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Halloween GLEs on October–November 2003, spectra and angular distribution: Revised results

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A precise study of solar energetic particles provides an important basis to understand their acceleration and propagation in the interplanetary space. A specific interest is paid to solar protons possessing energy high enough, so that they can induce an atmospheric cascade in the Earth's atmosphere, whose secondary particles reach the ground, eventually being registered by ground-based detectors e.g. neutron monitors. This particular class of events is called ground-level enhancements (GLEs). The solar cycle 23 provided several strong GLEs. The first strong GLE event of the cycle was observed on 14 July 2000 (the Bastille day event), while the last was observed on 13 December 2006. In addition, the period of late October - early November 2003 was characterized by strong cosmic ray variability and a sequence of three GLEs (the so-called Halloween GLEs) was registered, which 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 the Halloween GLEs. We modeled the particle propagation in the Earth's magnetosphere and atmosphere using a verified NM yield function computed at several altitudes above the sea level. The solar protons spectra and pitch angle distributions were obtained in their dynamical development throughout the events. We briefly discuss the revealed features of the Halloween events.

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1. Introduction

Sporadically, following solar eruptions, viz. solar flares, and coronal mass ejection (CMEs), solar ions can be accelerated to high energies, that is solar energetic particles (SEPs) [1, 2]. If their energy is about GeV/nucleon or even greater, similarly to the galactic cosmic rays (GCRs), they produce a shower of secondaries in the Earth's atmosphere, so that can be registered by ground-based detectors, such as neutron monitors (NMs) [3]. This special class of SEP events is called ground-level enhancements (GLEs) [4, 5] and can be studied using the worldwide NM network [6]. GLE events can last several hours, even in some cases tens of hours and differ from each other in spectra, duration, angular distribution are usually studied case by case. Their study is important in order to understand the possible acceleration scenarios and interplanetary transport [7–9].

2. Method of GLEs analysis using NM data

Methods for analysis of GLEs using NM data have been developed over several decades. They are based on modeling of the global NM network response and unfolding n model parameters over the experimental NM records [4, 10, 11].

The relative count rate increase of a given NM during GLE can be modelled by:

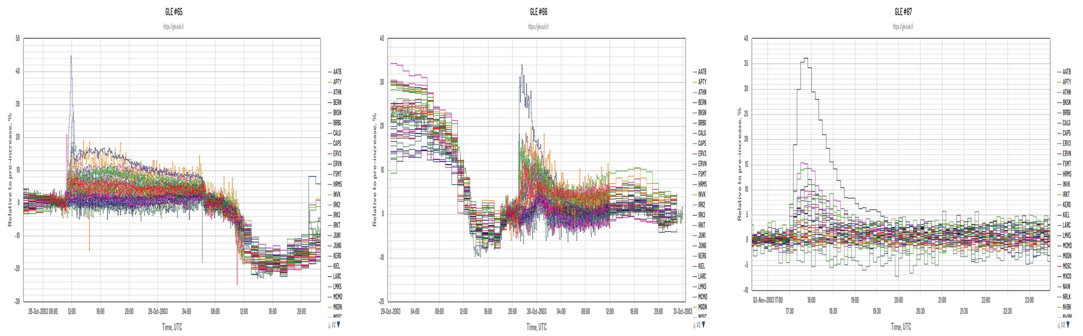
$$\frac{\Delta N(P_{\text{cut}})}{N(t)} = \frac{\sum_i \sum_k \int_{P_{\text{cut}}}^{P_{\text{max}}} J_{\text{sep}_\text{i}}(P,t) S_{i,k}(P) G_i(\alpha(P,t)) A_i(P) dP}{\sum_i \int_{P_{\text{cut}}}^{\infty} J_{\text{GCR}_\text{i}}(P,t) S_i(P) dP} \tag{1}$$

where N is the count rate due to GCR, $\Delta N(P_{\text{cut}})$ is the count rate increase due to solar particles. J_{sep} is the rigidity spectrum of SEPs i (proton or α-particle, usually considered only the former), $J_{\text{GCR}_\text{i}}(P,t)$ is the rigidity spectrum of the i component (proton or α-particle, etc...) of GCRs at given time t, $G(\alpha(P,t))$ is the pitch angle distribution, note that 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 obtained during the NM asymptotic cone computations. P_{cut} is the minimum rigidity cut-off of the station, accordingly, P_{max} is the maximum rigidity of SEPs considered in the model, whilst for GCR $P_{\text{max}}= \infty$. S_k is the NM yield function for vertical and for oblique incidence SEPs. Here the contribution of oblique SEPs to NM response, which is particularly important for modeling strong and/or very anisotropic events, is either modeled with the corresponding yield function either considering only vertical ones and using isotropic S_k similarly to [12].

Here, we assumed different spectral shapes, namely a modified power law with variable slope rigidity spectrum of SEPs similarly to [10, 13]:

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

where $J_{||}(P)$ is the particle flux with given rigidity P arriving from the Sun along the axis of symmetry whose direction is defined by geographic coordinate angles Ψ and Λ (latitude and longitude), γ is the power-law spectral exponent at rigidity P = 1 GV, $\delta\gamma$ is the rate of the spectrum steepening. We also assumed an exponential spectrum similarly to [13]:



(a) GLE 65 on 28 October 2003. **(b)** GLE 66 on 29 October 2003. **(c)** GLE 67 on 2 Nov. 2003.

Figure 1: NM count rate variation during the sequence of three Halloween GLEs. Data available at `gle.oulu.fi`.

$$J_{||}(P) = J_0 \exp(-P/P_0). \tag{3}$$

where $J_{||}$ is defined as in Eq. (2.3) and P_0 is a characteristic proton rigidity.

The pitch angle distribution in all cases was assumed to be a superposition of two Gaussian type ones, which allows us to model a bidirectional particle flow:

$$G(\alpha(P)) \propto \exp(-\alpha^2/\sigma_1^2) + B * \exp(-(\alpha - \pi)^2/\sigma_2^2) \tag{4}$$

where α is the pitch angle, σ_1 and σ_2 are parameters describing the width of the pitch angle distribution, B is a parameter corresponding to the contribution of the particle flux arriving from the anti-sun direction. The modeling of the global network NM response was carried out employing recently computed and validated NM yield function, [14–16]. The optimization was performed over the set of model parameters n by minimizing the difference between the modeled and measured NM responses, that is by inverse problem solution [17–21].

3. Halloween GLE events

Violent solar activity was observed in October–November 2003, which leaded to the sequence of three GLEs, with onsets occurring on 28 October (Fig.1a), 29 October (Fig.1b), and on 2 November (Fig.1c), respectively. The GLE on 28 October 2003 was associated with a large flare (4B, X17.2) occurred in the active region AR10486. The GLE 65 followed significant interplanetary disturbance related to previously ejected coronal mass ejection (CME) on 26 October with correspondence with a 3B/X1.2 flare in the same active region. The GLE 66 was characterized with a smaller NM count rate increases, thus this event was weaker. A strong Forbush decrease was also observed prior and during this event (Fig.1a,b), which was explicitly considered, i.e. a GCR flux reduce was taken into account during the analysis. The GLE 67 event on 2 November 2003 was related to an X8.3/2B solar flare, with onset at about 17:30–17:35 UT.

4. Results from the analysis

As first step we computed the asymptotic trajectories and cut-off rigidities of all NMs for the considered events, using MAGNETOCOSMICS code [22] employing a combination of IGRF model as internal field and the Tsyganenko 89 model [23] as the external field, respectively. This combination of magnetospheric models provides straightforward and precise computation [24]. As example we present the computed asymptotic directions for selected NMs during GLE # 65 (Fig.2).

Using NM data and the model described in Section 2, we derived the GLE particles rigidity spectra and PAD throughout the sequence of the Halloween events, as depicted in Figs.3–5.

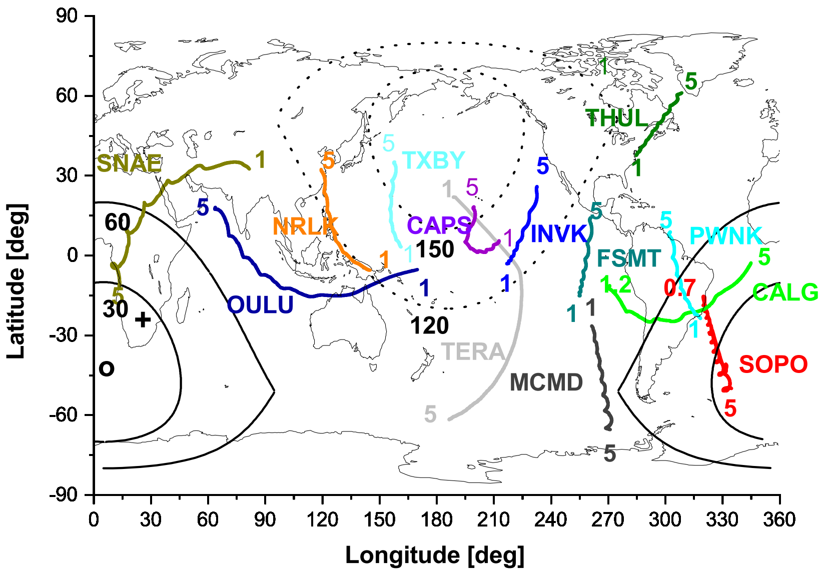


Figure 2: Asymptotic directions in GEO coordinates of selected NMs during GLE # 65 on 28 November 2003. The color lines and acronyms and numbers depict the asymptotic directions of NMs and rigidities in the rigidity range 1 – 5 GV. The lines of equal pitch angles relative to the anisotropy axis are plotted for 30° and 60° for sunward direction (solid lines), 120°, 150° for anti-Sun direction (dashed lines), respectively. The cross depicts the measured by ACE space-probe IMF direction.

During the event's onset of GLE # 65, relatively hard rigidity spectrum with moderate steepening of SEPs with gradual increase of the flux and moderate anisotropy fitted with single Gaussian shape, were derived (Fig.3). During the main phase of the event, a continuous softening of the spectra and fast isotropisation were observed. In the late phase, the event was depicted with pure power-law spectrum and nearly isotropic PAD.

During the complicated analysis of GLE # 66 occurred during deep Forbush decrease, we derived softer spectra and a single Gaussian PAD. Relatively fast softening and isotropisation of the SEPs were revealed. In general, GLE # 66 was with softer SEP spectra, smaller flux, but with similar PAD (Fig.4).

The GLE # 67 was characterized by a large anisotropy in its initial phase, since no significant increase at SANAE NM was observed, while stations with small pitch-angles, specifically SOPO,

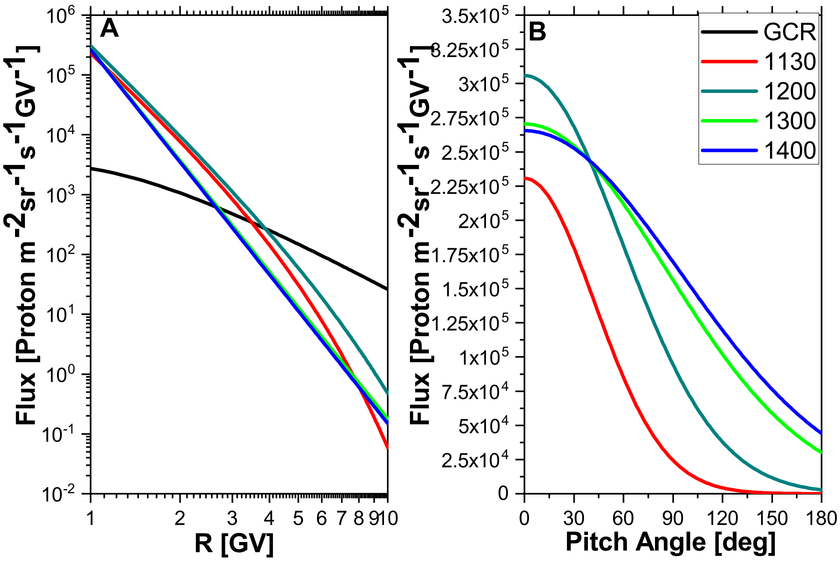


Figure 3: Derived spectra and PAD during selected stages of GLE # 65 on 28 October 2003.

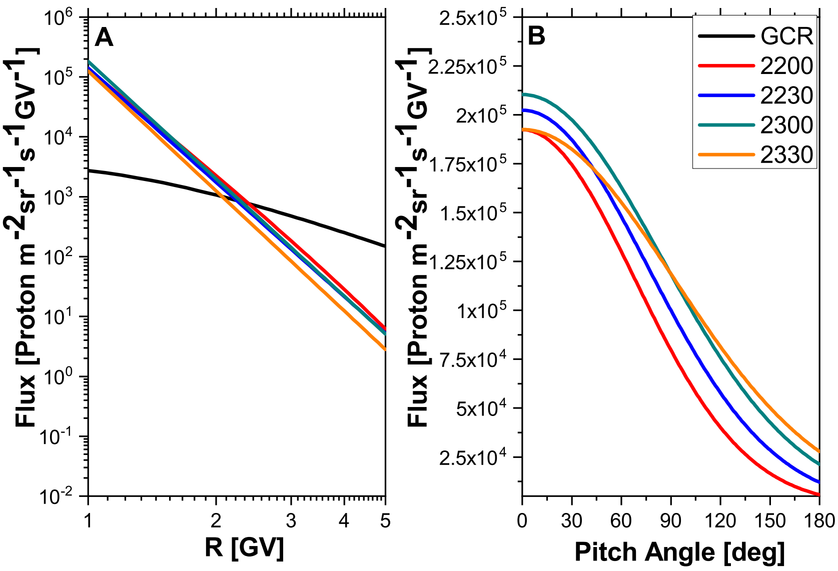


Figure 4: Derived spectra and PAD during selected stages of GLE # 66 on 29 October 2003.

TERA and MCMD exhibited significant count rate increases. In addition, there is a clear indication for a bidirectional particle flux (Eq.4), the details are given elsewhere [9, 25].

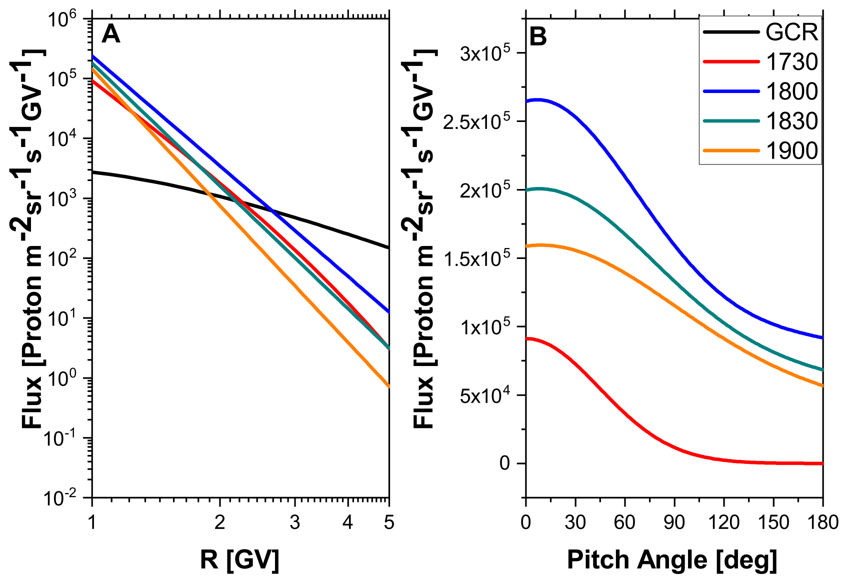


Figure 5: Derived spectra and PAD during selected stages of GLE # 67 on 2 November 2003.

5. Conclusions

Using NM records and verified method [26], we derived the rigidity spectra and PAD of SEPs during the sequence of the Halloween events in October–November 2003. The best fit of the global NM network response was achieved with a modified power-law rigidity spectrum (during the initial and main phase of the events) and a pure power-law during the late phase of the events. However, an exponential rigidity spectrum, specifically during the event onset and initial phase, showed similar quality of the fit (GLE # 65 and GLE # 67). The best fit for PAD was obtained using a singel Gaussian for GLE # 65 and GLE # 66, while for for GLE # 67, a complicated bi-directional particle flux and relatively strong anisotropy during the initial phase were revealed. In all cases, the anisotropy gradually decreased in the course of the events. The derived spectra and PAD give basis to study different scenarios of relativistic SEPs acceleration and the related terrestrial effects similarly to [27–29].

Acknowledgements

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