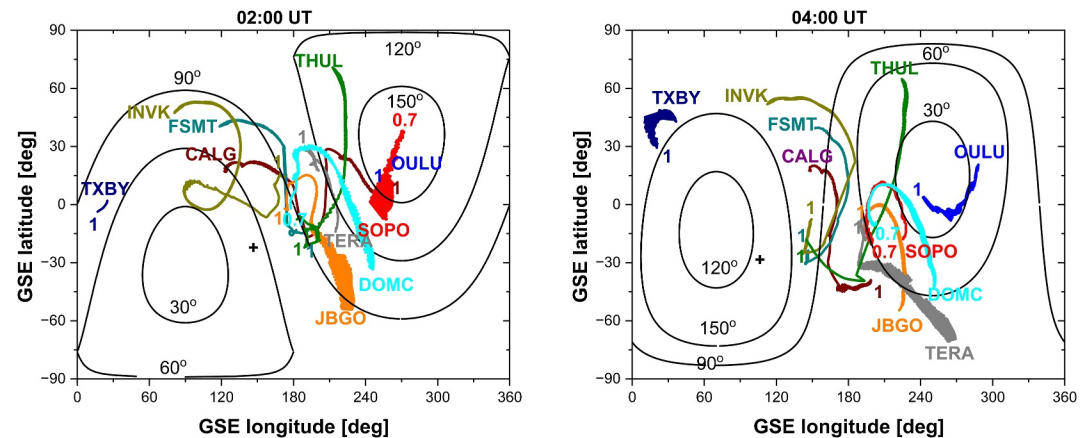


Figure 4. Computed asymptotic directions for selected NM stations during the GLE #74 onset (left panel) and late phase (right panel) on 11 May 2024. The standard abbreviations, the corresponding color lines, and numbers indicate the NM stations and their asymptotic directions, which are plotted in the rigidity range 1–5 GV, while DOMC and SOPO are plotted in the rigidity range 0.7–5 GV. The cross corresponds to the interplanetary magnetic field direction obtained by the Advanced Composition Explorer (ACE, Smith et al., 1998) space-probe. The lines of equal pitch angles relative to the derived anisotropy axis are plotted for 30°, 60° and 90° for sunward directions, and 150°, and 120°, for anti-Sun direction.

Table 5
5-min Spectra and Angular Distribution During GLE #74 on 11 May

Integration interval UT	j_0 [m ⁻² s ⁻¹ sr ⁻¹ GV ⁻¹]	γ	$\delta\gamma$	σ_1^2 [rad ²]	B	σ_2^2 [rad ²]	Ψ [degrees]	Λ [degrees]	$\mathcal{D}$ (%)
02:00–02:05	73,100	4.95	1.3	3.2	0.45	2.5	−15	−125	12.0
02:05–02:10	75,400	5.0	1.25	3.2	0.48	2.5	−18	−108	11.0
02:10–02:15	78,200	5.1	1.2	3.3	0.51	2.6	−22	−85	10.0
02:15–02:20	81,000	5.1	1.15	3.4	0.53	2.6	−10	−77	11.0
02:20–02:25	84,000	5.3	1.1	3.5	0.55	2.7	−5	−61	9.0
02:25–02:30	86,500	5.4	1.1	3.5	0.57	2.7	4	−58	10.0
02:30–02:35	89,700	5.5	0.95	3.6	0.55	2.8	15	−45	8.0
02:35–02:40	91,000	5.5	0.93	3.6	0.54	2.9	12	−51	8.0
02:40–02:45	93,200	5.52	0.91	3.7	0.56	3.0	8	−42	9.0
02:45–02:50	95,000	5.53	0.9	3.9	0.55	3.1	7	−41	10.0
02:50–02:55	96,300	5.55	0.9	4.0	0.56	3.1	−5	−35	9.0
02:55–03:00	97,400	5.55	0.88	4.1	0.55	3.2	−10	−49	10.0
03:00–03:05	98,500	5.57	0.85	4.2	0.57	3.3	−12	−38	10.0
03:05–03:10	99,700	5.6	0.83	4.2	0.55	3.3	−14	−35	9.0
03:10–03:15	101,000	5.63	0.8	4.2	0.51	3.3	−17	−31	10.0
03:15–03:20	102,300	5.65	0.77	4.3	0.51	3.4	−18	−30	10.0
03:20–03:25	103,000	5.65	0.75	4.3	0.48	3.4	−12	−31	9.0
03:25–03:30	104,200	5.67	0.74	4.4	0.45	3.5	−21	−35	9.2
03:30–03:35	104,700	5.7	0.72	4.4	0.44	3.5	−15	−40	9.0
03:35–03:40	105,200	5.7	0.7	4.5	0.42	3.5	−19	−57	8.7
03:40–03:45	101,200	5.72	0.68	4.6	0.41	3.6	−22	−39	9.0
03:45–03:50	97,200	5.74	0.68	4.6	0.42	3.7	−19	−12	10.0
03:50–03:55	94,800	5.82	0.65	4.7	0.39	3.8	−17	−5	11.0
03:55–04:00	87,000	5.85	0.65	4.7	0.40	3.8	−10	7	12.0
04:00–04:05	80,500	5.9	0.65	4.7	0.38	3.9	−7	10	12.0
04:05–04:10	80,100	5.9	0.63	4.9	0.39	4.1	−12	27	13.0
04:10–04:15	79,900	5.9	0.6	5.0	0.40	4.3	−10	35	11.0
04:15–04:20	79,400	5.95	0.57	5.2	0.42	4.4	−5	49	10.0
04:20–04:25	78,200	6.0	0.55	5.4	0.41	4.5	−14	59	11.0
04:25–04:30	77,100	6.0	0.51	5.5	0.40	4.7	−13	73	12.0
04:30–04:35	76,400	6.1	0.44	5.8	0.41	5.0	−22	95	13.0
04:35–04:40	75,500	6.1	0.4	6.0	0.38	5.3	−25	115	11.0
04:40–04:45	75,100	6.2	0.4	6.1	0.39	5.4	−21	120	12.0
04:45–04:50	74,900	6.2	0.38	6.1	0.40	5.5	−27	125	13.0
04:50–04:55	74,200	6.2	0.35	6.3	0.41	5.7	−30	135	12.0
04:55–05:00	73,800	6.3	0.33	6.4	0.42	5.8	−33	141	12.0
05:00–05:05	73,200	6.3	0.3	6.5	0.45	6.1	−37	151	12.0

Note. The best fit is achieved using a modified power-law rigidity spectrum (Equation 2) and double Gaussian PAD (Equation 4). The last column denotes values of the merit function (Equation 5).

trajectories (Bütikofer, 2018a; Cooke et al., 1991). The function A is derived during the asymptotic direction computations. In Equation 1, R_{cut} is the lower rigidity cutoff of the station and R_{max} is the maximum rigidity of SEPs considered in the model, in this case 20 GV, whilst for GCR $R_{\text{max}} = \infty$. S is a NM yield function (for details

see S. A. Koldobskiy et al., 2019; A. L. Mishev et al., 2020), verified using direct space-borne records by PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics, Adriani et al., 2017) and AMS-02 (Alpha Magnetic Spectrometer, Aguilar et al., 2021), and with good agreement with latitude and altitude survey(s) (for details see Lara et al., 2016; Nuntiyakul et al., 2018). We note that for polar sea-level stations, the integration is over 1 GV, which represents the atmospheric cutoff (Miroshnichenko, 2015; Poluianov & Batalla, 2022), except Dome C and South Pole with $R_{\text{cut}} = 0.7$ GV, because they are high-altitude polar stations with reduced atmospheric attenuation compared to sea level (Poluianov & Batalla, 2022). For all other stations, the integration is above the lower rigidity cutoff as given in Table 2. In addition, the response of Dome C mini NM is scaled following Lara et al. (2016).

4. Results

Using de-trended records from NMs stored in the International GLE database (<http://gle.oulu.fi>, the details given in Usoskin et al., 2020) and accounting for the reduction of the rigidity cutoff, by employing the method described in Section 3.2, we derived the spectra and angular distribution of SEPs during the event under study. The full list of the NM stations with the standard acronyms and location, altitude a.s.l., rigidity cutoff and type of detector is given in Table 2.

The best fit of the SEP spectra with $P > 1$ GV was described by a modified power-law:

$$j_{\parallel}(R) = j_0 R^{-(\gamma + \delta\gamma(R-1))} \quad (2)$$

where $j_{\parallel}$ is the differential particle intensity with rigidity R in GV along the axis of symmetry identified by geographic latitude Ψ and longitude Λ , and the power-law exponent is γ with the steepening $\delta\gamma$. At $R \leq 1$ GV, the rigidity spectrum of SEPs is approximated with:

$$j_{\parallel}(R) = j_0 R^{-(\gamma + \delta\gamma \cdot R)} \quad (3)$$

The PAD was approximated with a double Gaussian:

$$G(\alpha) \propto \exp(-\alpha^2/\sigma_1^2) + B \cdot \exp(-(\alpha - \pi)^2/\sigma_2^2), \quad (4)$$

where α is the pitch angle between the axis of symmetry of the particle distribution and the asymptotic viewing direction at rigidity R , associated with the arrival direction (Bombardieri et al., 2008; Cramp et al., 1997) and σ_1 is a parameter determining the PAD width. The terms B and σ_2 account for the normalization and PAD width for particles arriving from the anti-Sun direction.

The quality of the fit is quantified via the merit function, which represents a normalized residual, that is, the normalized square root of the sum of squared relative differences between the observed and modeled increases for each NM station, where m is the number of the NM stations (Dennis & Schnabel, 1996; Himmelblau, 1972):

$$D = \frac{\sqrt{\sum_{i=1}^m \left[\left(\frac{\Delta N_i}{N_i} \right)_{\text{mod.}} - \left(\frac{\Delta N_i}{N_i} \right)_{\text{meas.}} \right]^2}}{\sum_{i=1}^m \left(\frac{\Delta N_i}{N_i} \right)_{\text{meas.}}} \quad (5)$$

One can see that the merit function D is similar to the relative root mean square error (RMSE). It is more appropriate when observed values are variable in amplitude and when the fractional accuracy, which is one of the additional fit criteria, is important (e.g., see A. Mishev et al., 2024, and the discussion therein). We also employ additional criteria that determine the quality of the fit, namely an uniform distribution of D , and aiming for the relative difference between the observed and calculated NM increases to be not more than 10%–15% for each NM with statistically significant count rate increase.

For strong events, a satisfactory fit is achieved when the value of $D \leq 5\%$, however for weak events and/or events with a complicated angular distribution the merit function can be $\approx 10\text{--}15\%$, or even 20% in some cases (A. Mishev et al., 2018; Poluianov et al., 2024; Vashenyuk et al., 2006). We wish to emphasize that the

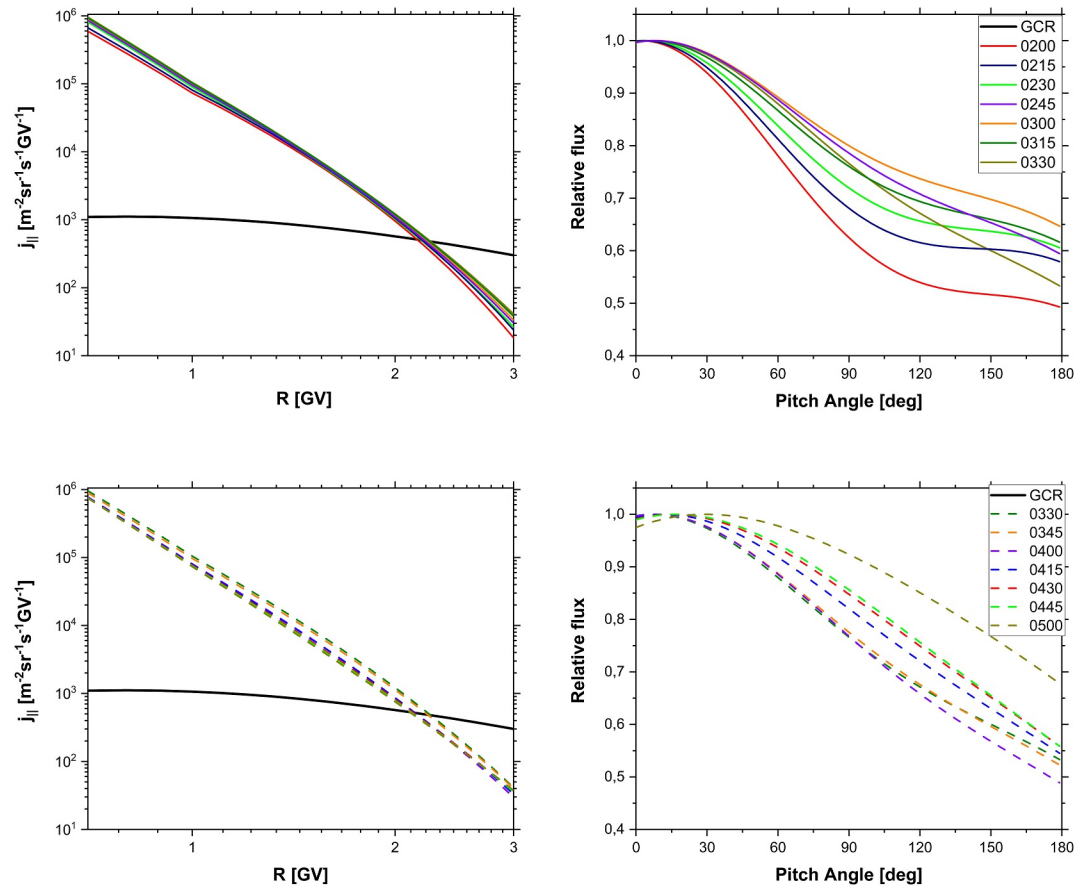


Figure 5. Reconstructed rigidity spectra (left panels) and PADs (right panels) of SEPs during different stages of GLE #74. The top panels correspond to the prompt component, whilst the bottom panels depict the delayed component.

combination (Aleksandrov, 1971; A. Mishev et al., 2005) of Levenberg-Marquardt algorithm (Levenberg, 1944; Marquardt, 1963) and ridge regression (Golub et al., 1999; Johansen, 1997; Leonov & Yagola, 1998; Tikhonov et al., 1995) employed in this study allows one to unfold the SEP spectra in a case of weak, highly fluctuated NM count rate increases (Engl et al., 1996; Golub & Van Loan, 1980; Poluianov et al., 2024, 2025; Yagola et al., 2002). Moreover, the variable regularization, that is, the employment of a variable damping parameter(s), allows us to have an adaptive control of the fitting procedure, eventually avoiding degeneracy (Yagola et al., 2002).

An illustration of the derived spectra and PAD throughout the event is given in Figure 5, the details are given in Table 5. The derived SEP spectra revealed moderate hardness. The spectral indices γ range from about 5 to about 6.3. The prompt component (PC) revealed harder spectra compared to the delayed component (DC), with spectral indices γ ranging from 4.95 at the event onset (02:00 UT) to ≈ 5.7 (03:30 UT). A notable steepening of the SEP spectra $\delta\gamma$, that is, a roll-off, was revealed, specifically during the initial (hard SEP spectra, gradually rising flux) and main phase of the event (moderately hard spectra, maximal flux). The steepening $\delta\gamma$ was 1.3 at the event onset, and constantly diminished to about 0.7.

The DC is characterized by softer spectra, with spectral indices γ ranging from 5.7 (03:30 UT) to 6.3 (03:30 UT). Therefore, the softening of the spectra of the DC is of the same range, yet the steepening is less pronounced, revealing $\delta\gamma$ ranging from about 0.7 (03:30 UT) to 0.3 (at 05:00 UT). In summary, the SEP spectra gradually softened throughout the event with notable roll-off, which persisted throughout the whole event, even in the late phase (soft spectra, gradually diminishing flux).

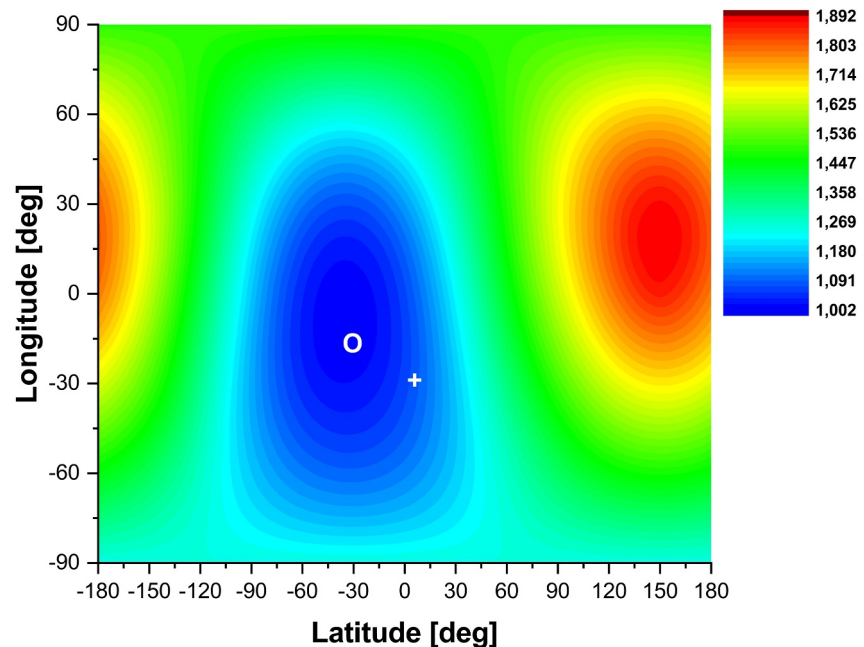


Figure 6. Contour plot of normalized to minimum D (see Table 5) for the best-fit solution as a function of the geographical coordinates of the apparent source position during GLE #74 at 03:00 UT. The small white oval corresponds to the derived apparent source position, while the white cross corresponds to the observed IMF direction based on ACE space probe measurements (Smith et al., 1998).

The major fraction of SEPs arrived from nearly the Sun's direction. However, a significant anti-Sun SEP flux was also revealed. The initial phase of the event, that is, the PC, was characterized by a moderate anisotropy with a distribution widths σ_1^2 and σ_2^2 of about π . Moreover, the width of the distribution gradually increased but remained of the same order. In contrast, the DC was characterized by a wider angular distribution, with σ_1^2 and σ_2^2 of about 2π . The features of the derived angular distribution explain the observed count rate increase of anti-Sun NMs, for example, Oulu and Thule.

We note that an inaccurate determination of the apparent source position would result in inaccurately derived SEP spectra and PADs (Bütikofer & Flückiger, 2015). Therefore, we performed a forward modeling over all possible apparent source positions and constructed the contour plot of the sum of variances for the best-fit solutions versus geographic coordinates, similarly to Cramp et al. (1997). An example using the SEP spectra and angular distribution reconstructions at 03:00 UT is presented in Figure 6. One can see that the forward modeling results agree well with the derived solutions; therefore, the model reasonably describes the experimental records. We emphasize that the apparent source position in Figure 6 does not coincide exactly with the minimum D , because during the analysis we also employed additional fit quality criteria as discussed in A. Mishev, Koldobskiy, Usoskin, et al. (2021); A. Mishev et al. (2024). The slight offset from the global minimum of D is within the uncertainty of the inversion, see the last column of Table 5.

We point out that the double regularization and the forward modeling ensure uniqueness and stability of the solution, that is, avoiding degeneracy. Therefore, the final fit is robust, allowing us explicitly to reduce the uncertainties of the derived GLE #74 features, compared to Papaioannou et al. (2025). The estimated precision of spectral reconstruction(s) is in the order of about 20–25%, which is slightly greater than certain previously studied moderately strong events (e.g., see A. Mishev et al., 2018, 2024, and the discussion therein), but reasonable, considering the more complicated analysis.

5. Discussion and Conclusion

Herein, we derived the spectral and angular characteristics of GLE-inducing SEPs during a strong event GLE #74 observed on 11 May 2024. The event occurred during highly disturbed interplanetary and magnetospheric

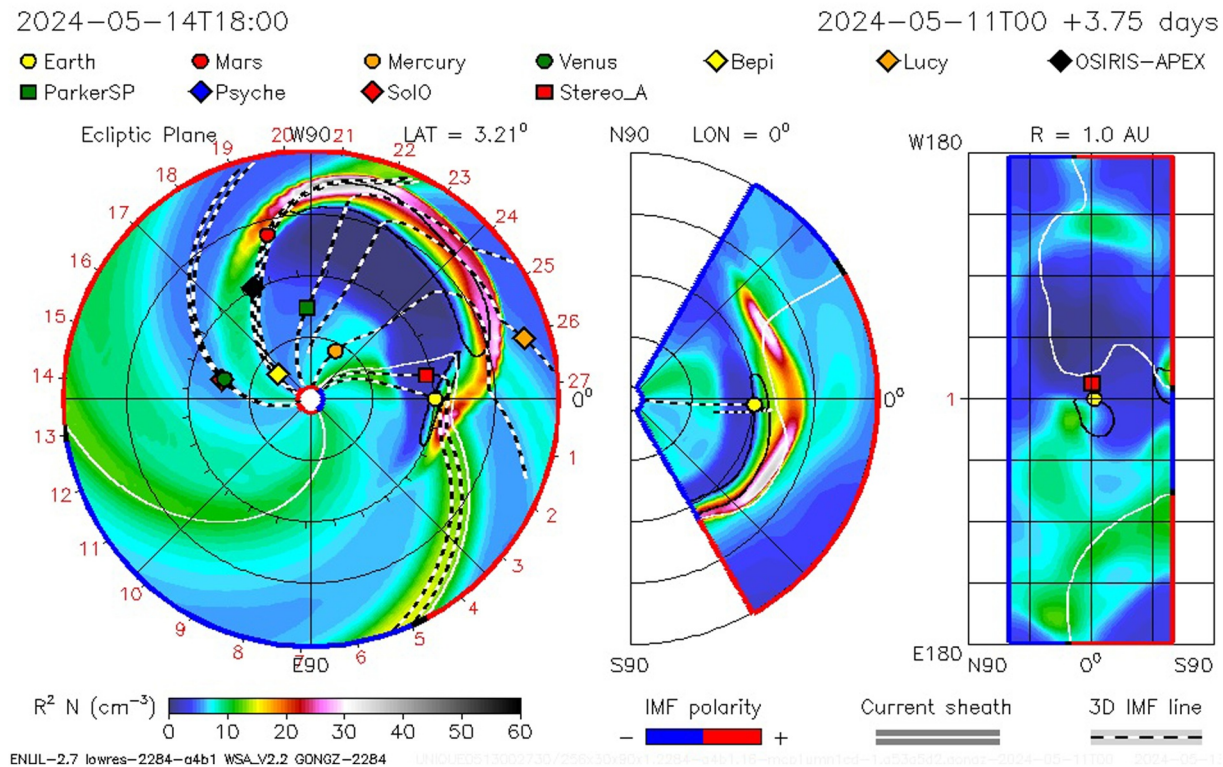


Figure 7. Radial solar wind velocity contour plots shown in the ecliptic (left panel), meridional (middle panel), and radial (right panel) planes for 11 May 2024 at 00:00 UT (source: <https://ccmc.gsfc.nasa.gov/>). The magnetic cloud beyond the Earth's orbit is clearly seen.

conditions, the negative Dst excursion of -406 nT and the magnetopause compression down to $\leq 4.96 R_E$ (Nose et al., 2015; Yamamoto et al., 2025). Their combination makes the analysis of this event particularly challenging, that is, to derive properly the contribution of SEPs to the NM count rate increase on one hand, and model the geomagnetospheric conditions on the other hand. Employing a state-of-the-art method for analysis and a new calibrated NM yield function for modeling detector responses, explicitly considering the disturbed geomagnetosphere, we derived the spectra of SEPs with a 5-min time resolution, which is reasonable considering the observed fluctuations in the NM count rate variation.

We examined several functional shapes of the spectra and PAD. The best fit was achieved with a modified power-law in the spectrum and a double-Gaussian as the angular distribution. We note that a satisfactory fit of the PAD was obtained with a single-Gaussian distribution. However, we favored the double-Gaussian, because it more accurately reproduces the count rate variation of anti-Sun looking NMs, see Figure 4. In addition, the presence of a complicated magnetic structure beyond the Earth obtained with ENLIL simulations (Odstrčil, 2003; Odstrčil et al., 2004), details given in Figure 7 (see also their Figure 5 in Kwak et al., 2024), implies complicated interplanetary transport as suggested by Ruffolo et al. (2006), giving a plausible explanation for anti-Sun arriving SEPs. We emphasize that analyses employing exponential or Ellison–Ramaty spectral fits do not satisfactorily reproduce the global NM response.

We compared our reconstructions with in situ measurements by GOES satellite. In detail, we used the data from the Solar and Galactic Proton Sensor (SGPS) detector (Kress et al., 2021) of GOES-16 satellite. SGPS detectors are significantly upgraded in terms of energy resolution and background level in comparison to Energetic Particle Sensor (EPS) detectors, which were used prior to GOES-16. We applied the method of SEP identification and integral flux calculation similar to Raukunen et al. (2022). We also computed the time-integrated fluence of particles throughout the event following the methodology of S. Koldobskiy et al. (2021). Figure 8 presents the results of these computations. Overall, there is a good agreement between GOES SGPS measurements and NM

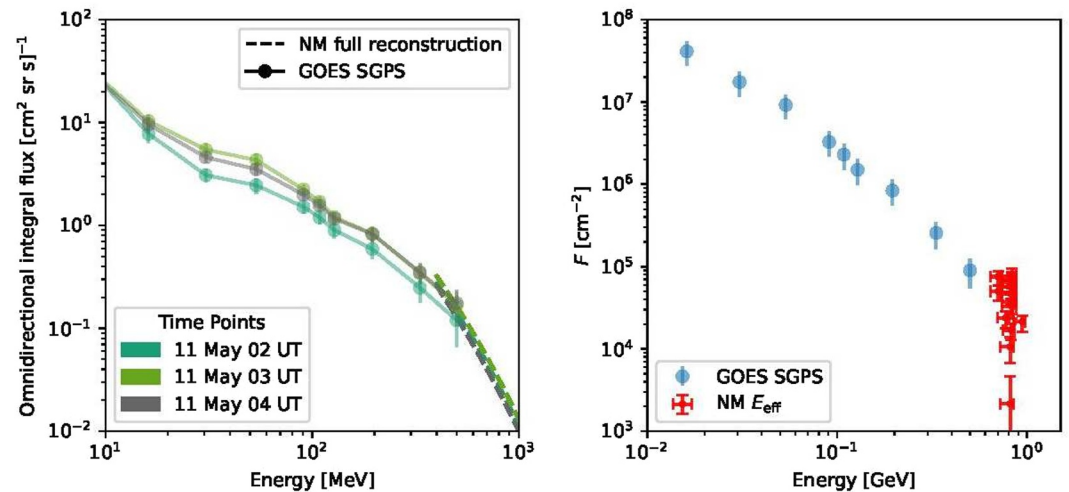


Figure 8. Left: Omnidirectional SEP flux as reconstructed by SGPS GOES and NM full analysis in 1-hr intervals. Right: SEP integrated fluence on 11 May 2024 as reconstructed from GOES SGPS detector and NMs. SGPS markers are the average of the westward- and eastward-looking detectors' measurements. The additional scaling of $1/(2\pi)$ is applied to NM full analysis data for both plots similarly to our previous studies (A. Mishev, Koldobskiy, Kocharov, & Usoskin, 2021; A. Mishev, Koldobskiy, Usoskin, et al., 2021).

reconstructions. We emphasize that despite the stormy conditions, the operation of the GOES satellite was nominal, see <https://www.ospo.noaa.gov/operations/goes/status.html>.

According to our analysis, the GLE-producing SEPs revealed moderately hard rigidity spectra ($\gamma \approx 5$) during the event initial phase with a significant steepening $\delta\gamma \approx 1.3$. The roll-off of the SEP spectra gradually decreased throughout the later phases of the event, but remained notable. Accordingly, the SEP spectra gradually softened during the event. We emphasize that because of the large fluctuations of the NM count rate variations, and the dynamic geomagnetospheric conditions, the uncertainties of the derived characteristics were larger than those for the previous weak GLE #72, namely of the order of 20–30%. In addition, a non-conservative approach, that is assuming a non-zero response of mid-latitude NM stations, would lead to a slightly harder SEP spectra, yet would not alter the whole picture.

We note, that the derived apparent source direction of SEPs during the event appears relatively close to the observed IMF direction, specifically in latitude, for example, see the upper panel of Figure 9. The difference between the arrival direction and the observed IMF in longitude could be explained as a result of the complicated angular distribution, that is, Sun-anti-Sun SEP flux, and the possible diffusion of high-energy SEP particles during their propagation in the interplanetary space, as discussed above.

Figure 10 shows the SEP intensity throughout the event, plotted together with the count rate variations of South Pole NM and the steepening of the spectra $\delta\gamma$. We note that according to Vashenyuk et al. (2009) and Klein and Dalla (2017) some GLEs exhibit a two-component time profile, with the so-called PC revealing a fast rise and characterized by an anisotropic particle distribution, and the DC revealing gradual behavior and usually less anisotropic. There are indications that the presence of the PC could be associated with particles accelerated in the flare (Aschwanden, 2012; Kocharov et al., 2023; McCracken et al., 2012, 2023; Vashenyuk et al., 2011).

Herein, one can speculate that we observe both PC and DC as shown in Figure 10. The PC is related to the initial rising of the South Pole NM. It revealed a notable roll-off of the SEP spectra $\delta\gamma$ of about 0.8–1.3. Pure flare acceleration mechanism (Benz, 2017; Klein & Trottet, 2001; Toriumi & Wang, 2019) should be ruled out, because the observation of a radio type II burst, which is a signature of a shock acceleration (Papaioannou et al., 2025). We emphasize that the discussed PC/DC paradigm for this specific event is speculative, and more detailed modeling of the interplanetary acceleration and transport is necessary, which is beyond the scope of this work.

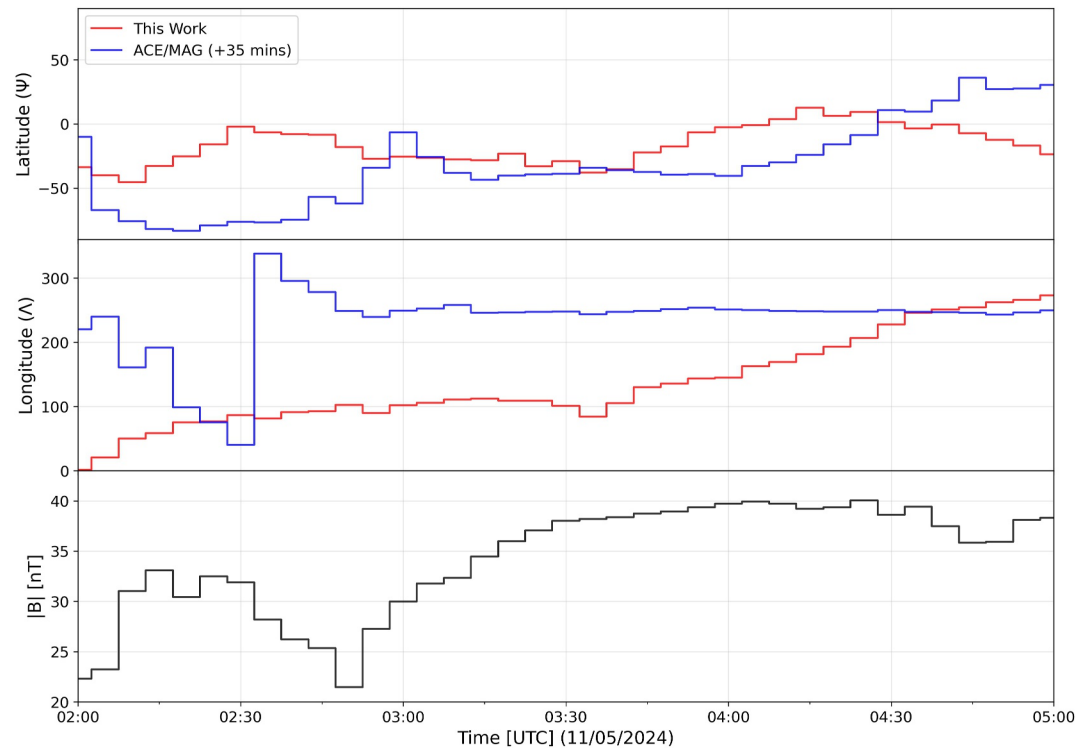


Figure 9. Latitude and longitude of IMF in GSE coordinates from ACE satellite measurements (blue line) and the derived coordinates of the apparent source position (red dots) for GLE #74. The interplanetary magnetic field data are corrected for the transit time between the L1 location and the Earth, considering the measured solar wind speed.

The features, including their constraints, of SEPs-producing GLE #74 derived in this study give a good basis to investigate the mechanism of their acceleration and propagation (Klein et al., 2014, 2022; Waterfall et al., 2022) as well as to assess specific space weather effects for example, exposure to radiation, which require good resolution reconstructions.

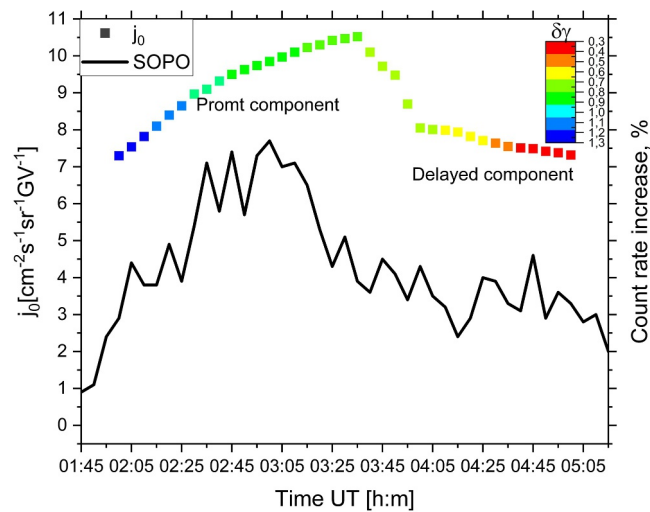


Figure 10. Evolution of SEP flux j_0 and spectral slope steepening $\delta\gamma$ for the prompt (PC) and delayed (DC) components as denoted in the color map (see Equations 2, 3 and Table 5), versus the count rate variation of SOPO (black line) during GLE #74.

Appendix A: Detrending of the NM Response

Since the GLE occurred on the background of the recovery phase after a Forbus decrease, the NM data need to be detrended to account for that. The detrending procedure was similar to that described in detail elsewhere (Usoskin et al., 2020). As the trend, we considered a second-order polynomial fitted to the period around the event, viz, two hours before (10-May-2024 23:00 through 11-May-2024 01:00) and 8 hr after (11-May-2024 16:00 through 24:00). This is illustrated in Figure A1 Appendix A (upper panel) for the Oulu NM. The detrended signal (lower panel) was used for the analysis. This was done for each NM separately. Both recorded and detrended data sets are available at <https://gle oulu.fi>.

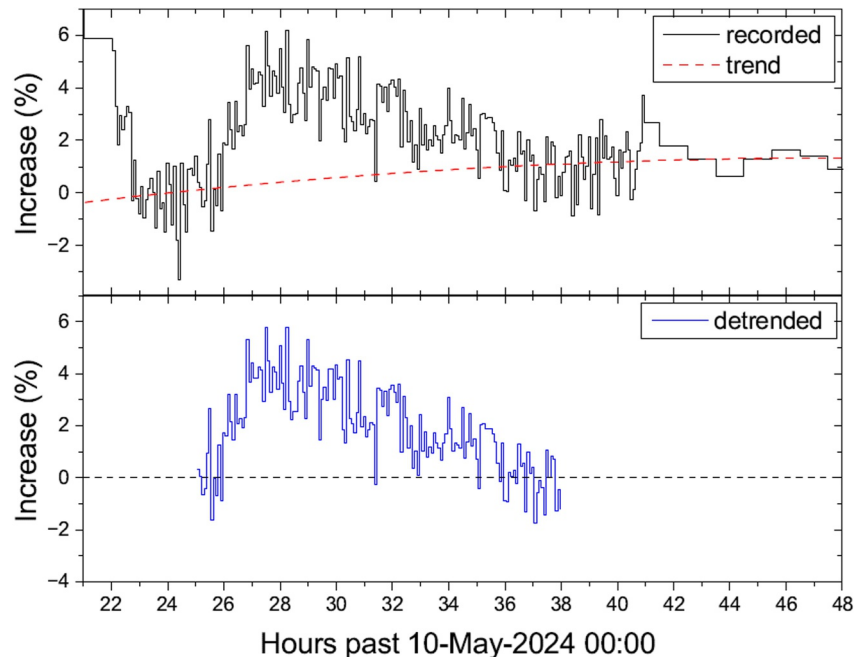


Figure A1. Example of the detrending of the GLE time profile for the Oulu NM data set. The black curve on the upper panel depicts the original recorded signal relative to the pre-increase count rate. The red dashed curve is the best-fit second-order polynomial background trend. The detrended increase is shown in the lower panel as the blue curve. Data are available at <https://gle oulu.fi>.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

Neutron monitor records used for the analysis of this event are publicly available from the International GLE database: <https://gle oulu.fi/>. The OTSO tool for computations of the rigidity cutoffs and asymptotic cones of the NMs is open-access and freely available from: <https://zenodo.org/records/19580673> (Larsen et al., 2023). The optimization was performed employing the MINPACK libraries: <https://www.netlib.org/minpack/> (More et al., 1980). The input parameters for the magnetospheric computations were retrieved from the OMNI database: spdf.gsfc.nasa.gov/pub/data/omni/.

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Acknowledgments

This work was supported by the Research Council of Finland (project 354280), European Research Council Synergy Grant (project 101166910), Horizon Europe Program Projects ALBATROS (GA 101077071) and SPEARHEAD (GA 101135044), and Space Resilience Finnish Centre of Excellence Project (374100). We acknowledge the support of the International Space Science Institute (Bern, Switzerland) ISSI team No. 585 (REASSESS). This work was partially supported by the National Science Fund of Bulgaria under contract KP-06-H64/3. We acknowledge all the PIs and colleagues from the neutron monitor stations, who kindly provided the data used in this analysis. HH thanks the financial support of JSPS Grants-in-Aids JP25K17436 and JP25H00635, the ISEE Director's Leadership Fund for FYs 2021–2026, Tokai Pathways to Global Excellence (Nagoya University) of the Strategic Professional Development Program for Young Researchers (MEXT), the Young researcher units for the advancement of new and undeveloped fields in Nagoya University Program for Research Enhancement, the Interdisciplinary Research Strategy Projects of the Institute for Space-Earth Environmental Research (ISEE), and Transdisciplinary Network linking Space-Earth Environmental Science, History, and Archaeology (JPMXP1324134720). Research was partially funded by ISEE International Joint Research Program "Digging the past: Uncovering the archival detector data for intense solar particle storms in mid-20 century." HH thanks World Data Center for Geomagnetism for allowing him access to the Dst index, Shun Imajo for his advice on recalculating the Dst index, Atsuki Shinbori and Nozomu Nishitani for their advice on magnetopause standoff distance estimates. Open access publishing facilitated by Oulun yliopisto, as part of the Wiley - FinELib agreement.

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