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Ground-Level Enhancement of December 13, 2006 in muon hodoscopes data

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Abstract: A wide-aperture hodoscope URAGAN registered muon rate increase during GLE of December 13, 2006 at six sigma level (ten-minute bins). The maximum of growth is at 03:00 UT. Capabilities of muon hodoscopes allow obtain 2D-pictures of muon flux, and for the first time the spatial-angular dynamics of GLE event is measured. Due to that asymptotic viewing 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.

Introduction

In the middle of December 2006 strong disturbances of IMF and geomagnetic conditions caused by influence of solar region AR10930 occurred. Several powerful X-ray flairs have been registered by means of satellites GOES11 and GOES12 [1]. The flare of Dec 13 is of a special interest since it was accompanied by a powerful proton event, which produced a sharp growth of cosmic ray flux in the near-Earth space and at ground level [2]. The neutron monitor network [3] registered the Ground-Level Enhancement event (GLE # 70).

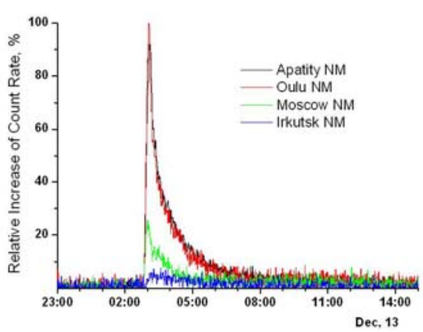

Figure 1: The GLE of December 13, 2006 in a number of neutron monitors: Apatity, Oulu, Moscow, Irkutsk.

In Figure 1 the increase of neutron rates of four neutron monitors with different threshold rigidities is presented. The difference in the increase effect was caused first of all by a great anisotropy. Thus the greatest increase was registered at Oulu and Apatity stations. Less strong increase was observed in Moscow due to higher geomagnetic cutoff (2.4 GV). All these three stations were looking nearly along anisotropy axis [3]. Irkutsk neutron monitor registered the low increase effect and delayed onset of GLE because of unfavorable acceptance direction [3]. It is remarkable that no effect was observed in neutron monitors with higher cutoff rigidity (Baksan – 5.6 GV, Athens – 8.0 GV). That can specify the upper limit in a spectrum of solar cosmic rays in this flare.

Additional information about the event of December 13, 2006 can give muon flux measurements at the ground level. Cosmic ray muons keep direction of primary particle motion that allows study angular cosmic ray flux variations by means of large-area muon detectors with high angular resolution.

This paper is devoted to study of GLE of December 13, 2006 on data of muon detectors of NEVOD Laboratory (MEPhI, Moscow) [4]. The total muon rate variations and also real-time dynamics of spatial-angular picture of muon flux during GLE event are discussed.

Muon hodoscopes

Experimental complex NEVOD is situated in Moscow Engineering Physics Institute. Geographic coordinates are 37°40' East longitude, 55°39' North latitude. Altitude above sea level is 163 m. The geomagnetic cut-off for vertical direction equals to 2.43 GV (IGRF). At present, two unique coordinate detectors, which allow register cosmic ray muons in wide regions of zenith angles and threshold energies are under operation in NEVOD.

The first in the world muon hodoscope TEMP [5] consists of two pairs of horizontal coordinate planes (X, Y) with sensitive area of 9 m^2. These pairs are vertically separated by 1 m. Each plane is assembled of narrow scintillator counters (2.5 cm×1 cm×300 cm) with PMT. Total number of counters is 512; angular resolution 1–2°. Data are continuously registered as intensity arrays with dimension 255×255 directional cells. Threshold muon energy is about 0.5 GeV.

The second multipurpose muon hodoscope URAGAN [6] has a modular structure. One supermodule (SM) of the hodoscope includes eight planes interlaid with 5 cm foam plastic and composed of 320 streamer tubes (1 cm×1 cm×350 cm) with external strips (along and across streamer tubes) forming two-dimensional readout system. Total area of each SM is about 11.5 m^2, and it includes 4864 data channels. The data processing system allows reconstruct muon tracks in the on-line mode and register muon flux from the upper hemisphere as continuous sequence of 2D-pictures. The setup provides detection of particles in a wide range of zenith angles (from 0 to 80°) with angular accuracy about 0.7°. Threshold muon energy is about 0.2 GeV (for vertical direction). In 2006, two URAGAN supermodules (SM10 and SM11) were under operation.

Integral counting rate data

URAGAN supermodules detected an intensity growth starting from 02:54 UT (see Figure 2). Maximum enhancement was found at 02:59 UT for SM10 and at 03:01 UT for SM11. In 10-minute counting rate summarized over URAGAN supermodules maximum enhancement value equals to 0.61 ± 0.09 % that exceeds six-sigma level (Figure 3).

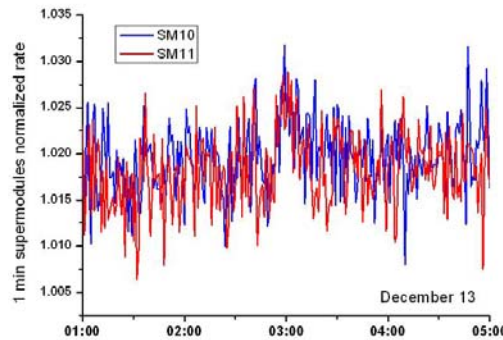

Figure 2: One-minute normalized counting rate of separate supermodules.

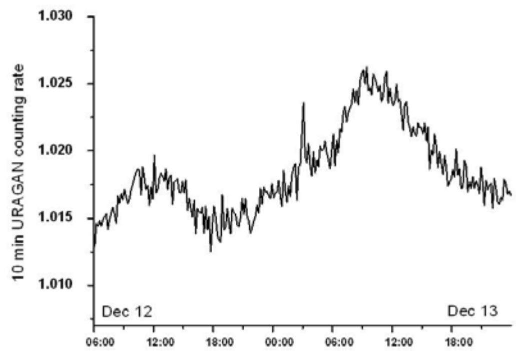

Figure 3: Total ten-minute normalized counting rate from URAGAN supermodules.

No muon flux increase was found in TEMP data (Figure 4). Dashed lines show ±3σ range. This fact can be explained by somewhat higher threshold energy for TEMP hodoscope (about 500 MeV) than for URAGAN that puts more strong restriction on rigidities of primary protons.

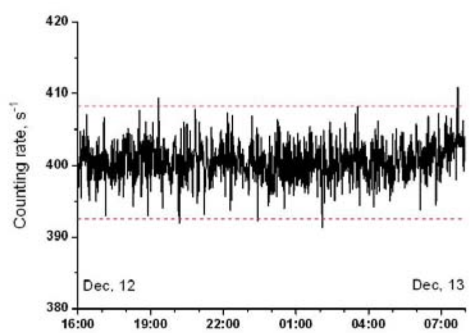

Figure 4: Rate of muon hodoscope TEMP at night Dec 12–13, 2006.

Muon flux 2D-dynamics during GLE

Muon hodoscope URAGAN allows register muon flux as continuous sequence of one-minute snapshots, thus conducting the filming of upper hemisphere in "muon light". On-line reconstruction gives values of both zenith and azimuth angles as projection angles θx, θy of muon track (in local coordinate system), on the basis of which the track is put in a corresponding cell of the angular matrix. In Fig. 5 the sequence of 2D-matrices with 4-minute step, obtained using sliding average over 5-minute intervals, is presented. Starting time of each averaging interval is indicated. Thin lines identify North-South and West-East directions. Colors show excess and deficit of muons from a certain direction in units of standard deviations.

From the figure it is clearly seen that muon hodoscope URAGAN detected GLE during about 10 minutes in rather narrow angular interval near the vertical direction.

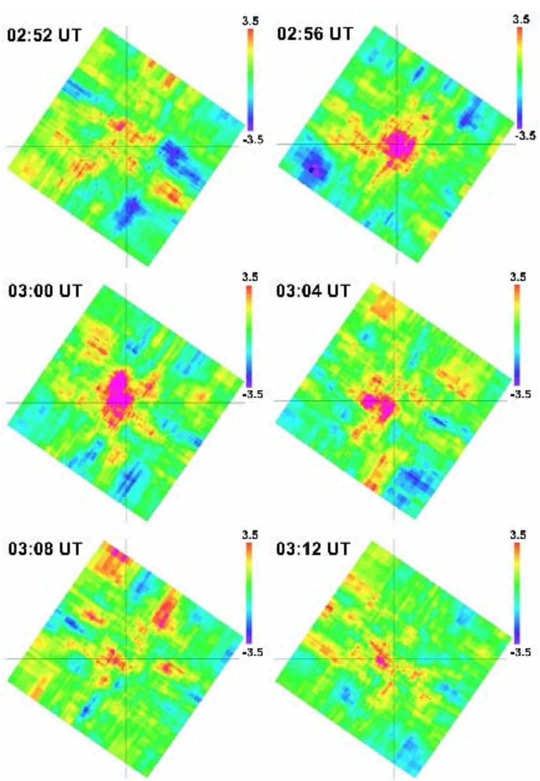

Figure 5: 2D-variations of muon flux during GLE event of December 13, 2006.

Comparison with neutron monitor observations

In Figure 6 the asymptotic direction map is shown with calculated asymptotic cones of the mid-latitude neutron monitors with geomagnetic cutoff of 2-4 GV [7]. At the beginning of the event, these neutron monitors looking along a direction of IMF have registered a sharp short-term peak (Figure 7). As analysis performed in [3] shows, the effective rigidity range of solar protons responsible for the peak is within the limits of 5-10 GV. By our estimates, the muon increase on the URAGAN hodoscope was caused by solar protons with similar values of rigidity.

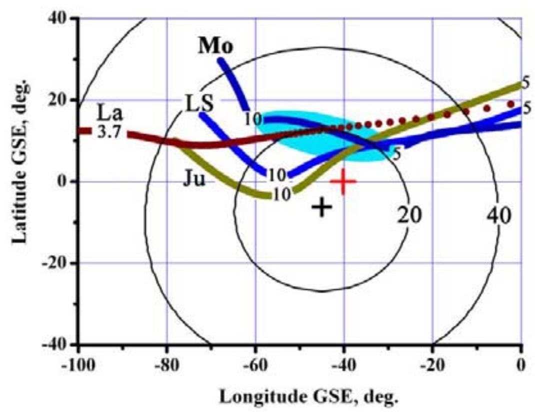

Figure 6: The derived anisotropy axis (black cross) and pitch angle grid circles (numbers are pitch angle values) for solar proton flux at 03.00 UT; IMF direction (ACE data) is indicated by a red cross; the asymptotic cones of some NM stations: Mo-Moscow, LS-Lomnitsky Stit, La-Larc, Ju-Jungfraujoch, numbers on thick lines are rigidities in GV; blue ellipse is magnetopause projection of muon enhancement spot in URAGAN matrix (Figure 5).

The ellipse in Figure 6 is the asymptotic projection of the muon increase angular cone in the hodoscope matrix. The area rounded by the ellipse included all calculated asymptotic directions of particles starting with different angles within the limits of red spot in Figure 5. The rigidity of primary protons was taken as 5 GV. So, the asymptotic arrival directions of particles forming the

GLE image in the hodoscope matrix is close to the direction of IMF and to calculated anisotropy axis of the relativistic solar proton flux registered by the neutron monitor network (see Figure 6). The angular dimensions of a narrow particle bunch causing the increase on URAGAN hodoscope (~30^{o}) is of the order of angular width of the pitch angle distribution in the same particle bunch detected by the neutron monitors [3].

The comparison with Moscow NM cone for different rigidities shows that in muon hodoscope, at least during the event maximum, the particles flux with rigidity 5 – 10 GV is seen above the background of galactic cosmic rays. It is also seen from Figure 6 that all asymptotic cones are intercepted at rigidities about 4–5 GV. Besides, the sharp profile of muon enhancement in URAGAN and of counting rate in neutron monitors with such cut-off rigidities (Fig. 7) evidences for a strong anisotropy of high-energy component of solar proton flux.

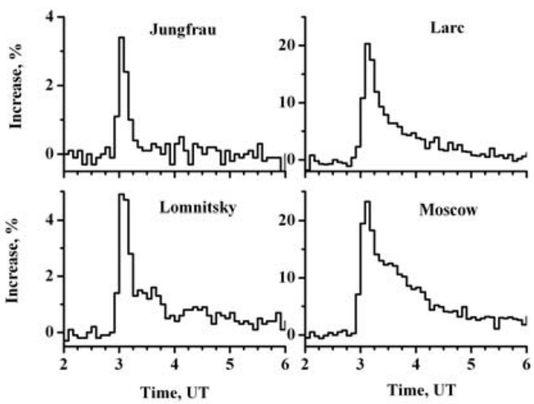

Figure 7: GLE at a number of neutron monitors looking along anisotropy axis. The sharp peak is nearly simultaneous with the URAGAN increase.

Discussion

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 detecting of a bunch was promoted by that the asymptotic acceptance cone of muon hodoscope appeared looking along the IMF. The moment of maximum in URAGAN data is at 03:00 UT that coincides with neutron monitor data. The muon peak is much sharper than the neutron one with width about 10 minutes. 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 registered the highly collimated short-lived bunch of relativistic solar protons. Such particle bunches usually are observed at initial phase of a GLE and belong to the so-called “prompt component” of relativistic solar protons [8].

Acknowledgments

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