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Ground level enhancement of December 13, 2006 observed by means of muon hodoscope

D.A. Timashkov [a,*], Yu.V. Balabin [b], N.S. Barbashina [a], R.P. Kokoulin [a], K.G. Kompaniets [a], G. Mannocchi [c], A.A. Petrukhin [a], O. Saavedra [d], V.V. Shutenko [a], G. Trinchero [c], E.V. Vashenyuk [b], I.I. Yashin [a]

[a] Moscow Engineering Physics Institute (State University), NEVOD, Kashirskoe Shosse, 31, 115409 Moscow, Russia
[b] Polar Geophysical Institute, Apatity Division, 184209 Apatity, Russia
[c] Istituto di Fisica dello Spazio Interplanetario – INAF, Torino 10133, Italy
[d] Dipartimento di Fisica Generale dell'Università di Torino, 10125 Torino, Italy

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ABSTRACT

A wide-aperture hodoscope URAGAN detected a muon rate increase during GLE of December 13, 2006 at six sigma level (for ten-minute bins). Maximum of the enhancement was observed at 03:00 UTC. Capabilities of muon hodoscopes allow obtaining 2D-images of muon flux and for the first time the two-dimensional dynamics of GLE event was measured. Due to the fact that asymptotic view cone of the hodoscope appeared looking along IMF, it was possible to trace in details the evolution of a short-lived and highly collimated relativistic particle bunch in the initial phase of the event.

1. Introduction

In the middle of December, 2006 strong disturbances of interplanetary magnetic field (IMF) and geomagnetic conditions caused by eruptions in the solar active region AR10930 occurred. Several powerful X-ray flares have been detected by satellites of GOES series [1]. The solar flare on Dec 13, 02:26 UTC is of a special interest since it was accompanied by a powerful solar proton event, which produced a sharp growth of cosmic ray flux both in the near-Earth space (Fig. 1) and at the ground level (Fig. 2). The neutron monitor network detected the ground level enhancement event (GLE) No. 70. The first such event was registered on February 28, 1942.

The difference in the increase profiles of neutron rates at four neutron monitors (Fig. 2) was caused first of all by a large anisotropy of the relativistic solar proton flux. The greatest increase was registered at Oulu and Apatity stations. A smaller increase was observed in Moscow due to a higher geomagnetic cutoff. All these three stations were looking nearly along anisotropy axis [3]. Irkutsk neutron monitor registered a low increase with a delayed onset of GLE because of unfavorable acceptance direction [3].

In Fig. 2, the integral counting rates of neutron monitors (1-min data) are presented. A separate neutron monitor cannot measure angular dynamics of cosmic ray variations. The information about angular distribution of relativistic solar protons may be obtained from muon flux measurements at the ground level. Cosmic ray muons keep direction of primary particles motion and their detection by means of large-area muon detectors with high angular resolution allows studying angular variations of cosmic ray flux. Besides, analysis of muon flux gives a possibility to study solar particle flux at energies as high as tens GeV [4]. Therefore cosmic ray muon experiments can shed the light to generation mechanism of solar cosmic rays at such energies. This problem is one of the most important tasks to be studied during the next solar cycle 24 [5–7].

Long-term experiment on measurements of muon flux variations is now being carried out in NEVOD Laboratory (MEPhI, Moscow) [8]. In this paper, unique muon data obtained during the GLE of December 13, 2006 are presented and comparison with neutron monitor data is discussed.

2. Setup description

Experimental complex NEVOD is situated in Moscow Engineering Physics Institute. Geographic coordinates are: 37°40′E, 55°39′N. Altitude above sea level is equal to 163 m. The geomagnetic cutoff for vertical direction equals to 2.43 GV (International Reference Geomagnetic Field – IGRF). At present, a unique coordinate detector (muon hodoscope URAGAN [9]) which allows simultaneously

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* Corresponding author. Tel./fax: +7 495 324 87 80.
E-mail address: DATimashkov@mephi.ru (D.A. Timashkov).

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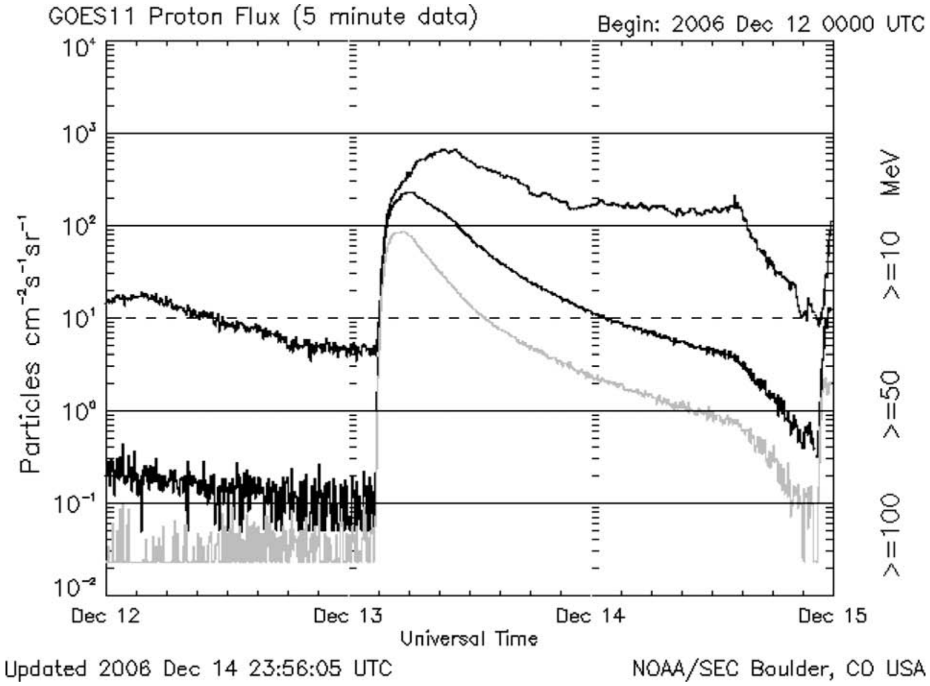

Fig. 1. Proton intensity increase for different energy thresholds after the X3.4/4B flare on December 13, 2006. Data from GOES11 spacecraft (NOAA) [1].

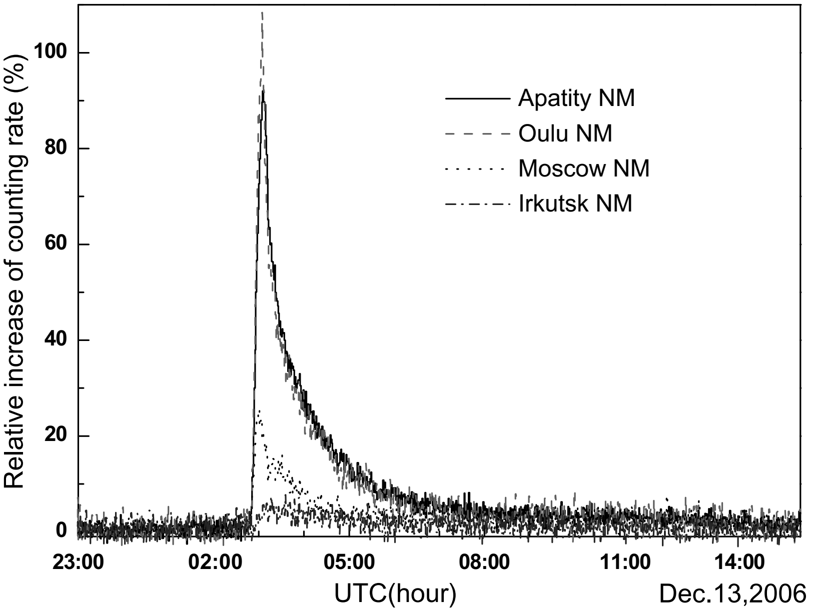

Fig. 2. GLE No. 70 event in 1-min data of a number of neutron monitors: Apatity, Oulu, Moscow, Irkutsk. Data from IZMIRAN database [2].

detect cosmic ray muons from different directions of upper hemisphere in a wide range of zenith anglesis under operation in NEVOD Laboratory.

2.1. Construction

The hodoscope is constructed on the basis of four upper supermodules of the DECOR coordinate detector [10] and is composed of separate horizontal supermodules (Fig. 3), each with area of 11.5 m^2, located on the cover (173 m a.s.l.) of water Cherenkov detector NEVOD. Since 2007 three supermodules of URAGAN are under operation. Each supermodule consists of eight layers of gas-discharge chambers equipped with orthogonal X–Y system of external readout strips (2560 X + 2304 Y channels for supermodule) with 1.0 and 1.2 cm steps, respectively. The layers alternate with continuous 5 cm thick foam plastic sheets. Each layer is an assembly of 20 streamer tube chambers, which consist of 16 tubes with inner cross-section of 9×9 mm^2 and length of 3.5 m housed in one plastic box. The chamber operation in the limited streamer mode is ensured by three-component gas mixture (Ar + CO$_2$ + n-pentane) and appropriate operating voltage. Charged particles (muons) passing through gas chambers cause streamer discharge which induces signals on X- and Y-strips. Each supermodule is located on an individual mobile platform, which allows to change its

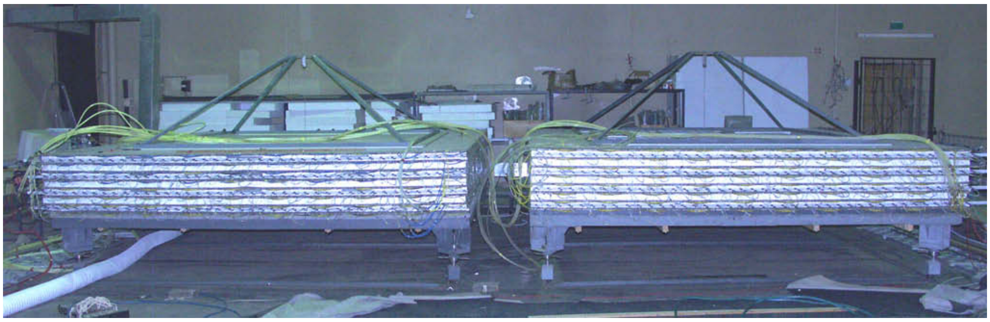

Fig. 3. Two supermodules of muon hodoscope URAGAN [10] which were under operation in December, 2006.

position with respect to other supermodules and to detecting system of the water Cherenkov detector NEVOD.

2.2. Triggering and data acquisition systems

The triggering and data acquisition system of the hodoscope (Fig. 4) has a distributed multi-level architecture. The modular organization makes it possible to easily change the configuration and extend the system with addition of supermodules. The basic element of the data acquisition system of the hodoscope is a specially developed fast readout card, which provides amplification, discrimination, formation, storage of signals and serial data transfer from 16 strips. The cards are connected to the strips of streamer chambers from two sides of each supermodule plane (along the *X* and *Y* axes, respectively) and are successively linked to each other to form 32 serial data communication channels. Each supermodule requires 160 *X* and 144 *Y* data acquisition cards and 8 cross-cards to connect signal lines and power supply.

A distinctive feature of the developed system is the presence of two circuits for data readout. The first circuit is formed by D-triggers of card control schemes and provides information about the triggered cards. The second circuit, formed by shift registers, makes it possible to obtain information from individual channels. The control scheme includes shift registers to the second circuit only when a given card contains triggered channels. Thus, data are read only from triggered cards, and as a result a necessary data acquisition rate is attained. The trigger signal on a plane is formed by data acquisition cards at triggering of any *X*-channel in this plane. The condition for triggering the supermodule measurement system is the coincidence of at least four trigger signals from different planes within 300 ns.

The average counting rate of one supermodule is about 1700 events per second. The readout time from a supermodule is determined by the number of triggered cards and does not exceed 38 μs for 99% events. This readout speed, taking into account the triggering probability, makes it possible to detect each muon with 93% probability. To transfer data to the computer memory and generate test sequences, a 32-channel digital input/output card is used, which is designed in the PCI standard and supports the PCI Bus Master protocol with maximum transfer rate of 12 Mb/s.

The instrumental tools of the measurement and trigger systems support the following operation modes.

1. Measurement of the counting rate of OR signals simultaneously from eight planes.
2. Testing the circuits of shift registers and D-triggers of readout cards.
3. Operation in the cyclic exposure mode according to the following algorithm:
   (i) expectation of the event with simultaneous measurement of "live time";
   (ii) triggering and interruption in the computer;
   (iii) acquisition of data from readout cards and their transfer through the direct memory access channel to the ring buffer of the computer at rate of 5 Mb/s.

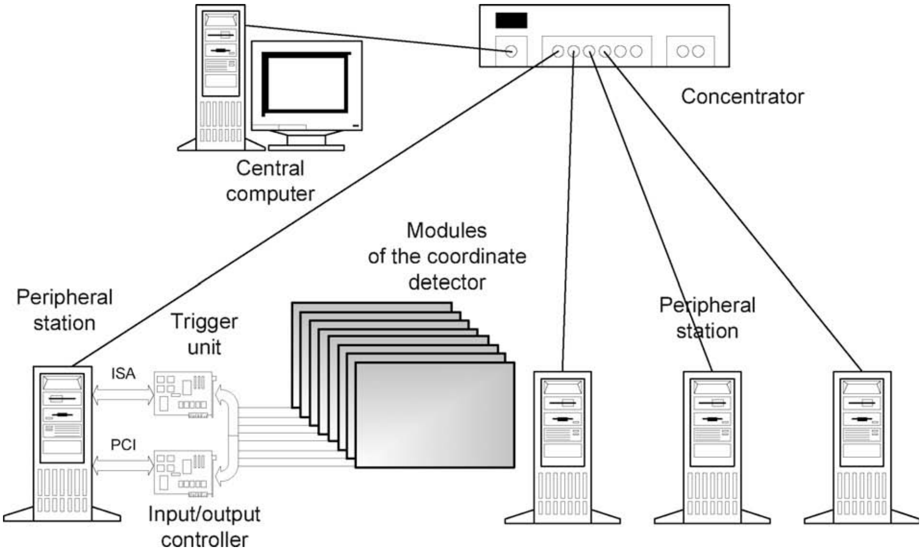

Fig. 4. Scheme of the triggering and data acquisition system of the hodoscope.

The supermodule response contains information about triggered strips in each of the *X*- and *Y*-projections. The track parameters (two projection angles) are reconstructed in real time mode using software based on the technique of histogram construction in each projection plane, and are accumulated in a 2D-directional array (zenith and azimuth angles, or pair of projection angles) with 1-min interval. Reconstruction algorithm provides a high spatial and angular accuracy of muon detection (1 cm and about 0.8°, respectively) in a wide range of zenith angles (from 0° to 84°). To reduce the reconstruction errors, only tracks passing within the area of the upper and bottom planes are taken into account (that is, tracks crossing all 8 planes of the SM). This demand decreases SM event rate approximately by 13%. Efficiency of reconstruction is greater than 90%, and one-minute matrices contain about 8×10^4 reconstructed events. The results of data processing are recorded on the hard disk and transferred, along with monitoring information, to the local computer net.

3. Data analysis

In December, 2006 the first part of the muon hodoscope composed of two supermodules (SM3 and SM4) was operated in the exposition mode. Thus the total area of the setup was equal to 23 m^2. Summed counting rate of reconstructed muon tracks in

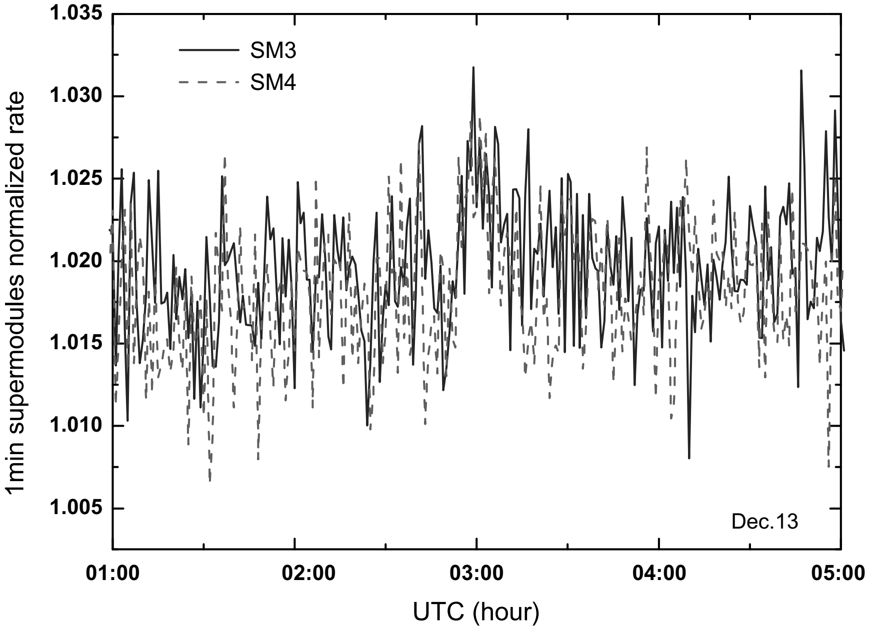

Fig. 5a. One-minute counting rate of separate supermodules.

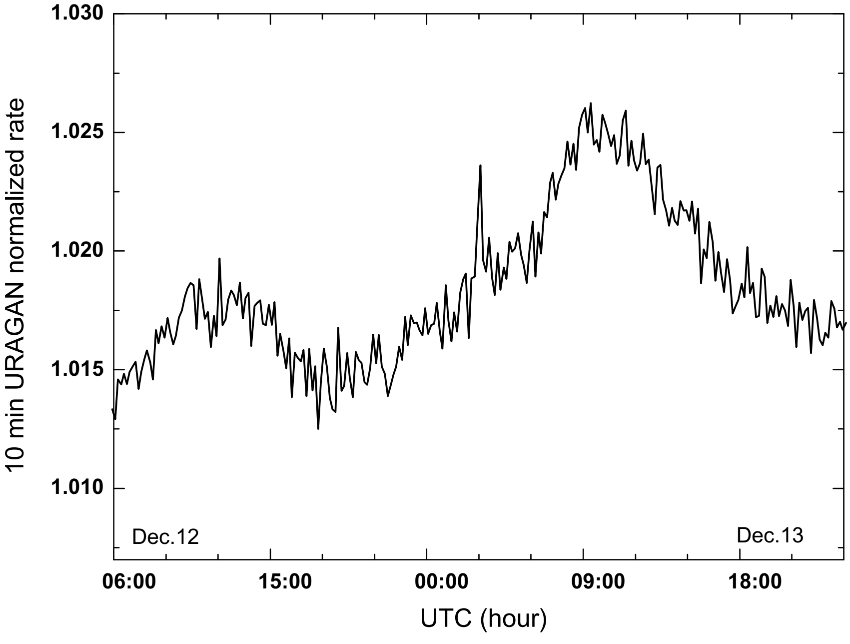

Fig. 5b. Total 10-min counting rate from two URAGAN supermodules.

both supermodules ensured statistical accuracy at 0.25% level for one-minute time interval.

3.1. Integral counting rate data

URAGAN supermodules detected an intensity rise starting from 02:54 UTC (see Fig. 5a). Maximum enhancement was observed at 02:59 UTC for SM3 and at 03:01 UTC for SM4. The increases in one-minute data of separate supermodules were equal to about 3 standard deviations. However, in 10-min counting rate summarized over URAGAN supermodules the maximum enhancement value equals to 0.61 ± 0.09% (at 03:00 UTC) that exceeds six sigma level (Fig. 5b).

Rigidities of primary solar protons, which produced secondary muons detected in URAGAN, may be evaluated by means of response functions of muon hodoscope and solar proton spectra. There are several estimations of the shape of solar proton energy spectrum [11]. For power-like dependence $\sim E^{-5.5}$, calculations give median rigidity near 7 GV. Evaluation of median rigidity for exponential solar proton spectra $\sim\exp(-E/0.33\text{ GeV})$ gives a lower value of median rigidity (about 3 GV).

3.2. 2D-dynamics of muon flux during the GLE

Muon hodoscope URAGAN allows to measure muon flux as continuous sequence of 2D snap-shots, thus conducting the filming of upper hemisphere in "muon light". To study muon flux fluctuations for every cell of the angular matrix the average number of muons (estimated for a long preceding period and corrected for atmospheric pressure) is subtracted, and results are divided by standard deviations. Obtained data array (matrix) is a "muon photograph" of the upper hemisphere with 1-min exposure. In Fig. 6 the sequence of muon matrices with 4-min time shift, obtained using the average over 5-min intervals, is presented. The edges of the images correspond to projection angles of 65°. Starting time of each averaging interval is indicated. Thin lines identify North–South and West–East directions. The color scales on the right show excess or deficit of muons arriving from a certain direction in units of standard deviations.

From the images it is clearly seen that the muon hodoscope URAGAN detected GLE effect during about 10 min in rather narrow angular interval centered near the vertical direction. Angular radius of muon enhancement spot is about 15–20°.

3.3. Comparison with neutron monitor observations

The worldwide network of neutron monitors can be used as multi-directional cosmic ray spectrometer. With use of calculated asymptotic cones of acceptance and solving a reciprocal task it is possible to obtain characteristics of the primary solar protons outside the atmosphere and magnetosphere from the data of neutron monitor worldwide network [3,11]. This kind of analysis includes several steps:

1. Definition of asymptotic viewing cones (taking into account not only vertical but also oblique arrival of incident particles) of the neutron monitor (NM) stations. The particle trajectories are calculated using the magnetosphere model of Tsyganenko, 2001 [12].
2. Calculation of the NM responses for various primary solar proton flux parameters.
3. Application of a least square procedure for determining primary solar proton parameters (namely, energy spectrum, anisotropy axis direction, and pitch-angle distribution) outside the magnetosphere by means of comparison of computed ground- based detector responses with observations.

In Fig. 7 the directional map in geocentric solar ecliptic (GSE) coordinate system is shown. Solid cross denotes anisotropy axis direction obtained from neutron worldwide network data (36 neutron monitor stations) for solar proton flux at 03:00 UTC. The direction is close to that of IMF direction (denoted by asterisk) according to ACE data [13]. Pitch-angle grid (relative to derived anisotropy axis) is indicated by thin circles; numbers on the circles are pitch-angle values.

In Fig. 7 the asymptotic cones of some NM stations with geomagnetic cutoff from 2.4 GV (Moscow) up to 4.5 GV (Jungfraujoch) [14] (Mo – Moscow, LS – Lomnitsky Stit, La – Larc, Ju – Jungfraujoch) are

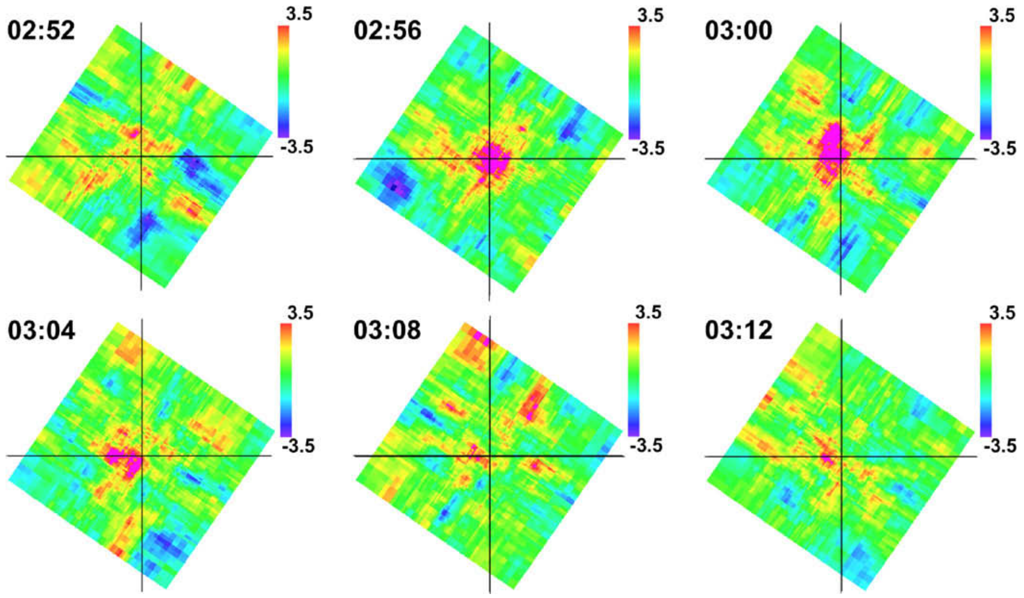

Fig. 6. Sequence of muon flux images during GLE event of December 13, 2006. The color scales on the right show excess or deficit of muons in units of standard deviations. Starting time (UTC) of each averaging interval is indicated on the left.

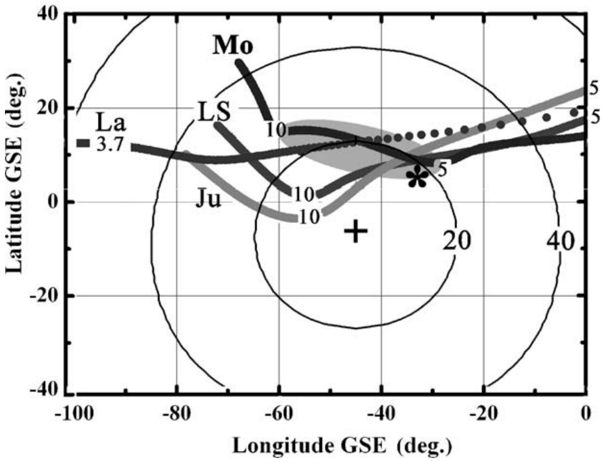

Fig. 7. The asymptotic cones of some neutron monitor stations (Mo – Moscow, LS – Lomnitsky Stit, La – Larc, Ju – Jungfraujoch) – thick dotted lines with numbers of rigidities in GV, and magnetopause projection of the muon enhancement spot (see Fig. 6) – shadowed ellipse. Solid cross and asterisk denote the anisotropy axis direction for solar proton flux at 03.00 UTC and IMF direction measured by ACE [13], respectively.

also shown as thick dotted lines with values of rigidities in GV. Parameters of these neutron monitors can be found elsewhere [2,15]. Each point of an asymptotic cone corresponds to a direction of arrival of proton with a given rigidity (which then reaches the atmosphere above a given station) to magnetosphere border (magnetopause). The ellipse in Fig. 7 represents the projection on magnetopause of a circular cone of directions formed by particles generating a stain in a field of sight of the hodoscope. The radius of a stain (Fig. 6) is taken equal to 20°. At projecting a stain to the magnetosphere border the rigidity was taken as 5 GV. The projecting itself was done by calculations of the trajectory of particle with the mass of proton (but the negative charge) launched up from the altitude 20 km above the hodoscope under corresponding angles. Rather good consent between a cone of acceptance of the anisotropic bunch by the hodoscope and asymptotic arrival directions

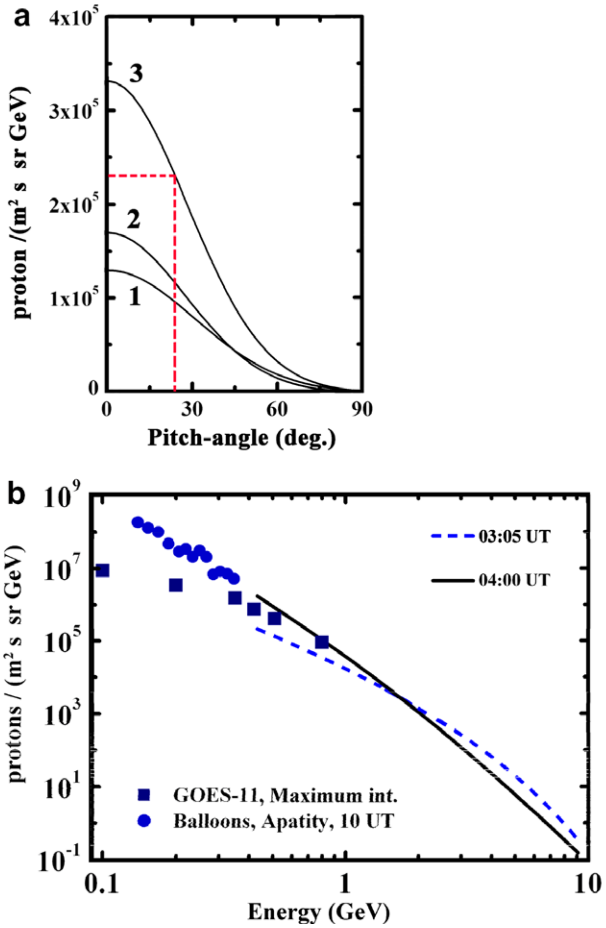

Fig. 9. Evolution of a pitch-angle distribution (left), numbers denote moments of time: (1) 02:57; (2) 03:00; (3) 03:05; and energy spectra (right) of relativistic solar protons derived from the neutron monitors data. The thick and dashed lines correspond to moments of time: 03:05 and 4:00, respectively. Points represent direct solar proton data measured by GOES-11 apparatus [1] and balloons [3].

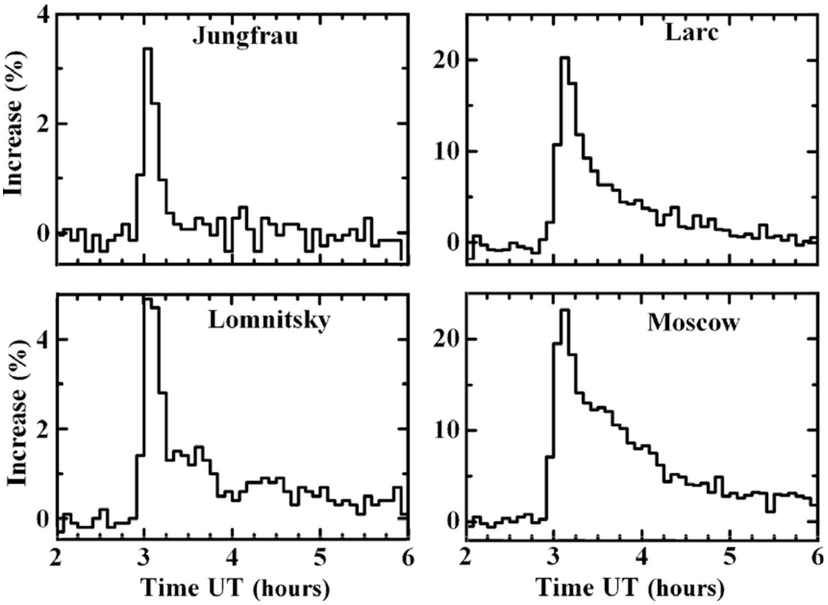

Fig. 8. December 13, 2006. Ground level increase in 5-min data of a number of neutron monitors looking approximately along the anisotropy axis. The sharp peak is nearly simultaneous with the URAGAN counting rate increase. Neutron monitors and their geomagnetic cutoffs are: Jungfraujoch (4.5 GV), Larc (3.0 GV), Lomnitsky Stit (3.5 GV), Moscow (2.4 GV).

of the particles which have caused the increase in neutron monitors, looking approximately in a direction of the interplanetary magnetic field, is seen.

Chosen neutron monitors also have registered a sufficiently short-lived increase by duration from 15 to 60 min (Fig. 8). The peak of intensity took place near 03:00 UTC, i.e. practically simultaneously with the muon burst in the URAGAN hodoscope. As shows analysis performed in [3], the effective rigidity range of solar protons responsible for the peaks is within the limits of 5–10 GV. Estimations of median rigidity for muon hodoscope URAGAN give similar values. These facts allow to conclude that near 03:00 both neutron and muon ground level setups have detected short-lived and highly collimated relativistic particle bunch in the initial phase of the event.

In Fig. 9 the evolution of pitch-angular distribution of relativistic solar protons (a) and their energy spectra (b) derived from the data of neutron monitors by means of the method described above are shown. The form of sought pitch-angular distribution in [3] was set as the Gaussian function. Characteristic width of the distribution (Fig. 9a) at a level of 0.7 of the maximum is of the same order of size as a stain from hodoscope data (Fig. 7), that also certifies a close conformity of the data of URAGAN hodoscope and independent definitions by neutron monitors. The importance of observations in the URAGAN array is that for the first time the angular images of collimated bunch of relativistic solar protons ejected from the Sun were observed directly. Earlier, angular shape of such bunches was observed only by indirect methods with the use of neutron monitor network.

4. Conclusions

Proton event of December 13, 2006 was detected not only by satellite detectors and neutron monitors at high and moderate geomagnetic latitudes, but also by ground-based muon hodoscope URAGAN. The moment of maximum in URAGAN data is at 03:00 UTC that coincides with neutron monitor data. The relative increase of 10-min counting rate is equal to 0.61 ± 0.09%. The muon peak in time profile of the event is much sharper than the neutron one with width about 10 min. Estimations of median rigidity of solar protons for muon hodoscope URAGAN give values about 5 GV.

It is important that at the time of the event the asymptotic arrival direction of particles coming to URAGAN hodoscope from zenith was close to the IMF direction and correspondingly to the calculated anisotropy axis of relativistic solar proton flux. Thus one can conclude that URAGAN hodoscope detected the highly collimated short-lived bunch of relativistic solar protons and for the first time angular dynamics images of the bunch were directly observed. Such particle bunches usually appear at initial phase of a GLE and belong to the so-called "prompt component" of relativistic solar protons [16].

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