A real-time search for solar neutron events in the data of high-altitude neutron monitors

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***Abstract*. Two types of the ground-level enhancements of the solar cosmic ray intensity are described. A method is proposed for evaluation of the solar neutron registration efficiency, and an efficiency index is introduced for monitoring of solar neutrons by the world-wide network of ground based neutron monitors.**

***Keywords*: Neutron Monitor, Cosmic Ray Variations, Solar Cosmic Rays**

I. INTRODUCTION

Since the time, when a possibility was shown for the neutrons of solar origin to reach the surface of the Earth and be registered by the ground-based detectors, creation of an effectively operating global detector system for registration of solar neutrons remains an important task of the cosmic ray physics. A specialized network of neutron telescopes [1] was created for that purpose. However, there are the common neutron monitors, where the most reliable effects of this sort have yet been observed; and only these observation we discuss hereafter. A subject of this work is to give a quantitative description of the possibility to register the solar neutrons both by each particular ground based detector, and by the global detector network as a whole. The description should be convenient for a reliable evaluation of this possibility in a real-time mode. This work is executed as a part of an application that is being developed for the NMDB project (www.nmdb.eu) of European Community´s Seventh Framework Programme.

II. TWO KINDS OF GROUND LEVEL COSMIC RAY ENHANCEMENTS: DISTINCTIONS AND SIMILARITIES

Shortly after the first messages about registration of solar neutrons it became clear, that the ground level enhancements (GLE) of the intensity of solar cosmic rays can be differentiated between the usual, proton ones, which are caused by accelerated charged particles of solar origin (protons and nuclei), and the unusual enhancements from solar neutrons. As a rule, the events of these two kinds are observed separately; nevertheless, there are possible (and have been observed in reality) the mixed events, when the enhancements of both types were present, either in turn, or simultaneously. An example of a pure solar neutron event is the enhancement of 3 June, 1982 [eg.2], an example of the mixed one — the event of May 24, 1990 (Fig. 1). A majority of GLEs may be reckoned among the proton class of events (not to forget, that in their generation partake also the nuclei); though a possible admixture of solar neutrons in some of the well known "usual" GLE events may not be totally excluded.

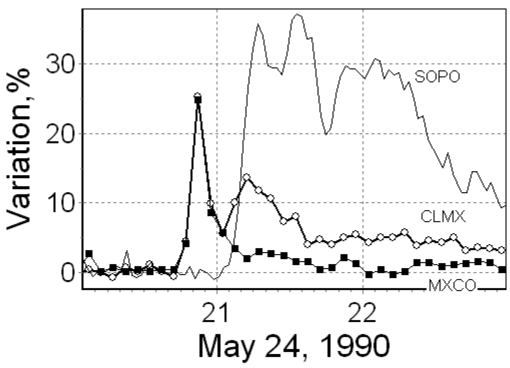

Fig. 1: The count rate variations at the neutron monitors Mexico (MXCO), Climax (CLMX), and South Pole (SOPO) during the GLE on May 24, 1990.

The properties of the enhancements of proton and neutron origin are partly similar, partly they are strongly different. Common features of these events are the following: (1) GLEs of both types result from the work of solar particle accelerator, and may be observed only after the powerful sporadic phenomena at the Sun; (2) both effects are connected with the particles having an energy above 500 MeV/nucleon; (3) their intensity diminishes with depth in the Earth's atmosphere. The list of differences is much longer; we enumerate here only some of them:

(1) Though the GLEs of both kinds are rare events, the neutron enhancements are more seldom than proton ones: both the total amount of these events, and the amount of stations where they are observed are lesser.

(2) The amplitude of neutron events, as a whole, is

lower: in events observed until today it does not exceed 25%, while in the case of proton GLEs the amplitudes up to some thousands of percents have been observed.

(3) Typical duration of neutron enhancements is about some minutes, while the proton ones can be going on many hours.

(4) The neutron events are more anisotropic: in contrast to usual GLE, the 100% anisotropy lasts up to the end of a neutron enhancement. Solar neutron events can only be observed by a group of cosmic ray stations at the same geographic zone, where the line of sight to the Sun through the atmosphere is minimal.

(5) The amplitude of a usual proton GLE is mainly determined by the cut-off rigidity R_c. Many proton GLEs have been registered only at high latitudes, where R_c is low. In contrast, the amplitude dependence of neutron GLEs is reversed: the lower is the latitude of a cosmic ray station, the more frequently it can be reached by the solar neutrons, and corresponding enhancements must be more intensive here.

(6) As a rule, the energy spectrum of a proton enhancement considerably changes in time, becoming much softer in the event's end. The spectra of neutron events are more stable.

(7) Observations of the usual GLEs, in contrast to neutron ones, depend strongly on the state of interplanetary magnetic field and on the condition of the inner heliosphere.

(8) It is generally accepted, that the usual proton GLEs are connected with the powerful solar flares, although many of these flares are not seen from the Earth, or are seen only partly being situated behind the western limb of the Sun. All the neutron GLEs, without any exception, must be connected with the observable flares on the Sun's disk because the neutrons propagate along straight lines.

(9) The solar sources of the proton enhancements are mostly concentrated at the western heliolongitudes. The sources of neutron events are expected to be distributed more uniformly over the visible disk, and the western longitudes western longitudes need not have any preference over the eastern ones.

Hence, the differences between the enhancements of proton and neutron- dominated GLEs are numerous and substantial. It is obvious, that a model of usual proton GLE, how good it could be itself, can not fit to the case of the events of solar neutron origin.

III. Expected effect of solar neutrons in a ground-based detector

A mostly adequate model of a neutron GLE should be simulation of the cascade processes in atmosphere after precipitation of cosmic ray particles, including the solar neutrons [3]. Such calculations, however, being rather difficult and time consuming, we consider here a simplified GLE description, appropriate to make fast estimations in real time.

It is obvious, that the effect of a neutron GLE must be the higher, the less is the atmosphere thickness h and the closer is the Sun to local zenith in the time of observation. The most favorable conditions then seem to be the low latitudes, summer season, local midday and mountain altitudes.

An expected amplitude of a neutron GLE may be written as:

$$SN_i = \frac{\Delta N_{SN}}{N_{GCR}}, \tag{1}$$

where N_{GCR} is the background count rate which is due mostly to the galactic cosmic rays (GCR), and ΔN_{SN} is an additional increase caused by solar neutrons. Because the variations of GCR intensity in our case is a secondary effect, it is possible express them through a rough approximation:

$$N_{GCR}(R_i, t) = N_0(1 - e^{-k(t)R_i^{-\beta(t)}})e^{-h_i/\lambda_i}, \tag{2}$$

where R_i is the rigidity, h_i — atmospheric pressure, and the two parameters k and β, both being the functions of time t, define the rigidity dependence of GCR intensity, while λ_i — its dependence on the altitude (λ_i is also a function of t, h_i and R_i, but all these dependencies are week and may be neglected here). $k(t)$ and $\beta(t)$ should be taken for the period of the maximum of solar activity [4], because these are the years when the powerful proton (and neutron) flares mostly occur.

The intensity of solar neutrons, in its turn, in the simplest case of a straightforward propagation may be written as

$$\Delta N_{SN\,i} \sim \cos\theta_i e^{-h_i/\lambda_i \cos\theta_i}, \tag{3}$$

where θ is the zenith angle of the Sun, and λ_i is usually supposed to be constant and equal to 125 g/cm^2. Account to the scattering of the particles on their way to Earth [5] may be done, with an appropriate aaccuracy, by a change in the above formula of $\cos\theta$ to $\cos^\alpha\theta$ with $\alpha < 1$.

IV. The solar neutron GLE on May 24, 1990

A favorite possibility for a check of our model is the most intensive GLE which has been registered on May 24, 1990 [6,7]. A majority of neutron monitor stations has registered in this event only its proton component. An example of such stations in Fig.1 is the station SOPO, while at the MXCO station obviously prevails the effect from solar neutrons. Some stations, as CLMX in Fig.1, have seen two subsequent signals both from solar neutrons and protons.

To check our model, we used all available data sets with a 5-min temporal resolution which had been collected in the GLE database [8,9]. Intensity enhancements were calculated relative to the mean hourly background level in the time space 19:00–20:00UT. The considered neutron enhancement affects two 5-min periods, which started at 20:45UT and 20:50UT. For these periods, according to the formulae (1-3), was calculated the

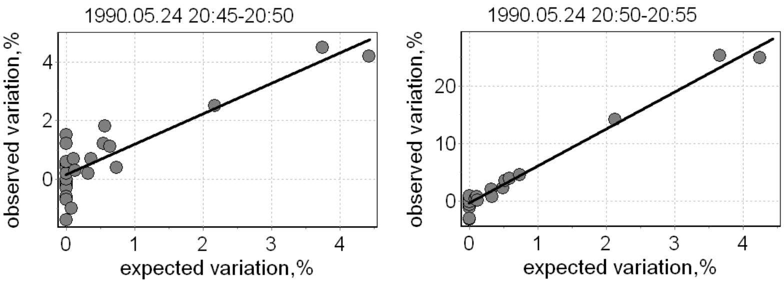

Fig. 2: Comparison of the calculated SN-indices with experimentally observed variations in the GLE event 1990.05.24.

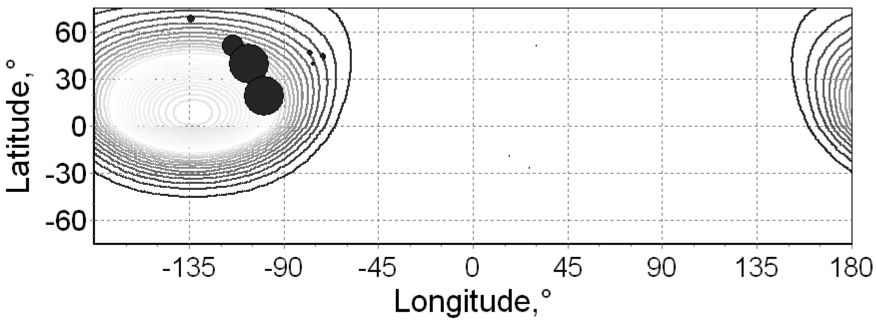

Fig. 3: Distribution of the expected SN-indices calculated for the moment 20:52:30UT 1990.05.24 (isolines), and the observed enhancement values of counting rate in this moment at the neutron monitor stations (black circles; their radius is proportional to the enhancement value).

SN-index, i.e. the expected amplitude of intensity enhancement caused by solar neutrons. The value of α parameter was selected by the least square method; the best fit there was $\alpha = 0.35 \pm ^{0.35}_{0.10}$. Calculation results are presented in Fig.2, where a sufficient agreement between the expected and observed values of SN-index can be seen: correlation coefficients are 0.85 for the left plot, and 0.99 for the right. This means, that (1) up to 20:55UT in the considered GLE have prevailed, indeed, the neutrons; (2) distribution of neutron enhancement over the cosmic ray stations is sufficiently well described by our model. A better correlation in our case might not be demanded because the 5-min data have a rather high statistical fluctuation, and the galactic CR variation can be distributed non-uniformly between the different stations.

A qualitative agreement between the expected and experimental enhancement amplitudes is seen also in Fig.3, where the stations with observed neutron signals are concentrated in the region with maximum value of SN-indices.

To test the discriminative ability of our model between the neutron- and proton-caused GLEs, the calculation was done for a later period of the same event of May 24, 1990, when the solar neutrons were just absent in the Earth's vicinity while the flow of charged particles remained strongly anisotropic. As it is seen in Fig.4, any correlation between the calculated and observed enhancement values in this time is absent, though the total intensity enhancement, due to solar protons and nuclei, in this period was even higher, than in the previous 20 min.

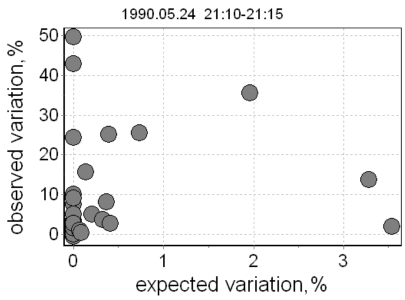

Fig. 4: An absence of correlation between the expected SN-indices and the real enhancement amplitude after the end of neutron signal on 1990.05.24.

V. Efficiency index of solar neutron monitoring by the NM network

The value of SN index, as defined by the formulae (1-3) and normalized to the conditions of some well-known GLE event, may be considered as a probable value of solar neutron effect by a single neutron monitor. For normalization we use the conditions at the Jungfraujoch station during the GLE June 3, 1982, which has been historically the first observed ground level event caused by

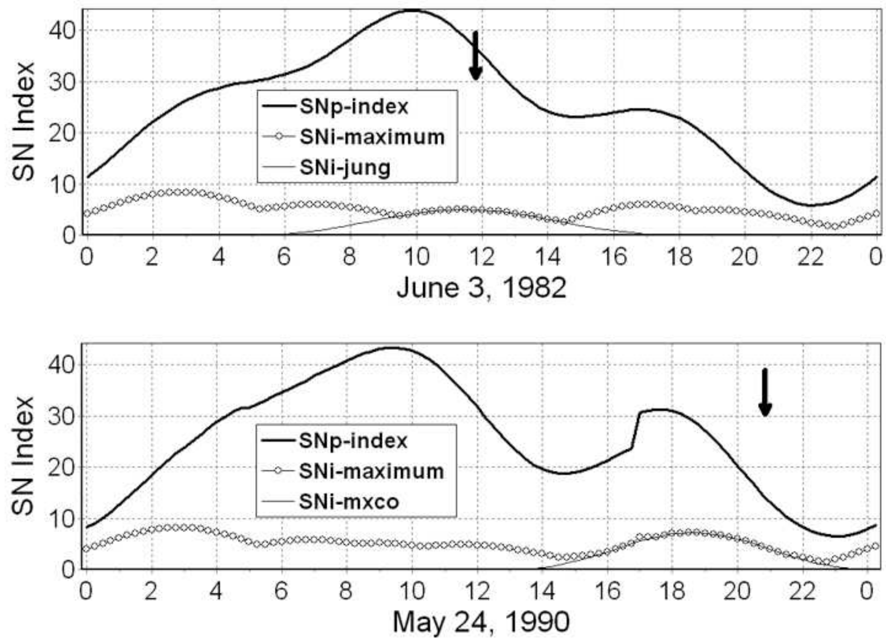

Fig. 5: Behavior of the SN-indices in the two GLE events. The thick curves SN_p correspond to planetary index; arrows mark the maximum of neutron intensity increase at the stations Mexico (above) and Jungfraujoch (below).

solar neutrons. Hence, the SN_i is an expected amplitude of neutron GLE as observed at a i-th neutron monitor under assumtion, that the Earth has been reached by the same number of solar neutrons, as at 11:44-11:55UT 1982.06.03. The highest of the all neuton monitors value of SN_i may be denoted as the maximum index SN_{max}, and as an efficiency estimation of the whole monitor network one may use the global, or planetary, index SN_p, which is a sum of expected enhancements of neutron origin at all neutron monitor stations being operating at a given time moment. Temporal distributions of the mentioned parameters during two GLE events are presented in Fig.5. In this figure is seen a daily variation of the planetary index SN_p which, obviously, is caused by a non-uniform distribution of the neutron monitors over the globe: its distinct minimum in UT night correspond to the noon period in Pacific ocean zone, where cosmic ray detectors are practically absent. Two maxima in SN_p distribution are connected with the European and American noons. Similarly, the uneven distribution of monitor stations should cause a seasonal dependence of SN_p index. It follows also from Fig.5, that the greatest of the known neutron GLEs have been observed under comparatively propitious, but not ideal, conditions. If the GLE event of May 24, 1990 had started earlier, the neutron effect on the Earth would have been more prominent, and would have been registered by a larger number of cosmic ray stations

VI. Conclusion

The model of CR variation in solar neutron GLEs, suggested in present report, may be used for evaluation of the registration efficiency of such events by the ground-base CR stations, and a systematic application of this model permits to estimate the efficiency of the whole world-wide monitor network for registration of solar neutrons in real time [10]. For an effective monitoring of neutron GLE it is necessary a real-time access to the data of a possibly large amount of cosmic ray stations; of a particular value are the data of the middle-latitude stations situated at a high altitudes above the sea level.

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