Halloween GLEs on October–November 2003, spectra and angular distribution- new revised results

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Abstract: 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 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 newly computed and 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 discussed the revealed features of the Halloween events.

Introduction, Method for GLE analysis using NM data & Halloween GLE events on October-November 2003

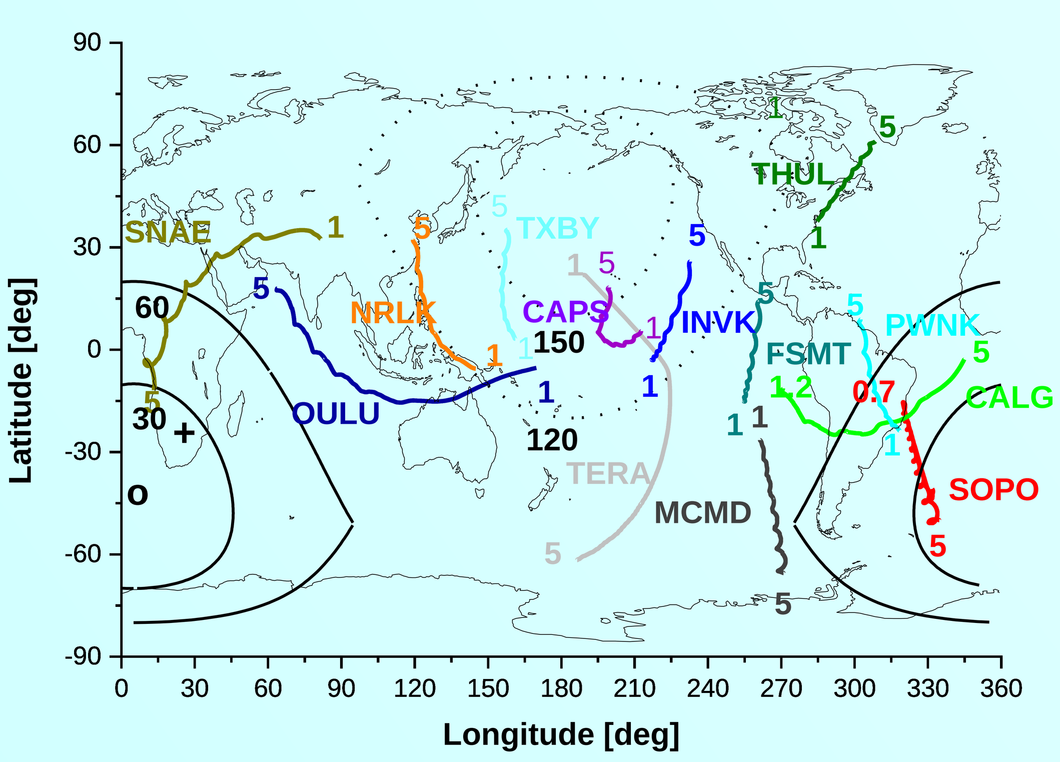
A specific class of solar energetic particles (SEP) events, that can be observed at ground level by registration of the sub-products of induced atmospheric shower, called ground-level enhancements (GLEs)], invokes specific interest, giving basis to understand the possible acceleration scenarios as well as the interplanetary transport.

As a result of solar eruptive processes, viz. solar flares, and/or coronal mass ejection (CMEs), solar ions can be accelerated to high energies, i.e. producing SEPs. They penetrate the Earth's atmosphere and if their energy is about GeV/nucleon or even greater, produce nuclear-electromagnetic-meson shower of secondaries, so that can be registered by ground-based detectors, specifically neutron monitors (NMs).

The methods for analysis of GLEs using NM data are based on modeling of the global NM network response and unfolding the model parameters over the experimental records. In summary the method involves consecutive steps of detailed computation of asymptotic cones and rigidity cut-off of each NM station used whose records are used in the analysis, modelling and corresponding optimization of the global NM response over experimental data points.

Here, we modeled the NM response using a new NM yield function computed for several altitudes, which is fully consistent with the experimental latitude and altitude surveys and was recently validated by achieving good agreement between model results and space-borne with AMS 02 and ground-based NM measurements [*Gil et al.*, 2015; *Lara et al.*, 2016; *Usoskin et al.*, 2017; *Nuntiyakul et al.*, 2018; *Koldobskiy et al.*, 2019; *Mishev et al.*, 2020]. Therefore, the response of each NM was modeled with a yield function corresponding to the exact station's altitude a.s.l., which allowed us to reduce model uncertainties related to the application of the double-attenuation-lengths method, i.e. normalization of high-altitude NM count rates to the sea level.

A violent solar activity was observed in October–November 2003, which leaded to the sequence of three GLEs, with onsets occurring on 28 October, 29 October, and on 2 November, 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 increase, 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 computations. 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.

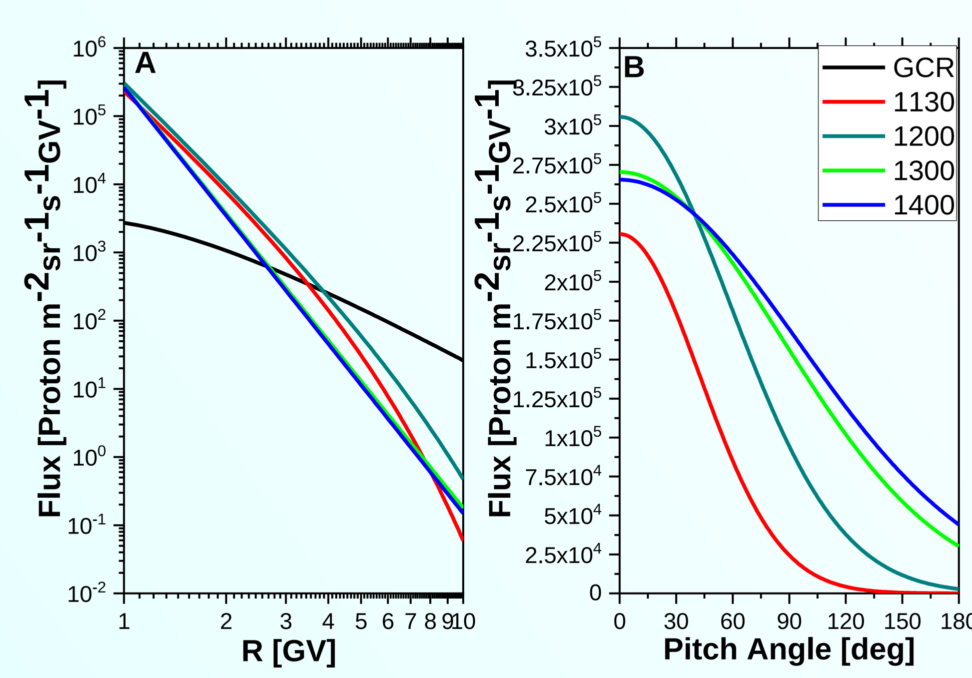


Asymptotic directions for selected NM stations during GLE# 65

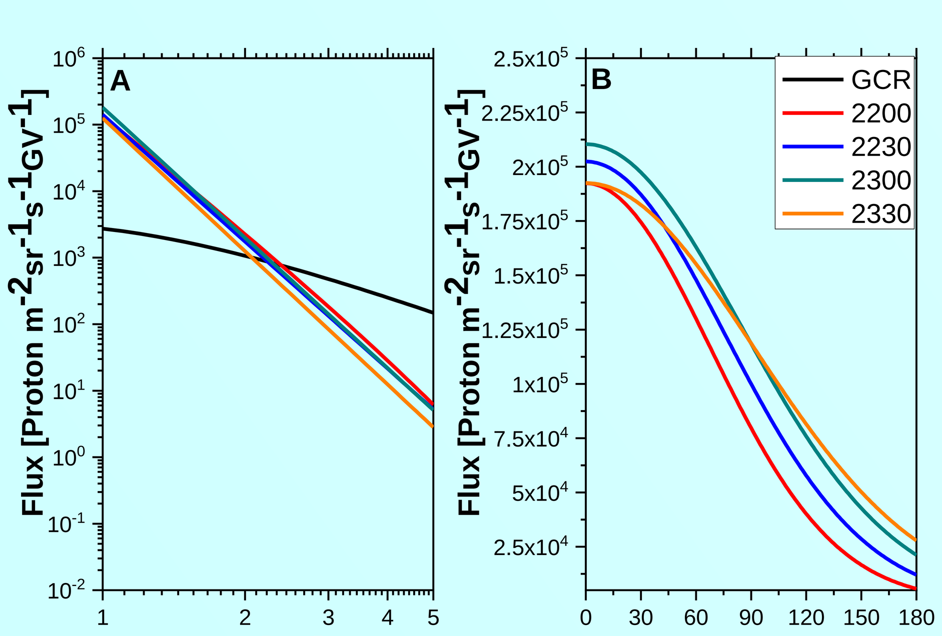
The relative count rate increase of a given NM during GLE is modelled using:

$$\frac{\Delta N(P_{cut})}{N(t)} = \frac{\sum_i \sum_k \int_{P_{cut}}^{P_{max}} J_{sep_i}(P,t) S_{i,k}(P) G_i(\alpha(P,t)) A_i(P) dP}{\sum_i \int_{P_{cut}}^{\infty} J_{GCR_i}(P,t) S_i(P) dP}$$

i.e. the ration of the count rate due to SEPs and GCR background, G is the pitch angle distribution, note for GCRs the angular distribution is assumed to be isotropic, A(P) is a discrete function =1 for allowed trajectories and =0 for forbidden trajectories. In the model are considered events with vertical and blique incidence SEPs. The contribution of oblique SEPs to NM response is particularly important for modeling strong and/or very anisotropic events, while for weak and/or moderately strong events it is possible to consider only vertical ones and using the YF for an isotropic case, which considerably simplifies the computations



Derived spectra and PAD during GLE# 65



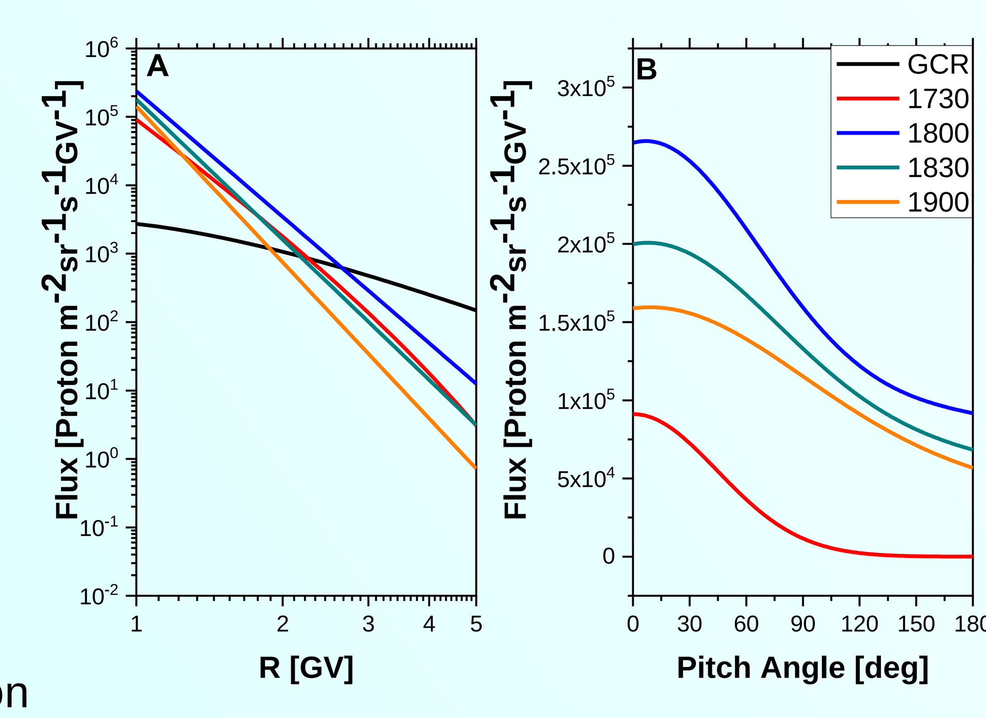
Derived spectra and PAD during GLE# 66

Here we assumed a modified power law with variable slope rigidity spectrum

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

The PAD is a superposition of two Gaussian like distributions

$$G(\alpha(P)) \sim exp(-\alpha^2/\sigma_1^2) + B*exp(-(\alpha-\alpha')^2/\sigma_2^2)$$



Derived spectra and PAD during GLE# 67

Thus, employing several consecutive steps, namely computation of asymptotic viewing directions and cut-off rigidity of all NMs used for the data analysis; making an initial guess of the optimization procedure and performing optimization using modeled and recorded NM response over a selected space of unknown parameters, allowed us to analyze the GLE # 71

Results & Discussion

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.2). During the main phase of the event, a constant softening of the spectra and fast isotropisation were observed. In the late phase the spectrum was depicted with pure power-law, with nearly isotropic PAD. During the complicated for analysis, occurring during deep Forbush decrease, GLE # 66, we derived softer spectra and 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.3). 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, TERA and MCMD exhibited significant count rate increases. In addition, there is a clear indication for a bidirectional particle flux.

In a summary using NM records, 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 modified power-law rigidity spectrum (during the initial and main phase of the events) and 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).