PROCEEDINGS OF SCIENCE

Spectra and anisotropy during GLE 74 on 11 May 2024 derived using neutron monitor data

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Study of solar energetic particles is important to provide the necessary basis to understand the mechanisms of their acceleration and propagation in interplanetary space. It is known that following solar eruptive processes, such as solar flares and/or coronal mass ejections, solar ions can be accelerated to high energies, even in the GeV/n range. In this latter case, the SEP energy is great enough to induce an atmospheric cascade in the Earth's atmosphere, which secondary particles can be registered by ground-based detectors, such as neutron monitors (NMs). This class of events is known as ground-level enhancements (GLEs). A notable event occurred on May 11, 2024, observed by NMs and particle detectors aboard spacecraft in near-Earth orbit. The event was observed during the deep phase of a significant Forbush decrease and one of the strongest geomagnetic storms, which make the analysis of this event particularly challenging. Here we performed a precise analysis of NM data records and derived the spectral and angular characteristics of the SEPs leading to this GLE. We modeled the particle propagation in the Earth's magnetosphere and atmosphere. The solar protons spectra and pitch angle distributions were obtained in their dynamical development throughout the event.

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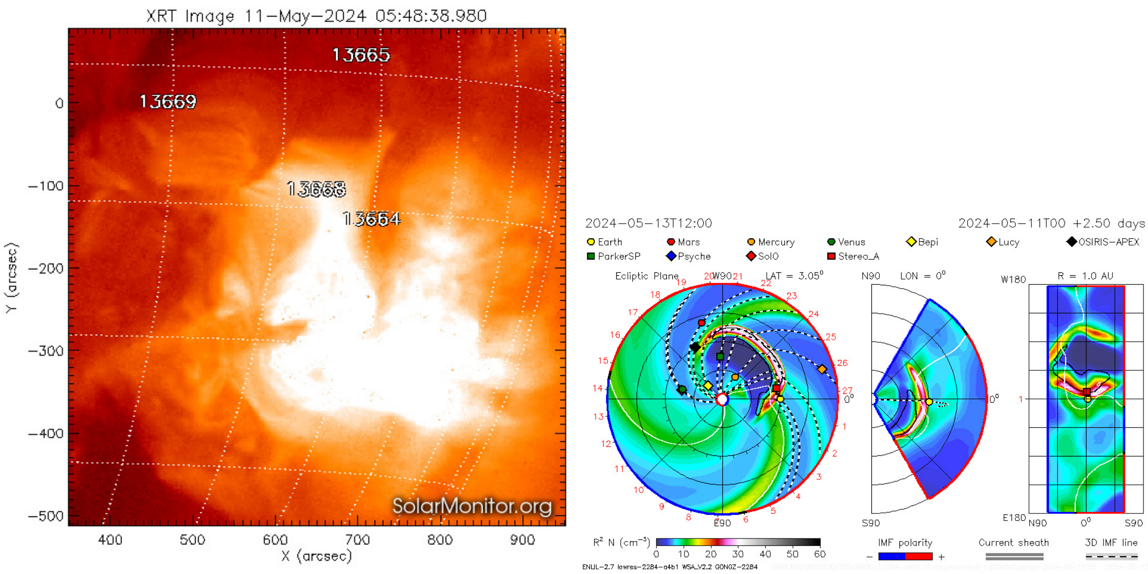
1. Introduction

Eruptive processes on the Sun, such as solar flares and/or coronal mass ejections (CMEs) accelerate solar ions up to the high-energy range, in some cases even up to the nearly relativistic and relativistic energy range. Those particles are known as solar energetic particles (SEPs) [1–4]. The SEP flux is greater than that of the background galactic cosmic ray (GCR) flux and can last for several hours [5]. Most of SEP events reveal energies of about 10 MeV/n region, occasionally up to 100 MeV/n, rarely, about several times per solar cycle, they can can be accelerated up to the GeV/n range [6]. When the SEP energy is in the 0.5 GeV/n range, it is sufficient to induce a complicated hadron-electromagnetic-muon particle shower in the Earth's atmosphere, which secondaries can reach the Earth's surface, eventually registered by convenient detectors such as neutron monitors (NMs) [7]. Such events, observed as an increase of count rate in particle detectors, are called ground level enhancements (GLEs) [8, 9]. Herein, we report selected observations and analysis of a notable event, that is GLE # 74 on 11 May 2024.

2. Observations of GLE 74 on May 11, 2024

As a result of a enhanced solar activity in the period of May 2024, the Sun produced several M and X class flares, as well as the accompanied CMEs. The eruptions were popped out by NOAA Active Region 13664, on the southeastern limb. Several strong flares were observed, namely on 8 May 2024 a X1.0 at 4:37 UT, M8.7 at 11:26, and X1.0 at 21:08, accompanied with CMEs. Even more flares and CMEs were observed on 9 and 10 May 2024. However, a complicated, that is, sympathetic eruption produced by NOAA AR 13668 and NOAA AR 13664 (Fig. 1a) triggered a flare, which accelerated solar ions, so that they were registered by the global NM network (Fig. 2).



(a) X 5.8 solar flare from AR 13664 and 13668.

(b) Heliospheric obtained with ENLIL model.

Figure 1: Solar eruption and heliospheric conditions as simulated with ENLIL model during during during GLE # 74.

As a result of the several consecutive eruptions as discussed above, the GLE74 occurred during disturbed interplanetary (Fig. 1b) and geomagnetospheric conditions, which shaped the NM count rate variation. A G5-class geomagnetic storm lasted from 10–13 May 2024, which peaked on 11 May 2024 with Disturbance Storm Time (Dst) index of –412 nT [10]. Most importantly, a deep Forbush decrease (FD) was also observed by NMs. The GLE onset was observed by the bulk of NMs, the count rate variation of selected NM stations is presented in Fig.2. The event revealed gradual increase and notable anisotropy. The proper determination of NM counts amplitudes was rather difficult, because SEP propagated under disturbed conditions due to the sequence of popped CMEs, the mentioned above FD and most importantly the severe geomagnetic storm.

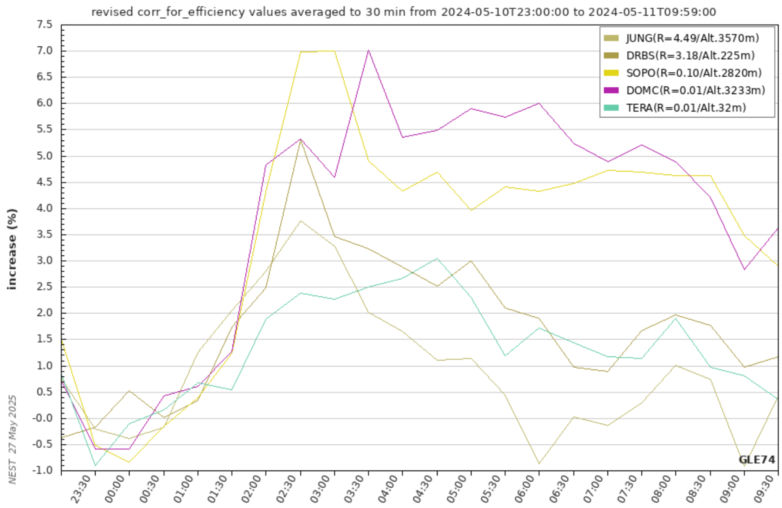


Figure 2: Count rate variation of selected NMs during GLE # 74 on 11 May 2024.

3. Analysis of GLE 74

Herein, we collected the available records from the global NM network and several space-probes. As a first step we modeled the magnetospheric conditions with OTSO (Open-source geomagneToSphere prOpagation tool) [11] employing combination of internal, that is, the International Geomagnetic Reference Field [12] and as external filed the Tsyganenko 01 (TSY01S) model [13]. We emphasize that TSY01S model is similar to Tsyganenko 01 (TSY01) model [14, 15], but is specifically parameterized for geomagnetic storm events. This combination of models provides realistic description of the geomagnetosphere during stormy magnetospheric conditions [16, 17]. Herein, we computed the variation of the effective rigidity cut-off during the event, that is, its reduction, which allowed us to properly estimate the contribution of SEPs to the NM counts. In addition, similarly to [18] we accounted the FD, so that we performed analysis with de-trended NM records.

The method for analysis of NM data 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 [19]. An illustration of the computed asymptotic directions of selected NMs is shown in Fig. 3.

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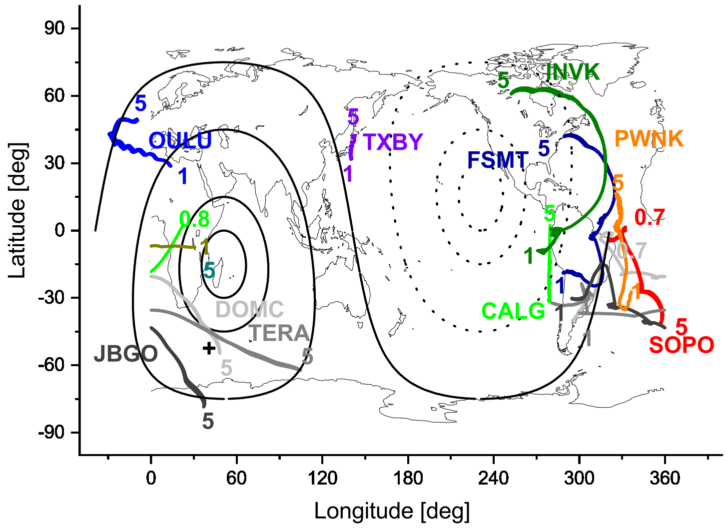

Figure 3: Asymptotic directions of selected NM stations and contour plots of equal pitch angles relative to the derived anisotropy axis during GLE # 74 on 11 May 2024. The cross depicts the interplanetary magnetic field (IMF) direction obtained by the Advanced Composition Explorer (ACE) satellite.

Herein, we employed method developed by [20–22], lately improved by us, the full description and applications are given elsewhere [23–25]. We emphasize that during the analysis it is necessary to repreduce the count rate increases of all stations with statistically significant responses as well as stations with marginal or zero responses [20, 25], the latter important to constrain the SEP flux, hardness of the spectra, angular distribution. For this particular event we assume all non-polar stations to be with zero response, because their count rate increases are due to geomagnetospheric effects, that is, reduction of the rigidity cutoff and the recovery of the FD. Therefore, our analysis is similar to [18].

4. Results from the analysis

Using the de-trended NM records, the method described above and employing combination of Levenberg-Marquardt algorithm [26, 27] and Ridge optimization [28], which allowed robust convergence [29], we derived the spectra and angular distribution of the SEPs during the GLE 74, an illustration presented in Fig. 4.

The best fit for the SEP spectra is obtained with modified power-law Eq. 1:

$$J_{\parallel}(P) = j_0 P^{-(\gamma+\delta\gamma(P-1))} \tag{1}$$

where the flux of particles with rigidity P in [GV] is along the axis of symmetry identified by geographic latitude Ψ and longitude Λ and the power-law exponent is γ with the steepening of $\delta\gamma$. Accordingly, the angular distribution of the arriving SEPs is depicted by complicated PAD Eq. 2, which account particles arriving from anti-sun direction:

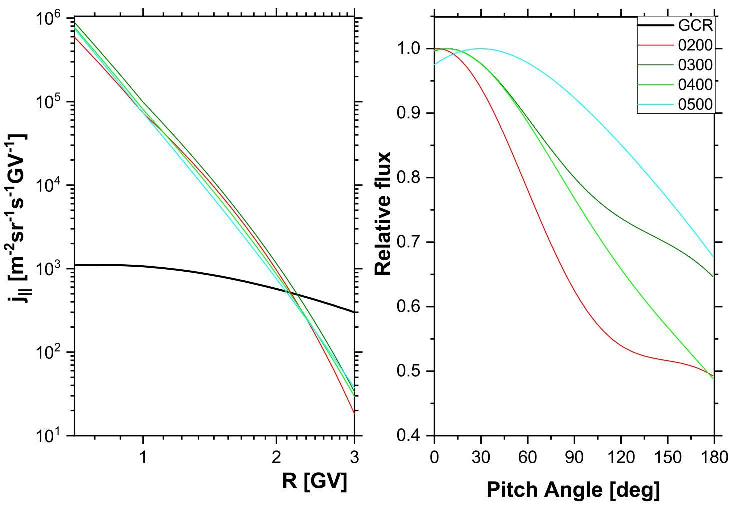

Figure 4: Derived rigidity spectra (left panel) and PAD (right panel) during selected stages of GLE # 74 as denoted in the legend. The black line on the left panel depicts the GCR background.

$$G(\alpha(P)) \sim exp(-\alpha^2/\sigma_1^2) + B * exp(-(\pi - \alpha)^2/\sigma_2^2) \tag{2}$$

where α is the pitch angle, σ_1 and σ_2 are parameters corresponding to the width of the pitch angle distribution.

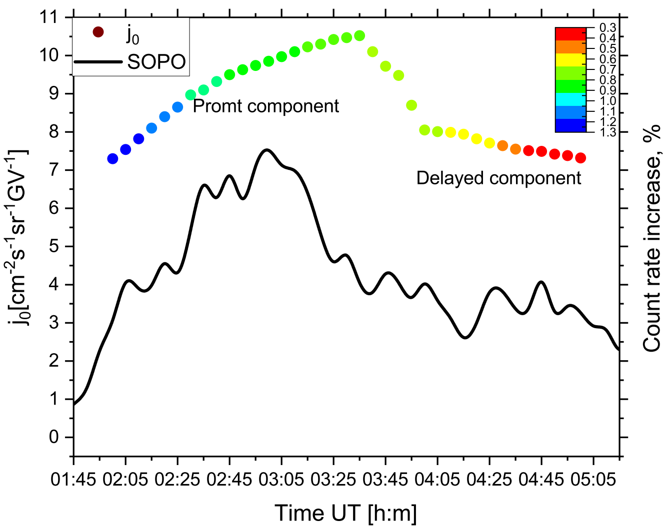

Figure 5: SEP intensity throughout the event within count rate increase variation of SOPO.

The derived SEP spectra were moderately hard with slopes γ ranging from about 5 during the event onset to about 6.3 at the late phase of the event. A significant roll-off of the spectra $\delta\gamma$, that is steepening in the high-rigidity/energy part, was observed, which gradually diminished throughout the event as depicted in Fig. 5. A notable anti-Sun SEP flux was observed, which resulted in a relatively broad angular distribution, specifically during the main phase (maximum particle flux) stage of the event.

5. Conclusions

Herein, we reported observations for GLE 74. We presented modeling and reconstruction of the spectral and angular characteristics of GLE causing SEPs. The analysis of this event was particularly challenging, because the count rate increase of NMs were shaped by a complex interplay between the direct signal from solar particles, the recovery of the FD, and the complex geomagnetospheric conditions. We showed that during the main phase of the event the rigidity spectrum exhibited moderate hardness with a notable spectral rollover ($\delta\gamma$). We would like to emphasize that a SEP flux from anti-Sun direction was detected, exhibiting a relatively broad angular distribution. The results from this study would allow the community further investigations related to SEP origin and propagation.

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