PROCEEDINGS OF SCIENCE

PoS(ICRC2023)1235

The Easter GLE on 15 April 2001, spectra and angular distribution–new revised results and related space weather effects

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A specific interest represents solar protons possessing energy enough to induce an atmospheric cascade in the Earth's atmosphere, whose secondary particles reach the ground, eventually registered by ground-based detectors e.g. neutron monitors. This class of events is known as ground-level enhancements (GLEs). The solar cycle 23 provided several strong GLEs, the first observed on 14 July 2000 (the Bastille day event), while the last was observed on 13 December 2006. The systematic study of relativistic SEPs provides an important basis to understand their acceleration and propagation in interplanetary space, as well as to quantify the related space weather effects such as radiation dose at flight altitudes. The Easter event on 15 April 2001 is among the strongest and accordingly, it is the focus of this study. Here we performed a precise analysis of neutron monitor records and derived the spectral and angular characteristics of the solar energetic particles during this event. We modeled the particle propagation in the Earth's magnetosphere and atmosphere using a newly computed and verified NM yield function computed at several altitudes above sea level. The solar protons spectra and pitch angle distributions were obtained in their dynamical development throughout the event. We assessed the radiation dose at flight altitude and compared the results with experimental measurements performed with the Liulin gamma probe.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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1. Introduction

Following strong solar eruptions such as solar flares and coronal mass ejections (CMEs), the Sun occasionally accelerates particles into the high-energy range, known as solar energetic particles (SEPs) [1]. Naturally, the SEP flux is greater than that of the galactic cosmic ray (GCR). Generally, it can last for several hours. A particular class of SEP events represents the ground level enhancements (GLEs) [2, 3], when the energy of SEPs exceed about GeV/nucleon, precisely 433 MeV/nucleon at sea level and ≈ 300 MeV/nucleon for high-mountain polar regions [4]. GLEs, when entering in the earth's atmosphere can produce secondary particles, eventually registered by ground-based detectors, $e.g.$ neutron-monitors (NMs) [5].

Historically, GLEs have been studied with ground-based instruments, namely NMs [6, 7], using the geomagnetosphere as a giant spectrometer, since stations at different locations are sensitive to a different range of the SEP spectra and arrival direction. GLE events are relatively rare, occurring a few times per solar cycle. However, they can pose a significant space weather threat, specifically at flight altitudes, where they can significantly increase the complex radiation field [8, 9].

In this paper, we analyzed a notable event, that is the event on 15 April 2001, GLE # 60, namely we derived the GLE causing SEP spectra. Then, using the derived spectra and updated Oulu CRAC:DOMO (Cosmic Ray Atmospheric Cascade: Dosimetric Model) radiation model, we computed the ambient dose equivalent at typical commercial jet flight altitude(s) and compared our model studies with dosimetric measurements performed during an intercontinental flight from Prague to New York (PRG-JFK) with mobile dosimetric unit (MDU) Liulin.

2. GLE # 60 on 15 April 2001

The event of 15 April 2001, known as the Easter GLE, namely GLE # 60 was among the strongest GLEs of solar cycle 23. It was registered by the global NM network, where the greater count rate increase of about 225 % was revealed by the South Pole (SOPO) NM. The event followed a notable increase of solar activity lasting from the end of March to mid-April 2001 leading to several M-class and nine X-class flares [10], the primary source related to this event was NOAA Active Region 9415 at S20 W85.

Herein, using a method based on the employment of validated NM yield function, [11, 12], robust optimization [13, 14] which was used for the analysis of a plethora of GLEs [15–17], we derived the spectra and anisotropy characteristics of SEPs, during GLE # 60. In general, methods for an analysis of GLEs using NM data employed modeling of the global NM network response and unfolding of a given number of model parameters over the experimental NM records [18], and consist of: computation of the asymptotic directions and cut-off rigidities for the NMs used in the data analysis; elaborating a convenient initial guess for the optimization, and performing the optimization itself over modeled and recorded NM responses [19–21].

An illustration of the computed asymptotic direction for selected NMs used for the analysis is presented in Fig. 1. Herein the magnetospheric computations allowing us to obtain the rigidity cut-off and asymptotic directions of each NM station used in the analysis were performed using a new open source tool OTSO [22] using the combination of Tsyganenko [23] and IGRF (epoch 2020) models as external and internal field respectively. This combination of models provides

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reasonable precision and straightforward computation of all the necessary inputs for the NM data analysis [24, 25].

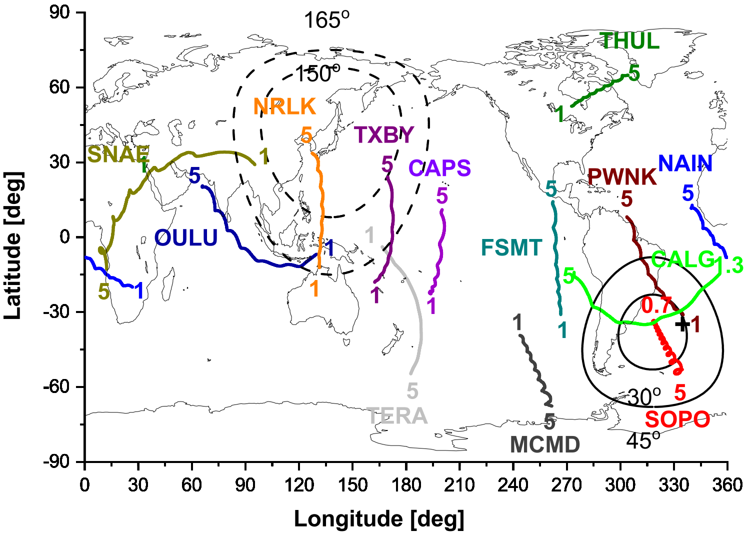

Figure 1: Asymptotic directions of selected NM stations and contour plots of equal pitch angles relative to the derived anisotropy axis during GLE # 60 on 15 April 2001. The cross depicts the interplanetary magnetic field (IMF) direction obtained by the Advanced Composition Explorer (ACE) satellite.

According to our analysis, the best fit for the spectral and angular distribution of SEPs is obtained using a modified power-law for the former and Gaussian for the latter, described analytically with Eq. 1 and Eq. 2, respectively.

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

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 $\delta\gamma$.

The angular distribution, that is the pitch angle distribution (PAD), was approximated with Gaussian:

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

where α is the pitch angle, σ accounts for the width of the distribution.

An illustration of the derived spectra and pitch angle distribution (PAD) is given in Fig. 2. The SEP spectra were hard during the initial (14:00-14:30 UT) and main phase of the event (14:30–16:00 UT) with a gradual rising of the particle flux. After the main phase of the event the derived SEP spectra were softer, and a considerable decrease in the particle flux compared to the initial stages of the event was observed.

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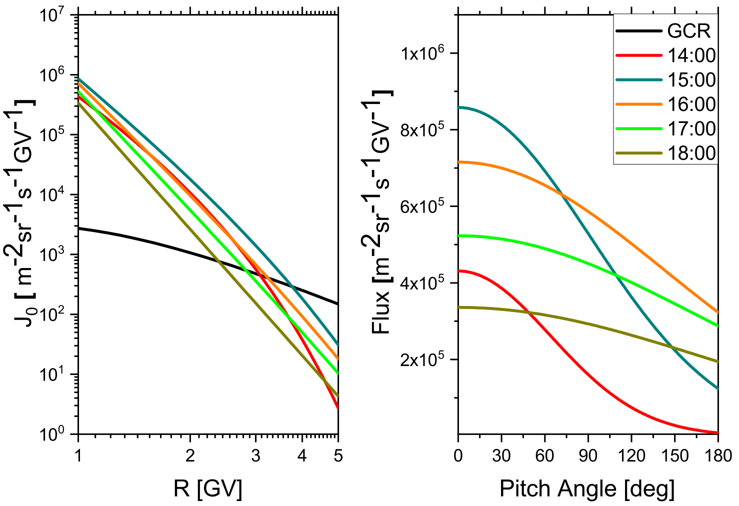

Figure 2: Derived rigidity spectra (left panel) and PAD (right panel) during selected stages of GLE # 60 as denoted in the legend. The black line on the left panel depicts the GCR particle flux computed with the force field model.

3. Computation of the dose at flight altitudes during GLE # 60

As was aforementioned during GLEs, the SEPs usually lead to an enhancement of the complex radiation field at flight altitudes. Recently, several models for computation of the exposure to radiation (dose) at flight altitudes have been developed [26, 27]. In this work, we employed the updated radiation model Oulu CRAC:DOMO [28]. The model is based on pre-computed yield functions, that is Monte Carlo simulated response matrix. The description, experimental verification, and comparison with other models and applications are given elsewhere [29–31].

The dose rate at a given h induced by a primary CR particle is the integral product of the primary CR particle spectrum with the corresponding yield function:

$$E(h, P_{cut}) = \sum_i \int_{T(P_{cut})}^{\infty} \int_{\Omega} J_i(T) Y_i(T, h) d\Omega dT, \tag{3}$$

where $J_i(T)$ is the differential energy spectrum of the primary $i-$th component of CRs (proton or $\alpha-$particle, the latter accounting effectively for all heavy particles) and the and Y_i is the corresponding effective dose/ambient dose yield function. The integration is conducted over the kinetic energy T, depending also on the rigidity cut-off P_{cut}, and Ω is the solid angle.

Using the derived spectra during GLE # 60 and the CRAC:DOMO model, we computed the exposure to radiation during the event, considered in this study. Fig. 3 depicts the global map of one-hour integrated ambient dose equivalent during the peak phase of GLE # 60. The Easter event was notable because the radiation field and the dose were measured during the PRG-JFK flight by an MDU Liulin device, [32], a device based on a silicon semiconductor detector, and extensively used for aviation and space dosimetry measurements [33].

For precise and realistic comparison between the model and experimental results, we explicitly considered the time evolution of the SEPs characteristics throughout the event and the geomag-

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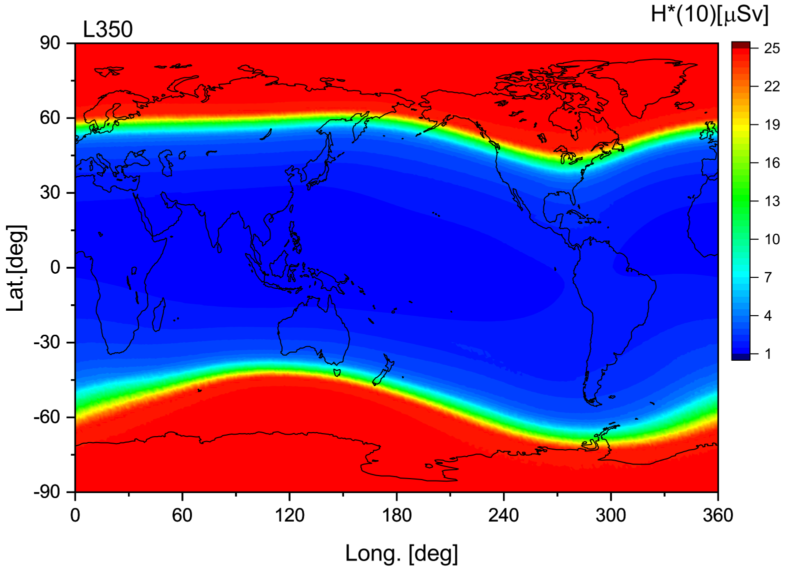

Figure 3: Map of the ambient dose equivalent integrated over 1h during the peak phase of GLE # 60.

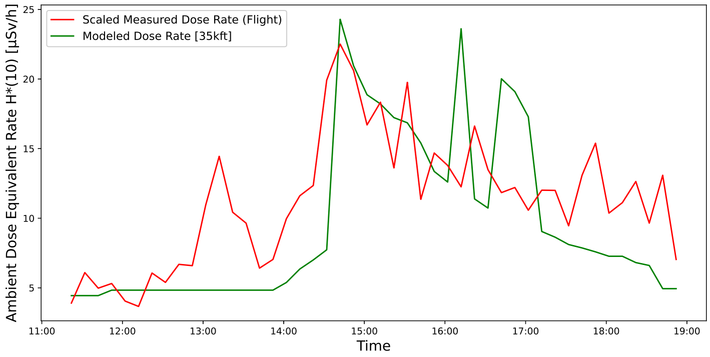

Figure 4: Modeled and measured ambient dose equivalent during GLE # 60 as denoted in the legend.

netospheric conditions [21]. We note that MDU Liulin possesses constrained sensitivity to the secondary hadron component of the CRs, specifically neutrons, so that can detect roughly 10–20% of these particles. Therefore, the corresponding scaling of the measurements is performed in order to account for all the contributions of the complex radiation field at flight altitude. The scaled values can be seen in Fig. 4, in which the scaled measurements agree well with the model results.

4. Conclusions

Herein, we derived characteristics, namely the SEP spectra, angular distribution, and apparent source position during GLE # 60, the so-called Easter event, that occurred on April 15 2001. Subsequently, using the reconstructed spectra and CRAC:DOMO model we computed the effective dose at L350 during GLE # 60 presented as a global map. We performed a comparison between

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our model full-chain computations of the ambient dose equivalent and MDU Liulin measurements and good agreement was derived.

Therefore, we claim that our full-chain method presented here provides a good basis to study the contribution of relativistic SEPs on the radiation field in the Earth's atmosphere at different scales and altitudes and allows the cross-calibration and referencing of other models employed in the field of the aviation dosimetry.

Acknowledgements

This work was supported by the Academy of Finland (project 330064 QUASARE and 321882 ESPERA). The work was also supported by HE program, project ALBATROS and by the National Science Fund of Bulgaria under contract KP-06-H28/4.

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