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Observation of muon flux increase during GLE of 14.07.2000 by means of large aperture hodoscope

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Ground level muon intensity observed by means of the TEMP setup was analyzed. The setup simultaneously and continuously registers cosmic ray muons in 4096 spatial directions with angular accuracy about 1-2 degrees for 1-minute time intervals. Detected muons correspond to primary protons with average energies about 30 GeV. It was found that there was no excess in the total cosmic ray flux (integrated over the hodoscope aperture) during 14.07.2000 related to GLE detected by the worldwide network of neutron monitors. However, in a narrow solid angle (related to direction of interplanetary magnetic field) some excess of intensity at the moment of GLE (10:30 UT) with the duration of several minutes was found. These results qualitatively agree with a similar observation at L3+C setup operated in CERN during that time period.

1. Introduction

The Ground Level Enhancement (GLE) event of 14.07.2000 has been detected by the worldwide network of neutron monitors (NMs). However, in NMs with high geomagnetic energy cutoff ($\geq$ 7 GeV) the exceeding counting rate had not been observed [1,2]. Perhaps, this effect is related with comparatively low angular resolution of NMs. Various theoretical models of acceleration of solar particles predict the possibility of existence of protons with energies up to $10^2 - 10^3$ GeV. The process of acceleration of high-energy protons may take a relatively short time of $\leq 10^1 - 10^3$ second [3].

The L3+C (CERN) setup that included a high-energy magnetic spectrometer was running during the time of the energetic solar flare of 14.07.2000. The filter of 30 m of molasses provided a 15 GeV cutoff for muon energy, corresponding to primary proton energy above 40 GeV. The 16-minute increase of a muon flux in a narrow interval of zenith and azimuthal angles was observed [4]. At the same period a large aperture muon hodoscope (TEMP) was in operation in Moscow.

2. Method

Muon hodoscope TEMP was constructed to investigate the solar-terrestrial physics in the primary energy region about 30 GeV [5]. The setup includes 512 plastic scitillators counters. Each of the counters represents a narrow strip; its length is 300 cm, cross-section is 2.5x1.0 cm^2. The photomultipliers coupled to each strip provide the effective registration of relativistic muons. The muon hodoscope is made of four layers. Each of the layers consists of 128 counters. Figure 1 shows the schematic view of the hodoscope. The neighboring layers (X,Y) form the coordinate axes. The distance between two pairs of layers is about 1 meter. The fifth layer of scintillators (Z) is added for trigger formation. To reject the soft component, a 5 cm thick lead filter is used. The setup is located at the ground level under 2 m w.e. filter. The passage of muon through all layers causes the signals in four coordinate counters. This provides the possibility of reconstruction of zenith θ and azimuth φ angles of muon direction with accuracy of about 1-2°. In the experiment, the one-minute matrix arrays of muon angular distribution of intensity $N_{ik}(t)$ are registered, certain zenith and azimuth angles correspond to each element ik [6].

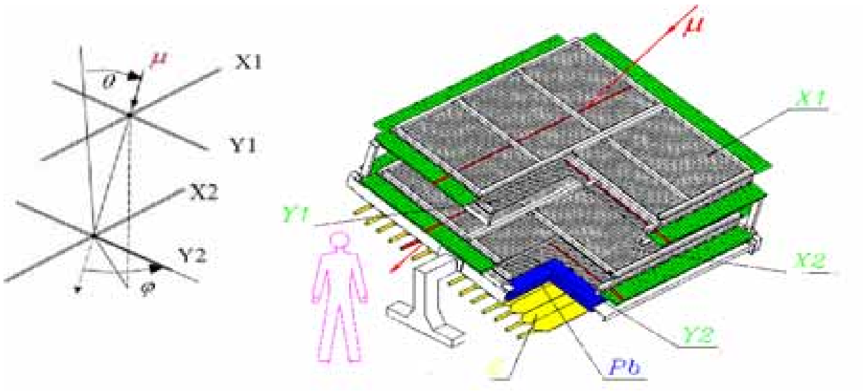

Figure 1. Scheme of the muon hodoscope (area 3 x 3 m^2). X1, Y1 and X2,Y2 are the upper and the lower layers of scintillators (4 x 128 counters). Z is additional trigger layer; Pb is 5 cm lead absorber.

We compared the TEMP integral intensity of muons with counting rate of Moscow NM [7] for the time interval including the high energetic solar flare of 14.07.2000. No significant excess of cosmic ray intensity at 10:30 (UT) in TEMP setup was observed (Figure 2). The decreasing of cosmic ray intensity at about 19:00 (15 July) is connected with Forbush decrease (FD) caused by Coronal Mass Ejection (CME) directed towards the Earth.

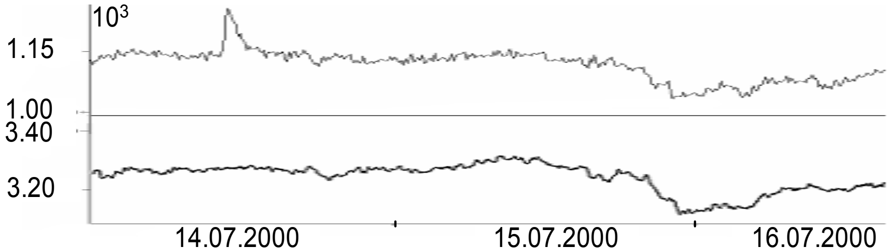

Figure 2. The intensity of cosmic rays (Moscow): NM (IZMIRAN, upper panel) [7] and TEMP (MEPhI, lower panel).

Then the analysis of counting rate in different spatial directions was performed. For the increase of statistical accuracy, the matrix data $N_{ik}(t)$ over 8°x 8° cells were analysed. It appeared that in one of the directions ($\theta \approx$ 60°) the excess of intensity was found. This direction is connected with a topology of an interplanetary magnetic field. The duration of the enhancement was equal to 3 minutes and its amplitude was 4.6 σ (about 40% excess in comparison with a quiet period). The counting rate for TEMP and L3+C installations is shown in Figure 3.

The difference of zenith angles of GLE observation in CERN and in Moscow makes about 30°, and it is related with the geographical positions of the setups. Azimuth of GLE direction is located in a N-W quadrant because of the influence of the Earth magnetosphere on a trajectory of protons with energy of tens GeV. Monte-Carlo calculation using CORSIKA [8] were used to estimate the mean energy of solar protons with several power law indexes γ, and under conditions of: starting energy of protons is more than 7 GeV; the energy of recorded muons is more than 0.4 GeV; the zenith angle θ of muon trajectory is fixed.

The analysis of the data indicated [9,10] that the value γ for GLE of 14.07.2000 was equal to about -6. For such γ, CORSIKA-based simulations show that the TEMP installation registered protons with energy about

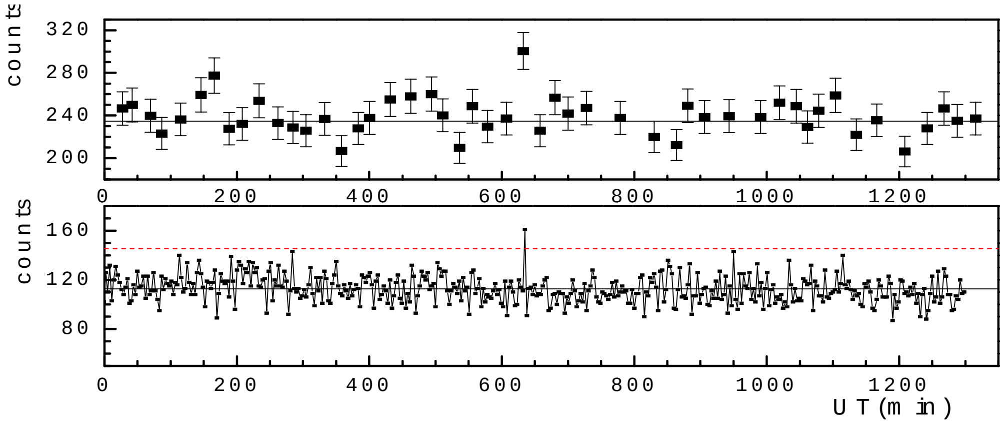

Figure 3. Muon counting rate (GLE 10:30 14.07.2000) in a narrow interval of spatial angles: experiment L3+C (with 16-minute bins) [4] - upper panel; TEMP (3-minute bins) - lower panel. The dashed line corresponds to 3 σ level.

50 GeV. A small duration of GLE ($\tau \approx 3$ minute) also confirms a high energy of solar protons. The estimation of a flux of solar protons is obtained from expression $\Delta N = j \cdot \delta\Omega \cdot S \cdot \tau$ and makes up the magnitude $j = (3.8 \pm 0.6) \times 10^{-4}$ $cm^{-2}sr^{-1}s^{-1}$. Value $\delta\Omega \cdot S$ is the aperture in the selected direction.

It is known that on 14.07.2000 (about 10:30) a full-halo Coronal Mass Ejection (CME) was observed by the SOHO spectrometer [11]. Forbush decrease on 15 July (18:30 UT) was caused by this CME directed towards the Earth (Figure 2). The expansion of the CME magnetic field may cause modulation of high-energy primary cosmic ray flux (PCR) passing through it [12].

A Fourier analysis of muon flux modulations connected with propagation of the CME front for several time intervals was carried out. Power spectral densities (PSD) were calculated for the time series from 11:30 UT 14.07.2000 up to 15:30 UT 15.07.2000 (Figure 4). The duration of separate series was equal to 180 minute each.

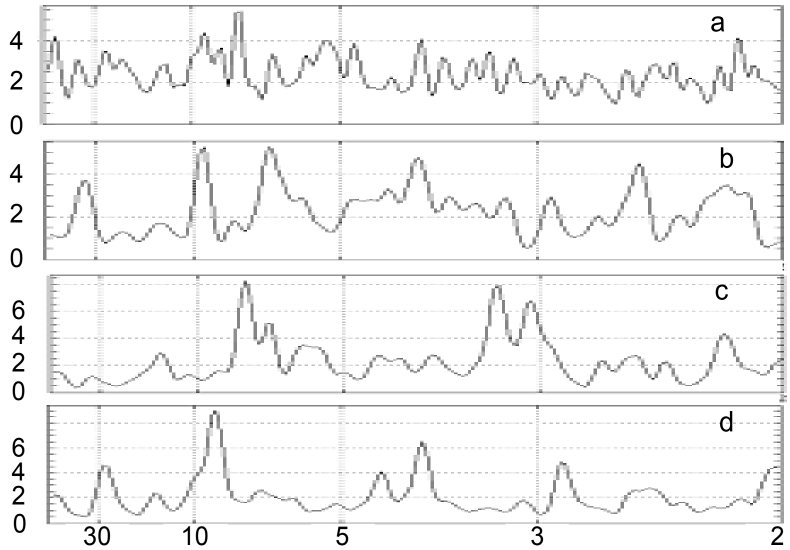

Figure 4. PSD functions for 4 time series: a – 11:30-15:30 14.07; b – 09:30-13:30 15.07; c – 13:30-17:30 15.07; d – 11:30-15:30 15.07 ("background" direction). X axis corresponds to harmonic period T (minute). Y axis is PSD amplitude.

Figure 4a corresponds to the moment of the solar flare, and no noticeable variations in it are visible. In the process of moving of the CME in the interplanetary space, the modulation of PCR increases. The PCR modulation near the Earth′s orbit is considerably different from known low-frequency fluctuations (Figure 4b, 4c). This phenomenon represents high-frequency oscillations with periods of about several minutes. It is necessary to note that the considerable modulation far away from the direction "towards the Sun" was also detected (Figure 4d). The modulation connected with CME was registered earlier (by about 7 hours) than FD occured. Such high frequency modulation may be used as an early predictor for Solar Weather monitoring.

4. Conclusions

The deployment of large-aperture detectors with high angular resolution allowed for registration of the excess of atmospheric muons connected with GLE of 14.07.2000. Magnetic field of the Earth and an increased thickness of the atmosphere at zenith angles $\theta \geq 60°$ represent a natural separator for selection of high-energy protons.

The model calculations (with CORSIKA) have shown that the registration of high-energy atmospheric muons (from a chain of transformations $p+N \rightarrow \pi \rightarrow \mu$) corresponds to the average energy of solar flare protons about 50 GeV. The muon flux corresponding to this GLE is equal to $(3.8 \pm 0.6) \times 10^{-4}$ $cm^{-2}sr^{-1}s^{-1}$.

The expansion of the CME magnetic field causes modulation of high-energy PCR passing through it. The characteristic period of harmonic fluctuations is about 3 – 10 minutes. This effect was found with the help of the TEMP setup [12] during registration of several FD, and it was repeated for the modulation connected with CME of July 2000.

5. Acknowledgements

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