

Article

Real-Time Detection of the Ground Level Enhancement 74 (GLE74) Event on 11 May 2024 by the A.Ne.Mo.S. GLE Alert++ System

Maria Gerontidou ^{1,*} , Norma B. Crosby ², Helen Mavromichalaki ¹ , Maria-Christina Papailiou ¹, Pavlos Paschalis ¹  and Mark Dierckxsens ² 

¹ Nuclear and Particle Physics Section, Physics Department, National and Kapodistrian University of Athens, 15784 Athens, Greece; emavromi@phys.uoa.gr (H.M.); mpapahl@phys.uoa.gr (M.-C.P.); ppaschalis@phys.uoa.gr (P.P.)

² Royal Belgian Institute for Space Aeronomy, 1180 Brussels, Belgium; norma.crosby@aeronomie.be (N.B.C.); mark.dierckxsens@aeronomie.be (M.D.)

* Correspondence: mgeront@phys.uoa.gr

Abstract

During a period of intense solar activity and highly disturbed geomagnetic conditions, a large Forbush decrease began on 10 May 2024 accompanied by a historic geomagnetic storm that lasted for four days. This extreme geomagnetic disturbance classified as G5 according to “NOAA Space Weather Scale for Geomagnetic Storms” is referred to in the literature as the Mother’s Day Storm. This resulted from multiple, at least seven, Coronal Mass Ejections (CMEs) that had been occurring since 7 May. In addition, on 11 May, a powerful X5.8 class solar flare, reaching its maximum at 01:32 UT, was followed by an abrupt increase in proton flux with energies > 100 MeV (with onset on 11 May at 01:45 UT and peaking at 02:45 UT), as recorded by GOES satellites. This resulted in a Ground Level Enhancement (GLE), identified as GLE74, occurring on 11 May 2024 during the recovery phase of the deep Forbush decrease (~15%). This Solar Energetic Particle (SEP) event consisted of both impulsive and gradual components, where the high-energy tail of the gradual component was recorded by several stations of the worldwide ground-based neutron monitor network. Approximately 15 minutes after the onset of the SEP event and 40 minutes prior to its peak, an alert was issued by the GLE Alert++ system of the Athens Neutron Monitor Station of the National and Kapodistrian University of Athens (NKUA), available as a federated product on the ESA SWE Portal under the Space Radiation Expert Service Centre. In this paper, a description of the solar activity, i.e., solar flares and CMEs, occurring during this time period is given. Moreover, recordings of cosmic ray data obtained by ground-based neutron monitors are used to perform a detailed analysis of GLE74. Finally, the response of the NKUA GLE Alert++ system to GLE74 is thoroughly presented.

Keywords: cosmic rays; ground level enhancements; solar energetic particles; solar flares; coronal mass ejections; GLE alert



Academic Editor: Ezio Caroli

Received: 16 December 2025

Revised: 13 January 2026

Accepted: 24 January 2026

Published: 31 January 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Ground Level Enhancements (GLEs) are one of the most important manifestations of cosmic rays’ sporadic/non-recurrent variations [1]. They were discovered long before the Space Age [2]; i.e., the first event, GLE01, was registered in February 1942 using ground-based ionization chambers. Likewise, the next three GLEs were also detected

using the same method [3]; however, their parameters were not defined. From 23 February 1956 (GLE05), GLE events have been recorded by ground-based detectors, i.e., neutron monitors (NMs). Since the 1960s, cosmic rays have also been observed using space-based instruments.

GLEs are directly linked to eruptive events occurring on the Sun, i.e., solar flares or coronal mass ejections (CMEs) [3–5]. During these events, charged particles (mainly protons), which constitute the primary solar cosmic rays, are accelerated to near-relativistic energies and are propagated in interplanetary space, resulting in SEP events [5–9]. Eventually, if well-connected to Earth, these near-relativistic particles enter the Earth's atmosphere. In turn, they interact with its molecules and create a cascade, which leads to secondary solar cosmic rays.

SEP events typically cover an energy range from 10 to 100 MeV. In case of particles with higher energy, effects measurable at the Earth's surface are generated [10]. More precisely, these effects are detectable at mountainous polar regions (for SEPs of 300 MeV nucleon^{−1}) and sea level (for SEPs of 433 MeV nucleon^{−1}) [11].

The GLE is the most energetic manifestation of SEP events. A GLE can initially be classified as an SEP event that is sufficiently energetic to cause an increase in secondary cosmic rays [12]. A study by Papaioannou et al. [13] defines the GLE as the high-energy end of SEPs. Similarly, ref. [14] states that extreme SEP events result in GLEs. Moreover, SEP events that are characterized by a sufficiently hard spectrum and high intensity can be registered by ground-based monitors [15,16].

Consequently, GLEs can occur when the Earth's atmosphere is penetrated by high-energy protons. A more detailed description defines a GLE as the sudden increase in cosmic ray intensity (protons of energies higher than 433 MeV at sea level) above the ever-present background of galactic cosmic rays registered by ground-based detectors, such as muon detectors, but mainly NMs [17–19]. This is a short-term increase, i.e., lasts for several hours [20–22] and can range from a few up to 1000 percent, according to the energy/flux of the accelerated particles and the measurement site [23], e.g., satellites may also register the increase in the cosmic ray flux [24,25]. In a more contemporary definition, Poluianov et al. [26] argue that “a GLE event is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located neutron monitors including at least one neutron monitor near sea level and a corresponding enhancement in the proton flux measured by a space-borne instrument(s)”.

GLE events are not frequent events, since approximately only one event per year is registered. The GLE occurrence depends on the solar cycle [22,27], since these events are more probably observed during the maximum and decay phase of the solar cycle [28,29]. In total, 77 events have been recorded up to today, with GLE01 on 28 February 1942 being the first [30] and GLE77 on 11 November 2025 is the most recent [31] (<https://gle oulu.fi/#/>, accessed on 1 July 2025). The largest GLE that was ever recorded by NMs is GLE05 (4573% peak count increase) on 23 February 1956 [28,32–34]. Additionally, the most intense GLE recorded with contemporary in situ measurements was GLE42 (29 September 1989) [1]. A complete list of all GLE events can be found either in the high-resolution Neutron Monitor Database (NMDB, <https://www.nmdb.eu/nest/>, accessed on 1 July 2025) or the OULU GLE Database (<https://gle oulu.fi/#/>, accessed on 1 July 2025). The NMDB database was implemented in the frame of the Seventh Framework Programme of the European Commission (<https://www.nmdb.eu/>, accessed on 1 July 2025), while the Sodankylä Geophysical Observatory at the University of Oulu is responsible for operating the GLE OULU Database. Both tools allow the user to select and display any recorded GLE event using data from the worldwide NM network.

Nowadays, extreme SEPs and GLEs are of great interest due to their contribution to fundamental research and impact on technological applications [35]. These space weather phenomena are responsible for diminishing the performance and reliability of spacecraft operation (satellite electronics) in addition to ground-based systems (navigation, telecommunications, and high-potential power grid systems), and as a result, can affect a wide range of human activities [36–39]. Their technological effects are extensive and include various direct damage, such as single-event effects, single-event upsets, polar cap absorption, etc. [40,41].

Furthermore, extreme SEPs and GLEs may also have a significant effect on human health or even human life [42–44]. Aviation flights as well as space missions are directly affected not only by galactic cosmic rays but also by space environment phenomena such as SEP events. Even though the health risk from galactic cosmic rays can be regulated through a number of limitations and directions imposed by airline companies (for example, limited airtime in the polar regions and annual radiation exposure allowances), the threat posed by SEPs is less controllable because these events are unpredictable. Consequently, air crews and passengers are exposed to major threats during SEP events due to enhanced radiation doses.

Whether the risk from enhanced radiation doses due to extreme SEPs involves acute health effects or not, it is still significant and poses a serious threat to human health. This could be during a manned spaceflight outside the Earth's magnetosphere (e.g., to the Moon or Mars) or a long-term health threat during aircraft aviation at high latitudes (i.e., polar regions) with recurring itineraries. That is why exposure to cosmic rays' radiation for a commercial aviation crew was suggested to be treated as an occupational hazard by the International Commission on Radiological Protection in 1991. This was also supported by the European Atomic Energy Community (EURATOM) in 1996 and finally became legal regulation in member states in 2014. Therefore, it is essential that air crew radiation doses, mainly due to galactic cosmic rays, should be monitored continuously. In addition, as previously noted, monitoring extreme SEP events is equally important since they can enhance the level of radiation in the atmosphere at flight altitudes [4,34,45].

The radiation exposure at flight altitudes can be calculated using different models that have been developed over the last years [46–48]. It is interesting to note that these models are in agreement when it comes to calculating radiation doses due to galactic cosmic rays, but in case of a GLE occurrence, when both galactic cosmic rays and SEPs are responsible for the radiation exposure, results from various models differ [41,49,50]. In a study by Larsen and Mishev [34], it is argued that the estimation of the radiation dose during a GLE event can use real-time NM data as proxy. In this way, nowcasting models could be developed to help mitigate the hazardous effects of upcoming GLE events.

May 2024 was marked by the emergence of a significant sunspot active region (AR13664), which initiated several solar eruptions. These events led to the observation of a large Forbush decrease (~15%), a GLE, and an extreme geomagnetic storm (Dst index = −412nT on 11 May at 02:00 UT). In fact, the historic geomagnetic storm on 10–13 May 2024 was scaled as G5 (NOAA Space Weather Scale for Geomagnetic Storms) and ranks as the sixth-largest storm since 1957 [51,52].

GLE74 is the second GLE event of solar cycle 25 and was recorded by NMs located around the Earth, during the ascending phase of this solar cycle. This event was registered on 11 May 2024, from 2 UT to 10 UT, during the recovery phase of a Forbush decrease on 10 May 2024 [32]. GLEs can be observed during the recovery phase of a Forbush decrease [53,54], as happened with GLE65, GLE66, and GLE67 of solar cycle 23, which were recorded in late October–early November 2003, a time period known as Halloween Storms due to the intense solar activity [29]. During the GLE74 event, the GLE Alert ++ system

of the Athens Neutron Monitor Station (A.Ne.Mo.S.) of the National and Kapodistrian University of Athens (NKUA), available as a federated product on the ESA SWE Portal¹ under the Space Radiation Expert Service Centre, issued an alert. The ‘GLE Alert++ system’ is an online public application. Users, i.e., all those who are registered in the application through the ESA website (<https://swe.ssa.esa.int/web/guest/anemos-federated>, accessed on 1 July 2025), are able to subscribe to GLE alert emails and have access to data concerning previous GLE events.

In this work, GLE74 is presented and analyzed. The study includes a thorough description of the solar activity using satellite recordings, i.e., data on solar flares, CMEs, and protons, and a detailed analysis of ground-based recordings (cosmic ray data from NMs). The GLE Alert ++ system’s response to this event is explicitly discussed.

2. Observations

A brief background to solar activity conditions during the first half of May 2024 is given in Section 2.1, followed by terrestrial cosmic ray conditions using ground-based neutron monitor recordings in Section 2.2.

2.1. Satellite Recordings

On 1 May 2024, a new active region, designated AR13664, appeared on the southeastern limb of the visible side of the solar disk. AR13664, which started as a bipolar group (with two penumbrae and some intermediate sunspots in between, Figure 1a) evolved quickly, during 3–7 May, when it crossed the central meridian. From there on, the AR continued to develop and finally consisted of compact penumbra containing most of the spots on 9 May. On 14 May, the region rotated over the limb after being rather stable for some time [52]. According to [54], the eruptive events taking place in this period were associated with two ARs 13664/8, since AR13668 (S15W55) was merging with AR13664 (S17W62). In the following, the merged AR13664/8 is identified as AR13664.

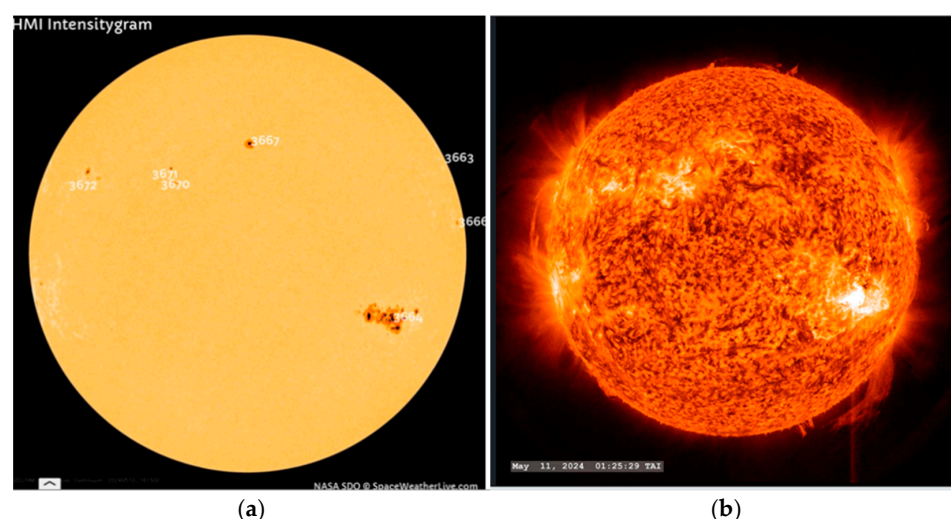


Figure 1. Sunspots of AR13664 on 11 May 2024 from NASA SDO/HMI (a), the X5.8 solar flare on 11 May 2024 generated from AR13664 from NASA SDO/AIA 304 (b).

Between 4 and 15 May 2024, AR13664 generated 12 X-class flares (Figure 1b) and numerous M-class flares. Consequently, a significant number of Interplanetary CMEs (ICMEs), associated with the aforementioned active region, were produced. These events resulted in the acceleration of SEPs directed towards the Earth. Satellite data from the Large Angle Spectroscopic Coronagraph (LASCO) show that four ICMEs had an effect on the interplanetary space [52]. The shock registered on 10 May 2024, at 17:05 UT compressed the

magnetosphere (to $5.04R_E$) and triggered a large Forbush decrease [55,56]. The strongest solar flare occurred on the western limb (WL), and part of it extended beyond the visible solar disk on 14 May at 16:46 UT and was of class X8.7. It was related to a CME of speed 2010 km/s [52].

Figure 2a shows the soft X-ray flux continuously above the M1 level from 9 May to 12 May provided by GOES-16. The majority of these flares were produced while the AR was in the visible solar hemisphere, and only four were produced when the merged AR had crossed the western limb into the far side. The solar flare X5.8 on 11 May at 01:23 associated with GLE74 (see Figure 1) is indicated by the vertical red dotted line in Figure 2. Moreover, Figure 2b displays the proton fluxes for the energy channels > 10 MeV, > 50 MeV, and > 100 MeV during the above-mentioned time period. The green arrow marks the time when the proton flux > 10 MeV reached the threshold corresponding to a minor solar radiation storm (S1 level) at 13:30 UT on 10 May. The red arrow indicates a subsequent, more intense S2-level solar radiation storm that occurred at 16:40 UT on 10 May.

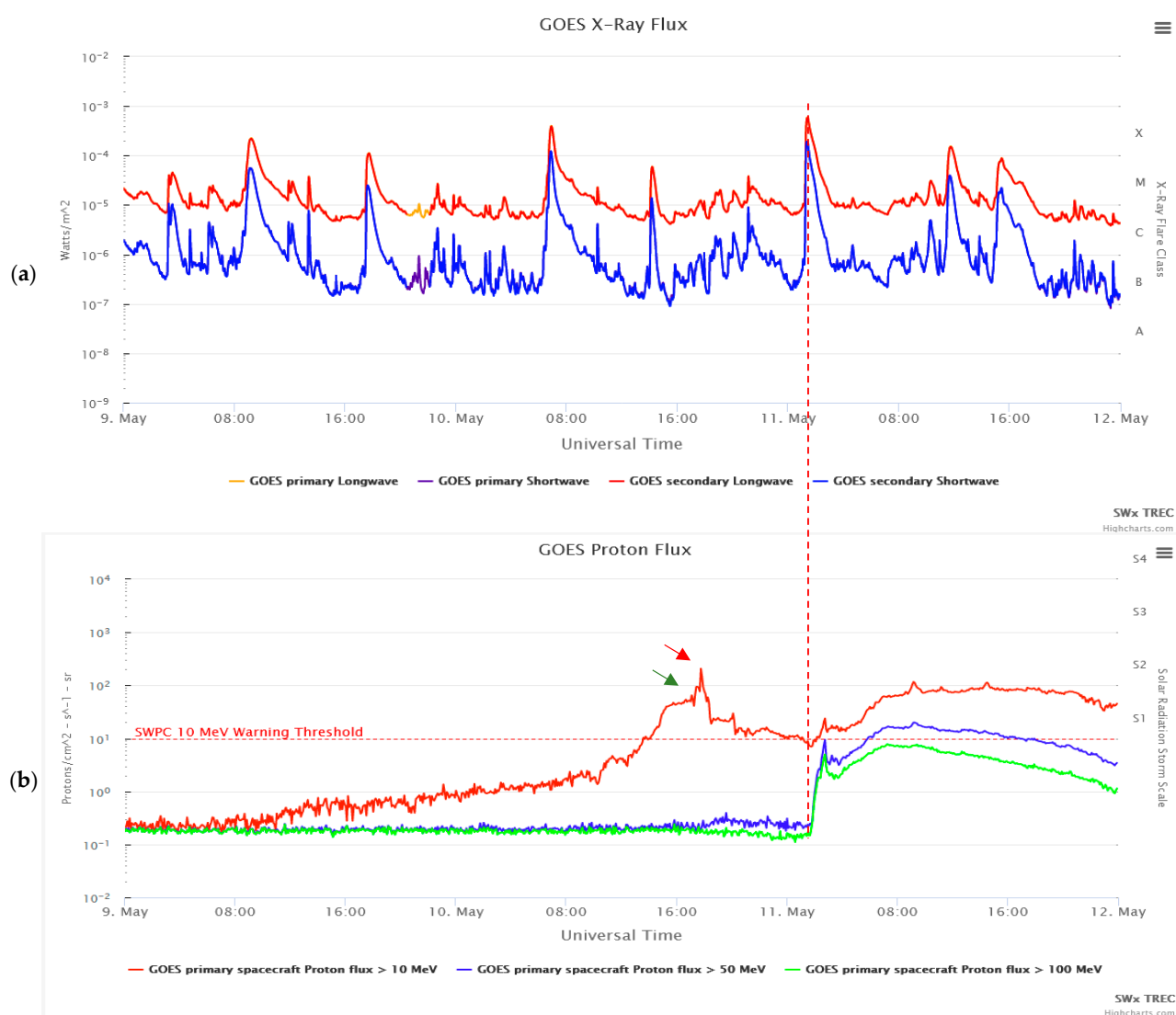


Figure 2. (a) GOES-16 X-ray flux in $0.5\text{--}4.0\text{ \AA}$ and $1.0\text{--}8.0\text{ \AA}$, as derived from <https://lasp.colorado.edu/space-weather-portal/>, accessed on 1 July 2025). (b) GOES proton fluence for energy > 10 MeV (red line), > 50 MeV (blue line), > 100 MeV (green line). The red dotted line is fixed on solar flare X5.8 on 11 May at 01:23 associated with the GLE74.

AR13664 and the aforementioned solar flares resulted in at least 19 major CMEs (with width $\geq 60^\circ$), including 10 halo CMEs, which were registered by the Large Angle Spectroscopic Coronagraph (LASCO) from 5 May to 15 May 2024.

An X1.0 flare at 21:40 UT and an M9.8 flare at 22:27 UT, both recorded on 8 May, took place successively and resulted in a single halo CME registered at 22:24 UT with speed 947 km/s. This halo CME is connected to the Sudden Storm Commencement (SSC) on 10 May at 17:05 UT. Moreover, this CME piled up with three more CMEs connected to AR13664, two of them being halos and related to M-class flares.

On 9 May and 10 May, two X-class solar flares (X1.1 at 09:24 and X3.8 at 07:12 UT, respectively) resulted in two CMEs, with speeds of 1226 km/s and 1006 km/s, respectively. Furthermore, another X-class solar flare (X5.8 on 01:36 UT) recorded on 11 May was connected to an even faster ICME (1512 km/s).

Given the above, it is evident that the Forbush decrease on 10 May 2024, the associated GLE74, and the historic geomagnetic storm are not linked to a single ICME. Instead, they were the result of complex solar activity and disturbed interplanetary conditions, making their analysis particularly challenging. The simultaneous arrival of multiple CMEs contributed to the unique circumstances that gave rise to these historic events.

2.2. Ground-Based Recordings

In response to these disturbed interplanetary conditions, resulting in disturbed geomagnetic conditions, several ground-based neutron monitors recorded an increase in their data during this period. As can be seen in Figure 3 (NM stations of the NMDB) and Figure 4 (NM stations of the Bartol Research Institute), GLE74 took place against a highly disturbed background during the deep phase of a large Forbush decrease.

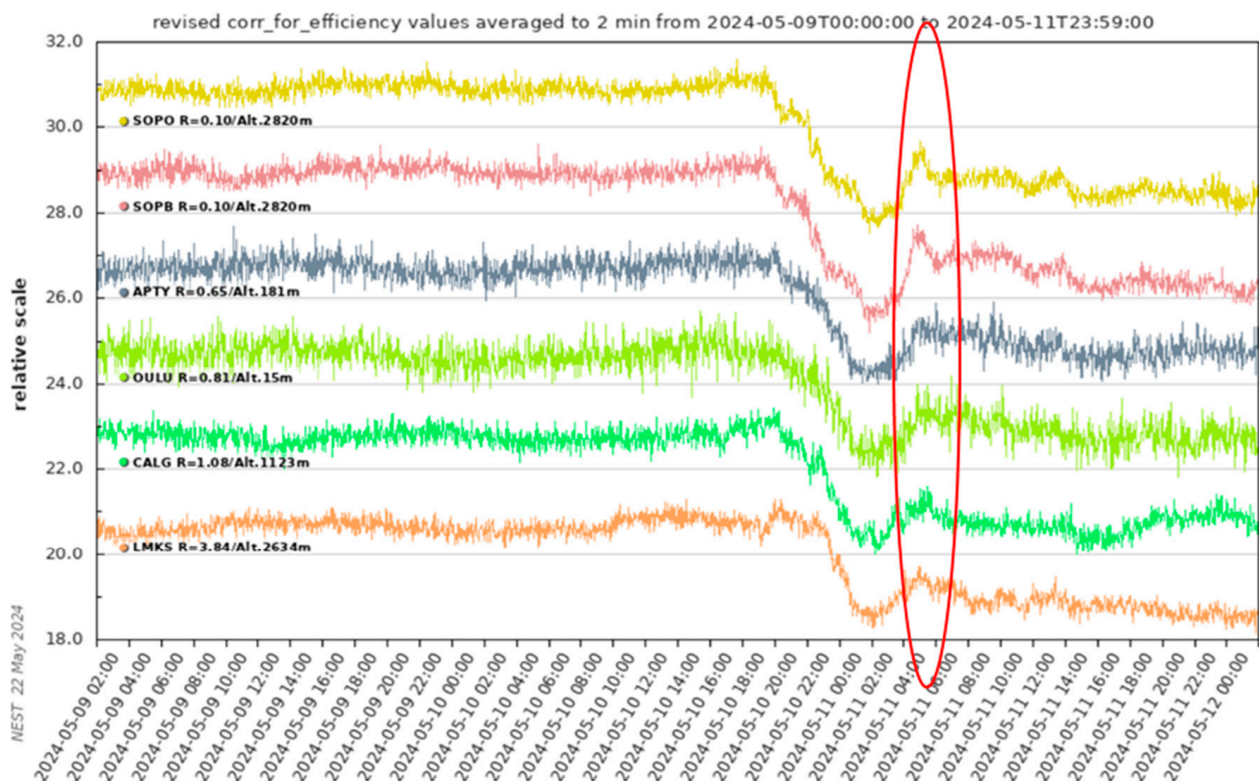


Figure 3. Several NM stations recorded enhancements (highlighted in the red oval) in their data (NMDB; <https://www.nmdb.eu/nest/>, accessed on 1 July 2025).

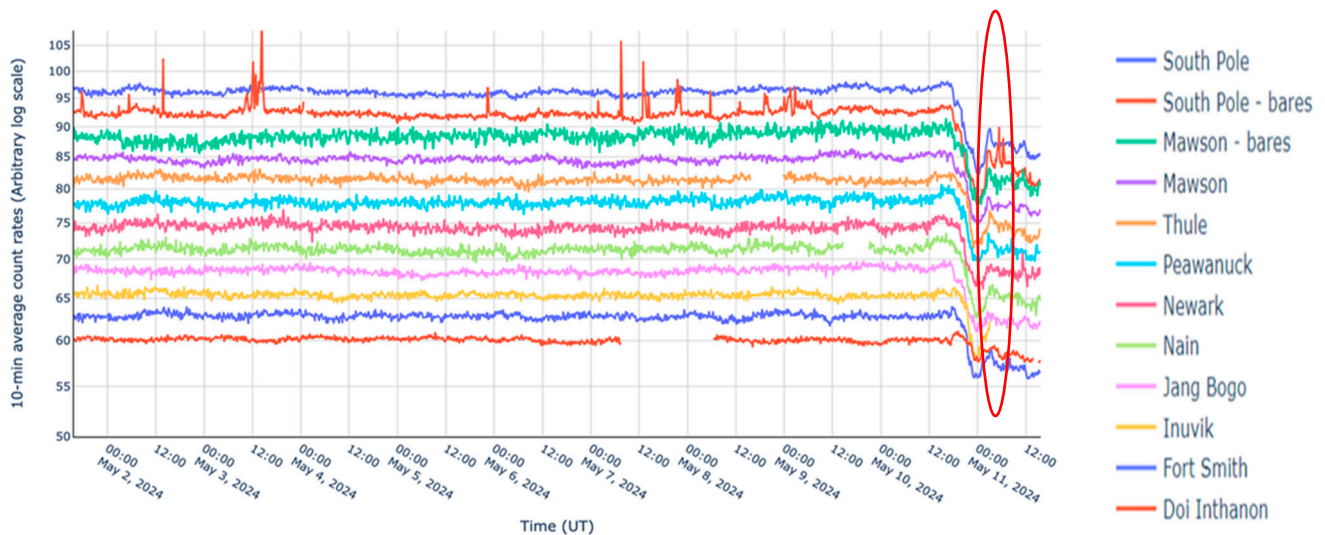


Figure 4. NM stations of the Bartol Research Institute, University of Delaware, USA recorded the event (highlighted in the red oval) (<https://neutronm.bartol.udel.edu/~pyle/json/index.html>, accessed on 1 July 2025).

The list of the 39 NM stations that detected an increase in cosmic ray intensity, including those displayed in Figures 3 and 4, is presented in Table 1. The columns correspond to the station's abbreviation, geographical location in degrees (latitude, longitude), altitude (m), rigidity (GV), base period (date and time) used for the estimation of the increase, approximate maximum increase (%), and date and time of maximum intensity according to the Oulu GLE database (<https://gle.oulu.fi/#/>, accessed on 1 July 2025). The base period used for the estimation of the increase for this particular event was hard to select because GLE74 evolved during the recovery phase of a Forbush decrease. The base period was selected as a short (2 h) time period around the main decrease and before the maximum increase.

Table 1. The maximum increase in cosmic ray intensity (%) recorded by several NM stations as provided by <https://gle.oulu.fi/#/> (accessed on 1 July 2025) in relation the pre-increase baseline time interval. Stations marked with grey color are those that contributed to the general GLE alert.

Station	Latitude (°)	Longitude (°)	Altitude (m)	Rigidity (GV)	Pre-Increase Baseline Time Interval Date/Time (MM.DD. HH:MM)	Maximum Increase		
						Increase _{max} %	Date (MM.DD)	Time (UT)
AATB	43.14	76.6	3340	6.69	05.10 23:00–05.11 01:00	4.8	05.11	03:00
APTY	67.55	33.33	177	0.65	05.10 23:00–05.11 01:00	7.46	05.11	04:00
BKSN	43.28	42.69	1700	5.6	05.10 23:00–05.11 01:00	5.57	05.11	03:10
BRBG	78.06	14.22	70	0.0	05.10 23:00–05.11 01:00	4.26	05.11	03:00
CALG	51.08	−114.13	1128	1.2	05.10 23:00–05.11 01:00	5.66	05.11	03:25
CALM	40.64	−3.16	708	6.95	05.10 23:30–05.11 01:30	5.52	05.11	04:35
DOMB	75.1	−123.38	3233	<0.01	05.10 23:00–05.11 01:00	9.23	05.11	04:20
DOMC	75.1	−123.38	3233	<0.01	05.10 23:00–05.11 01:00	7.51	05.11	03:35
DRBS	50.1	4.6	225	3.18	05.10 23:30–05.11 01:30	4.12	05.11	02:55
FTSM	60	−112	0	0.3	05.10 23:00–05.11 01:00	5.83	05.11	03:20
INVK	68.35	−133.72	21	0.3	05.10 23:00–05.11 01:00	6.02	05.11	03:20
IRK2	51.62	100.92	2000	3.64	05.10 23:00–05.11 01:00	5.34	05.11	05:40
IRK3	51.62	100.92	3000	3.64	05.10 23:30–05.11 01:30	5.57	05.11	02:45
JBGO	74.6	164.2	30	0.3	05.10 23:30–05.11 01:30	5.34	05.11	02:50
JUN1	46.55	7.98	3570	4.5	05.10 23:30–05.11 01:30	4.3	05.11	02:50
JUNG	46.55	7.98	3475	4.5	05.10 23:30–05.11 01:30	4.49	05.11	02:35
KIEL	54.34	10.12	54	2.36	05.10 23:30–05.11 01:30	8.47	05.11	02:45
LMKS	49.2	20.22	2634	3.84	05.10 23:30–05.11 01:30	4.95	05.11	02:55
MOSC	55.47	37.32	200	2.43	05.10 23:00–05.11 01:00	5.68	05.11	02:35

Table 1. Cont.

Station	Latitude (°)	Longitude (°)	Altitude (m)	Rigidity (GV)	Pre-Increase Baseline Time Interval Date/Time (MM.DD. HH:MM)	Maximum Increase		
						Increase _{max} %	Date (MM.DD)	Time (UT)
MRNY	−66.55	93.02	30	0.03	05.10 23:00–05.11 01:00	5.18	05.11	04:10
MWSB	−67.60	62.88	30	0.22	05.10 23:00–05.11 01:00	7.58	05.11	02:55
MWSN	−67.60	62.88	30	0.22	05.10 23:00–05.11 01:00	5.11	05.11	02:40
MXCO	19.33	260.82	2274	8.2	05.10 23:30–05.11 01:30	3.49	05.11	03:10
NAIN	56.6	−61.7	0	0.3	05.10 23:30–05.11 01:30	5.67	05.11	03:45
NANM	40.37	44.25	2000	~7.1	05.10 23:30–05.11 01:30	5.16	05.11	02:45
NEWK	39.68	−75.75	50	2.4	05.10 23:30–05.11 01:30	5.16	05.11	03:30
NRLK	69.26	88.05	0	0.63	05.10 23:00–05.11 01:00	3.57	05.11	05:00
NVBK	54.48	83.00	163	2.91	05.10 23:00–05.11 01:00	6.07	05.11	05:40
OULU	65.02	25.5	15	~0.8	05.10 23:00–05.11 01:00	6.39	05.11	04:10
PSNM	18.59	98.49	2565	16.8	05.10 23:00–05.11 01:00	2.04	05.11	03:00
PWNK	55	−85	0	0.3	05.10 23:00–05.11 01:00	5.84	05.11	03:00
ROME	41.86	12.47	0	6.27	05.10 23:00–05.11 01:00	4.6	05.11	02:45
SNAE	−71.67	−2.85	856	0.73	05.10 23:30–05.11 01:30	5.45	05.11	03:10
SOPB	−90	0	2820	0.1	05.10 23:30–05.11 01:30	9.96	05.11	02:45
SOPO	−90	0	2820	0.1	05.10 23:30–05.11 01:30	8.67	05.11	03:00
TERA	−66.65	140	32	0.0	05.10 23:30–05.11 01:30	4.1	05.11	04:30
THUL	76.6	−68.8	260	0.3	05.10 23:00–05.11 01:00	6.94	05.11	03:20
TXBY	71.6	128.9	0	0.48	05.10 23:00–05.11 01:00	6.07	05.11	02:55
YKTK	62.02	129.72	105	1.65	05.10 23:00–05.11 01:00	5.67	05.11	02:50

Even though this event does not fit the conventional shape of a GLE, i.e., a significant increase above the background level, it meets the criteria of the GLE definition provided by [26]. Therein, is stated that a GLE is recorded by at least two differently located NMs (i.e., in this case, OULU, SOPO, and LMKS) including at least one NM near sea level (i.e., OULU), as can be seen in Figure 3, and a corresponding enhancement in the proton flux measured by a space-borne instrument(s) (see Figure 2).

Moreover, it is important to note that the reason middle- and low-latitude NMs also recorded an increase in their count rates is connected to the highly disturbed geomagnetic conditions occurring in this time period. The Dst-index reached the value of −412 nT, the Kp-index was 9, and the Ap-index was 274 nT. Therefore, this event is characterized by complexity due to its different signatures in high- and middle/low-latitude stations.

In addition, the wide temporal distribution of the peak intensities indicates a strong anisotropy of this event. The anisotropic nature of a GLE is a key factor considered when triggering a GLE Alert. Focusing on the neutron monitors that contribute to the GLE Alert++ system (as described in Section 3), Figure 5 presents the asymptotic directions for three selected stations—OULU, SOPO, and LMKS—covering a rigidity range of 1–5 GV. The calculations of asymptotic direction are based on the back-tracing particle trajectory method [57], through the International Geomagnetic Reference Field (IGRF) model and Tsyganenko 89 geomagnetic field models [58,59]. The aforementioned asymptotic directions denote the directions of the velocities of trial particles as they cross the magnetospheric boundary. From Figure 5, it is determined that the SOPO NM has the narrowest asymptotic cone among the selected stations.

It is noteworthy that the exceptional character of this event resulted in spectacular auroral displays visible across various locations around the globe [52,58–61]. Typically, auroras are observed at high latitudes in the northern and southern hemispheres. However, due to the intensity of the G5-class geomagnetic storm, auroras were seen at much lower latitudes, including regions such as Greece, Armenia, and Switzerland.

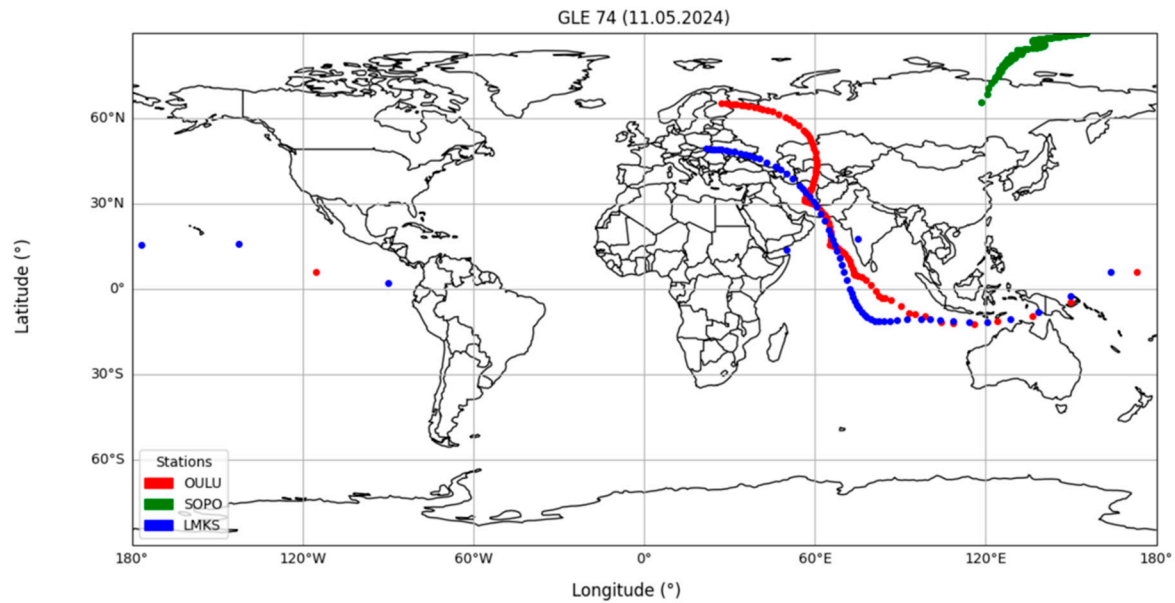


Figure 5. Asymptotic directions for selected NM stations that contributed to the triggering of the GLE Alert++ system.

3. Real-Time Provision of the GLE Alert by the GLE Alert++ System

On 11 May 2024, at 02:05 UT, the real-time GLE Alert++ system [62] issued an Alert. Specifically, the GLE Alert ++ system responded successfully by issuing an alert 20 min after the onset of the SEP event at energies > 100 MeV and 40 min prior to its peak. The system's response to the event is divided into three stages: (i) pre-alert status, (ii) alert status, and (iii) post-alert status. All three stages are de-scribed below.

3.1. Pre-Alert Status

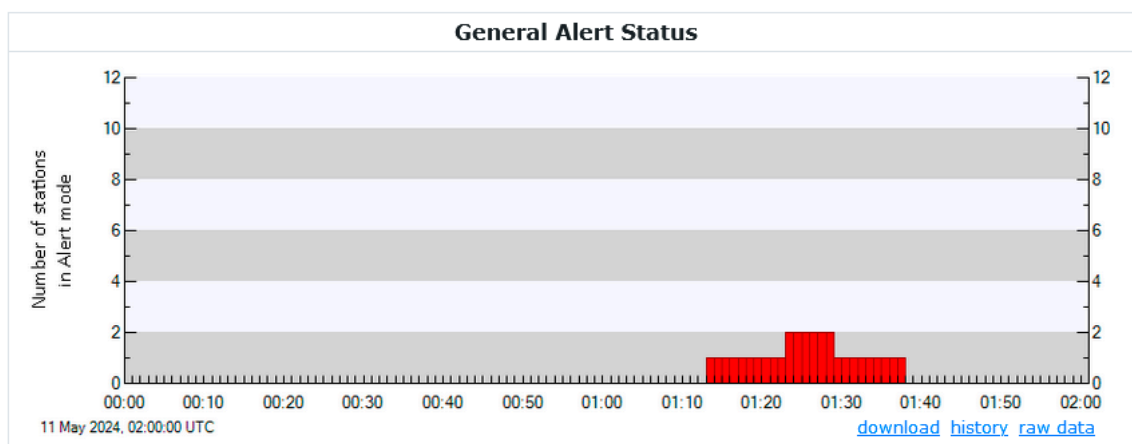
The first stage refers to 11 May 2024 and covers the time period of 1:13–1:37 UT. At this point, as can be seen in Figure 6, two NM stations (FSMT and YKTK) enter the warning status from 01:23 to 01:28 (see Table 2). From 01:38 UT to 02:00 UT, the system remains in the quiet status.

Table 2. Raw data of the GLE Alert ++ system for the time period from 01:13 UT to 01:37 UT on 11 May 2024. The columns represent the station's timestamp, the number of stations, the station's abbreviation, and the GLE status.

Station Timestamp	Number of Stations	Station	GLE Status
2024-05-11 01:13:00	1	FSMT	WATCH
...	...	...	...
2024-05-11 01:22:00	1	FSMT	WATCH
2024-05-11 01:23:00	2	FSMT YKTK	WARNING
...	...	...	...
2024-05-11 01:28:00	2	FSMT YKTK	WARNING
2024-05-11 01:29:00	1	YKTK	WATCH
...	...	...	...
2024-05-11 01:37:00	1	YKTK	WATCH

SAT, 11 MAY 2024, 02:00:00 UTC

STATUS: **QUIET**



Station Status				
☐ AATB	☐ APTY	☐ ATHN	☐ BKSJ	☐ CALM
☐ DRBS	☐ FSMT	☐ INVK	☐ IRK2	☐ IRK3
☐ IRKT	☐ JUNG	☐ JUNG1	☐ KERG	☐ KIEL2
☐ LMKS	☐ NAIN	☐ NEWK	☐ OULU	☐ PWNK
☐ ROME	☐ SOPB	☐ SOPO	☐ TERA	☐ THUL
☐ TXBY	☐ YKTK			

Summary		
☐	Total	[27]
☐	Alert	[0]
☐	Warning	[1]
☐	Watch	[2]
☐	Quiet	[19]
☐	Delayed	[1]
☐	Offline	[4]

Figure 6. Evolution of the GLE Alert ++ for GLE74. The pre-alert status: NM stations FSMT and YKTK are in warning status.

3.2. Alert Status

On 11 May 2024, at 02:01, the system again enters the watch status, triggered by the OULU station. One minute later, a second station (SOPO) contributes to the warning status. Once the LMKS station entered in alert status, a general alert status was issued at 02:05 UT (see Table 3). While the system was in the general alert status, at 02:06 UT, a fourth NM contributed to the alert status (i.e., SOPB), as shown in Figure 7. The alert notification was sent to all users at 02:07 UT. The system was in the general alert status until 02:19 UT. The polar stations SOPO and SOPB continued to register increases, and as a result, the system alternated between warning and watch status for 34 min (Tables 3 and 4).

Table 3. Raw data of the GLE Alert ++ system for the time period from 02:01 UT to 02:21 UT on 11 May 2024. The columns represent the station's timestamp, the number of stations, the station's abbreviation, and the GLE status.

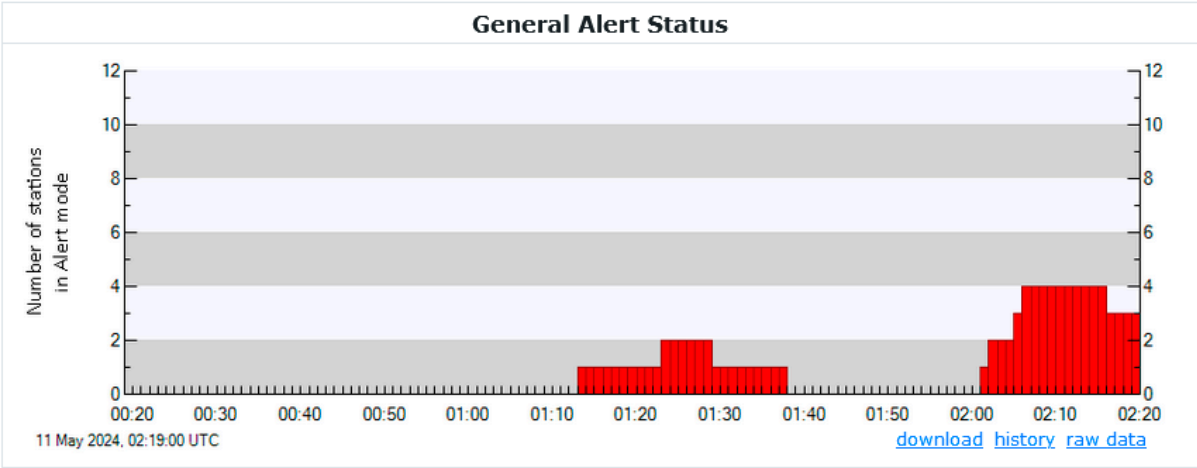
Station Timestamp	Number of Stations	Station	GLE Status
2024-05-11 02:01:00	1	OULU	WATCH
2024-05-11 02:02:00	2	OULU SOPO	WARNING
2024-05-11 02:03:00	2	OULU SOPO	WARNING
2024-05-11 02:04:00	2	OULU SOPO	WARNING

Table 3. Cont.

Station Timestamp	Number of Stations	Station	GLE Status
2024-05-11 02:05:00	3	LMKS OULU SOPO	ALERT
2024-05-11 02:06:00	4	LMKS OULU SOPB SOPO	ALERT
...	...	...	...
2024-05-11 02:15:00	4	LMKS OULU SOPB SOPO	ALERT
2024-05-11 02:16:00	3	LMKS SOPB SOPO	ALERT
...	...	...	...
2024-05-11 02:19:00	3	LMKS SOPB SOPO	ALERT
2024-05-11 02:20:00	2	SOPB SOPO	WARNING
2024-05-11 02:21:00	2	SOPB SOPO	WARNING

SAT, 11 MAY 2024, 02:19:00 UTC

STATUS: ALERT



Station Status									
☐  AATB	☐  APTY	☐  ATHN	☐  BKSJ	☐  CALM					
☐  DRBS	☐  FSMT	☐  INVK	☐  IRK2	☐  IRK3					
☐  IRKT	☐  JUNG	☐  JUNG1	☐  KERG	☐  KIEL2					
☐  LMKJ	☐  NAIN	☐  NEWK	☐  OULU	☐  PWNK					
☐  ROME	☐  SOPB	☐  SOPO	☐  TERA	☐  THUL					
☐  TXBY	☐  YKTK								

Summary		
☐	Total	[27]
☐ ●	Alert	[3]
☐ ●	Warning	[0]
☐ ●	Watch	[3]
☐ ●	Quiet	[16]
☐ ●	Delayed	[1]
☐ ●	Offline	[4]

Figure 7. Evolution of the GLE Alert ++ for GLE74. The alert status: Real-time Alert on 11 May 2024 at 02:05 UT.

Table 4. Raw data of the GLE Alert ++ system for the time period from 02:22 UT to 02:55 UT on 11 May 2024. The columns represent the station's timestamp, the number of stations, the station's abbreviation, and the GLE status.

Station Timestamp	Number of Stations	Station	GLE Status
2024-05-11 02:22:00	0		QUIET
2024-05-11 02:23:00	0		QUIET
2024-05-11 02:24:00	1	SOPB	WATCH
...	...	...	...
2024-05-11 02:34:00	1	SOPB	WATCH
2024-05-11 02:35:00	2	SOPB SOPO	WARNING
...	...	...	...
2024-05-11 02:52:00	2	SOPB SOPO	WARNING
2024-05-11 02:53:00	1	SOPB	WATCH
2024-05-11 02:54:00	1	SOPB	WATCH
2024-05-11 02:55:00	0		QUIET

As mentioned above, the NM stations that triggered this alert were OULU with cut-off rigidity $R = 0.81$ GV and altitude 15 m above sea level (asl), SOPO with cut-off rigidity $R = 0.10$ GV and altitude 2820 m asl, and finally, LMKS with cut-off rigidity $R = 3.84$ GV and altitude 2634 m asl. Figure 8 shows the recordings of the four NM stations that contributed to the GLE Alert.

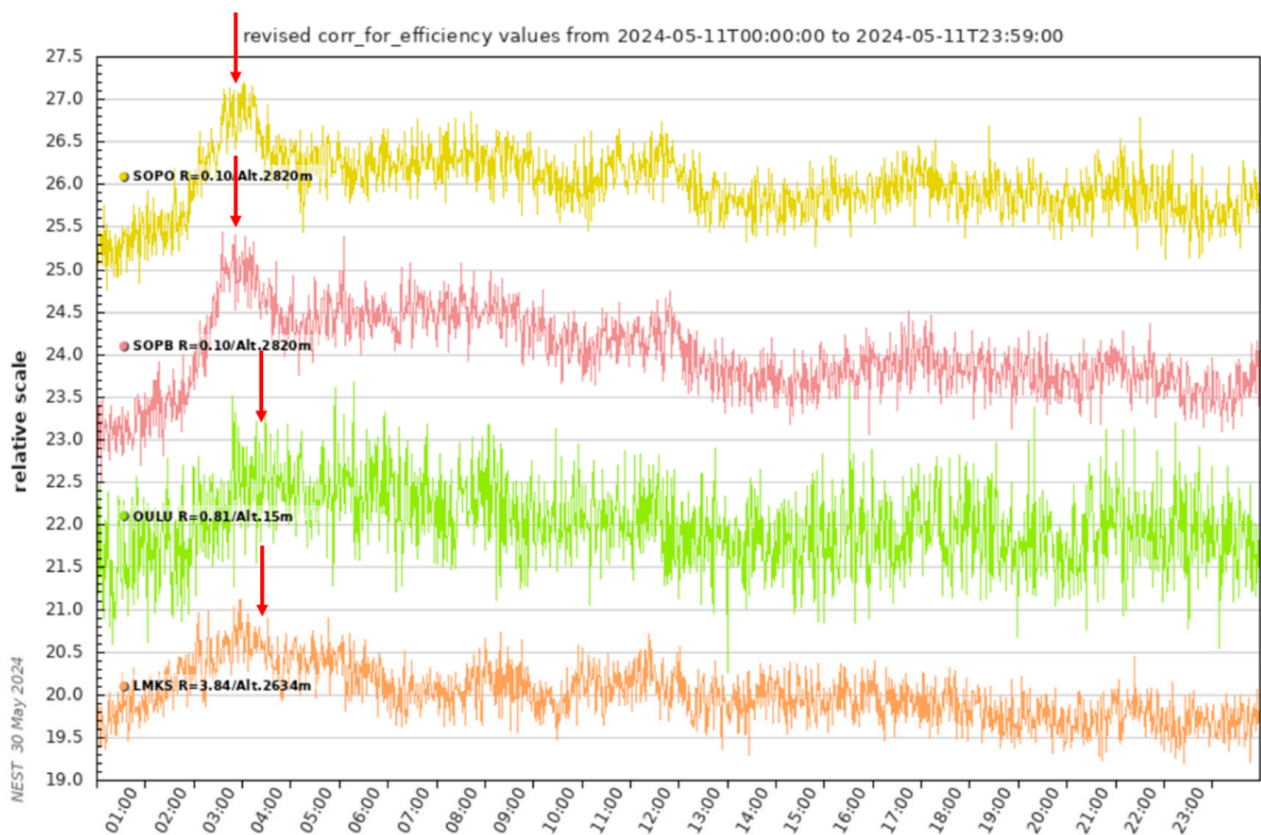


Figure 8. Recordings from the four NM stations that contributed to the GLE Alert (the red arrows define the time of the maximum increase).

Screenshots of the GLE Alert++ system on 11 May 2024 during the evolution of the alert for the stations OULU, SOPO, LMKS, and later SOPB are shown in Figure 9.

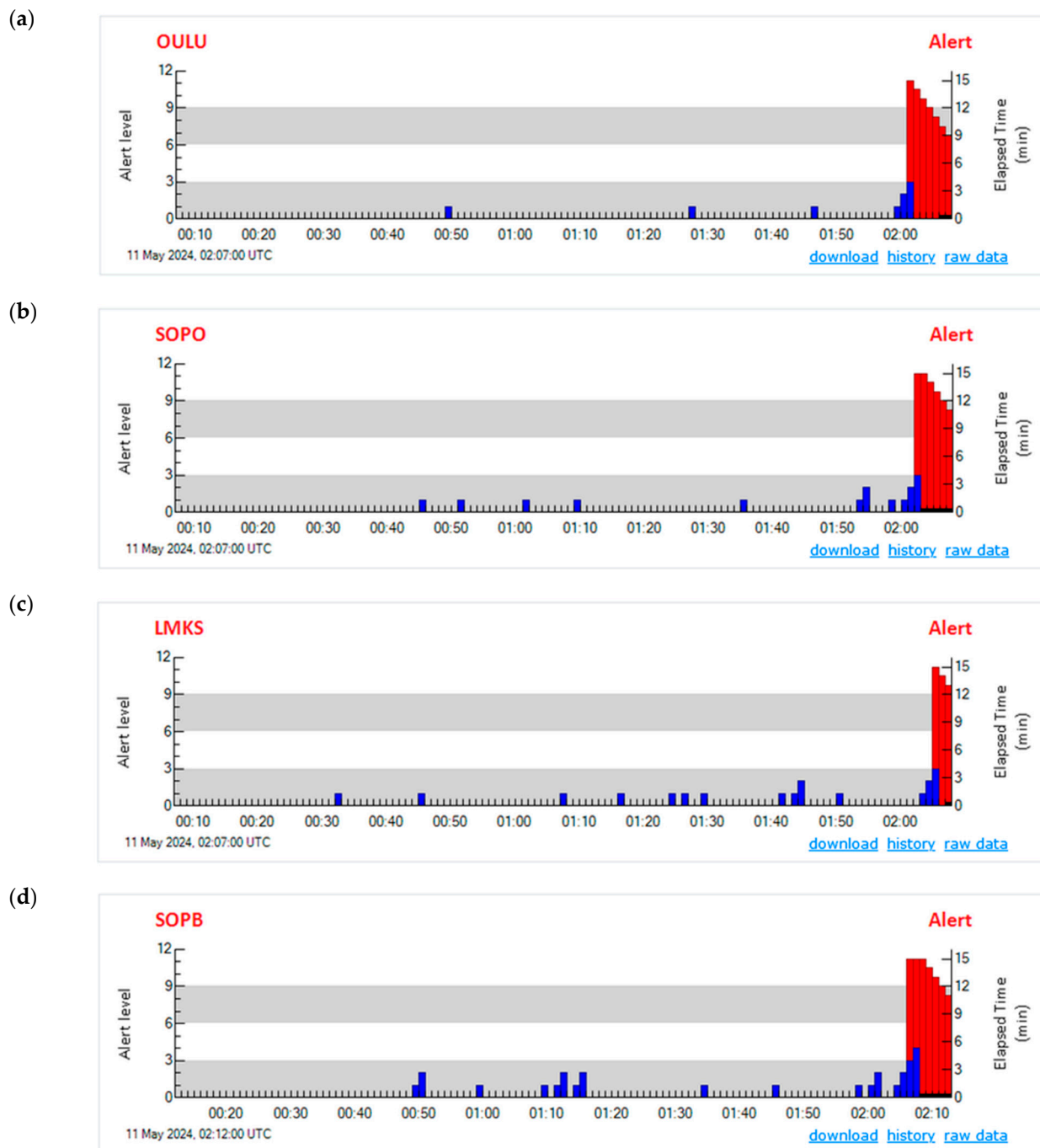


Figure 9. Screenshots of the GLE Alert++ system on 11 May 2024 during the GLE74 event for the stations (a) OULU, (b) SOPO, (c) LMKS, and later (d) SOPB in alert status. The blue bars indicate the alert status of the station (level 1: Watch, level 2: Warning and level3: Alert), while the red bars indicate the general Alert status (three stations in Alert mode).

At this point, it should be mentioned that the GLE Alert ++ system issued an alert based on the measurements of the stations LMKS, OULU, and SOPO, i.e., stations marked with gray in Table 1. Even though these stations registered a much smaller enhancement (4.95%, 6.39%, and 8.67%, respectively), the time of each station entering an alert mode (02:01 UT, 02:02 UT, and 02:05 UT) is of key importance for the alert system.

3.3. Post-Alert Status

After the alert, the GLE Alert++ system switched again to the warning status at 02:35 UT, which continued until 02:52 UT because OULU and LMKS had returned to the quiet status (Table 4), while polar stations SOPO and SOPB continued to be in the alert mode (Figure 10).

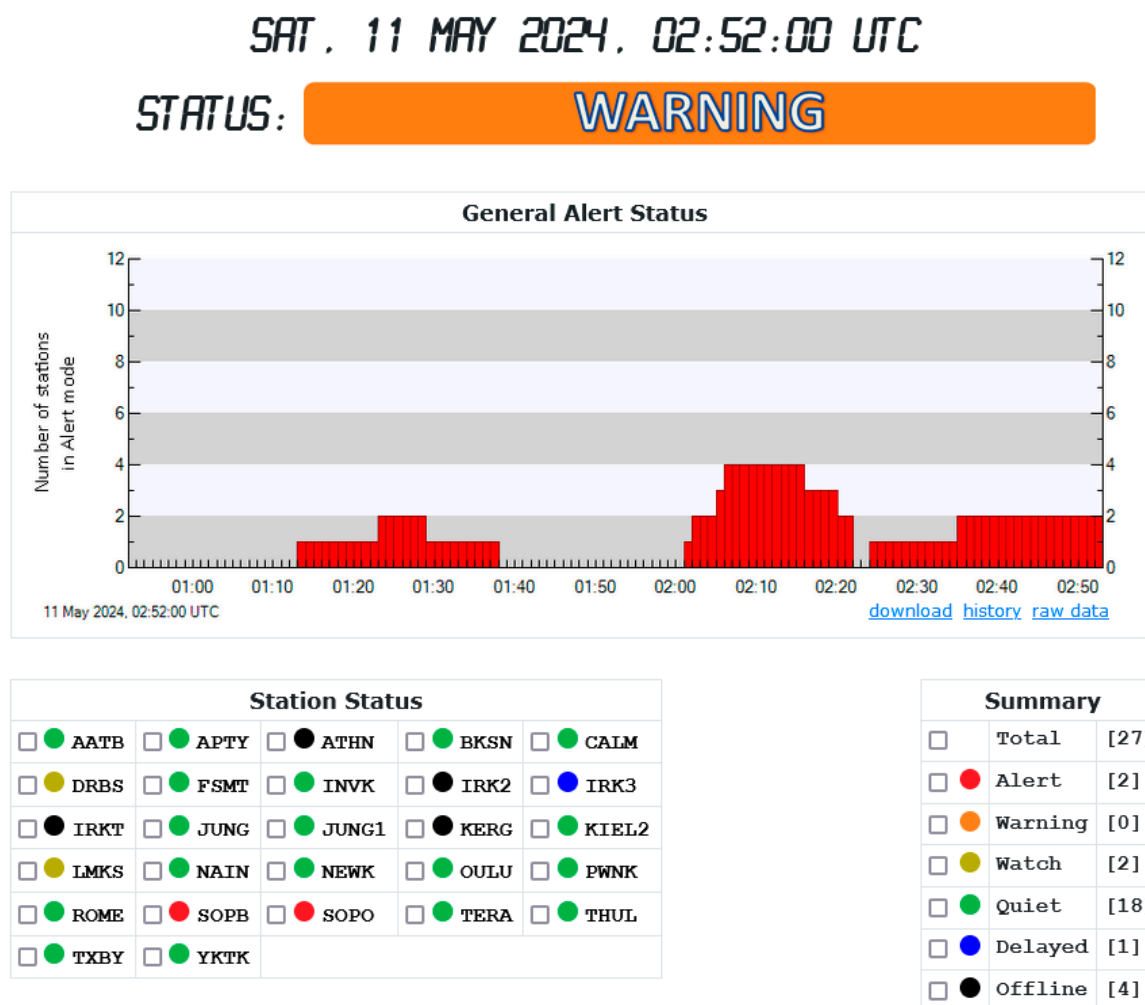


Figure 10. Evolution of the GLE Alert ++ for GLE74. The post-alert status.

4. Discussion and Conclusions

GLE events as recorded by the worldwide neutron monitor network are cosmic ray phenomena that have gradually interested the scientific community and are currently playing a significant role in the field of space weather studies. For example, ref. [63] focuses on the derivation of particle spectral and angular characteristics and ultimately the computation of the dose rate during a GLE. Moreover, ref. [64] obtains the rigidity spectrum and anisotropy of GLE particles in their dynamic evolution during GLE72 on 10 September 2017. Furthermore, in the frame of the the EU 2020 HESPERIA project, a software package was developed for the direct inversion of GLEs based on neutron monitor data. The release processes of relativistic SEPs used several models, amongst which were the propagation of relativistic SEPs from the Sun to the Earth, their transport in the Earth's magnetosphere and atmosphere, and the detection of the nucleon component of the secondary cosmic rays by neutron monitors [65].

The Mother's Day event, due to its uniqueness and complexity, has been studied by several scientists and groups worldwide [66–68]. Even though not much time has passed

since the occurrence of the event, various investigations in the scientific literature have not only examined the solar and following interplanetary conditions that led to this event but also the ionospheric, technological, and geospace impact of the event [52,56,69,70]. Geomagnetic storms can generally affect a variety of technological systems from satellites and communications or navigation systems to power grids. Specifically, the Global Navigation Satellite System (GNSS) signals' quality may be affected since these signals are transmitted through the ionosphere [71].

The extreme geomagnetic storm in May 2024 had an important ionospheric impact (i.e., the ionosphere's dynamics were altered), which has been widely investigated [72] in different areas around the world, mostly of middle or low latitude, e.g., Italy [73], Mexico [61], and India [74]. For example, ref. [75] mentions not only the auroras that were generated during this storm and were visible at latitudes lower than usual both in the northern and southern hemispheres, i.e., $\sim 35^\circ$ N [76] and $\sim 37^\circ$ S [60], but also a considerable ionospheric impact with a characteristic drop in plasma density, as recorded on 11 May. The latter led to a negative ionospheric storm recorded not only at the critical F2-layer frequency (foF2) but also in the Total Electron Content (TEC) [73]. A similar study was conducted in [74]. Ionospheric disturbances caused by the severe G5 geomagnetic storm on 11 May, along with the impact on the GPS kinematic precise point positioning (PPP), were also studied in Danilchuk et al. [77]. Therein, it was concluded that the ionosphere and consequently the positioning were remarkably affected by geomagnetic activity. Therefore, applications that are based on navigation and communication systems could be seriously threatened during such disturbances.

Beyond the aforementioned impacts, the effects on the radiation dose were not at the expected typical levels. For example, Larsen and Mishev [34] studied the Eastern Event (GLE60), which occurred on 15 April 2001, and showed that during a 7.5 h flight from Prague to New York, a pilot was exposed to nearly 2.5% of the typical annual radiation dose. In contrast, no increase in radiation dose was observed during GLE74.

The worldwide Neutron Monitor Network acts as a probe for disturbances in interplanetary space and therefore is a significant scientific tool. The high-resolution NMDB allows different scientific applications concerning space weather monitoring to be developed, such as warnings for upcoming extreme events. Amongst them is GLE Alert++. In the case of 11 May 2024, the GLE Alert ++ system successfully issued an alert.

It is important to highlight that the GLE Alert++ system can detect not only typical GLEs but also challenging cases such as GLE74, which took place under very disturbed geomagnetic conditions. The alert signal was issued by the GLE Alert++ system of the Athens Neutron Monitor Station of the National and Kapodistrian University of Athens, which is available as a federated product on the ESA SWE Portal under the Space Radiation Expert Service Centre, 15 minutes after the onset of the SEP event and 40 minutes prior to its peak.

Moreover, unlike the usual GLEs, where the largest count-rate increases are observed mainly at polar stations, this event also exhibited significant enhancements at neutron monitors with higher cutoff rigidities, indicating a relatively "harder" energy spectrum.

Regarding the anisotropy characteristics, the analysis of asymptotic viewing directions reveals a wide asymptotic cone, suggesting a broad angular distribution of the arriving particles. This finding is consistent with the results of Papaioannou et al. [78], who reported that the angular distribution of SEPs during GLE74 was not narrowly beamed along a single magnetic field axis, but instead showed a relatively broad distribution, with a substantial flux arriving from the anti-Sunward direction during the main phase.

This successful detection proves that the assessment of the GLE Alert++ that took place back in the year 2022 was of significant importance for upgrading the functionality of

the tool and increasing its reliability [79]. It is essential to conduct periodic evaluations of the GLE Alert++ tool to ensure the continuous integrity and quality of the NM data used as inputs for the algorithm.

Author Contributions: Software, P.P.; writing—original draft preparation, M.-C.P. and M.G.; writing—review and editing, M.G., N.B.C. and M.D.; supervision, H.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by ESA SSA SWE Space Radiation Expert Service Centre activities (ESA contract number 4000113187/15/D/MRP) and the ESA Space Safety Programme’s network of space weather service development and pre-operational activities (ESA contract number 4000134036/21/D/MRP). The high-resolution Neutron Monitor Database (NMDB), was funded by the European Union. A.Ne.Mo.S was supported by the Special Research Account of Athens University (70/4/5803).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The authors would like to thank the cosmic ray data providers of the high-resolution Neutron Monitor Database (NMDB), and all the solar, interplanetary, and geomagnetic data providers.

Conflicts of Interest: The authors declare no conflicts of interest.

Note

- ¹ To access the services on the ESA SWE Portal, the user needs to register for an account, which is free.

References

1. Storini, M.; Kudela, K.; Cordaro, E.G.; Massetti, S. Ground-level enhancements during solar cycle 23: Results from SVIRCO, LOMNICKY STIT and LARC neutron monitors. *Adv. Space Res.* **2005**, *35*, 416–420. [\[CrossRef\]](#)
2. Forbush, S.E. Three unusual cosmic-ray increases possibly due to charged particles from the sun. *Phys. Rev.* **1946**, *70*, 771. [\[CrossRef\]](#)
3. Usoskin, I.; Koldobskiy, S.; Kovaltsov, G.A.; Gil, A.; Usoskina, I.; Willamo, T.; Ibragimov, A. Revised GLE database: Fluences of solar energetic particles as measured by the neutron-monitor network since 1956. *Astron. Astrophys.* **2020**, *640*, A17. [\[CrossRef\]](#)
4. Vainio, R.; Desorgher, L.; Heynderickx, D.; Storini, M.; Flückiger, E.; Horne, R.B.; Kovaltsov, G.A.; Kudela, K.; Laurenza, M.; McKenna-Lawlor, S.; et al. Dynamics of the Earth’s Particle Radiation Environment. *Space Sci. Rev.* **2009**, *147*, 187–231. [\[CrossRef\]](#)
5. Klein, K.-L.; Dalla, S. Acceleration and Propagation of Solar Energetic Particles. *Space Sci. Rev.* **2017**, *212*, 1107–1136. [\[CrossRef\]](#)
6. Reames, D.V. Particle acceleration at the Sun and in the heliosphere. *Space Sci. Rev.* **1999**, *90*, 413–491. [\[CrossRef\]](#)
7. Cliver, E.W.; Kahler, S.W.; Reames, D.V. Coronal Shocks and Solar Energetic Proton Events. *Astrophys. J.* **2004**, *605*, 902. [\[CrossRef\]](#)
8. Desai, M.; Giacalone, J. Large gradual solar energetic particle events. *Living Rev. Sol. Phys.* **2016**, *13*, 3. [\[CrossRef\]](#) [\[PubMed\]](#) [\[PubMed Central\]](#)
9. Firoz, K.A.; Gan, W.Q.; Li, Y.P.; Rodríguez-Pacheco, J.; Kudela, K. On the Possible Mechanism of GLE Initiation. *Astrophys. J.* **2019**, *872*, 178. [\[CrossRef\]](#)
10. Kuwabara, T.; Bieber, J.W.; Clem, J.; Evenson, P.; Pyle, R.; Munakata, K.; Yasue, S.; Kato, C.; Akahane, S.; Koyama, M.; et al. Real-time cosmic ray monitoring system for space weather. *Space Weather* **2006**, *4*. [\[CrossRef\]](#)
11. Mishev, A.; Poluianov, S. About the Altitude Profile of the Atmospheric Cut-Off of Cosmic Rays: New Revised Assessment. *Sol. Phys.* **2021**, *296*, 129. [\[CrossRef\]](#)
12. Hubert, G.; Aubry, S. Study of the impact of past extreme solar events on the modern air traffic. *Space Weather* **2021**, *19*, e2020SW002665. [\[CrossRef\]](#)
13. Papaioannou, A. What do we learn from ground level enhancements? In NMDB@Athens: Proceedings of the Hybrid Symposium on Cosmic Ray Studies with Neutron Detectors, 26–30 September 2022; Kiel University Publishing: Kiel, Germany; pp. 113–130, ISSN 2748-3150(Electronic).

14. Guo, J.; Li, X.; Zhang, J.; Dobynde, M.I.; Wang, Y.; Xu, Z.; Berger, T.; Semkova, J.; Wimmer-Schweingruber, R.F.; Hassler, D.M.; et al. The first ground level enhancement seen on three planetary surfaces: Earth, Moon, and Mars. *Geophys. Res. Lett.* **2023**, *50*, e2023GL103069. [[CrossRef](#)]
15. Shea, M.A.; Smart, D.F. Space Weather and the Ground-Level Solar Proton Events of the 23rd Solar Cycle. *Space Sci. Rev.* **2012**, *171*, 161–188. [[CrossRef](#)]
16. Aschwanden, M.J. GeV Particle Acceleration in Solar Flares and Ground Level Enhancement (GLE) Events. *Space Sci. Rev.* **2012**, *171*, 3–21. [[CrossRef](#)]
17. Souvatzoglou, G.; Mavromichalaki, H.; Sarlanis, C.; Mariatos, G.; Belov, A.; Eroshenko, E.; Yanke, V. Real-time GLE alert for the December 13, 2006 event, at the ANMODAP center. *Adv. Space Res.* **2009**, *43*, 728–734. [[CrossRef](#)]
18. Miroshnichenko, L.; Vashenyuk, E.; Pérez-Peraza, J. Solar cosmic rays: 70 years of ground-based observations. *Geomagn. Aeron.* **2013**, *53*, 541–560. [[CrossRef](#)]
19. Papaioannou, A.; Kouloumvakos, A.; Mishev, A.; Vainio, R.; Usoskin, I.G.; Herbst, K.; Rouillard, A.P.; Anastasiadis, A.; Gieseler, J.; Wimmer-Schweingruber, R.F.; et al. The first ground-level enhancement of solar cycle 25 on 28 October 2021. *Astron. Astrophys.* **2022**, *660*, 9. [[CrossRef](#)]
20. Anashin, V.; Belov, A.V.; Eroshenko, E.; Kryakunova, O.; Mavromichalaki, H.; Ishutin, I.; Sarlanis, C.; Souvatzoglou, G.; Vashenyuk, E.; Yanke, V. The ALERT signal of ground level enhancements of solar cosmic rays: Physics basis, the ways of realization and development. In Proceedings of the 31st International Cosmic Ray Conference (ICRC 2009), Łódź, Poland, 7–15 July 2009.
21. Mavromichalaki, H.; Paouris, E.; Karalidi, T. Cosmic-ray modulation: An Empirical relation with solar and heliospheric parameters. *Sol. Phys.* **2007**, *245*, 369–390. [[CrossRef](#)]
22. Souvatzoglou, G.; Papaioannou, A.; Mavromichalaki, H.; Dimitroulakos, J.; Sarlanis, C. Optimizing the real-time ground level enhancement alert system based on neutron monitor measurements: Introducing GLE Alert Plus. *Space Weather* **2014**, *12*, 633–649. [[CrossRef](#)]
23. Pomerantz, M.; Duggal, S. Interplanetary acceleration of solar cosmic rays to relativistic energy. *J. Geophys. Res.* **1974**, *79*, 913–919. [[CrossRef](#)]
24. Núñez, M.; Reyes-Santiago, P.J.; Malandraki, O. Real-time prediction of the occurrence of GLE events. *Space Weather* **2017**, *15*, 861–873. [[CrossRef](#)]
25. Malandraki, O.E.; Crosby, N.B. Solar energetic particles and space weather: Science and applications. In *Solar Particle Radiation Storms Forecasting and Analysis*; Malandraki, O.E., Crosby, N.B., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2018; Volume 444, pp. 1–26.
26. Poluianov, S.V.; Usoskin, I.G.; Mishev, A.L.; Shea, M.A.; Smart, D.F. GLE and Sub-GLE Redefinition in the Light of High-Altitude Polar Neutron Monitors. *Sol. Phys.* **2017**, *292*, 176. [[CrossRef](#)]
27. Mavromichalaki, H.; Paschalis, P.; Gerontidou, M.; Papailiou, M.-C.; Paouris, E.; Tezari, A.; Lingri, D.; Livada, M.; Stassinakis, A.N.; Crosby, N.; et al. The Updated Version of the A.Ne.Mo.S. GLE Alert System: The Case of the Ground-Level Enhancement GLE73 on 28 October 2021. *Universe* **2022**, *8*, 378. [[CrossRef](#)]
28. Shea, M.A.; Smart, D.F. A summary of major solar proton events. *Sol. Phys.* **1990**, *127*, 297–320. [[CrossRef](#)]
29. Kravtsova, M.V.; Olemskoy, S.V.; Sdobnov, V.E. Ground level enhancements of cosmic rays on October–November 2003. *J. Atmos. Sol.-Terr. Phys.* **2021**, *221*, 105707. [[CrossRef](#)]
30. Mavromichalaki, H. The physics of cosmic rays applied to space weather. In *Advances in Solar and Solar-Terrestrial Physics*; Maris, G., Demetrescu, C., Eds.; Research Signpost Editing House (India): Trivandrum, India, 2012; Volume 135–161.
31. Volkov, E.; Chelidze, K.; Gromushkin, D.; Khokhlov, S.; Khomchuk, E.; Petrukhin, A.; Shulzhenko, I. The observation of Ground Level Enhancement GLE 77 by the neutron detectors of the Experimental Complex NEVOD. *arXiv* **2025**, arXiv:2511.23048. [[CrossRef](#)]
32. Mavromichalaki, H.; Papailiou, M.-C.; Livada, M.; Gerontidou, M.; Paschalis, P.; Stassinakis, A.; Abunina, M.; Shlyk, N.; Abunin, A.; Belov, A.; et al. Unusual Forbush Decreases and Geomagnetic Storms on 24 March, 2024 and 11 May, 2024. *Atmosphere* **2024**, *15*, 1033. [[CrossRef](#)]
33. Belov, A.; Eroshenko, E.; Mavromichalaki, H.; Plainaki, C.; Yanke, V. A study of the ground level enhancement of 23 February 1956. *Adv. Space Res.* **2005**, *35*, 697–701. [[CrossRef](#)]
34. Larsen, N.; Mishev, A. Relationship between NM data and radiation dose at aviation altitudes during GLE events. *Space Weather* **2024**, *22*, e2024SW003885. [[CrossRef](#)]
35. Baker, D.N. What is space weather? *Adv. Space Res.* **1998**, *22*, 7–16. [[CrossRef](#)]
36. Wrenn, G.L.; Rodgers, D.J.; Ryden, K.A. A solar cycle of spacecraft anomalies due to internal charging. *Ann. Geophys.* **2002**, *20*, 953–956. [[CrossRef](#)]
37. Wrenn, G.L. Chronology of ‘killer’ electrons: Solar cycles 22 and 23. *J. Atmos. Sol.-Terr. Phys.* **2009**, *71*, 1210–1218. [[CrossRef](#)]
38. Rama Rao, P.V.S.; Gopi Krishna, S.; Vara Prasad, J.; Prasad, S.N.V.S.; Prasad, D.S.V.V.D.; Niranjana, K. Geomagnetic storm effects on GPS based navigation. *Ann. Geophys.* **2009**, *27*, 2101–2110. [[CrossRef](#)]

39. Chapman, S.C.; McIntosh, S.W.; Leamon, R.J.; Watkins, N.W. Quantifying the solar cycle modulation of extreme space weather. *Geophys. Res. Lett.* **2020**, *47*, e2020GL087795. [\[CrossRef\]](#)
40. Dyer, A.C.R.; Ryden, K.A.; Hands, A.D.P.; Dyer, C.; Burnett, C.; Gibbs, M. Zenith: A radiosonde detector for rapid-response ionizing atmospheric radiation measurements during solar particle events. *Space Weather* **2018**, *16*, 261–272. [\[CrossRef\]](#)
41. Larsen, N.; Mishev, A.L. Analysis of the ground level enhancement GLE 60 on 15 April 2001, and its space weather effects: Comparison with dosimetric measurements. *Space Weather* **2023**, *21*, e2023SW003488. [\[CrossRef\]](#)
42. Baker, D.N.; Daly, E.; Daglis, I.; Kappenman, J.G.; Panasyuk, M. Effects of Space Weather on Technology Infrastructure. *Space Weather* **2004**, *2*. [\[CrossRef\]](#)
43. Eastwood, J.P.; Biffis, E.; Hapgood, M.A.; Green, L.; Bisi, M.M.; Bentley, R.D.; Wicks, R.; McKinnell, L.-A.; Gibbs, M.; Burnett, C. The Economic Impact of Space Weather: Where Do We Stand? *Risk Anal.* **2017**, *37*, 206–218. [\[CrossRef\]](#)
44. Buzulukova, N.; Tsurutani, B. Space Weather: From solar origins to risks and hazards evolving in time. *Front. Astron. Space Sci.* **2022**, *9*, 1017103. [\[CrossRef\]](#)
45. Al Anid, H.; Lewis, B.; Bennett, L.; Takada, M.; Duldig, M. Aircrew radiation dose estimates during recent solar particle events and the effect of particle anisotropy. *Radiat. Prot. Dosim.* **2014**, *158*, 355–367. [\[CrossRef\]](#)
46. Mertens, C.; Meier, M.; Brown, S.; Norman, R.; Xu, X. Nairas aircraft radiation model development, dose climatology, and initial validation. *Space Weather* **2013**, *11*, 603–635. [\[CrossRef\]](#)
47. Copeland, K. CARI-7A: Development and validation. *Radiat. Prot. Dosim.* **2017**, *175*, 419–431. [\[CrossRef\]](#)
48. Hands, A.; Lei, F.; Davis, C.; Clewer, B.; Dyer, C.; Ryden, K. A new model for nowcasting the aviation radiation environment with comparisons to in situ measurements during gles. *Space Weather* **2022**, *20*, e2022SW003155. [\[CrossRef\]](#)
49. Bütikofer, R.; Flückiger, E.O. Differences in published characteristics of GLE 60 and their consequences on computed radiation dose rates along selected flight paths. *J. Phys. Conf. Ser.* **2013**, *409*, 012166. [\[CrossRef\]](#)
50. Bütikofer, R.; Flückiger, E. What are the causes for the spread of gle parameters deduced from nm data? *J. Phys. Conf. Ser.* **2015**, *632*, 012053. [\[CrossRef\]](#)
51. Paul, K.S.; Moses, M.; Haralambous, H.; Oikonomou, C. Effects of the Mother's Day Superstorm (10–11 May 2024) over the Global Ionosphere. *Remote Sens.* **2025**, *17*, 859. [\[CrossRef\]](#)
52. Hayakawa, H.; Ebihara, Y.; Mishev, A.; Koldobskiy, S.; Kusano, K.; Bechet, S.; Yashiro, S.; Iwai, K.; Shinbori, A.; Mursula, K.; et al. The Solar and Geomagnetic Storms in May 2024: A Flash Data Report. *arXiv* **2025**, arXiv:2407.07665. [\[CrossRef\]](#)
53. Usoskin, I.; Braun, I.; Gladysheva, O.; Horandel, J.; Kovaltsov, G.; Jamsen, T.; Starodubtsev, S. Forbush decreases of cosmic rays: Does the recovery phase depend on energy? *Theor. Comput. Sci.* **2008**, *37*, 3265. [\[CrossRef\]](#)
54. Wang, R.; Liu, D.; Zhao, X.; Hu, H. Unveiling key factors in solar eruptions leading to the solar superstorm in 2024 May. *Astron. Astrophys.* **2024**, *692*, A112. [\[CrossRef\]](#)
55. Riggi, F.; Hertle, L.; Abbrescia, M.; Avanzini, C.; Baldini, L.; Ferroli, R.; Batignani, G.; Battaglieri, M.; Boi, S.; Boike, J.; et al. High latitude observation of the Forbush decrease during the May 2024 solar storms with muon and neutron detectors on Svalbard. *Adv. Space Res.* **2025**, *76*, 1225–1239. [\[CrossRef\]](#)
56. Abunina, M.A.; Shlyk, N.S.; Belov, A.V.; Belov, S.M.; Abunin, A.A. On the features of great Forbush effect during May 2024 extreme geomagnetic storm. *Adv. Space Res.* **2025**, *76*, 7578–7586. [\[CrossRef\]](#)
57. Smart, D.F.; Shea, M.A.; Flückiger, E.O. Magnetosphere models and trajectory computations. *Space Sci. Rev.* **2000**, *93*, 305–333. [\[CrossRef\]](#)
58. Tsyganenko, N.A. A magnetospheric magnetic field model with a warped tail current sheet. *Planet. Space Sci.* **1989**, *37*, 5–20. [\[CrossRef\]](#)
59. Kurt, V.; Belov, A.; Kudela, K.; Mavromichalaki, H.; Kashapova, L.; Yushkov, B.; Sgouropoulos, C. Onset Time of the GLE 72 Observed at Neutron Monitors and its Relation to Electromagnetic Emissions. *Sol. Phys.* **2019**, *294*, 22. [\[CrossRef\]](#)
60. Karan, D.K.; Martinis, C.R.; Daniell, R.E.; Eastes, R.W.; Wang, W.; McClintock, W.E.; Michell, R.G.; England, S. GOLD observations of the merging of the Southern Crest of the equatorial ionization anomaly and aurora during the 10 and 11 May 2024 Mother's Day super geomagnetic storm. *Geophys. Res. Lett.* **2024**, *51*, e2024GL110632. [\[CrossRef\]](#)
61. Crosby, N.; Mavromichalaki, H.; Malandraki, O.; Gerontidou, M.; Karavolos, M.; Lingri, D.; Makrantonis, P.; Papailiou, M.; Paschalis, P.; Tezari, A. Very high energy solar energetic particle events and ground level enhancement events: Forecasting and alerts. *Space Weather* **2004**, *22*, e2023SW003839. [\[CrossRef\]](#)
62. Mishev, A.; Usoskin, I. Application of a full chain analysis using neutron monitor data for space weather studies. In Proceedings of the 25th European Cosmic Ray Symposium (ECRS 2016), Turin, Italy, 4–9 September 2016.
63. Mishev, A.; Usoskin, I.; Raukunen, O.; Paassilta, M.; Valtonen, E.; Kocharov, L.; Vainio, R. First Analysis of Ground-Level Enhancement (GLE) 72 on 10 September 2017: Spectral and Anisotropy Characteristics. *Sol. Phys.* **2018**, *293*, 136. [\[CrossRef\]](#)
64. Bütikofer, R.; Agueda, N.; Heber, B.; Galsdorf, D.; Vainio, R. Assessment of Source and Transport Parameters of Relativistic SEPs Based on Neutron Monitor Data. *arXiv* **2016**, arXiv:1612.08922. [\[CrossRef\]](#)

65. Gonzalez-Esparza, J.A.; Sanchez-Garcia, E.; Sergeeva, M.; Corona-Romero, P.; Gonzalez-Mendez, L.X.; Valdes-Galicia, J.F.; Aguilar-Rodriguez, E.; Rodriguez-Martinez, M.; Ramirez-Pacheco, C.; Castellanos, C.I.; et al. The mother's day geomagnetic storm on 10 May 2024: Aurora observations and low latitude space weather effects in Mexico. *Space Weather* **2024**, *22*, e2024SW004111. [\[CrossRef\]](#)
66. Blanco, J.; Moreno, M.; Pérez, D.; Guerrero, C.; Comazzi, A.; Solana, P.; Población, O.; García Tejedor, J.I.; Gregorio, S.; Carretero, A. Solar event of May 11, 2024 some conclusions on the behavior of cosmic rays. In Proceedings of the 39th International Cosmic Ray Conference, Geneva, Switzerland, 15–24 July 2025; Volume 1276. [\[CrossRef\]](#)
67. Mishev, A.; Mishev, A.; Larsen, N.; Koldobskiy, S.; Usoskin, I. Spectra and anisotropy during GLE 74 on 11 May 2024 derived using neutron monitor data. In Proceedings of the 39th International Cosmic Ray Conference, Geneva, Switzerland, 15–24 July 2025; Volume 1335. [\[CrossRef\]](#)
68. Thakur, P.; Vichare, G. Some Interesting Observations of Cosmic Ray Variations during the Extreme Solar Storm on 2024 May 10–11. *Astrophys. J.* **2025**, *991*, 50. [\[CrossRef\]](#)
69. Tulasi Ram, S.; Veenadhari, B.; Dimri, A.P.; Bulusu, J.; Bagiya, M.; Gurubaran, S.; Parihar, N.; Remya, B.; Seemala, G.; Singh, R.; et al. Super-intense geomagnetic storm on 10–11 May 2024: Possible mechanisms and impacts. *Space Weather* **2024**, *22*, e2024SW004126. [\[CrossRef\]](#)
70. Pierrard, V.; Verhulst, T.G.W.; Chevalier, J.-M.; Bergeot, N.; Winant, A. Effects of the Geomagnetic Superstorms of 10–11 May 2024 and 7–11 October 2024 on the Ionosphere and Plasmasphere. *Atmosphere* **2025**, *16*, 299. [\[CrossRef\]](#)
71. Park, J.; Spogli, L.; Azeez, A.; Alfonsi, L.; Cesaroni, C.; Romano, V.; Akande, A. The impact of Mother's Day Storms in May 2024 on Precise Point Positioning at mid-latitudes. *Ann. Geophys.* **2025**, *68*, A214. [\[CrossRef\]](#)
72. Carmo, C.S.; Dai, L.; Wrasse, C.M.; Barros, D.; Takahashi, H.; Figueiredo, C.A.O.B.; Wang, C.; Li, H.; Liu, Z. Ionospheric response to the extreme 2024 mother's day geomagnetic storm over the Latin American sector. *Space Weather* **2024**, *22*, e2024SW004054. [\[CrossRef\]](#)
73. Spogli, L.; Alberti, T.; Bagiacchi, P.; Cesaroni, C.; Coco, I.; Di Mauro, D.; Ippolito, A.; Marcocci, C.; Pezzopane, M.; Pica, E.; et al. The Effects of the May 2024 Mother's Day Superstorm over the Mediterranean Sector: From Data to Public Communication. *Ann. Geophys.* **2024**, *67*, PA218. [\[CrossRef\]](#)
74. Jain, A.; Trivedi, R.; Jain, S.; Choudhary, R.K. Effects of the Super Intense Geomagnetic Storm on 10–11 May, 2024 on Total Electron Content at Bhopal. *Adv. Space Res.* **2025**, *75*, 953–965. [\[CrossRef\]](#)
75. Paul, K.S.; Haralambous, H.; Moses, M.; Oikonomou, C.; Potirakis, S.M.; Bergeot, N.; Chevalier, J.-M. Investigation of the Ionospheric Response on Mother's Day 2024 Geomagnetic Superstorm over the European Sector. *Atmosphere* **2025**, *16*, 180. [\[CrossRef\]](#)
76. Foster, J.C.; Erickson, J.; Nishimura, Y.; Zhang, S.R.; Bush, D.C.; Coster, A.J.; Meade, E.; Franco-Diaz, E. Imaging the May 2024 extreme aurora with ionospheric total electron content. *Geophys. Res. Lett.* **2024**, *51*, e2024GL111981. [\[CrossRef\]](#)
77. Danilchuk, E.; Yasyukevich, Y.; Vesnin, A.; Klyusilov, A.; Zhang, B. Impact of the May 2024 Extreme Geomagnetic Storm on the Ionosphere and GNSS Positioning. *Remote Sens.* **2025**, *17*, 1492. [\[CrossRef\]](#)
78. Papaioannou, A.; Mishev, A.; Usoskin, I.; Heber, B.; Vainio, R.; Larsen, N.; Jarry, M.; Rouillard, A.P.; Sheshvan, N.T.; Laurenza, M.; et al. The High-Energy Protons of the Ground Level Enhancement (GLE74) Event on 11 May 2024. *Sol. Phys.* **2025**, *300*, 73. [\[CrossRef\]](#)
79. Mavromichalaki, H.; Paschalis, P.; Gerontidou, M.; Tezari, A.; Papailiou, M.-C.; Lingri, D.; Livada, M.; Stassinakis, A.; Crosby, N.; Dierckxsens, M. An Assessment of the GLE Alert++ Warning System. *Atmosphere* **2024**, *15*, 345. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.