PoS PROCEEDINGS OF SCIENCE

Sensitivity of the world-wide neutron monitor network to solar neutrons: A revised approach

Anton Artamonov
Sodankylä Geophysical Observatory (Oulu unit), University of Oulu, Oulu, Finland.
E-mail: anton.artamonov@oulu.fi

Gennady Kovaltsov
Ioffe Physical-Technical Institute of Russian Academy of Sciences, St. Petersburg, Russia.
E-mail: gen.koval@mail.ru

Alexander Mishev[*†]

ReSolve CoE University of Oulu, Finland.
E-mail: alexander.mishev@oulu.fi

Ilya Usoskin
ReSolve CoE University of Oulu, Finland.
Sodankylä Geophysical Observatory (Oulu unit), University of Oulu, Oulu, Finland
E-mail: ilya.usoskin@oulu.fi

Observations of intense sporadic solar-neutron events provide a unique opportunity to study energetic processes of particle acceleration during solar flares. Such neutrons are produced in nuclear reactions of high-energy (from several hundred MeV/nuc to several GeV/nuc) particles in the solar atmosphere and surface. The existing neutron monitor (NM) network provides a continuous record of cosmic ray intensity over several solar cycles but can also serve as a suitable detector for solar neutrons. Here we revisit the sensitivity of the world wide neutron monitor network to solar neutrons using a newly computed yield function for solar neutrons. The yield function was computed using a Monte-Carlo simulation of the neutron-induced atmospheric cascade and updated information about the NM detection efficiency. The simulation was performed with the PLANETOCOSMICS code, which incorporates the full complexity of the atmospheric cascade development, namely secondary particle propagation and attenuation in the Earth's atmosphere. The yield function incorporates also the detection efficiency of NM to secondary CR particles. Subsequently a technique based on the modelled NM response to solar neutrons is applied in order to estimate the sensitivity of world wide neutron monitor network to solar neutrons. The results are widely discussed in application of the solar neutron event.

The 34th International Cosmic Ray Conference,
30 July- 6 August, 2015
The Hague, The Netherlands

[*]Speaker.
[†]also at Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences.

1. Introduction

The existing neutron monitor (NM) network provides a continuous record of cosmic ray intensity over several solar cycles. It is known that some solar flares and eruptive events, such as coronal mass ejections (CMEs) can accelerate protons and other ions to high energies [1]. In addition, eruptive processes may produce a small amount of neutrons [2]. In fact, they are secondary particles produced by collisions of ions in the solar photosphere, namely during interactions between the accelerated proton, heavy ion and the surrounding atmosphere [3]. Solar neutron events (SNE) provide unique opportunity to study particle acceleration mechanisms using records from satellite/ground-based detectors. Solar neutrons bring crucial information concerning the acceleration site, such as energy spectrum, elemental composition of solar flare, magnetic field and magnetohydrodynamic turbulence [4, 5, 6]. Solar neutrons travel straight through the interplanetary space and geomagnetosphere being unaffected by magnetic fields, a fraction of them decay during the travel and finally they enter the Earth atmosphere producing a cascade. A convenient instrument for observation of SNEs is the ground-based worldwide neutron monitor network [7, 8].

2. Newly computed yield function and sensitivity of neutron monitor network to solar neutrons

The NM yield function at given altitude h for a primary particle with given incidence α is defined as

$$S_n(E,h,\alpha) = \sum_i \int \int A_i(E',\theta) F_i(h,E',\theta) dE' d\Omega \tag{2.1}$$

where $A_i(E,\theta)$ is the detector area multiplied by registration efficiency, F_i is the flux of secondary particles (neutrons, protons, muons, pions) per primary particle of type i, E' is the secondary particle's energy, θ is the angle of incidence of secondaries. The newly computed NM yield function for primary solar neutrons is shown in Fig.1. The computations are fulfilled similarly to [9] using the PLANETOCOSMICS code [10] with NRLMSISE2000 atmospheric model [11].

The response of a NM to solar neutrons increases as a function of the altitude h above the sea level. It is maximal for neutrons with vertical incidence. The yield function diminish with increasing the solar neutron angle of incidence with respect to the zenith. The response of a given NM depends on the geographical position, the spectrum of solar neutrons at the Earth's orbit, the type and number of NM counters. In a time interval Δt of a SNE the response of a NM to solar neutrons N_n with incidence α as (counts s^{-1}) is defined as

$$N_n(h,\alpha) = \int_t^{t+\Delta t} \int_{E>0}^{\infty} F_n(E,t') \cdot S_n(E,h,\alpha) \cdot dE \cdot dt' \tag{2.2}$$

where $F_n(E,t')$ is the spectrum of solar neutrons at the Earth's orbit (m^{-2} s^{-1} MeV^{-1}, E is the solar neutron energy, $S_n(E,h)$ (m^2) is the sensitivity of NM to solar neutrons. The response of NM network is a function of the zenith angle of the Sun α can be approximated as [7]:

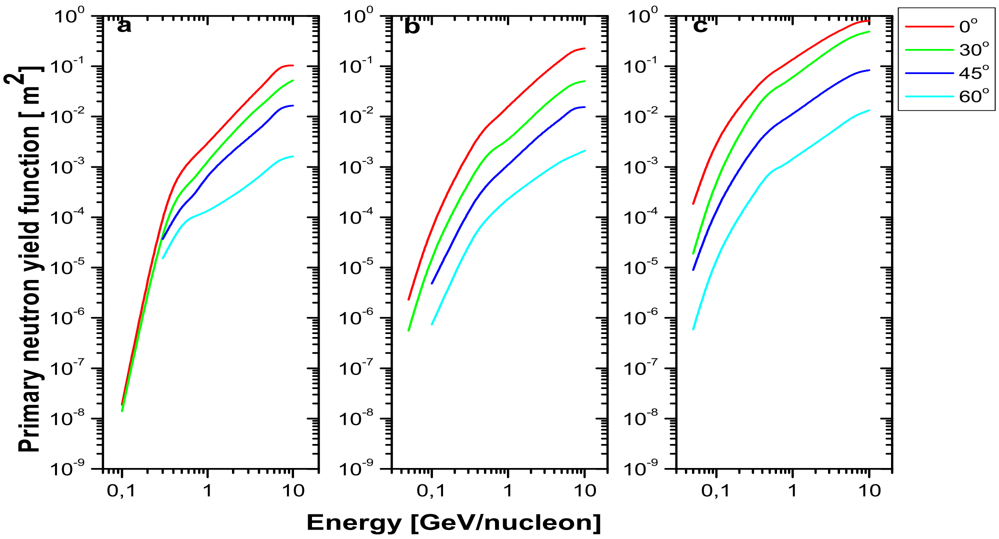

Figure 1: Primary neutron yield function for 6NM64 for solar neutrons with incidence of 0°, 15°, 30°, 45° and 60° at several altitudes. a) sea level b) 3000 m a.s.l. c) 5000 a.s.l..

$$\cos\alpha = \sin\varphi \cdot \sin\left(\frac{2\pi}{365}t_d\right) \cdot \sin\varepsilon + \cos\varphi \cdot \sqrt{1-\sin^2\left(\frac{2\pi}{365}t_d\right)\sin^2\varepsilon} \cdot \cos\left(\pi \cdot \left(\frac{T}{12}+\frac{\lambda}{180}-1\right)\right) \quad (2.3)$$

where φ and λ are the latitude (-90°:90°) and longitude (0°:360°) of the NM location, respectively, ε=23.5° is the inclination of the equator relative to the ecliptic plane, t_d is the number of days after the spring equinox (1:365 days), T is the time UT in hours (0:24 hours). During the computations we used a time step of 6 min. Therefore, the response of a given NM is a function of the altitude above the sea level, the zenith angle of the Sun, the NM location and the energy of solar neutrons.

3. Results of the modelling

Here we consider mountain NMs summarized in Table 1 during two periods: 1990 and 2010. We present in Fig. 2 the sensitivity of the world neutron monitor network to an intense SNE similar to that of 24 May 1990 as a function of time of occurrence of the event.

The sensitivity of NMs network is maximal in the summer period from 4:00 to 11:00 UT (figure 2a) in the case of 1990, accordingly from 4:00 to 12:30 UT (figure 2b) in the of 2010. The NM network has a period of low sensitivity to a SNE. namely during the winter between 20:00 and 08:00 UT or during the summer between 23:30 and 01:00 UT. This gap could be reduced by installation of new NM at a proper location. We propose to expand the existing NM network with a new NM at the Canary Islands, for example at the existing facility of Roque de los Muchachos Observatory (Coordinates: 28.76°N 17.89°W, Altitude: 2396 metres). This new station eventually

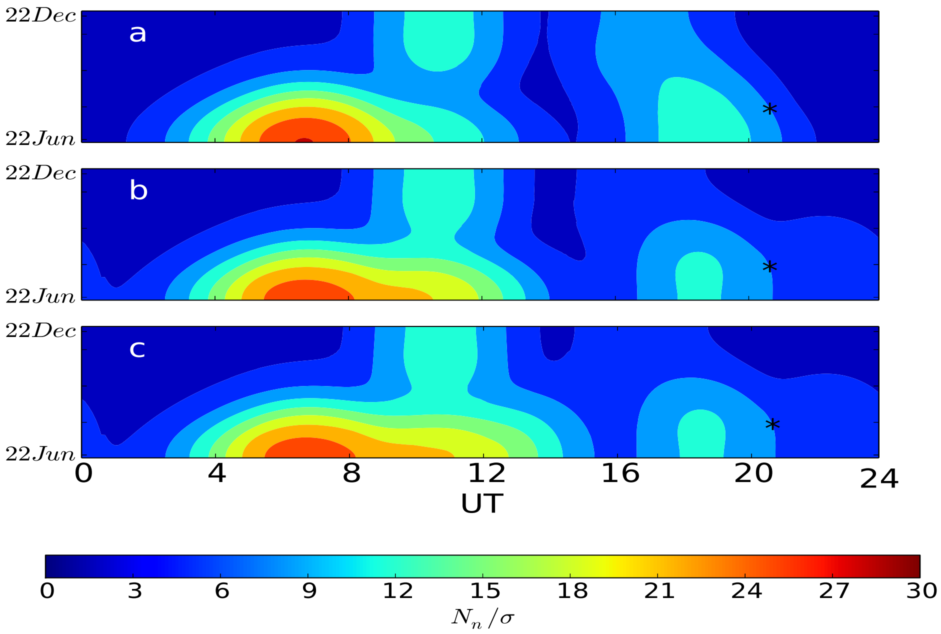

Figure 2: The sensitivity of the world neutron monitor network to an intense SNE similar to that of 24 May 1990 as a function of time of occurrence of the event. The real time of the event of 24.05.1990 is denoted by asterisk in the figure. a) The world NM network corresponding to the epoch 1990 b) The world NM network corresponding to the epoch 2010 c) The world NM for the epoch 2010 expanded with a 12NM64 at Canary islands.

improves the sensitivity of the existing NM network for registration of SNEs if it occurs in the order of 10 to 120 %.

4. Conclusion and discussion

We have presented a new computation of the primary neutron yield function for 6NM64 at various altitudes and various angles of incidence. Subsequently, we reassess the sensitivity of the world NM network for registration of solar neutrons. Several cases are studied, namely NM network at the 1990, present situation (year 2010) and a network with a new NM station at Canary islands. It is shown that the NM network is a suitable tool for research of high-energy solar-flare neutrons. In order to improve to sensitivity of the NM network for solar neutrons we propose a new NM at Canary islands, which would fill the existing gap and could considerably improve further studies.

Acknowledgements

We acknowledge the financial support by the Academy of Finland to the ReSoLVE Center of Excellence (project No. 272157).

Table 1: List of NMs used in this study. The table summarizes geographical coordinates (latitude and longitude), rigidity cut-off P_c, altitudes of NMs above the sea level, type of NM, UT time of local noon T, the signal to noise ratio N_n/σ. The operational period is denoted as 0 for non-operation, accordingly x for operation.

Name	latitude	longitude	P_c, [GV]	altitude, [m]	type	T_{noon}, [UT]	N_n/σ, max	1990,	2010,
ALMA B	43.25	76.92	6.61	3340	18NM	6.872	29.1	x	x
Tsumeb	-19.20	17.58	9.15	1240	18NM	10.828	15.1	x	x
Mexico	19.33	260.82	9.53	2274	6NM	18.612	13.2	x	x
Lomnický Štit	49.20	20.22	3.84	2634	8NM	10.652	10.5	x	x
Irkutsk2	52.37	100.55	3.64	2000	12NM	5.310	10.4	x	x
Irkutsk3	51.29	100.55	3.64	3000	6NM	5.309	10.3	x	x
Tbilisi	41.43	44.48	6.73	510	18NM	9.013	9.6	x	x
Irkutsk1	52.47	104.03	3.64	435	18NM	5.065	6.7	x	x
Chacaltaya	-16.31	291.85	13.10	5200	12IGY	16.541	5.7	x	x
Jungfraujoch	46.55	7.98	4.49	3475	18IGY	11.468	3.5	x	x
Potchefstroom	-26.68	27.10	6.94	1351	12IGY	10.193	1.9	x	x
Tashkent	41.2	69.37	7.5	565	18NM	7.359	11.8	x	0
Huancayo	-12.03	284.67	12.92	3400	12IGY	17.022	8.8	x	0
Calgary	51.08	245.87	1.08	1128	12NM	19.609	7.9	x	0
Hafelekar	47.31	11.38	4.38	2290	3NM	11.202	7.8	x	0
Climax	39.37	253.82	2.99	3400	12IGY	19.079	5.5	x	0
ESOI	33.3	35.78	10.8	2055	6NM	9.623	13.6	0	x
Jungfraujoch	46.55	7.98	4.49	3475	3NM	11.468	8.5	0	x
Bure	44.63	5.91	5.00	2252	3NM	11.632	7.7	0	x
Baksan	43.28	42.69	5.6	1700	6NM	9.212	3.7	0	x

References

[1] M. Aschwanden, *GeV particle acceleration in solar flares and ground level enhancement (gle) events*, *Space Science Reviews* **171** (2012), no. 1-4 3–21.

[2] L. Biermann, O. Haxel, and A. Schlüter, *Neutral cosmic rays produced in the Sun*, *Naturforsch A* **6** (1951), no. 1 47–48.

[3] L. Dorman, *Solar Neutrons and Related Phenomena*. Astrophysics and Space Science Library 365, Springer, Dordrecht, 2010.

[4] R. E. Lingenfelter, E. J. Flamm, E. H. Canfield, and S. Kellman, *High-energy solar neutrons: 1. production in flares*, *Journal of Geophysical Research* **70** (1965), no. 17 4077–4086.

[5] X.-M. Hua and R. Lingenfelter, *Solar flare neutron production and the angular dependence of the capture gamma-ray emission*, *Solar Physics* **107** (1987), no. 2 351–383.

[6] J. Valdes-Galicia, Y. Muraki, K. Watanabe, Y. Matsubara, T. Sako, L. Gonzalez, O. Musalem, and A. Hurtado, *Solar neutron events as a tool to study particle acceleration at the sun*, *Advances in Space Research* **43** (2009), no. 4 565–572.

[7] I. Usoskin, G. A. Kovaltsov, H. Kananen, and P. Tanskanen, *The world neutron monitor network as a tool for the study of solar neutrons*, *Annales Geophysicae* **15** (1997) 375–386.

[8] R. J. Murphy, B. Kozlovsky, G. Share, X.-M. Hua, and R. Lingenfelter, *Using gamma-ray and neutron emission to determine solar flare accelerated particle spectra and composition and conditions within the flae magnetic loop*, *The Astrophysical Journal. Supplement Series* **168** (2007), no. 1 167–194.

[9] A. Mishev, I. Usoskin, and G. Kovaltsov, *Neutron monitor yield function: New improved computations*, *Journal of Geophysical Research* **118** (2013) 2783–2788.

[10] L. Desorgher, E. Flückiger, M. Gurtner, M. Moser, and R. Bütikofer, *A Geant 4 code for computing the interaction of cosmic rays with the earth's atmosphere*, *International Journal of Modern Physics A* **20** (2005), no. A11 6802–6804.

[11] J. Picone, A. Hedin, D. Drob, and A. Aikin, *Nrlmsise-00 empirical model of the atmosphere: Statistical comparisons and scientific issues*, *Journal of Geophysical Research* **107** (2002), no. A12.