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 atmosphere 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), involves 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.

Here, we assumed a modified power law with variable slope as fitted to the ground-based NM data, with a reduced model complexity concerning the various latitude bands, while a GCR flux reduction was taken into account during the computations. The GLE 67 event on 2 November 2003 was related to an X9.3/2B solar flare, with onset at about 17:30–17:35 UT. The relative count rate increase of a given NM during GLE 67 is modeled using:

\[
\text{Relative Count Rate Increase} = \frac{N_{\text{GLE}} - N_{\text{B}}}{N_{\text{B}}}
\]

where \(N_{\text{GLE}}\) is the count rate during the GLE event and \(N_{\text{B}}\) is the background count rate.

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 isotropization 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 isotropization 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 SNAE NM was observed, while stations with small pitch-angles, specifically SOPO, TERA and MCMID 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).