Relativistic solar particle dynamics during the December 13, 2006 GLE

Eduard V. Vashenyuk, Yury V. Balabin, Boris B. Gvozdevsky

Abstract — **The characteristics of relativistic solar protons have been obtained using the methods of optimization based on the data of ground detectors of cosmic rays during the event of December 13, 2006, which occurred under the conditions of solar activity minimum. The dynamics of relativistic solar protons during the event has been studied. It has been indicated that two populations (components) of particles exist: fast and delayed (slow). The prompt component with a hard energy spectrum and strong anisotropy manifested itself as a pulse-shaped enhancement at Apatity and Oulu stations, which received particles with small pitch-angles. The delayed component had a wider pitch-angle distribution, as a result of which an enhancement was moderate at Barentsburg station and at most neutron monitors of the global network. The energy spectra obtained from the ground-based observations are in good agreement with the direct measurements of solar protons on GOES-11 spacecraft**.

1. Introduction

The solar cosmic ray (SCR) event of December 13,2006, occurred at the ground level during the decline phase of solar cycle 23. This event was related to an X3.4/2B flare with S06 W24 heliocoordinates. A flare was accompanied by radio bursts of types II and IV and by a halo coronal mass ejection (CME) (www.izmiran.rssi.ru/space/solar/forecast). Radio emission of type II (the probable instant of generation of relativistic SCRs began at 02.26 UT. This event occurred when the conditions on the Sun and in the interplanetary medium corresponded to a solar cycle minimum. An abrupt intensification in the active region (AR) 10930 occurred against a background of an almost complete absence of sunspots. Nevertheless, the event of January 13, 2006, is among large events and was registered by more than 30 neutron monitors of the global network. The present work analyzes the dynamics of relativistic solar protons (RSPs), the characteristics of which were obtained using the optimization methods based on the data from the global network of neutron monitors [1], [2], [3]. The determination of the primary RSP parameters includes several stages. (1) The determination of asymptotic acceptance cones for the studied neutron monitors by calculating the trajectories of particles with different rigidities in the [4] magnetosphere model. The calculations are performed from 1 to 20 GV at a rigidity step of 0.001 GV. One of these trajectories was directed vertically upward, and remaining particles were launched at a zenith angle of 20° from eight equidistant radial directions. Thus, we determine the asymptotic cone of particles that fall on a neutron monitor not only from the vertical but also from the oblique directions. (2) The calculation of neutron monitor responses to an anisotropic flux of solar protons with specified parameters. (3) The determination of the parameters of relativistic proton fluxes outside the Earth's magnetosphere with the help of the least squares technique by comparing the calculated neutron monitor responses with observations. The detailed description of our GLE modeling technique is given in [1].

This paper extends the study of the 13.12.2006 GLE started in [2] and [3].

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2. Observations

The GLE 13.12.2006 in its initial phase showed a large anisotropy. In Fig. 1 characteristic intensity-time profiles at selected NM stations are shown. The early onset, fast rise and maximal amplitude of increase were registered by the stations Oulu (104 %) and Apatity (81 %) according to 1-min data. The fast rise to a maximum has also registered the Moscow NM (Fig. 1), and other European mid-latitude stations [5]. At the NM in Barentsburg (Spitsbergen) the increase started 5 minutes later than in Apatity. It had the slow growth and only 36 % maximal increase. In the majority of other stations of the worldwide network the increase was even smaller. So, the next to Barentsburg station Thule (Greenland) showed the increase of ~ 21 %. Nearly the same effect registered Southern polar stations McMurdo and SANAE.

3. Results of Model Study

The results of the modeling are presented in figs. 2-5.. As the NM data show (see below) during the initial phase of the event the RSP flux arrived at the Earth as a collimated bunch from a direction close to an average IMF. In Fig. 2 the map of celestial sphere in solar-ecliptic (GSE) coordinates with asymptotic cones (for vertically incident particles) for a number of NM stations is shown. The cones are calculated in a range of rigidities from 1 to 20 GV. In Fig. 2 the name of stations is put at the 20 GV edge of an asymptotic cone. As illustration, the asymptotic directions of the 1 GV and 20 GV particles are indicated for the Barentsburg station. Lines of equal pitch angles relative to the calculated direction of the anisotropy axis at 3.00 UT are also shown here. It is seen, that the anisotropy axis corresponds to an average direction of a

Parker IMF spiral (43° to the West of the Sun-Earth line) and almost coincides with the IMF direction (ACE spacecraft data). At the same time an early increase was registered by only the stations with asymptotic cones within a limit of 50° relative to the calculated anisotropy axis. These are Apatity, Oulu, Moscow and some mid-latitude European stations where

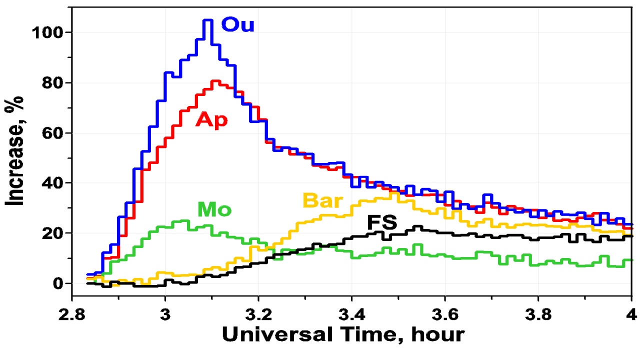

Fig.1. Intensity-time profiles during the GLE 13.12.2006 at the neutron monitor stations: Ou-Oulu, Ap-Apatity, Mo-Moscow, Bar- Barentsburg, FS- Fort Smith.

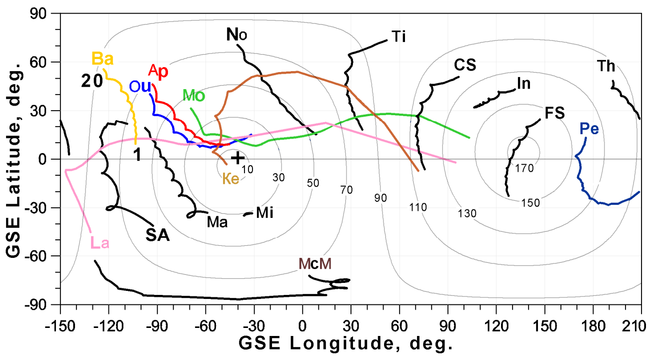

Fig.2. The derived anisotropy axis and pitch angle grid lines for solar proton flux at 03.00 UT. IMF direction (ACE data) is indicated by cross. The asymptotic cones (1-20 GV), the title is placed at the 20 GV end, are shown for the following NM stations: Th-Thule, Bar-Barentsburg, McM-McMurdo, Sa-SANAE, Ma-Mawson, Ou-Oulu, Ap-Apatity, Mo-Moscow, Mi-Mirny, No-Norilsk, Ti-Tixie, CS-Cape Shmidt, In-Inuvik, FS-Fort Smith, Pe-Pewanuk, Th-Thule.

increase began at 02.50-02.52 UT. An asymptotic cone of the Fort Smith station was looking to the anti-sun direction (Fig. 2). Thus the intensity-time profile at Fort Smith characterizes behavior of backward (to the Sun) flux of RSP. The increase at Fort Smith started at 3.05 UT, which is 15 minutes later than the onset of direct RSP flux (Apatity, 02.51 UT). The increase rate of backward flux was very slow. At Barentsburg station, which registered particles of the direct flux with only large pitch angles (> 60°), the increase began slightly earlier**,** at 02.58 UT**.** However, the intensity rise was also very slow. Dynamics of the direct (from the Sun) and the backward (to the Sun) fluxes of RSPs can be traced by the evolution of pitch-angle distributions (PAD) of RSP derived at consecutive moments of time (Fig. 3).

The PADs with numbers from 1 up to 3 (Fig.3) characterize a collimated bunch of particles directed from the Sun. A PAD curve of the flux being close to a Gaussian. This collimated flux was registered from 02.56 to 3.05 UT. Since 3.10 UT an appreciable backward (to the Sun) flux of particles has appeared.

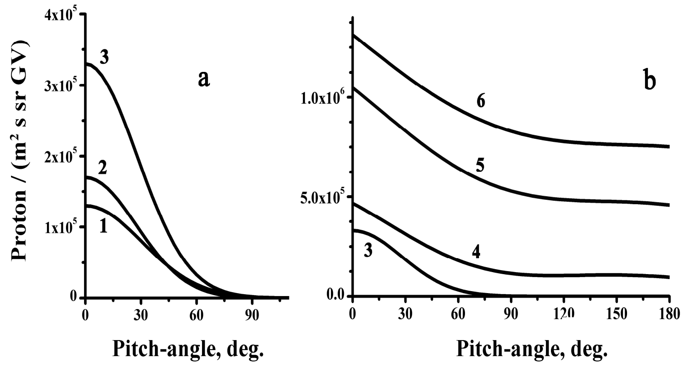

Fig.3. Dynamics of derived pitch-angle distributions. Numbers denote moments of time: 1- 02.57, 2-3.00, 3-3.05, 4-03.20, 5-03.30 6-4.00 UT.

The profile 4 corresponds to the moment of time 03.20 UT. According to Fig. 3, the simultaneous intensity rise of derived flux of solar protons from both the Sun and the opposite directions continued up to 4.00 UT (profile 6), though the intensity-time profiles of NMs showed a decline (Fig. 1). The cause of discrepancy is that the PAD profiles in Fig. 3 are constructed for protons with rigidity 1 GV (430 MeV) that corresponds to the lower limit of a NM response. The main contribution to the NM response is given by solar cosmic rays in the rigidity range 2-10 GV. The growth in intensity of solar protons with energy up to 500 MeV up to 4 UT proves to be true by direct solar proton data on the GOES-11 spacecraft.

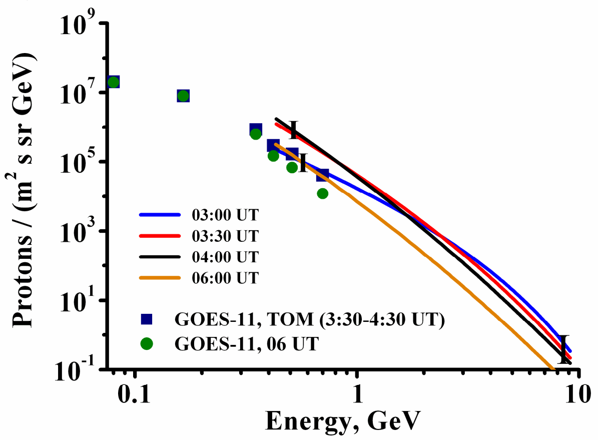

Fig.4. The derived energetic spectra of RSP at different moments of time. Direct solar proton data (GOES-11).are shown by blacked squares, TOM spectrum (3.30-4.30 UT). Filled green circles are measurements at 06.00 UT.

Fig.4 shows the derived energetic spectra dynamics from 3.05 to 4.00 UT. The spectrum derived at 3.05 UT belongs to the direct RSP flux and its form differs from a power law. On the contrary, the spectrum derived at 4.00 UT, during the event decline phase has a pure power law form. In Fig. 4 the data on direct solar protons in adjacent energy interval from 100 to 500 MeV obtained by GOES-11 spacecraft are shown also. It is seen a good agreement between the spectra, derived from

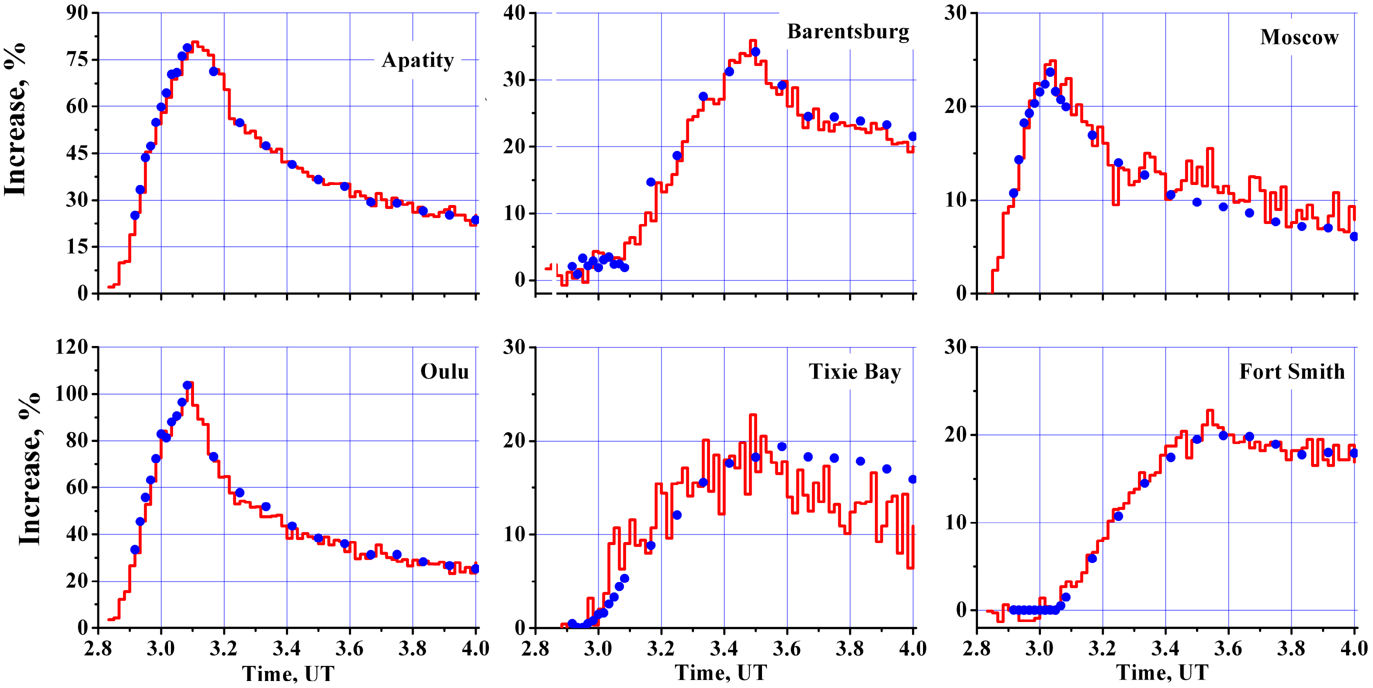

Fig.5. The increase profiles a number of neutron monitor stations during the 13.12.2005 GLE. Points are the modeled responses.

ground based observations, and those of the directly measured solar proton fluxes. Differential intensities of protons in different energy channels of the GOES 11 were taken at the times of a maximum (3.30-4.30 UT) in a given energy channel (TOM spectrum). This can explain their good consent with a spectrum of the maximal fluxes for relativistic solar protons energies where maximum was observed at ~03.05 UT (Fig.1). An asymptotic cone of the Fort Smith station was looking to the anti-sun direction (Fig. 2). Fig. 5 shows increase profiles at a number of NM stations during the GLE. One can see good agreement of modeled (points) and observed responses.

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