PROCEEDINGS OF SCIENCE

Spectra and anisotropy during GLE # 4 on 19 November 1949 derived using historical records

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A methodological study of solar energetic particles provides the necessary basis to understand the mechanisms of their acceleration and propagation in interplanetary space. According to the current paradigm, following solar eruptive processes, such as solar flares and/or coronal mass ejections, solar ions can be accelerated to high energies. In most cases, the energy of the accelerated solar ions is several tens of MeV/n, yet in some cases, it exceeds 100 MeV/n and occasionally reaches the GeV/n range. In the latter case, the energy is sufficient for solar ions to generate an atmospheric cascade in the Earth's atmosphere with secondary particles reaching the ground and registered by ground-based detectors. This particular class of events is known as ground-level enhancements (GLEs). At present, 73 GLEs in total have been detected, starting with the Forbush first observations in 1942. The first three events were registered only by ionization chambers; the fourth event was recorded by ionization chambers, muon telescopes, and a non-standard neutron monitor. Using the historical records of ionization chambers, namely their count-rate increases, and a state-of-the-art model, we assessed the spectra of GLE # 4 that occurred on 19 November 1949. We employed a method adapted from neutron monitor data analysis, that is, modelling the ionization chamber responses and other detectors and optimization over the experimental count rate increases. Hence, we assessed the GLE # 4 spectra, hgere presenting preliminary results.

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1. Introduction

Systematic study of solar energetic particles (SEPs) provides a reliable basis to understand their acceleration mechanism and propagation in the interplanetary space [1]. Following solar eruption, e.g. solar flare(s) and/or coronal mass ejection (CME), SEPs can be accelerated to several tens of MeV/nucleon [2]. In some cases, SEPs are accelerated to energy exceeding 100 MeV/nucleon or even to the GeV range. In the latter case the SEP energy is high enough to generate a particle shower in the Earth's atmosphere yielding secondary particles, which can reach the ground and eventually be registered by ground-based detectors e.g. neutron monitors (NMs) [3]. This class of events is called ground-level enhancements (GLEs) [4, 5]. Over the years GLEs have been routinely studied using NM records. The spectral and angular characteristics of SEPs in the vicinity of Earth are usually derived by modelling of the global NM network response and corresponding optimization, yet the first events, namely GLEs 1–4 have been registered by ionization chambers. Here we study GLE # 4 by employing a method adapted from NM data analysis, that is, by modelling the ionization chamber responses and subsequent optimization over the experimental count rate increases, we accordingly assessed the GLE # 4 SEP spectra.

2. GLE # 4 on 19 November 1949

Systematic measurements of cosmic ray (CR) variations dated from the mid thirties years of 20^{th} century, when the first network of detectors was established [6]. Lately, standardized Compton-Bennett ionization chambers (ICs) operated by Scott Forbush, registered the first confirmed SEPs in 1942 [7], see Fig.1, by several stations. The events were observed as increases in the cosmic ray intensity, lately suggested to be caused by charged particles with solar origin [8].

The event of 19 November 1949 was observed as a sudden increase with onset at 10:45 UT recorded by several Compton-Bennett ICs shielded with 12-cm Pb, the geographic distribution of several selected stations is shown in Fig. 2, some details for the stations are given in Table 1. The event lasted for several hours. For instance the Cheltenham IC revealed an increase of about 40 %, the additionally shielded detector at Climax, Colorado, located at high-altitude namely 3500 meters above sea level recorded an increase of about 180 %, which corresponds to more than 200 % at non shielded detector. The experimental NM at Manchester, UK, recorded an increase of about 550 %, whilst the high rigidity cut-off detector at Huancayo revealed marginal increase, for details see [9] and the recent summary by [10].

Historically, GLEs have been studied with ground-based NMs [11], exploiting the spectrometric capabilities of the geomagnetosphere, because stations at different locations are sensitive to a different range of the SEP spectra and arrival direction . However, the GLE # 4 was recorded by ICs and an experimental NM at Manchester UK, which implies a challenging procedure for the data analysis, since even standardized, the detectors possessed unknown responses.

3. Assessment of the SEP spectra during GLE # 4

Here, we used digitized historical records from all detectors available during GLE # 4, specifically the standardized ionization chambers [10], more details will be presented as forthcoming

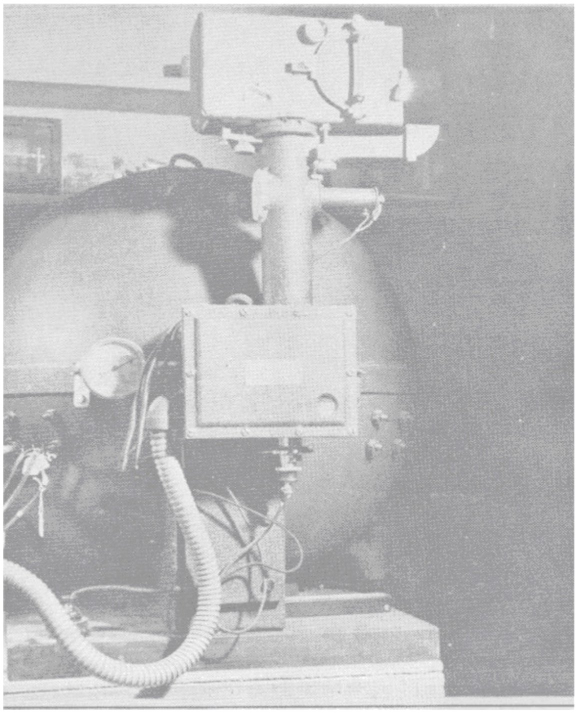

Figure 1: Standardized Compton-Bennett ionization chamber as operated at Huancayo.

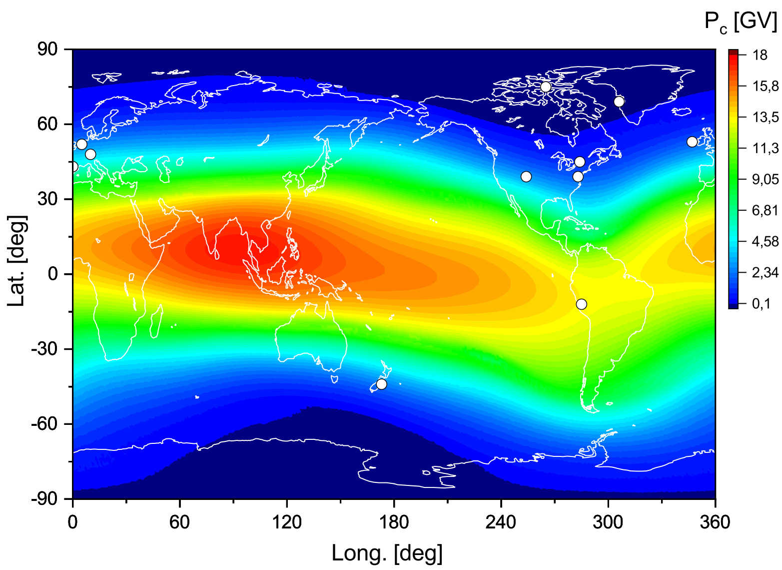

Figure 2: Distribution map of the stations observed the GLE # 4 along the rigidity cut-offs.

work. The next step, we exploit the fact that the major event of 23 February 1956, that is GLE # 5 was recorded by different detectors including ICs and NMs. Therefore an overlap of several detectors, namely ICs exists between GLE GLE # 4 and GLE # 5. A plausible assumption is that the response of the ICs remains relatively unchanged over the years, and that they can be used in a

Table 1: Stations, geographic coordinates with corresponding geomagnetic cut-off rigidities and altitudes above sea level, and type of the instrument registered GLE # 4.

Station	latitude [deg]	Longitude [deg]	P_c [GV]	Altitude [m]	Type
Christchurch	43.25S	173.36E	2.55	8	IC
Godhavn	69.12N	53.30W	0.01	9	IC
Cheltenham	38.42N	76.48W	1.97	72	IC
Climax	39.24N	106.12W	2.96	3500	IC
Huancayo	12.0S	75.18W	13.45	3350	IC
Moscow	55.44N	37.38E	2.43	200	IC
Manchester	53.28N	14.0W	1.71	10	NM
Ottawa	45.24N	75.36W	1.22	101	GM
Resolute Bay	74.43N	94.59W	0.1	17	GM
Yakutsk	62.03N	129.73E	1.64	105	IC

similar manner as NMs for data analysis. The latter implies a similar shape of ICs response function as the NM one, considering some specifics of NMs [12–14]

Then using a method based for NM data analysis, namely modeling of the global NM network response and unfolding the spectra described with model parameters (unknowns) by optimization over the experimental NM records [15], here based on a validated NM yield function, [16, 17], robust optimization [18, 19] which was used for the analysis of several GLEs, including comparison with direct space probe measurements [20–22], we derived the spectra and anisotropy characteristics of SEPs, during GLE # 5.

Next, using the derived spectra during GLE # 5 we performed a forward modeling of the count rate increase of ICs during the GLE # 5, and the corresponding scaling factor between NM and IC was assessed, explicitly considering the energy threshold of the latter [9]. We note that the registration of SEPs at ground is chiefly function of the type of detector, its location, that is the rigidity cut-off, incidence and asymptotic direction. The threshold of ICs in order to register SEP is about 4 GeV/n [9].

Subsequently, using the scaled response of the IC and the same method as for NM data analysis, we assessed the spectra during the GLE # 4. An illustration of the computed asymptotic direction for selected ICs used for the analysis is presented in Fig. 3, whilst additional details have been presented in [9]. The asymptotic directions were computed using the combination of Tsyganenko [23] and IGRF (epoch 2020) models as external and internal field respectively, which provides reasonable precision and straightforward computation of all the necessary inputs for the data analysis [24, 25].

According to our analysis the best fit for the the SEP spectra is obtained using a modified power-law given in 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 $\delta\gamma$.

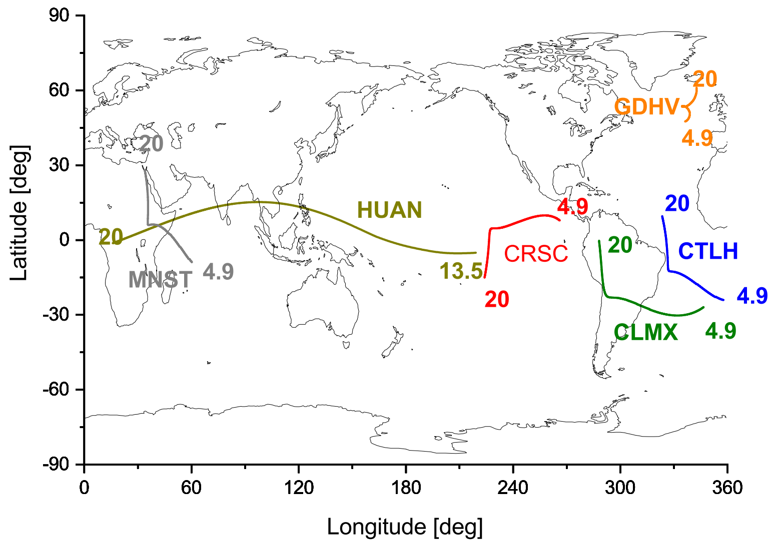

Figure 3: Asymptotic directions of selected ICs in geographic coordinates during GLE # 4 on 19 November 1949.

4. Conclusions

Using digitized historical records from ICs and NMs we assessed the SEP spectra during GLE # 4, which was the strongest event recorded during the pre-NM era.

The derived SEP spectra are slightly softer, and with smaller flux compared to that during GLE # 5. The presented here study is the initial step for studying historical strong SEP events leading to GLEs, and open a new window in the solar physics research.

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