PROCEEDINGS OF SCIENCE

Extreme solar particle event of 774 AD: reference as the worst-case scenario for space weather

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Violent eruptive processes on the Sun can lead to an acceleration of solar energetic particles, which accordingly result in notable space weather effects, specifically an increase of the complex radiation field at aviation altitudes. A specific class represents events observed by ground-based detectors such as neutron monitors (NMs), the ground-level enhancements (GLEs). Here, we considered for study a specific event, namely the strongest known, yet not directly observed, that is the extreme solar particle event of 774 AD discovered on the basis of cosmogenic-isotopes measurements. After a convenient scaling of a GLE # 5 and employing the corresponding radiation model we computed the ambient dose at aviation altitudes during the 774 AD event. Since the spectrum of solar protons during 774 AD can not be directly obtained, as a first step we derived the spectra of the solar protons during the GLE # 5, the strongest directly observed by NM measurements. The GLE # 5 is assumed as a conservative approach because of the hardest derived spectra. The global map of the ambient dose was computed under realistic reconstruction of the geomagnetic field during the 774 AD epoch, obtained on the basis of archeo-paleomagnetic measurements. We show that the 774 AD event represents a significant space weather threat and can be used as a reference for the worst-case scenario for radiation dose received during GLEs at aviation altitudes.

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1. Introduction

Flux consisting of high-energy subatomic particles is constantly present in the vicinity of the Earth, those particles are known as cosmic rays (CRs). When entering into the Earth's atmosphere, the low-energy, that is deka-MeV CRs are absorbed, yet particles in the hundred MeV and GeV range and above produce secondaries following consecutive interactions with the atmospheric constituents, so that each collision adds new particles, therefore is producing next generation of particles. In such a way a complicated nuclear-electromagnetic-muon cascade known as an extensive air shower is developed in the atmosphere [1]. CRs originating from the Galaxy, called galactic cosmic rays (GCRs), determine the slightly variable radiation field at aviation altitudes, also governed by the shielding provided by the geomagnetosphere, the latter due to deflection of the incoming CR particles, being charged they are experiencing Lorentz force when propagating in the geomagnetic field.

Besides, solar eruptive processes such as solar flares and coronal mass ejections (CMEs) accelerate particles to high energies, called solar energetic particles (SEPs) [2]. The SEP flux is greater than that of GCRs, spanning from tens of MeV/n in most cases, reaching occasionally 100 MeV/n, and rarely GeV/n range. SEPs possessing energy of ≈ 300 MeV/n or about 433/n MeV for the high-mountain polar region and sea level respectively [3], produce secondary CRs which can reach the ground, eventually registered by the ground-based detectors such as neutron monitors [4]. Those events are known as ground-level enhancements [5, 6]. GLEs are relatively rare compared to the bulk of SEPs. They occur several times per solar cycle, yet with a significant space weather impact [7, 8], including an increased radiation threat to astronauts and aircrews/frequent travelers during transpolar flights [9].

In this work we focus on specific SEP events, that is extreme solar particle events (ESPEs) producing a notable signal on cosmogenic isotopes [10, 11], specifically on the strongest ever recorded - the 774 AD SEP event [12].

2. The 774 AD SEP event

Extreme SEPs can be revealed by cosmogenic isotopes measurements, e.g., radiocarbon-^{14}C; half-life= 5.73x10^3 years, produced via secondary CRs interactions with the atmospheric constituents i.e. neutron capture ^{14}N (n,p)^{14}C. The event of 774 AD is the largest SEP event ever identified so far [10, 12].

For a realistic computation of space weather effects during the 774 AD-like SEP event, it is necessary to perform a full-chain analysis, starting from the estimation of spectra, magnetospheric conditions, that is reconstruction of the geomagnetospheric field at the epoch and employment of the corresponding radiation model [13]. We note, that the strongest directly recorded by NMs event, that is GLE # 5 occurred on 23 February 1956, is not strong enough to produce a notable cosmogenic isotope signal [14]. On the other hand, it is known that SEP event magnitude correlates with the spectrum hardness, that is, stronger events reveal hard spectra [15]. Hence, the GLE # 5 occurred on 23 February 1956 revealed one of the hardest spectra [16, 17]. Therefore, a convenient scaling of GLE # 5, so that to be consistent with the cosmogenic production during 774 AD event, gives the possibility for realistic estimation of the SEP spectra, yet the realistic spectrum during 774

AD might have been softer than that of GLE# 5 [18]. Therefore, we also considered an event with a softer SEP spectrum, e.g. GLE # 45 occurred on 24 October 1989.

The SEP spectra during GLE# 5 and GLE# 45, were derived employing a robust method for an analysis of GLEs using NM data records. The method is based on modeling of the global NM network response and unfolding of a given number of model parameters over the experimental NM records [19]. Its consists of computation of the asymptotic directions and cut-off rigidity for the NMs used in the data analysis and optimization of modeled over the recorded NM count rate increases [13, 20, 21], the latter performed using Levenberg-Marquardt algorithm [22, 23] with additional Tikhonov-like inversion [24–26]. The method also employed new generation of validated NM yield functions for the modeling [27, 28] and was used for the analysis of a number of events [29–31]. The spectra of the GLE# 5 and GLE# 45 were fitted with modified power-law Eq. 1:

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

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 $\delta\gamma$.

An illustration of the derived spectra, scaled to be consistent with the actual cosmogenic production during 774 AD are shown in Fig. 1.

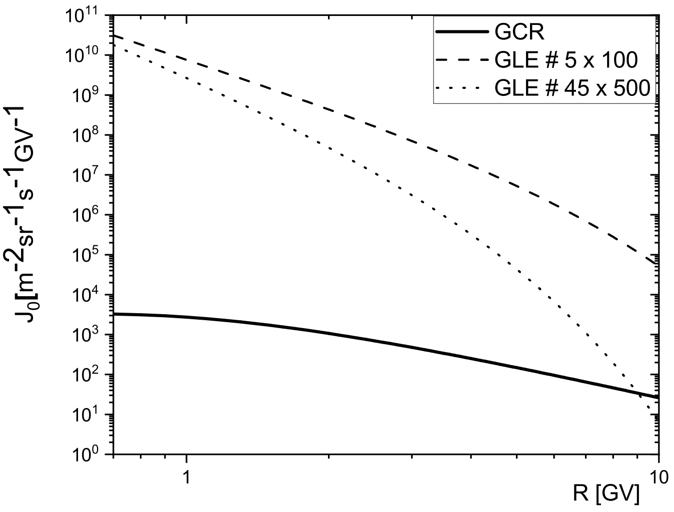


Figure 1: The spectra of GLE # 5 and GLE # 45 scaled to 774 AD as denoted in the legend.

3. Assessment of space weather effects during 774 AD event

Herein we computed the ambient dose H* during 774 AD event using the aforementioned scaled SEP spectra, namely during GLE # 5 with a scaling factor ≈ 100, as a conservative approach, and GLE # 45, with a scaling factor ≈ 500 as a realistic approach (see Fig. 1). In addition, we assumed 24h duration of the event, similarly to other strong GLEs [17], and that the 774 AD extreme SEP was a single event, but a sequence of events such as the Halloween events or September-October 1989 [16]. Then we employed a corresponding radiation model described below.

The dose rate (effective, ambient, ambient dose equivalent) at a given altitude h induced by a primary CR particle is the integral product of the primary CR particle spectrum with the corresponding yield function:

$$E(h, P_{cut}) = \sum_i \int_{T(P_{cut})}^{\infty} \int_{\Omega} J_i(T) Y_i(T, h) d\Omega dT, \tag{2}$$

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. The model description is given elsewhere [32], where details about experimental verification and comparison with other models/computations is given in [33–35]. We note that usually a significant anisotropy during strong SEP events is revealed, yet for the computation of the space weather effects during 774 AD event we assumed an isotropic angular distribution of the solar protons similar to [33, 36]. This assumption is due to the fact, that is is not possible to reveal the anisotropy of the event on the basis of cosmogenic isotopes measurements.

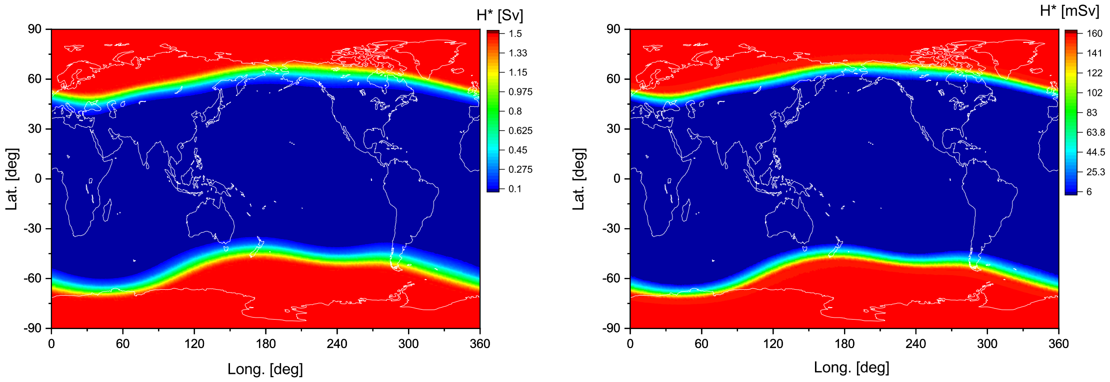
Last, in order to model the effects of the GCRs background and the SEPs itself we assumed a moderately active Sun, that is with the modulation parameter of about 500 MV and modeled realistically the geomagnetic field, the latter using paleomagnetic reconstructions, hence, we computed the effective geomagnetic rigidity cutoffs on a step 1x1 deg. applying an eccentric dipole approximation [37]. Herein, we employed a global geomagnetic field model, whic covers the Holocene, namely CALS10k.2 [38], where the details are given elsewhere [39, 40].

In Fig. 2, we present an illustration of the global distribution of the ambient dose H* at an altitude of 40 kft a.s.l., integrated over a typical time span of transpolar flight, that is six hours of 774 AD-like event, considering the aforementioned assumptions. We note, that L400, that is altitude of 40 kft (≈ 12 200 m a.s.l.) is typical for transpolar flight. One can see that H* reached a maximum in the polar region, where the magnetospheric shielding is weak and would lead to severe effects including acute radiation syndrome.

4. Conclusions

A methodological study of specific space weather effects, such as exposure to radiation at flight altitudes during historical extreme SEP events, gives the necessary basis to assess the worst-case scenario during severe radiation storms. In this study by state-of-the-art modeling under plausible assumptions of event duration, spectral shape and considering realistic reconstructions of the geomagnetic field during the epoch, we studied the space weather effects during the 774 AD event assuming two scenarios: a conservative by employing hard spectra scaled from GLE # 5, and a realistic one by employing softer spectra scaled from GLE # 45, namely computed the global map of flight integrated H*.

We stress, that the 774 AD event is the strongest ever observed on the basis of cosmogenic-isotope records. Therefore, on the basis of a convenient scaling, namely with a factor of 100 from



(a) Worst case scenario

(b) Realistic scenario

Figure 2: Global map of the integrated ambient dose at altitude 40 kft over the first 6h starting from the event onset during 774 AD event.

the GLE # 5, it can be used to assess the worst-case scenario for a specific threat, such as the radiation doses at flight altitudes. The presented here computations can serve a as reference for studying the worst-case scenario during severe radiation storms of solar origin..

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