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The first GLE (# 73 – 28-Oct-2021) of solar cycle 25: study using space-borne and NM data

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The first solar proton event of solar cycle 25 was detected on 28 October 2021 by several neutron monitors (NMs) in the polar region; the strongest signal was registered by the DOMC/DOMB monitors located at the Antarctic plateau at Concordia French-Italian research station, as well as the fleet of space-borne instruments. It is identified as the GLE (ground-level enhancement) # 73 in the International GLE database. Here, we report the observations and the study of this event on the basis of the global NM network and SOHO/ERNE records. We present the derived angular and spectral features of solar energetic protons, including their dynamical evolution throughout the event employing a state-of-the-art model based on analysis of the neutron monitor data. We discuss the origin of the prompt and delayed components of the GLE-inducing solar protons. Several applications of the derived results are discussed.

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1. Introduction

Occasionally solar eruptions as solar flares and/or coronal mass ejections produce solar energetic particle (SEP) events, observed as enhancements of fluxes of protons, heavy ions and electrons [1]. Systematic study of SEP properties is important in order to reveal particle acceleration on the Sun. A specific interest represent SEPs with energy reaching about GeV/nucleon or even greater values, which can produce secondary particles in the Earth's atmosphere, eventually registered by ground-based detectors, *e.g.* neutron-monitors (NMs), known as ground-level enhancements (GLEs) [2, 3].

GLEs can be studied with ground-based instruments, namely NMs [4, 5]. Stations at different geographic regions are sensitive to a different part of the SEP spectra and arrival direction [6]. Since GLEs occur sporadically and naturally differ from each other in spectra, particle flux, anisotropy, duration and time evolution, they are studied on a case-by-case basis. In this work, we present observations and analysis of the first event of solar cycle 25, that is GLE # 73 occurred on 28 October 2021 [7].

2. GLE # 73 on 28 October 2021

The first GLE event of the current Solar Cycle 25 was observed on 28 October 2021. The count rate increase of the bulk of the NM stations was weak (below 20% in respect to the galactic cosmic ray (GCR) background), where the greatest signal was registered low rigidity cut-off region stations [7], namely South Pole SOPO (5.4%) and South Pole Bare SOPB (5.7%), DOMC (7.3%) and DOMB (14%), standard and bare monitors, respectively. We emphasize that high-altitude polar NMs have greater sensitivity in energy to SEPs compared to the sea-level stations due to the reduced atmospheric attenuation of about 300 MeV/nucleon for the former and about 430 MeV/nucleon for the latter [8]. The event was associated with a class X1.0 flare located at S28W01 and an asymmetric halo coronal mass ejection (CME), brightest over the southern hemisphere of the Sun [9].

3. Analysis of NM records during GLE # 73

For reliable analysis of NM records it is necessary to possess enough NM stations [10]. The methods for an analysis of GLEs using NM data are based on modeling of the global NM network response and unfolding n model parameters over the experimental records of m NMs [11, 12].

In general, the relative count rate increase of a given NM during GLE can be modelled using:

$$\frac{\Delta N(P_{\mathrm{cut}})}{N(t)} = \frac{\sum_i \sum_k \int_{P_{\mathrm{cut}}}^{P_{\mathrm{max}}} J_{\mathrm{sep_i}}(P,t) S_{i,k}(P) G_i(\alpha(P,t)) A_i(P) dP}{\sum_i \int_{P_{\mathrm{cut}}}^{\infty} J_{\mathrm{GCR_i}}(P,t) S_i(P) dP} \tag{1}$$

where $N(t)$ is the count rate due to GCR, $\Delta N(P_{\mathrm{cut}})$ is the count rate increase due to solar particles. J_{sep} is the rigidity spectrum of SEPs i (proton or α-particle), $J_{\mathrm{GCR_i}}(P,t)$ is the rigidity spectrum of the i component (proton or α-particle, etc...) of GCR at given time t, $G(\alpha(P,t))$ is the pitch angle distribution, note for GCRs the angular distribution is assumed to be isotropic, A(P) is a discrete function with $A(P)$=1 for allowed trajectories and $A(P)$=0 for forbidden trajectories. Function A is derived during the asymptotic cone computations. P_{cut} is the minimum rigidity cut-off of the station, accordingly, P_{cut} is the maximum rigidity of SEPs considered in the model, whilst for GCR $P_{\mathrm{max}} = \infty$. S_k is the NM yield function for vertical and for oblique incidence SEPs, k=13. The contribution of oblique SEPs to NM response is particularly important for modeling strong and/or very anisotropic events, while for weak and/or moderately strong events it is possible to consider only vertical ones and using S_k for an isotropic case, which considerably simplifies the computations [13], as in this study.

Here we employed a method based on employment of validated NM yield function, [14, 15] and robust optimization [16, 17] which was used for the analysis of a plethora of GLEs [18–20]. An illustration of the computed asymptotic direction for several selected NMs used for the analysis is presented in Fig. 1. Here the magnetospheric computations, that is the rigidity cut-off and asymptotic directions of each NM station used in the analysis were performed using a new open source tool OTSO [21] using the combination of Tsyganenko [22] and IGRF (epoch 2020) models as external and internal field respectively. This combination of models provides reasonable precision and straightforward computation of all the necessary inputs for the NM data analysis [23, 24].

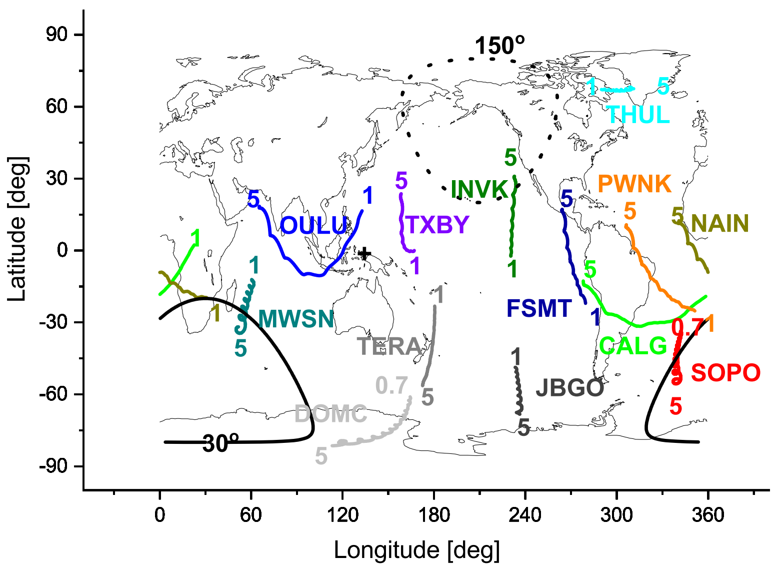

Figure 1: Asymptotic directions of selected NM stations during GLE # 73 on 28 October 2021 at 16:00 UT. The cross depicts the interplanetary magnetic field (IMF) direction obtained by the Advanced Composition Explorer (ACE) satellite. The lines of equal pitch angles relative to the derived anisotropy axis are plotted for 30°, for sunward directions, and 150° for anti-Sun directions.

Accordingly the results from the analysis, that is the derived spectra and PAD are shown in Fig. 2. The spectra are moderately hard, exhibited an important steepening, specifically during the event onset. A gradual softening of the spectra throughout the event was revealed. The PAD was relatively wide, considerably wider to beam-like events as GLE # 69 and GLE # 70 [13]. The intensity of the prompt component of SEPs gradually increased reaching peak at 18:15 UT.

In addition in Fig. 3 we depict the contour plot of the sum of variances for the best-fit solutions vs. geographic coordinates, obtained by forward modeling over all the possible apparent source

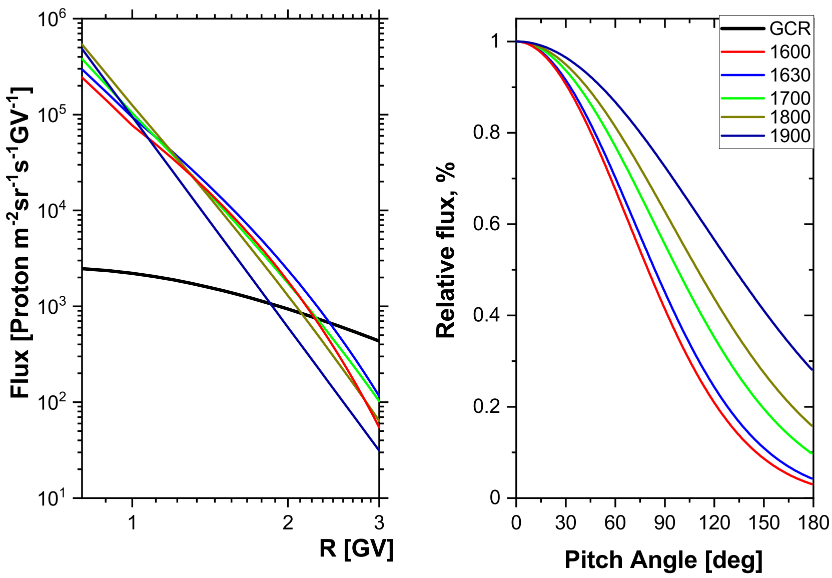

Figure 2: Derived rigidity spectra (left panel) and PAD (right panel) during various stages of GLE N° 73 on 28 October 2021 as denoted in the legend. The black line on the left panel depicts the GCR particle flux computed with the force field model.

positions. Here we would like to emphasize that an erroneous apparent source position assessment usually leads to a nonprecise assessment of the derived PADs and spectra. One can see that the results of the forward modeling were satisfactory, i.e., the derived solutions are of reasonable quality, implying that the model well described the experimental NM records.

We present in Fig. 4 the time profile of the proton net flux with the time evolution of the spectrum slope. It is seen that in the late phase of the event, the spectrum is a pure power law, typical for the GLE's delayed component.

The high-energy detector HED of SOHO/ERNE is based on silicon detectors and a scintillator. They are allowing proton flux anisotropy measurements in the deka-MeV energy range. Here, we divided the field of view of HED into the five sectors Fig. 5, where the time-intensity profiles of protons are plotted in panel as well as similar indices for the GLE-producing protons arriving within the field of view of HED.

One can see that in the 28 October 2021 event, the anisotropy of relativistic protons was surprisingly low compared to the anisotropy of deka-MeV protons. Besides, the anisotropy direction in the deka-MeV range and the anisotropy direction in the GeV range were also different. For instance at lower energies, more particles arrived from the north and west, consistently with the observed direction of the interplanetary magnetic field, while the relativistic protons arrived preferentially from the south, similarly to the eruption center location on the solar disk.

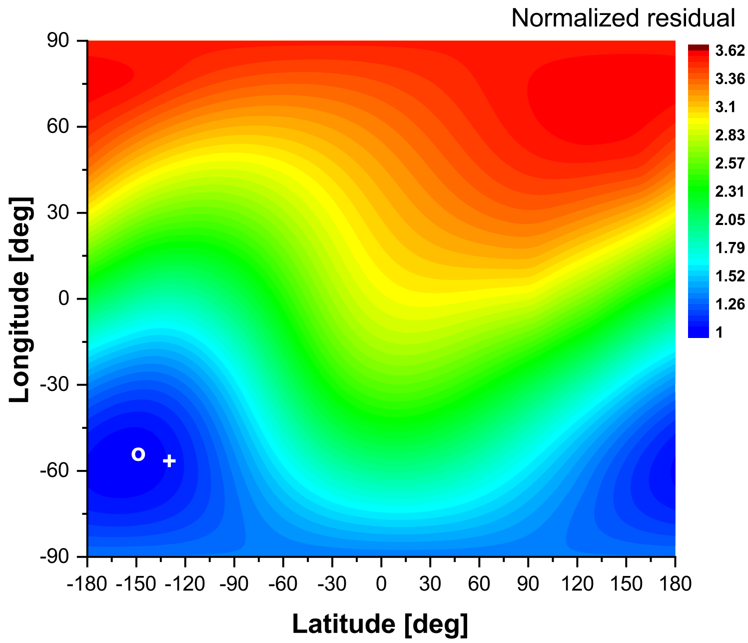

Figure 3: Contour plot of the residual of the solution of the inverse problem for the best-fit vs. geographic latitude and longitude during the main-late phase of GLE #73, that is at 17:30 UT, vs. the minimal residual. The small circle depicts the derived apparent source position, the cross depicts the IMF direction measurements by the ACE space-probe.

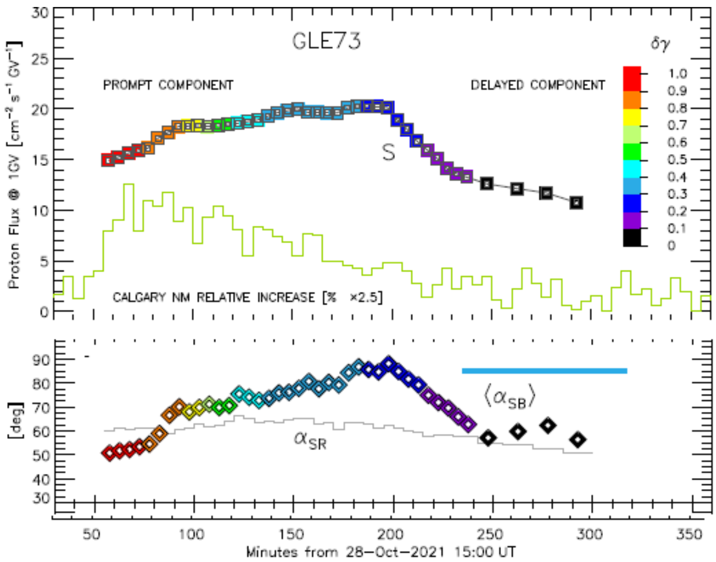

Figure 4: Upper panel: net flux of the GLE-producing solar protons, S, and a sample of the NM counting rate profile. Lower panel: average angle between the proton flux S and magnetic field B, $\langle \alpha_{SB} \rangle$.

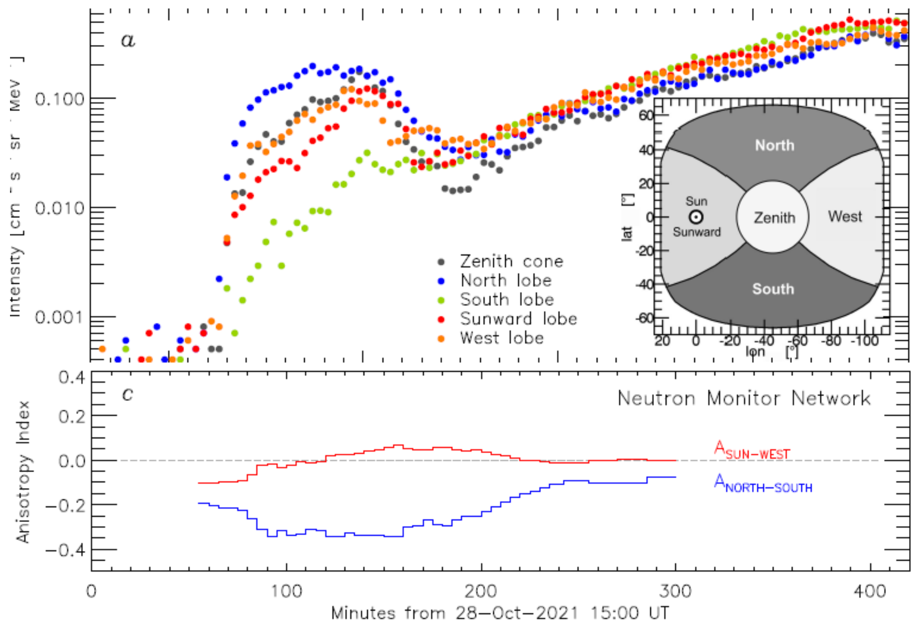

Figure 5: Sectoral intensities of the ERNE/HED-observed protons, their anisotropy indices, and anisotropy indices of GeV protons observed by the NM Network.

4. Conclusions

Here we derived the spectral and PAD of high-energy SEPs during the first GLE event of Solar Cycle 25, GLE # 73 on 28 October 2021. The best is obtained with a modified power-law for the SEP spectra and a single Gaussian for the PAD with a distribution width of about π. The latter can be a result of a perpendicular transport of the SEPs.

According to the timing analysis of the ERNE-observed deka-MeV proton emission, $\approx$ 16:10 UT, the CME had already expanded to heliocentric distances $> 4R_\odot$. Therefore, the deka-MeV protons could be accelerated by the CME shock in the solar wind, while the high-energy protons observed by the global NM network started before 15:50 UT, when the CME was still low in the corona, below $1.5R_\odot$. This fact supports the idea of a coronal origin of the prompt component of GLE event(s). The derived results in this work, give a good basis to study common morphology of various GLEs [25], as well as to reveal the mechanism of acceleration of the different SEP populations [26, 27].

Acknowledgements

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