Solar Cosmic Ray study with Neutron Monitors of a Various Design

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Abstract: The modeled and observed responses of neutron monitors of two various types: the standard 3NM-64 and a leadless 4NMD one at the SANAE South African Antarctic station during a number of large GLE events were compared to precise the specific yield of the NMD at low rigidity range. The parameters of primary relativistic solar protons outside magnetosphere: rigidity spectrum, anisotropy direction and pitch angle distribution were determined on data of the worldwide NM-64 neutron monitor network by modeling technique. Then the response of both neutron monitors NM64 and leadless NMD was calculated using the specific yield functions (SYF) obtained earlier in the latitude and high-altitude survey of both instruments [7,8]. By fitting to observations the SYF for the NMD detector was adjusted so that it precisely described the response of leadless neutron monitor during a number of GLE events.

1. Introduction

Neutron monitors of different design can be useful in analysis of ground level solar cosmic ray events [8]. The method of estimation of relativistic solar proton spectra based on a relation between count rates of two neutron monitors: covered by lead and leadless one was proposed by Mischke et al. [5]. The method is based on different specific yields of these detectors, and correspondingly different responses to a given solar proton spectrum. This method was repeatedly used then for estimating of rigidity spectrum of solar protons during GLE events [1,7,8]. On the data of two neutron monitors: the standard three tubes 3-NM-64 and the four tubes neutron moderated detector without lead, 4NMD at SANAE station in Antarctica. Stoker [8] performed a comprehensive study of relativistic solar proton events. The 27 GLEs that occurred from 1966 to 1992 were studied using the specific yields of neutron monitors of different design that were determined in the latitude and altitude surveys on ships and aircrafts. It is necessary to note, that these measurements were made for galactic cosmic rays (GCR), having a rigid energetic spectrum and allowed obtaining the reliable values of specific yield for rigidity range > 2 GV. Stoker [8] in his study of relativistic solar proton events used a relation for specific yield, obtained from latitude survey and adjusted for the rigidity range < 2 GV. We carried out the further improvement of specific yield from [8] for leadless monitor by adjusting it to observable responses in several recent GLEs.

Parameters of primary relativistic solar protons outside magnetosphere were determined on data of the worldwide NM-64 type neutron monitor network by modeling technique [10]. Thus we used a specific yield for the NM-64-type instrument, obtained by Debrunner et al. [3]. This specific yield function has shown the adequacy at calculation of the response of the NM-64-type instrument to solar cosmic rays. By fitting the modeled responses to observations we adjusted a specific yield for the NMD-type detector so that it could precisely describe the response of leadless neutron monitor during a number of GLE events.

2. Instrumentation and specific yield function

The 3-NM-64 neutron monitor is a standard IQSY type surrounded by the 5 cm thick lead producer and polyethylene moderator and reflector. The neutron monitor without a lead producer is more sensitive to low rigidity (~ 1 GV) primary cosmic rays than the NM-64 neutron monitor. The 4 tube neutron moderated detector (4NMD) consists of 4 neutron sensitive tubes BP28 Chalk River each of which with its polyethylene cylinder placed inside a paraffin wax cylinder with a wall thickness of 7.5 cm [8]. A pair of neutron monitors: with and without lead producer can be used for estimating spectral exponent of the relativistic solar protons. The count rate of a neutron monitor at a time t at sea level may be expressed as

$$N(R_C, t) = \int_{Rc}^{\infty} S(R) \cdot J(R,t) \mathrm{d}R \qquad (1)$$

where $N(R_C, t)$ is neutron monitor count rate at location with an effective cutoff rigidity R_C, S(R) is the specific yield function for the primary particles of rigidity R, and J(R,t) is primary differential flux at time t. Specific yield function may be determined from (1) via latitude survey of N (R):

$$S(R,x) = -(dN/dR) / J(R) \qquad (2)$$

Stoker [8] obtained expressions for S(R) both for rigidity ranges R> 2 GV and R<2 GV:

$$\begin{cases} S(R > 2\ GV) = \left(\frac{dN}{dR}\right) / J(R) \\ S(R < 2\ GV) = \exp\left(\mathrm{d} + \mathrm{e} \cdot \ln R + \mathrm{f} \cdot (\ln R)^2\right) \end{cases} \qquad (3)$$

where constants have different meanings for the NM-64 and NMD detectors. For the NM-64 they are: d=-9.934, e=9.363, f=-3.643. At rigidities R>2 GV the calculated from (3) specific yield function is close to the one of [3]. We obtained the specific yield for a NMD detector in a wide rigidity range by modifying the S(R) function for NMD so that it accurately described response of NMD instrument in the ground level solar cosmic ray events. We did it by adjusting parameters of the S(R) (3) by fitting the calculated responses to observed ones of the 4NMD detector in a number of GLEs registered at SANAE station. In one case the data of leadless "Bare" detector at South Pole station during the GLE 69 (20.01.2005) [1] were studied. We obtained an expression for the S(R) function for the NMD-type detector:

$$\begin{cases} S_{BMD}(R > 4\ GV) = S(R) \cdot \frac{1.6}{\sqrt{R}} \\ S_{BMD}(R < 4\ GV) = S(R) \cdot \frac{1.6}{\sqrt[6]{R}} \end{cases} \qquad (4)$$

3. Ground based data processing and modeling technique

The worldwide network of ground-based detectors may be considered as a united multidirectional solar proton spectrometer in the relativistic energy range. With the modeling of the NM responses to anisotropic solar proton flux and then comparing them with observations the parameters of primary solar protons outside the magnetosphere can be obtained [2,6,11]. Our recent modeling technique [10], in general, is similar to that of [2]. This kind of analysis requires the data of no less than 20-25 ground-based cosmic ray stations, and consists of a few steps:
1. Definition of asymptotic viewing cones (taking into account not only vertical but also oblique incident on detector particles) of the NM stations under study by the particle trajectory computations in a model magnetosphere [9].
2. Calculation of the NM responses at variable primary solar proton flux parameters.
3. Application of a least square procedure of optimization for determining primary solar proton parameters (namely, energy spectrum, anisotropy axis direction, and pitch-angle distribution) outside the magnetosphere by comparison of computed ground based detector responses with observations. The two attenuation lengths method [4] is used for NM data barometer correction.

4. The GLE 60: April 15, 2001

The cause of the event was a solar flare X 14.4/2B, heliocoordinates S20 W85 which started at 13.36 UT. Fig. 1a shows the derived by modeling technique from the NM-64 worldwide network energetic spectra of relativistic solar protons for the early (14:30 UT) and late (15:30 UT) phases of the event respectively. The derived spectra for the early and late event phases are markedly differ. Nevertheless, rather good agreement between the observed responses of neutron monitors 3-NM-64 and 4NMD and modeled ones is observed.

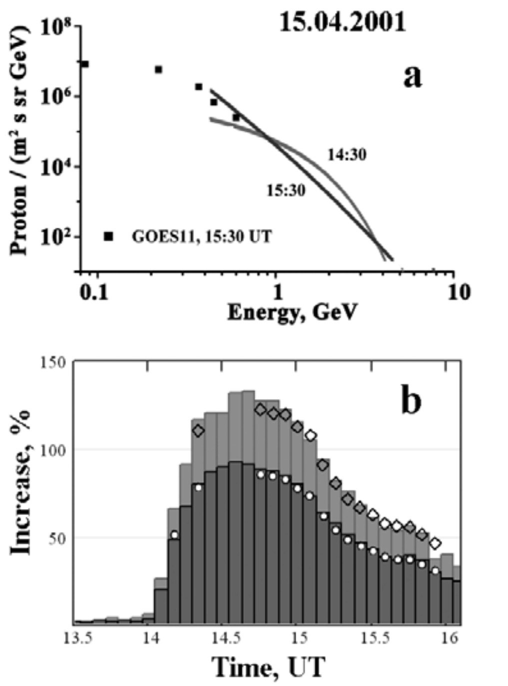

Figure 1. **a** - derived energetic spectra of relativistic solar protons in the GLE 60. Direct solar proton data are obtained by the GOES-11 spacecraft; **b** - GLE 60 on the data of SANAE neutron monitors 3-NM-64 and 4NMD. Filled histograms are experimental data: dark is 3-NM-64, gray is 4NMD. Modeled responses of the 3-NM-64 are light circles and 4NMD are rhombi.

5. The GLE 69: January 20, 2005

The GLE of January 20, 2005 was largest one for the last 50 years. The parent solar flare 2B/X7.1 had heliocoordinates N14, W61. The type II radio onset was reported at 06.44 UT. The GLE was extremely anisotropic. The maximal increase effect (~ 5000 %) registered the 3-NM-64 neutron monitor at the South Pole station. The 1.5 times greater increase registered a leadless “Bare” neutron monitor [1]. The event was registered also by a pair of a covered by lead 3-NM-64 and a leadless neutron monitor 4NMD at the SANAE station. Fig. 2a shows the derived from ground based NM-64 instrument network energetic spectra for the early (07:00 UT) and late (08:00 UT) phases of the event. Fig. 2b shows the observed and modeled responses of the 4NMD and 3-NM-64 instruments at the SANAE station during the GLE 69. The increase profile consists of two peaks, one of which obviously is connected with

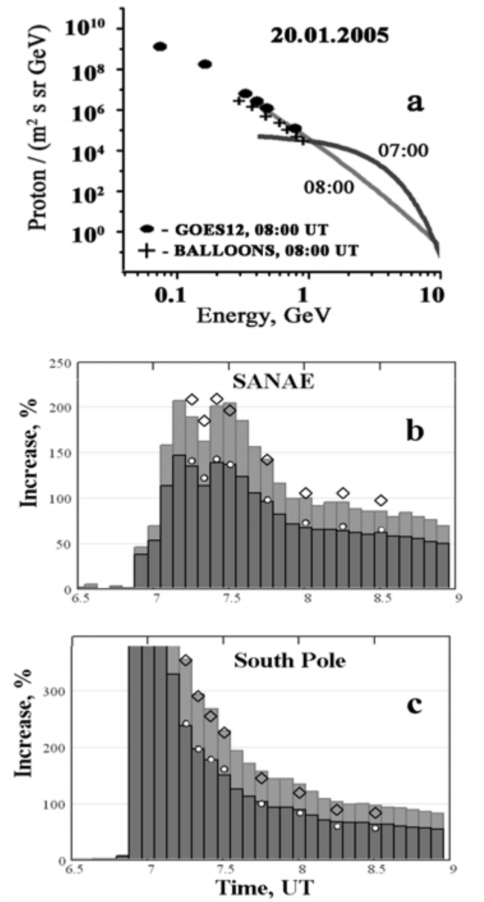

Figure 2. **a** - derived energetic spectra of relativistic solar protons in the GLE 69. Direct solar proton data are measured by GOES-12 spacecraft and balloons launched in Apatity; **b** - GLE 69, on the data of SANAE 3-NM-64 and 4NMD instruments; **c** - GLE 69 on the data of South Pole 3-NM-64 and NM “Bare”; designations are the same as in Fig.1b.

the prompt component (PC) of solar protons and the second one with the delayed component (DC) [10]. Fig. 2c shows the observed and modeled responses for a leadless “Bare” detector and the 3-NM-64 neutron monitor at South Pole. One can see a good consent between observed responses of the covered by lead and leadless neutron monitors at the two different stations and various solar proton spectra.

6. The GLE 70: December 13, 2006

The GLE 70 occurred on the late decline phase of the solar cycle 23. The event was connected to a flare X3.4/2B, heliocoordinates S06 W24 as well as CME and radio emissions of types II and IV. The onset of the II type was reported at 02.26 UT. Despite the GLE occurred nearly in conditions of solar minimum, it was rather large and has been registered by more than 30 neutron monitor stations around the world. Fig. 3a shows a characteristic solar proton spectra derived before (03:05 UT) and after (04:00 UT) maximum of the increase respectively. The direct solar proton data measured by the GOES-11 spacecraft and balloons launched in Apatity are shown as well in Fig.3a. In Fig.3b the increase profiles of a pair of neutron monitors: 3-NM-64 and 4NMD at SANAE station are shown with the modeled responses. One can see the good agreement between observed and modeled responses for the 4NMD leadless neutron monitor and the standard 3-NM-64 type instrument at variable energetic spectra of solar protons

7. Conclusions

The responses of neutron monitors of two various types: the standard 3-NM-64 with covered by lead neutron counter tubes and the leadless neutron moderated detector (NMD) during a number of large GLE events have been studied. By fitting the modeled responses of the NMD detector to observations during GLE events the specific yield function of the leadless neutron monitor defined earlier in latitude surveys has been modified that it described also the response to solar cosmic rays. The obtained expression for specific yield function of the leadless neutron monitor allows modeling the response of this instrument over a wide range of changes of relativistic solar proton spectrum.

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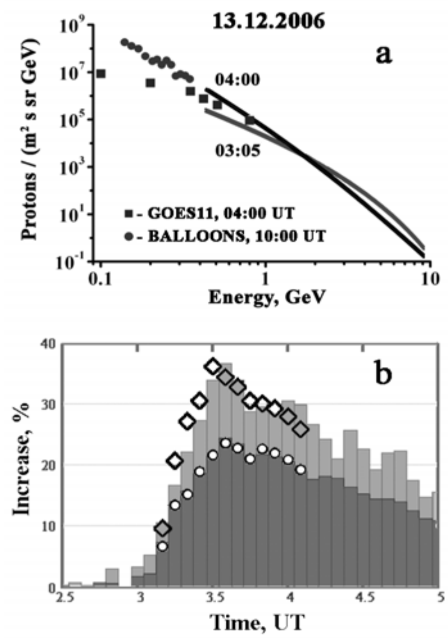

Figure 3. **a -** derived energetic spectra of relativistic solar protons in the GLE 70 [10]. Direct solar proton data are measured by GOES-11 spacecraft and balloons launched in Apatity; **b** - GLE 70, on the data of SANAE neutron monitors 3-NM-64 and 4NMD; designations are the same as in Fig.1b.

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