KIEL-UP • DOI: 10.38072/2748-3150/p36

The GLE # 73 on 28 October 2021: spectra, angular distribution and terrestrial effects

Alexander Mishev [1], Leon Kocharov [1], Sergey Koldobskiy [1], Nicholas Larsen [1],
Esa Riihonen [2], Rami Vainio [2], Ilya Usoskin [1]

Correspondence

1 Sodankylä Geophysical Observatory, University of Oulu, Finland, alexander.mishev@oulu.fi, leon.kocharov@oulu.fi, sergey.koldobskiy@oulu.fi, nicholas.larsen@oulu.fi, ilya.usoskin@oulu.fi

2 University of Turku, Finland, rami.vainio@utu.fi

Keywords

solar energetic particles; ground level enhancement; neutron monitor; data analysis; terrestrial effects

Abstract

The first solar proton event observed at ground, that is ground level enhancement, of solar cycle 25 was detected on 28 October 2021 by several neutron monitors (NMs), specifically those in the polar region as well as by space-borne instruments. It was identified as the GLE (ground-level enhancement) #73 in the International GLE database. The strongest signal at the ground was registered by the DOMC/DOMB monitors located at the Antarctic plateau at the Concordia French-Italian research station. Here, we report the observations and the study of this event using the global NM network and SOHO/ERNE records. We present the derived angular and spectral characteristics of solar energetic protons, including their dynamical evolution throughout the event. Several applications are discussed, namely the terrestrial effects of the GLE particles during the event.

1. Introduction

A methodological study of high-energy particles originating from the Sun, that is, the solar energetic particles (SEPs), specifically their properties such as spectra and angular distribution provides a unique opportunity and basis to reveal important and still open questions as their acceleration and propagation in the interplanetary space (e.g. Reames 1999, Kocharov et al. 2021). A specific interest represents a particular class of SEPs, namely particles believed to be the tail of the spectrum, that is, particles with energy reaching about GeV/nucleon or even greater values. Solar protons with energy above some 300 MeV/nucleon produce, following consecutive interactions, a shower of secondary particles in the Earth's atmosphere, so that they can be registered at ground by convenient detectors, that is neutron-monitors (NMs) (for details see Dorman 2004, Mishev and Poluianov 2021). This specific class of events is known as ground-level enhancements (GLEs) (Shea and Smart 1982, Poluianov et al. 2017).

In addition, GLE particles can significantly affect the complex radiation field in the atmosphere as well as the atmospheric ionization, thus playing an important role in atmospheric chemistry and physics (Usoskin et al. 2011, Mironova et al. 2015). Since GLEs occur sporadically and differ from each other, specifically in spectra, angular distribution, duration, and geomagnetic conditions (Moraal and McCracken, 2012) they are naturally studied case-by-case. Here, we consider the latest occurred event upon the submission of the paper, that is, GLE # 73 observed on 28 October 2021.

2. GLE # 73: Observation and data analysis

The first GLE of the current solar cycle 25 was observed on 28 October 2021, notably by several low-rigidity cut-off NMs, as well as by space-borne instruments (for details see Papaioannou et al. 2022). The event was associated with an X1.0 solar flare at S28W01 and an asymmetric halo CME. The peak of the soft X-ray emission was at 15:35 UT. At ground, the peak count rate increase was registered by South Pole SOPO (5.4%) and South Pole Bare SOPB (5.7%), DOMC (7.3%) and DOMB (14%), standard and bare monitors, respectively. A detailed report of radio, and X-ray observations is given by Klein et al. (2022).

For the analysis of this event, we used the fact that NMs at different geographic locations are sensitive to a different part of the SEP spectra and arrival direction, that is, one can use the geomagnetosphere as a giant spectrometer (Bieber and Evenson, 1995; Mishev and Usoskin 2020). Using the relationship between NM count rate and primary particles given with the expression:

$$N(P_c, h, t) = \sum_i \int_{\{P_c\}}^{\infty} S_i(P, h) \cdot J_i(P, t) \cdot \mathrm{d}P \tag{1}$$

where $N(P_c,h,t)$ is the count rate of the NM, S_i is the NM yield function, which accounts for the particle propagation in the atmosphere and the registration efficiency of the device itself, $J_i(P,t)$ is the rigidity spectrum of incoming SEPs, P_c is the rigidity cut-off of the station, we can model each NM station counting rate. Here, using Eq. (1), we model the NM count rate increase due to SEPs. Subsequently, on the basis of the method, details given in (Mishev and Usoskin, 2016; Mishev et al. 2018, 2021), which was initially developed by Cramp et al. (1997); Vashenyuk et al. (2006), we unfold the GLE characteristics, that is spectra, apparent source position and pitch angle distribution (PAD).

The method involves the computation of asymptotic directions and rigidity cut-offs of all NMs used for the data analysis; making a convenient initial guess of the optimization procedure and performing the optimization itself by minimizing the difference between modeled and recorded NM responses over a selected space of unknown parameters. Here, the rigidity cut-off and asymptotic directions were computed using a new open-source tool OTSO (Larsen et al. 2022), employing a combination of the IGRF + TSY 89 models (Tsyganenko 1989), which provides reasonable precision and straightforward computation of the needed parameters for the data analysis (Kudela et al. 2008; Nevalainen et al. 2013). An illustration of computed asymptotic directions of selected NMs is given in Fig. 1. Thus, using data from the international GLE database and the Neutron Monitor Database NMDB (Mavromichalaki et al. 2011), and the aforementioned method, we derived the spectra during GLE # 73. The best fit for the SEP spectra according to our analysis is depicted by modified power-law Eq. (2)

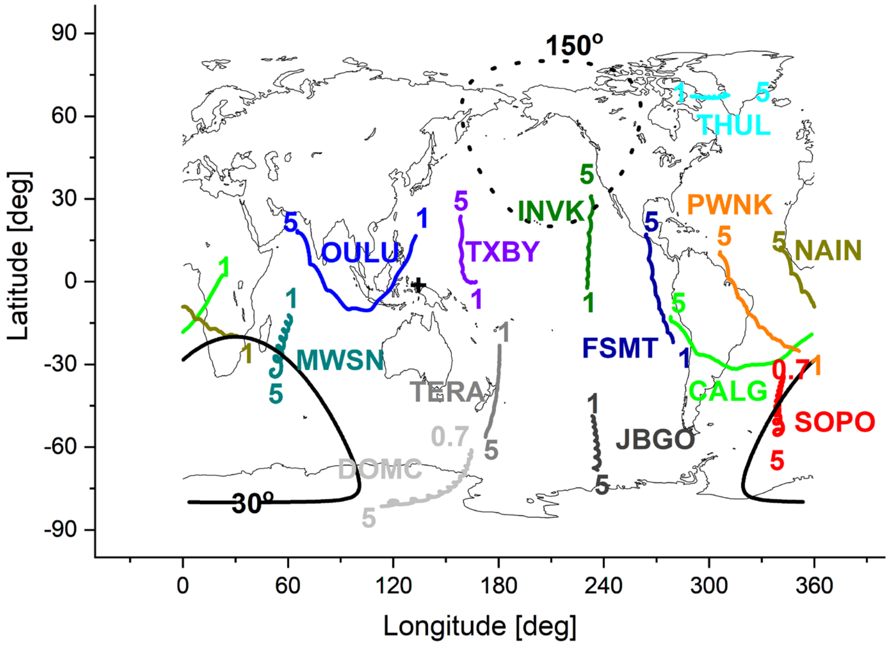

Fig. 1: Asymptotic directions of several NMs during to the event onset of GLE #73. The cross corresponds to the interplanetary magnetic field (IMF) direction obtained by the Advanced Composition Explorer (ACE) satellite. The lines of equal pitch angles relative to the derived anisotropy axis are plotted for 30° and 150° respectively.

$$J(P) = J_0 P^{-(\gamma+\delta\gamma(P-1))} \tag{2}$$

Accordingly, the angular distribution was approximated with Gaussian, see Eq. (3).

$$G(\alpha(P)) \sim \exp(-\alpha^2/\sigma^2) \tag{3}$$

The derived spectra and PAD are presented in Fig. 2, whereas the details are reported in (Mishev et al. 2022a). The derived spectra were moderately hard, with a considerable steepening during the event onset, which vanished in the late stage of the event. The SEP spectra revealed a gradual softening throughout the event. The derived PAD was relatively wide, considerably wider compared to beam-like events. In addition, analysis based on SOHO/ERNE shows that the anisotropy of relativistic protons was surprisingly low compared to the anisotropy of deka-MeV protons, notably revealing different anisotropy direction (Mishev et al. 2022a). While, the low-energy protons arrived predominantly from the north and west, which is consistent with the observed direction of the interplanetary magnetic field, the relativistic protons arrived from a location near the eruption center.

KIEL-UP • DOI: 10.38072/2748-3150/p36

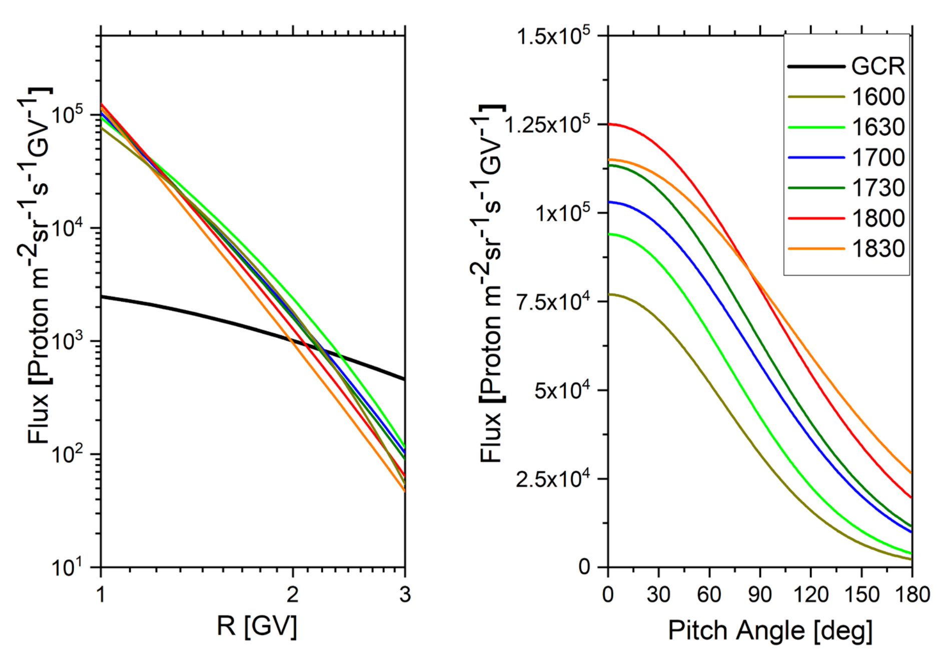

Fig. 2: Derived rigidity spectra and PAD during GLE #73. The solid black line depicts the GCR flux. Time [UT] corresponds to the start of the five-minute interval over which the data are integrated.

3. Atmospheric ionization effect

During GLEs the increased intensity of high-energy particles entering the atmosphere is greatly increased, leading to enhanced ionization, namely SEPs result in important space weather issues, specifically over the polar caps, where the geomagnetic shielding is marginal (Usoskin et al. 2011).

Using the derived spectra during the GLE # 73 and employing a model originally developed by Usoskin and Kovaltsov (2006), and recently verified by stratospheric balloon-borne measurements (Mishev et al. 2022b), we computed the ion production rate in the atmosphere due to GCRs and SEPs over the GLE # 73. In order to realistically quantify the terrestrial effects of the precipitating high-energy SEPs, specifically for atmospheric physics and chemistry studies, we normalized the ion production rate to a given period, namely to 24 hours, employing the recombination model by Krivolutsky et al. (2006) and assuming isotropic distribution (Pätsi and Mishev 2022), that is, we computed the 24h averaged ionization effect similarly to (Mishev and Velinov 2018, 2020). Employment of an isotropic distribution during these computations is reasonable, because of the wide angular distribution of incoming SEPs and none the least the fast isotropization of the event. The computed ionization effect in the upper atmosphere, that is, at a depth of 25 g/cm^2 is presented in Fig. 3, and in the region of Regener-Pfotzer maximum (Regener and Pfotzer 1935), at a depth of 200 g/cm^2, in Fig. 4.

One can see that the ionization effect was notable in the upper atmosphere (about 300% in the polar region, 120% in the sub-polar region, 40% at mid-latitudes and marginal or null in high rigidity cut-off region), yet considerably diminished at lower altitudes, e.g. at Regener-Pfotzer maximum, (less than 30% in the polar region), due to the softer SEP spectra compared to the GCRs spectra.

KIEL-UP • DOI: 10.38072/2748-3150/p36

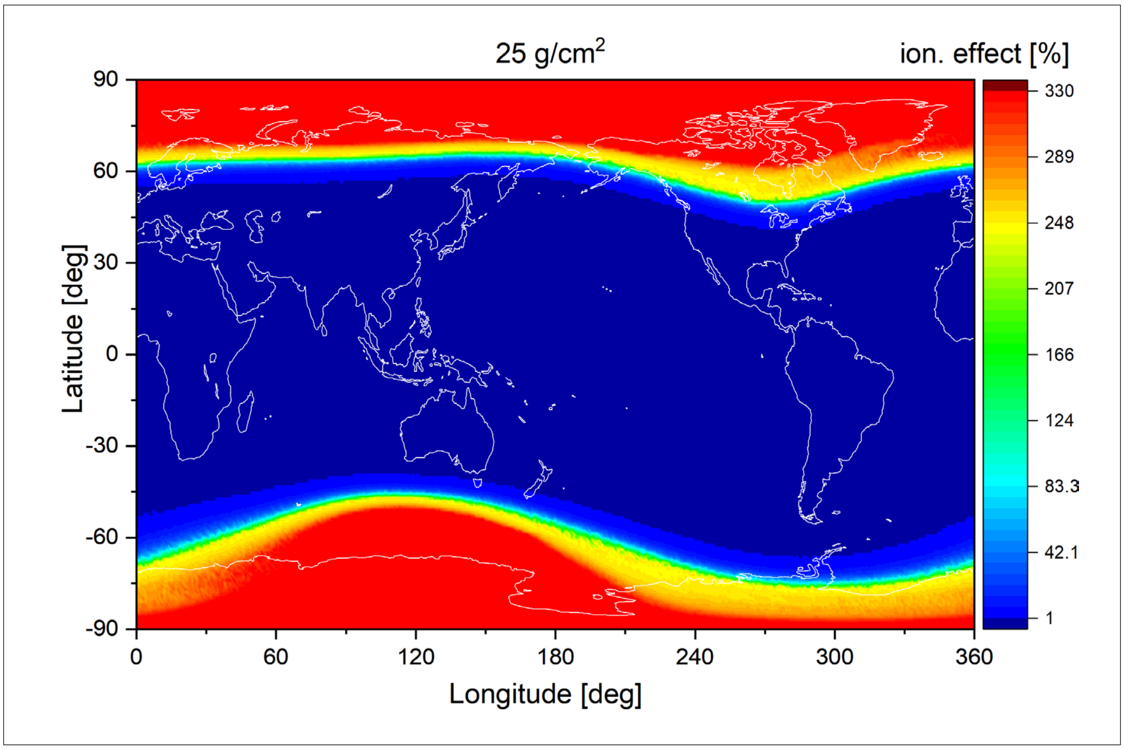

Fig.3: Averaged ionization effect during GLE # 73 at a depth of 25 g/cm^2.

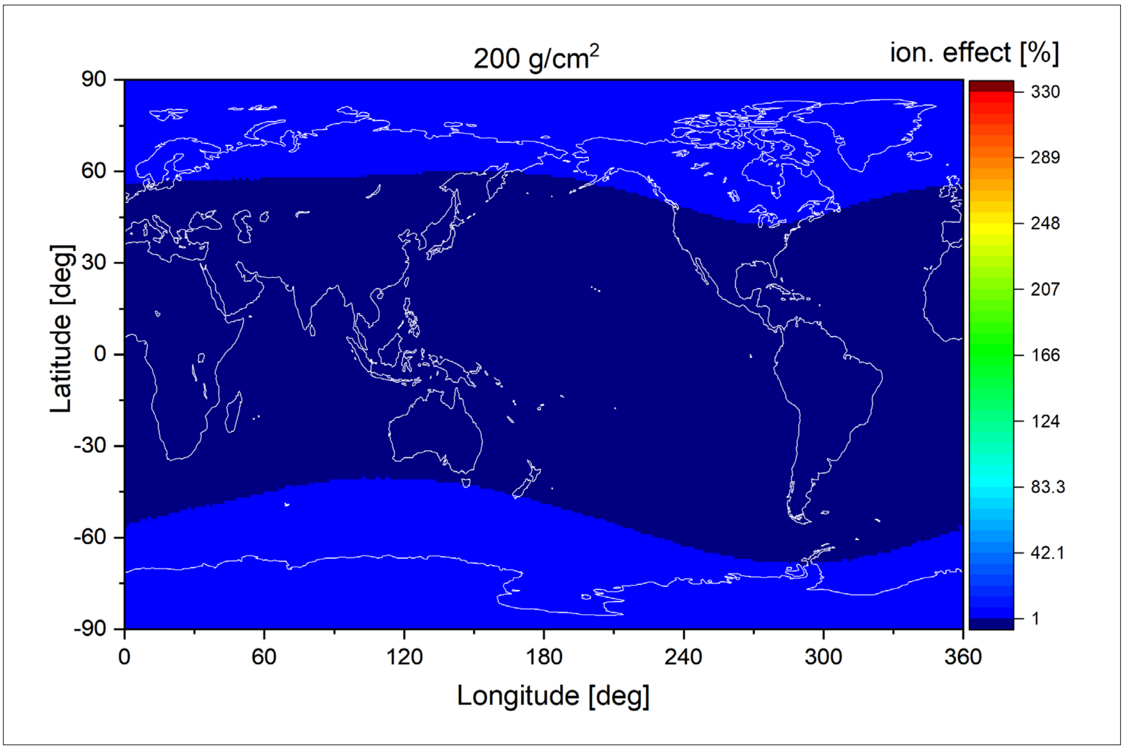

Fig.4: Averaged ionization effect during GLE # 73 at a depth of 200 g/cm^2.

4. Conclusion

In the present study here, we derived the spectral and angular characteristics of high-energy SEPs during the first GLE event of solar cycle 25, namely GLE# 73, which occurred on 28 October 2021. The best fit was achieved with a modified power-law in the spectrum and a simple Gaussian PAD. Moderately hard SEP spectra were derived, with considerable steepening, specifically during the event initial stage.

Subsequently, employing a Monte Carlo-based numerical model, we assessed for the first time, the atmospheric ionization effect during the GLE # 73. It is shown, that the effect was moderate in the polar region, whilst at mid- and high rigidity cut-off regions was barely seen.

The study presented here, representing full chain analysis of GLEs using NM records, namely derivation of SEP spectra and computation of terrestrial effects, provides the necessary basis to study the impact of precipitating high-energy particles in the Earth's atmosphere at different scales.

Acknowledgements

This work was supported by the Academy of Finland (projects 330064 QUASARE, 321882 ESPERA) and the University of Oulu grant SARPEDON.

References

Bieber, J., Evenson, P. 1995, Spaceship earth – an optimized network of neutron monitors, in: Proc. of 24th ICRC Rome, Italy, 28 August – 8 September 1995, 1316–1319.

Cramp, J.L., Duldig, M.L., Flückiger, E.O., Humble, J.E., Shea, M.A., Smart, D.F. 1997, The October 22, 1989, solar cosmic enhancement: ray an analysis the anisotropy spectral characteristics. Journal of Geophysical Research 102(A11), 24 237.

Dorman, L.: 2004, Cosmic rays in the earth's atmosphere and underground, Kluwer Academic Publishers, Dordrecht.

K-L. Klein, S. Musset, N.Vilmer, C. Briand, S. Krucker, A. Battaglia, N. Dresing, C. Palmroos, and D. Gary, 2022, The relativistic solar particle event on 28 October 2021: Evidence of particle acceleration within and escape from the solar corona, Astronomy and Astrophysics 663, A173, https://doi.org/10.1051/0004-6361/202243903

Kocharov, L., Omodei, N., Mishev, A., Pesce-Rollins, M., Longo, F., Yu, S., Gary, D.E., Vainio, R., Usoskin, I. 2021, Multiple sources of solar high-energy protons. Astrophysical Journal 915, 12, https://doi.org/10.3847/1538-4357/abff57

Kudela, K., Bučik, R., Bobik, P. 2008, On transmissivity of low energy cosmic rays in disturbed magnetosphere. Advances in Space Research 42(7), 1300-1306, https://doi.org/10.1016/j.asr.2007.09.033

Larsen, N, Mishev, A, Usoskin, I. 2023, A New Open-source Geomagnetosphere propagation tool (OTSO) and its applications, Journal of Geophysical Research: Space Physics, 128, e2022JA031061, https://doi.org/10.1029/2022JA031061

Mavromichalaki, H., Papaioannou, A., Plainaki, C., Sarlanis, C., Souvatzoglou, G., Gerontidou, M., Papailiou, M., Eroshenko, E., Belov, A., Yanke, V., Fluckiger, E.O., Butikofer, R., Parisi, M., Storini, M., Klein, K.-L., Fuller, N., Steigies, C.T., Rother, O.M., Heber, B., Wimmer-Schweingruber, R.F., Kudela, K., Strharsky, I., Langer, R., Usoskin, I., Ibragimov, A., Chilingaryan, A., Hovsepyan, G., Reymers, A., Yeghikyan, A., Kryakunova, O., Dryn, E., Nikolayevskiy, N., Dorman, L., Pustil'Nik, L. 2011, Applications and usage of the real-time neutron monitor database. Advances of Space Research 47, 2210-2222, https://doi.org/10.1016/j.asr.2010.02.019

Mironova, I., Aplin, K., Arnold, F., Bazilevskaya, G., Harrison, R., Krivolutsky, A., Nicoll, K., Rozanov, E., Turunen, E., Usoskin, I. 2015, Energetic particle influence on the earth's atmosphere. Space Sci. Rev. 194, 1-96, https://doi.org/10.1007/s11214-015-0185-4

Mishev, A., Poluianov, S. 2021, About the altitude profile of the atmospheric cut-off of cosmic rays: New revised assessment. Solar Physics 296(8), 129, https://doi.org/10.1007/s11207-021-01875-5

Mishev, A., Usoskin, I. 2016, Analysis of the ground level enhancements on 14 July 2000 and on 13 December 2006 using neutron monitor data. Solar Physics 291(4), 1225-1239, https://doi.org/10.1007/s11207-016-0877-2

Mishev, A., Usoskin, I., 2020, Current status and possible extension of the global neutron monitor network. Journal of Space Weather and Space Climate 10, https://doi.org/10.1051/swsc/2020020

Mishev, A., Velinov, P. 2018, Ion production and ionization effect in the atmosphere during the Bastille day GLE 59 due to high energy SEPs. Advances n Space Research 61, 316–325. https://doi.org/10.1016/j.asr.2017.10.023

Mishev, A., Velinov, P. 2020, Ionization effect in the earth's atmosphere during the sequence of October–November 2003 Halloween GLE events. Journal of Atmospheric and Solar-Terrestrial Physics 211, 105484, https://doi.org/10.1016/j.jastp.2020.105484

Mishev, A., Usoskin, I., Raukunen, O., Paassilta, M., Valtonen, E., Kocharov, L., Vainio, R. 2018, First analysis of GLE 72 event on 10 September 2017: Spectral and anisotropy characteristics. Solar Physics 293, 136, https://doi.org/10.1007/s11207-018-1354-x

Mishev, A.L., Koldobskiy, S.A., Kocharov, L.G., Usoskin, I.G. 2021, GLE # 67 event on 2 November 2003: An analysis of the spectral and anisotropy characteristics using verified yield function and detrended neutron monitor data. Solar Physics 296(5), 79, https://doi.org/10.1007/s11207-021-01832-2

Mishev, A. , Kocharov, L. , Koldobskiy, S. , Larsen, N. , Riihonen, E., Vainio, R., Usoskin, I. 2022a, High-Resolution Spectral and Anisotropy Characteristics of Solar Protons During the GLE N 73 on 28 October 2021 Derived with Neutron-Monitor Data Analysis, Solar Physics 297, 5, 88, https://doi.org/10.1007/s11207-022-02026-0

Mishev, A. , Binios, A., Turunen, E., Leppänen, A-P., Larsen, N. , Tanskanen, E., Usoskin, I., Envall, J., Iinatti, T., Lakkala, P. 2022b, Measurements of natural radiation with an MDU Liulin type device at ground and in the atmosphere at various conditions in the Arctic region, Radiation Measurements 154, 106757, https://doi.org/10.1016/j.radmeas.2022.106757

Moraal, H., McCracken, K. 2012, The time structure of ground level enhancements in solar cycle 23. Space Sci. Rev. 171, 85–95.

Nevalainen, J., Usoskin, I., Mishev, A. 2013, Eccentric dipole approximation of the geomagnetic field: Application to cosmic ray computations. Advances in Space Research 52(1), 22-29, https://doi.org/10.1016/j.asr.2013.02.020

Papaioannou, A., Kouloumvakos, A., Mishev, A., Vainio, R., Usoskin, I., Herbst, K., Rouillard, A. P., Anastasiadis, , Gieseler, J., Wimmer-Schweingruber, R., Küh, P. 2022, The first ground level enhancement of solar cycle 25 on 28 October 2021. Astronomy and Astrophysics 660, L5, https://doi.org/10.1051/0004-6361/202142855

Pätsi, S., Mishev, A. 2022, Ionization effect in the Earth's atmosphere due to cosmic rays during the GLE # 71 on 17 May 2012, Advances in Space Research 69, 2893–2901.

Poluianov, S.V., Usoskin, I.G., Mishev, A.L., Shea, M.A., Smart, D.F. 2017, GLE and sub-GLE redefinition in the light of high-altitude polar neutron monitors. Solar Physics 292(11), 176, https://doi.org/10.1007/s11207-017-1202-4

Reames, D.V. 1999, Particle acceleration at the sun and in the heliosphere. Space Science Reviews 90(3-4), 413-491.

Regener, E., Pfotzer, G. 1935, Vertical intensity of cosmic rays by threefold coincidences in the stratosphere. Nature 136, 718–719.

Shea, M.A., Smart, D.F. 1982, Possible evidence for a rigidity-dependent release of relativistic protons from the solar corona. Space Science Reviews 32, 251-271.

Tsyganenko, N.A. 1989, A magnetospheric magnetic field model with a warped tail current sheet. Planetary and Space Science 37(1), 5-20, https://doi.org/10.1016/0032-0633(89)90066-4

Usoskin, I., Kovaltsov, G. 2006, Cosmic ray induced ionization in the atmosphere: Full modeling and practical applications. Journal of Geophysical Research 111.

Usoskin, I., Kovaltsov, G., Mironova, I., Tylka, A., Dietrich, W. 2011, Ionization effect of solar particle GLE events in low and middle atmosphere. Atmos. Chem. Phys. 11, 1979–1988.

Vashenyuk, E.V., Balabin, Y.V., Perez-Peraza, J., Gallegos-Cruz, A., Miroshnichenko, L.I. 2006, Some features of the sources of relativistic particles at the sun in the solar cycles 21–23. Advances Space Research 38(3), 411-417, https://doi.org/10.1016/j.asr.2005.05.012

Open Access