Application of verified neutron monitor yield function for GLE analysis

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Abstract: Systematic study of solar energetic particles provides an important basis to understand their acceleration and propagation in the interplanetary space. After solar eruptive processes, such as solar flares and/or coronal mass ejections solar ions are accelerated to high energy. In the majority of cases, the maximum energy of the accelerated solar ions is several tens of MeV/nucleon, but in some cases, it exceeds 100 MeV/nucleon or even reaches GeV/nucleon range. In this case, the energy is high enough, so that solar ions generate an atmospheric cascade in the Earth's atmosphere, where secondary particles reach the ground, eventually registered by ground-based detectors, specifically neutron monitors. This particular class of events is known as ground-level enhancements (GLEs). Several methods for analysis of GLEs, using neutron monitor data were developed over the years. Here, we present a method for assessment of the spectral and angular features of the GLEs using data from the world-wide NM network, namely by modeling the global neutron monitor network response with new verified yield function. The method is based on consecutive steps, specifically detailed computation of asymptotic cones and rigidity cut-off of each station used in the analysis and optimization of global neutron monitor response over experimental and modeled count rate increase. The method is compared with other methods, including in-situ measurements. A very good agreement between our method and space-borne measurements with PAMELA space probe, specifically the derived fluence of solar protons during GLE 71 was achieved, therefore verification of the method is performed.

Introduction & Method for GLE analysis using NM data

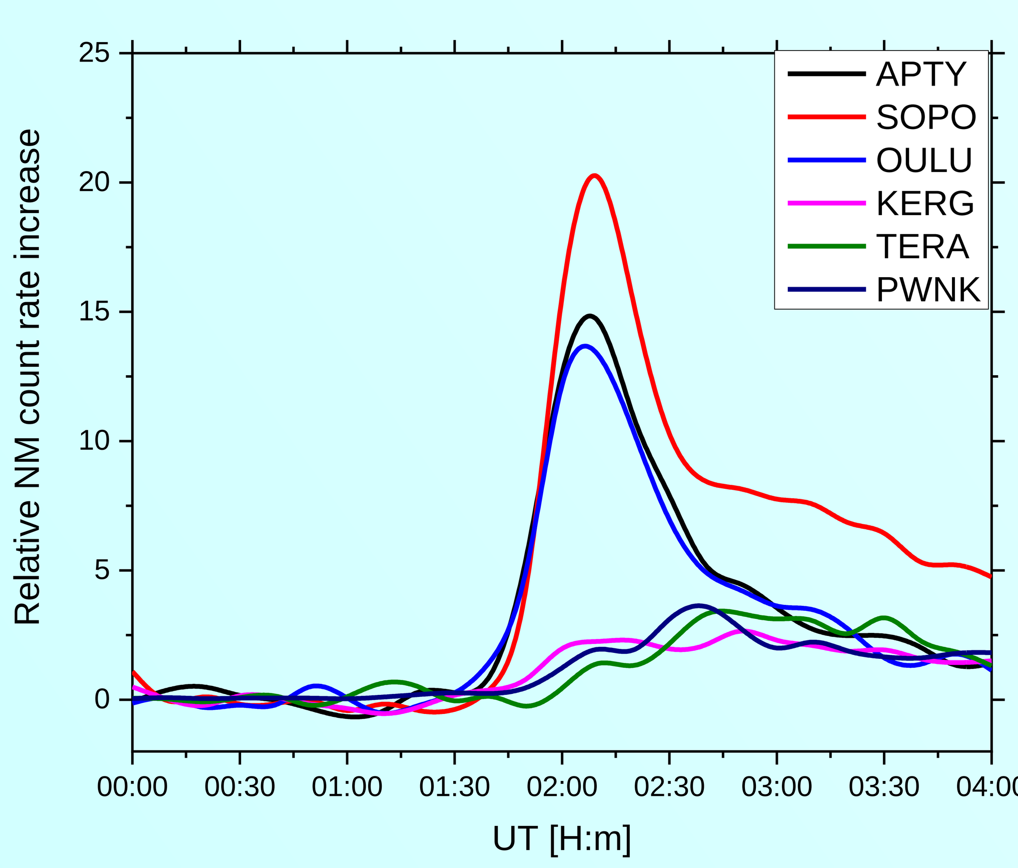
A specific class of solar energetic particles (SEP) events, that can be observed at ground level by registration of the sub-products of induced atmospheric shower, called ground-level enhancements (GLEs)], invokes specific interest, giving basis to understand the possible acceleration scenarios as well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

Here, we performed a revised analysis of 17 May 2017 GLE # 71, using newly computed and verified NM yield function for several altitudes and compared the derived fluence with direct measurements e.g. by the PAMELA space probe.

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.*, 2019b; *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

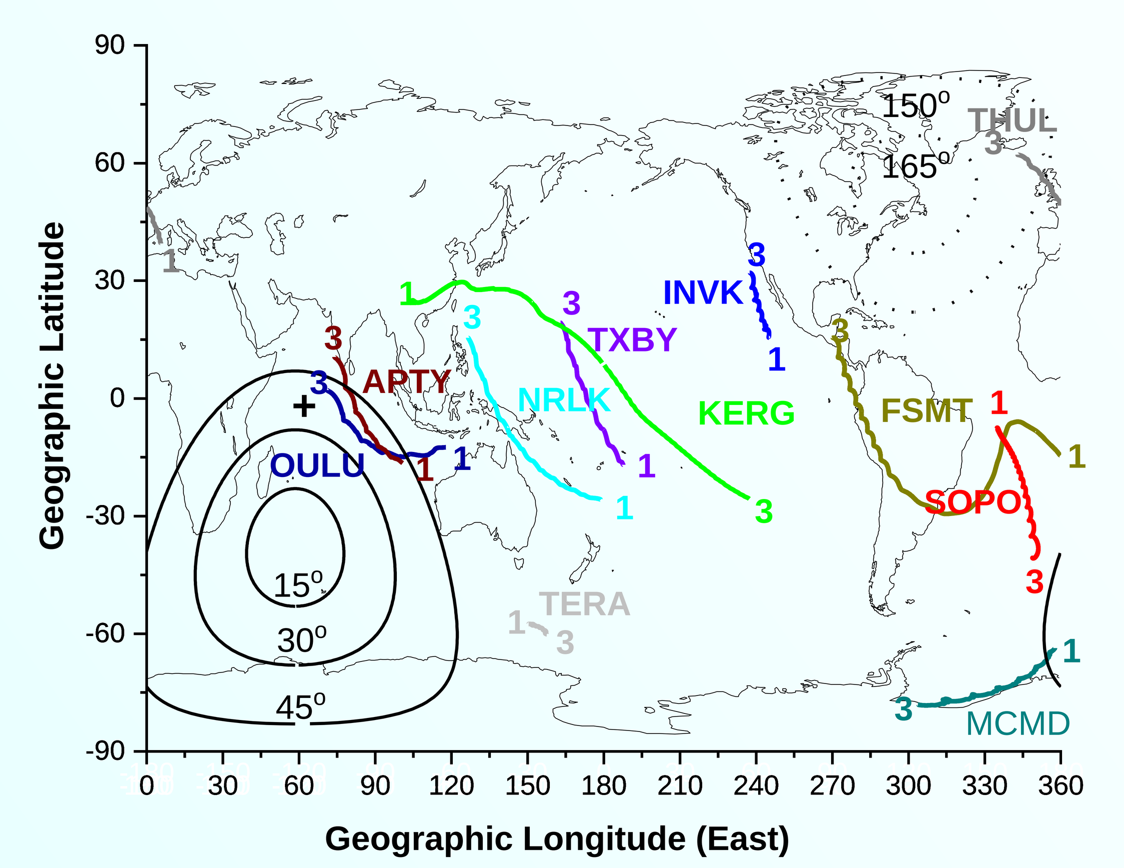


Profiles of count rate variation of selected polar NMs during GLE 71 on 17 May 2012.

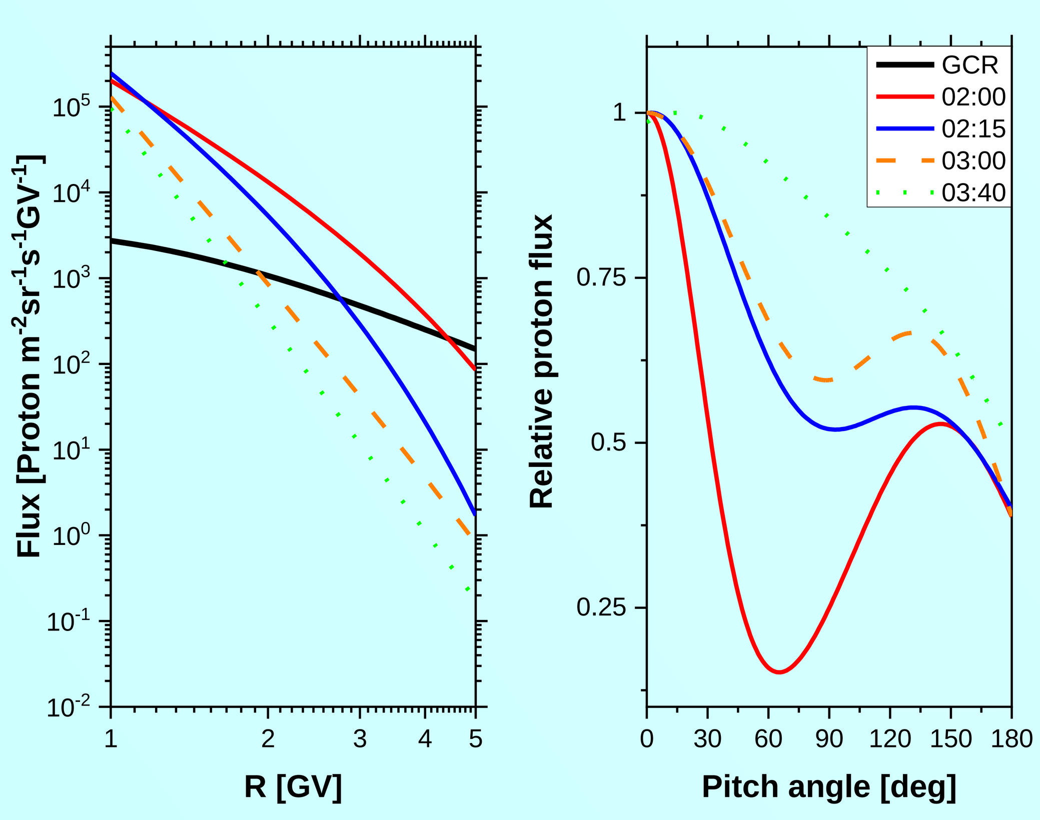
The relative count rate increase of a given NM during GLE is modelled using:

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

i.e. the ration of the count rate due to SEPs and GCR background, G is the pitch angle distribution, note for GCRs the angle 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



Asymptotic directions for selected NM stations during GLE# 71



Derived spectra and PAD during GLE# 71

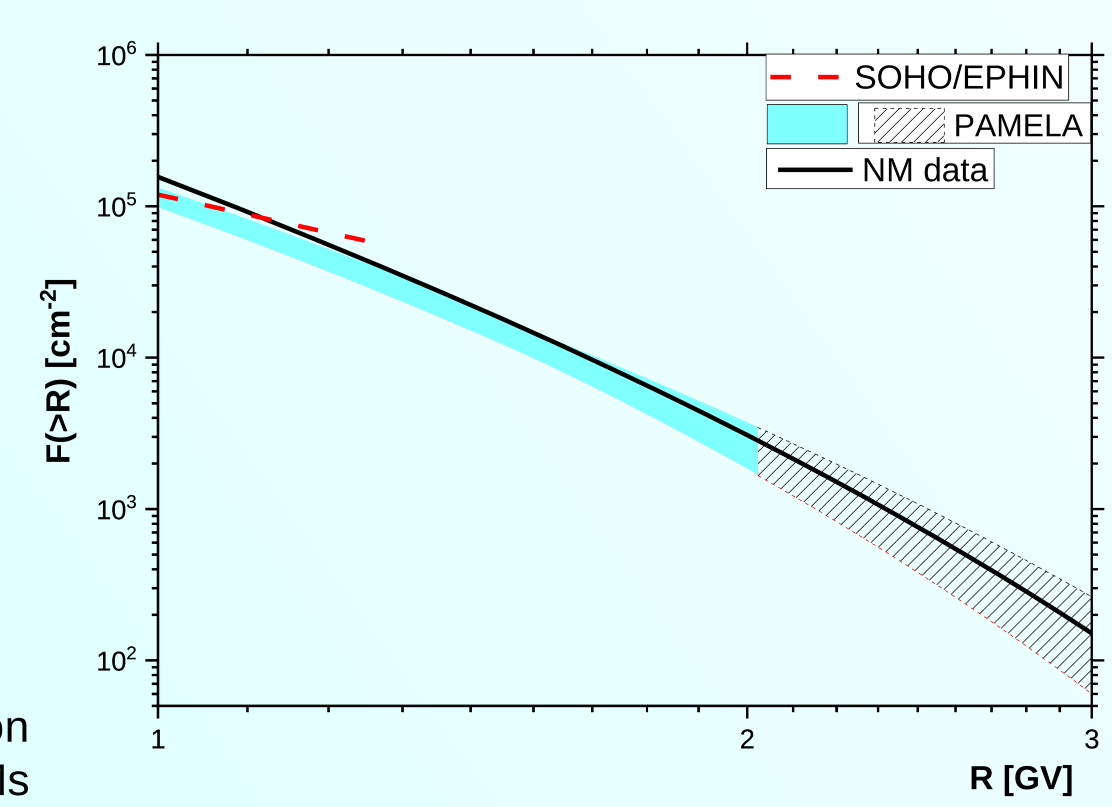
Here we assumed a modified power law with variable slope rigidity spectrum

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

The PAD is a superposition of two Gaussian like distributions

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

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



Integrated SEP fluence during GLE# 71

Results & Discussion

GLE # 71 occurred on 17 May 2012, following eruptions in the active region NOAA 11476, which produced a CME and a M5.1 flare at 01:25 UT. The active region was on the west side at N07 W88, so that the Earth was well magnetically connected to the eruption core. On the ground, the global NM network recorded a moderate even weak enhancement of the count rates of several stations around 01:50 UT, with slightly greater signals observed in APTY, OULU, and SOPO/SOPB NMs. Using de-trended NM records retrieved from the GLE database (for details see the http://gle.oulu.fi, we derived the spectral and angular characteristics of SEPs in Fig.3. We distinguished three phases of the event: initial (01:50–02:25 UT), when a relatively hard spectrum, a constant increase of SEP flux and complicated PAD were derived; main phase (02:25–03:05 UT), when a steady softening of the SEP spectra and decrease of the SEP flux were derived, accordingly a tendency of decrease of the steepening XW of the spectrum was observed, and late phase of the event (after 03:05 UT), when a pure power-law SEP spectrum and wider a nearly isotropic in the very late phase PAD were revealed. The event integrated particle fluence and very good agreement with the direct measurements made by PAMELA space-probe was achieved (Fig.4), We note, that PAMELA allowed one to reveal SEPs over GCR background for rigidities less than about 2 GV. Therefore, the spectra and PAD in the higher-energy range is retrieved using olely the global NM network. Besides, good agreement with SOHO/EPHIN measurements fitted with pure power-law, specifically in the energy range 300-700 MeV/nucleon, was also seen.