

Computations of cosmic ray propagation in the Earth's atmosphere, towards a GLE analysis

A Mishev^{1,2} and **I Usoskin**¹

¹ Sodankyla Geophysical Observatory (Oulu unit), University of Oulu, P.O.Box 3000, FIN-90014, Oulu, Finland

² Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 72 Tsarigradsko chaussee, 1784 Sofia, Bulgaria

E-mail: alexander.mishev@oulu.fi

Abstract. Computation of solar energetic particles propagation in the magnetosphere and atmosphere of the Earth is very important for ground level enhancement analysis. Detailed simulations of solar energetic particles events starting from asymptotic direction computation and NM detector response make it possible to build a strategy for inverse problem solution i.e. obtaining the characteristics of solar energetic particles on the basis on ground measurements. In this study a simulation of cosmic ray atmospheric cascade is carried out with PLANETOCOSMICS code. Energy spectra of secondary particles, namely neutrons and protons are obtained at various altitudes in the rigidity range of 0.7 GV to 1 TV of primary particles. Considering updated results for NM-64 detection efficiency the specific yield function for the standard neutron monitor is obtained for vertically and obliquely incident primary particles. The obtained results and applications are discussed.

1. Introduction

The Earth is constantly hit by high energy particles - cosmic ray. The primary cosmic ray (CR) particles from galactic or solar origin impinge the Earth's atmosphere, collide with an atmospheric nucleus and produce new, energetic particles, which also collide with air nuclei etc...Each collision adds a large number of particles to the developing cascade. A major challenge is the reconstruction of primary particle characteristics from ground-based data records.

The measurements performed by the worldwide network of neutron monitors (NM) are used to determine characteristics of solar energetic particles (SEP)s near Earth [1]. In a such analyses a key point is the application of a precise NM yield function. The difference between experimentally measured and theoretically derived yield functions is of the order of 2 [2]. At the same time an essential progress of computation of NM specific yield function is carried out [2, 3, 4]. However, specifically in a low rigidity range are observed differences [2, 4]. For the precise determination of a NM yield function a realistic transport through the atmosphere of secondary particle as well as NM detection information efficiency are necessary. This could be performed on the basis of Monte Carlo simulation tools.

2. NM-64 yield function

The NM yield function incorporates the propagation of particles through the Earth's atmosphere and the neutron monitor detection response to secondary particles, mainly neutrons and protons.

Therefore the NM yield function converts the ground-level particle intensities to count rates. On the basis of the yield function could be determined the response function by convolution of the cosmic ray spectra with the yield function. The expected count rate is obtained by integration of resulting response functions. The integral response function (count rates) is directly measured during latitude survey of NM performed with mobile station [5]. The NM counting rate is presented as:

$$N(P_c, h, t) = \int_{P_c}^{\infty} \sum_i Y_i(P, h) j_i(P, t) dP = \int_{P_c}^{\infty} W_T(P, h, t) dP \quad (1)$$

where $N(P_c, h, t)$ is the NM counting rate, P_c is the geomagnetic cutoff, h is the atmospheric depth and t represents time. The $Y_i(P, h)$ represents the NM yield function for primaries of particle type i , $j_i(P, t)$ represents the primary particle rigidity spectrum of type i at time t and W_T is the total differential response function.

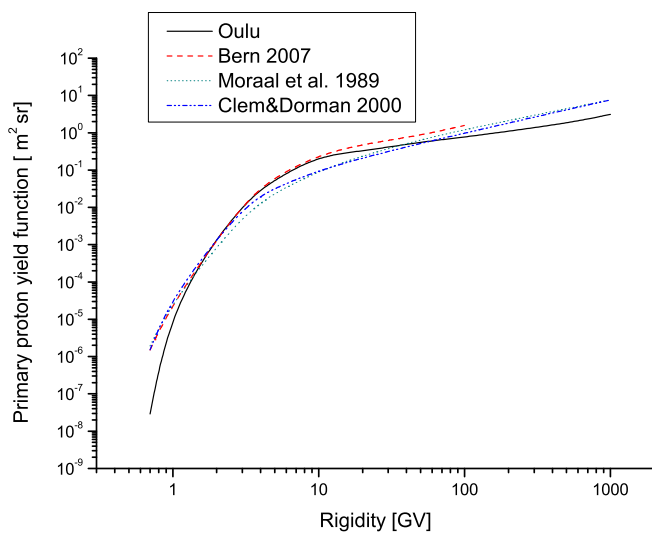


Figure 1. Comparison of new computed proton yield function for 6NM-64 at sea level.

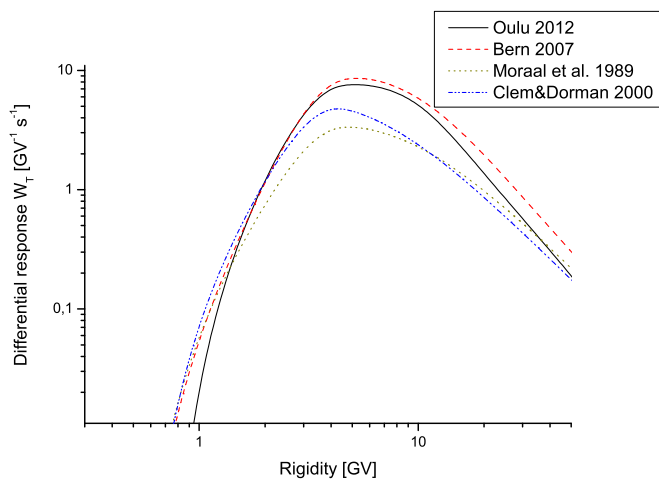


Figure 2. Comparison of total differential response during solar minimum for 6NM-64 at sea level.

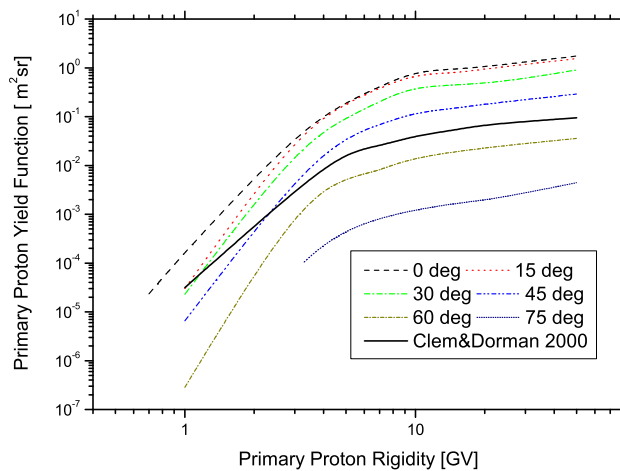


Figure 3. Proton yield function for 6NM-64 at sea level for various incidence compared with [2] for 45 degrees.

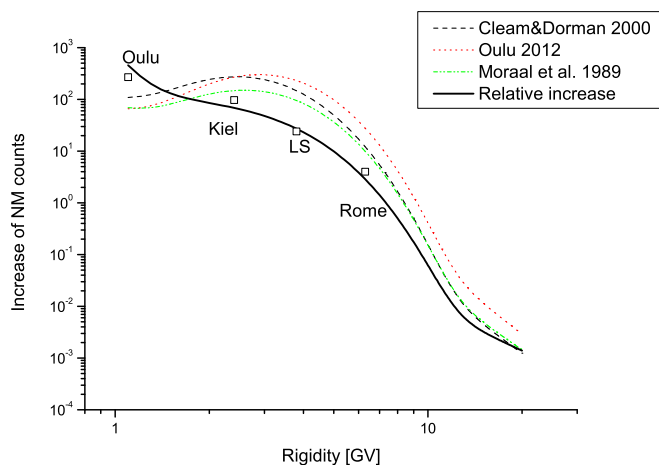


Figure 4. Calculated increase of 6NM-64 count at sea level using various yield functions.

In recent studies based on NM data, the yield function is applied. In general it is evaluated for specific conditions (sea level). The NM yield function is defined as

$$Y_i(P, h) = \sum_i \int \int A_i(E, \theta) F_{i,j}(P, h, E, \theta) dE d\Omega \quad (2)$$

where $A_i(E, \theta)$ is the effective area of the NM (detector area multiplied by registration efficiency), $F_{i,j}$ is the differential secondary particle flux of j space (neutrons, protons, muons, pions) per primary i , E is respectively the secondary particle energy, θ is the angle of incidence of secondaries and Ω is the solid angle.

Obviously the information about detection efficiency of a neutron monitor is necessary. In this study we use an updated version of NM registration efficiency [2] and detailed simulation of cosmic ray induced cascade. The main contribution to the counting rates at ground level comes from neutrons and protons [2]. It was recently demonstrated by Monte Carlo simulations that in a high energy range the response of neutrons and protons is in practice the same [2, 4].

The secondary neutron and proton spectra are obtained on the basis of PLANETOCOSMICS

[6] simulations. Using updated information for standard NM-64 registration efficiency and equation (2) we compute the yield function. The computed proton yield function for 6NM-64 at sea level is presented in figure 1. The corresponding total differential response during solar minimum for 6NM-64 at sea level is shown in figure 2. In this case the GCR spectrum is according force field model as in [7].

The contribution of obliquely incident primaries is also important [8], they may be responsible for anomalies observed in latitude surveys. With this in mind similar simulations are carried out. The computed 6NM-64 proton yield function for various angles of incidence is presented in figure 3.

3. Summary and discussion

The new computed NM yield function demonstrates a good agreement with previous results (figure 1). It slightly differs, specifically in a low rigidity range and above some 100 GV rigidity. This is due to the isotropic primary particle flux, which was considered instead of vertical of previous works [2], as well as the different registration efficiency. In addition, the Bern 2007 [4] parametrization is not consistent in a high rigidity range.

The total response function $W_T(P, h, t)$ has a maximum value in the range of 4-6 GV at sea-level depending on the solar modulation at time t . The obtained total response function is in a good agreement with previous results. It is more consistent with Bern 2007 parametrization [4]. The computed yield function for protons with various incidence agrees with [2], the primary proton yield function for 45 degrees of incidence as shown in figure 3.

On the basis of obtained new NM yield function, an increase of NM count rate is estimated as a function of rigidity for GLE 69 on 20 January 2005. The spectra are taken from [9]. It is compared with other parametrization as well as experimental data with good agreement (figure 4).

The computed NM yield function permits to perform further GLE analysis with good precision on the basis of well known methods.

Acknowledgments

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreement N 262773 (SEPServer). The authors warmly acknowledge Dr. John Clem from Bartol Research Institute and Dr. B.B. Gvozdevsky and E.A. Maurchev from Polar Geophysical Institute - RAS for the updated information concerning NM registration efficiency. We acknowledge also Prof. V. Mahmutov from Lebedev Physics Institute of RAS for information related to PLANETOCOSMICS simulations.

References

- [1] Mavromichalaki H, Papaioannou A, Plainaki C and al 2011 *Advances in Space Research* **47** 2210
- [2] Clem J and Dorman L 2000 *Space Science Reviews* **93** 335
- [3] Vashenyuk E V, Balabin Yu V and Stoker P H 2007 *Advances in Space Research* **40** 331
- [4] Fluckiger E O, Moser M R, Pirard B, Butikofer R and Desorgher L 2008 Proc. of 30th International Cosmic Ray Conference, July 3 - 11, 2007, Merida, Yucatan, Mexico, vol. 1, 289
- [5] Moraal H, Potgieter M S, Stoker P H and van der Walt A 1989 *J. Geophys. Res.* **94** 1459
- [6] Desorgher L, Fluckiger E O, Gurtner M et al. 2005 *International Journal of Modern Physics A* **20** 6802
- [7] Usoskin I G, Alanko-Huotari K, Kovaltsov G A, and Mursula K 2005 *J. Geophys. Res.* **110** A12108
- [8] Clem J Bieber J W Evenson P et al . 1997 *J. Geophys. Res.* **102** 26919
- [9] Vashenyuk E V, Balabin Yu V, Gvozdevskii B B and Karpov S N 2006 *Geomagnetism and Aeronomy* **46** 424