Detection of Solar particle events in March 2012 at BEO Moussala

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Abstract. The solar activity was very high in March 2012. There were four geoeffective solar flares associated with Earth-directed coronal mass ejections (CMEs) during the period between 5-10 March. The magnetic disturbances in the interplanetary magnetic field produced two consecutive Forbush decreases between March 08 and 13. Both of them were registered by neutron component detector of SEVAN instrument and by the muon telescope at BEO Moussala. The obtained results are presented showing the level of measuring capability of the cosmic ray devices operating in BEO Moussala.
Key words: Cosmic rays; CME, cherenkov muon telescope, SEVAN

1.Introduction

The Basic Environmental Observatory (BEO) Moussala is complex research facility for cosmic ray, atmosphere physics and chemistry studies. The observatory is located at peak Moussala (2925 m a.s.l., $42^{'}17^{o}$ N, $23^{'}58^{o}$E) with rigidity cut-off of 6.3 GeV. The cosmic ray measurements are performed with water cherenkov muon telescope [1] and SEVAN complex device [2] for registration of neutron, high energy muons and low energy particles, mainly electrons of secondary cosmic rays. There are registered three Forbush decreases due to the strongest in last seven years Solar eruptions during the period of 8th-15th March 2012. The obtained results are compared with satellite data from NOAA sources and confirmed by other SEVAN network detectors and neutron detectors.

The Forbush decrease (FD) is variation in density and anisothropy of cosmic rays intensity due to disturbances caused of solar wind [3]. FD are classified in two types - recurrent and Non-recurrent. When FD has slow and time-dependent symmetric trend it is assumed as recurrent. This effect is supposed to follow corotating high speed solar wind fluxes [4]. The Non-recurrent FD is consequence of short in time interplanetary events caused by solar flare. The trend is sudden and sharp for less than a day, then slowly restore to normal values.

2.Equipment

The fully operating cosmic ray equipment of BEO Moussala consists of Muon telescope and SEVAN complex device. The Muon telescope produces results of hard charged component, separated in directional positions - vertical, South-North, North-South, West-East, East-West. The flux intensitying interval is 15 seconds. The Sevan equipment measures particle flux variations, separating hard and soft charged and neutral component. The flux intensity time interval is 1 minute. However, for purpose of this paper we selected to use only neutron data from SEVAN device, due to availability of more detailed and precise muon data from muon telescope.

2.1. Muon Telescope

The muon telescope was specially developed and constructed for BEO Moussala observatory of the Institute for Nuclear Research and Nuclear Energy - BAS. The continuous measurements began in August 2006 [1]. The telescope is operational for continuous measuring the intensity of the muon component of the cosmic rays and data are used for exploring its variations and possible correlations with environmental parameters. The accuracy of the telescope is 0.27% [1] in vertical direction and better than expected because of the higher muon flux intensity at this altitude.

Fig. 1. Muon Telescope.

The telescope is constructed with 8 water Cherenlkov detectors connecting 12 coincidence channels. Each of the detectors includes a mirror tank with distilled water and photomultiplier with preamplifier mounted at its housing (Fig. 1). The dimensions of the detectors are 50x50x12.5cm, and the distilled water layer used as radiator is 10cm. When a cosmic rays muon passes through the radiator, Cherenkov light is generated if the energy of the muon is high enough that its speed is greater than the speed of light in the water. Part of the Cherenkov photons reaches the photocathode of the photomultiplier after multiple reflections from the mirror walls of the container. The 2.5 inch photomultiplier tubes type FEU-110 or FEU-139 are used.

2.2. SEVAN complex device

The SEVAN complex device is a part of the developing SEVAN cosmic ray network. The SEVAN detector and the network have been developed in the CRD-YPI of Yerevan Physic Institute (YerPhi) as an element of the Instrument Development Program for the International Heliophysical Year. The device that operates in Moussala is installed in 2008 in colaboration between YerPhi and INRNE [5]. The detector works permanently since then. One of the major advantages of this multi-particle detector is simultaneously measurements of basic components of the secondary cosmic flux initiated by primary particles in the terrestrial atmosphere.Fluxes of neutrons and gammas, charged components of low energy and high energy muons are measured by a basic detector of SEVAN network. The obtained diverse information gives the opportunity to estimate the energy spectra of the highest energy solar cosmic rays and distinguish as very rare events of direct solar neutron detection.

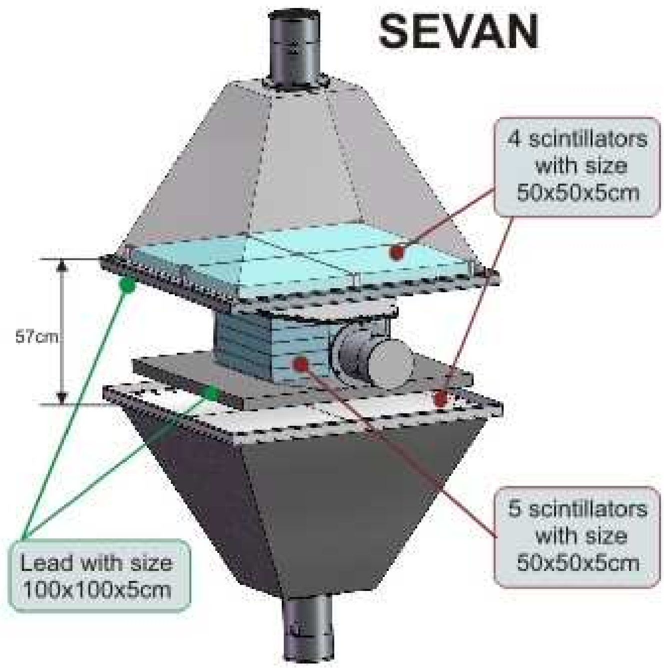

Fig. 2. SEVAN Telescope.

Construction of the SEVAN detector is based on three plates of 50x50x5 cm plastic scintillators slabs separated by lead absorbers. The middle plate consists of 5 plates constructing thick assembly. This part is enclosed as 'sandwich' from up and down by lead absorbers and thin plates of 4 scientilators in parallel. The neutral particles pass through upper plate and due to nuclear reactions stop at tick assembly. The signal in thin plates registers charged particles - the coincidence in upper and low plate is a result of muon traversal (See Fig. 2).

3. Data verification

For purpose of this study we used a real time short data series enclosed in March 2012 measurements only. It is the time period approximately starting 1 week before CME arrival on earth and 1 week after space weather return to resting mode. In addition, the SEVAN device is run out of operational mode in the end of month. The selected data set is sufficient for registration report in comparison for both hard and neutral nuclear component of secondary cosmic rays during events.

Moreover, the raw data used for research consist of uninterrupted time series - 1 minute neutral particles data from SEVAN and 15 seconds intervals for different direction coincidences from Muon telescope. The raw measurements data is available in real time and stored in specially dedicated data server. However, the control of data quality is established for data verification before final data set to be performed. The procedure used for data verification differs for both devices due to device operational possibilities. The muon telescope produces operational control meta data in addition to raw measurements. Assuming any operational problems, the corresponding measurements are removed from operational data set. Conversely, the SEVAN does not support real time meta data production and this step is removed from data quality procedure for it.

In next step neutral and muon data undergo data filtering for severe data outliers. This procedure removes all items outside the 3σ confidence interval of estimated value for $\bar{y}$ from time series

$$y_1, y_2, ...y_n \tag{1}$$

where n is index for one hour back in time. The most and very distant data from local 1 hour time series is removed with filtering. The statistical effect is lower data deviations with trade-off of data removal in theoretical estimation of removal of 2 records in 6 hours data set for neutral particles and 4 for 3 hours measurements for muon data (See Fig. 3).

The data is thermodynamically corrected with 10 minutes pressure data from Vaisala meteorological station. The calibration coefficients are calculated over all data except this during the space weather disturbances from March 8th and 15th.For pressure calibration we used General Linear Models (GLM). In proposed GLM model we assume that every dependent variable $\bar{y}$ is generated from a particular distribution in the non-linear family. Then the expected value $\mu = Ey$ and variation Dy are dependent on link function

$g(\mu)$ of linear predictors X with β regression coefficients. The mean value for exponentially distributed data is:

$$Ey = \mu = g(\beta X)^{-1} \tag{2}$$

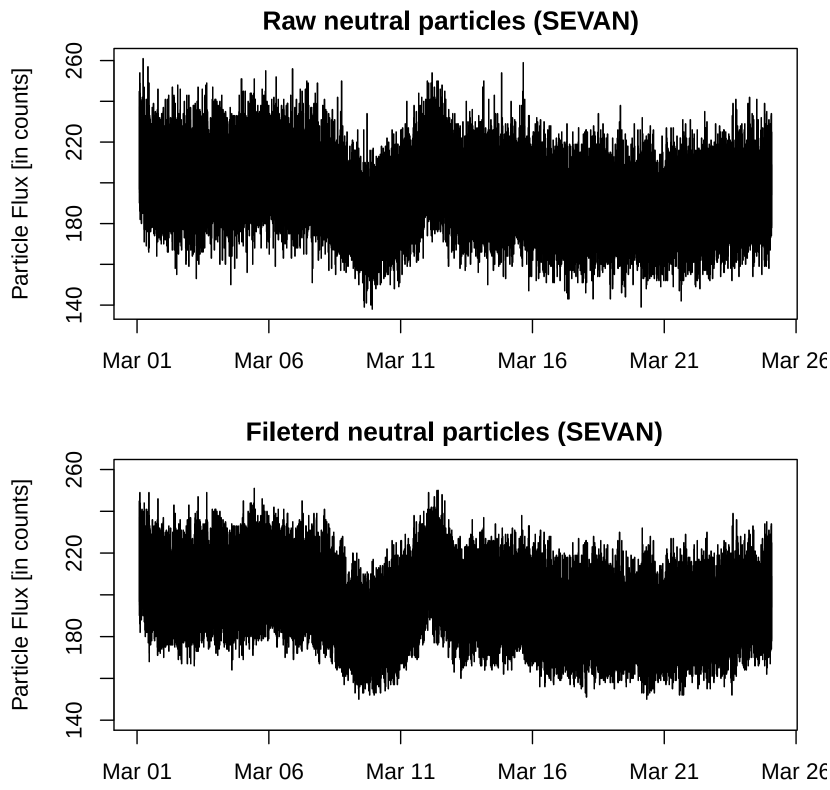

Fig. 3. Graphics of raw and filtered data for neutral particles measured with SEVAN for the period March 1- March 25 2012. The first hour of March 1 is missing from filtered data due to filter calibration.

In final step the data fluctuation and trend are fitted by 3 minute two-side exponential smoothing. The newly estimated values show trend in solar events produced by weighted in time period distance $t = \tau$ with coefficients λ:

$$x(t = \tau) = \lambda_0 \Delta x_\tau + \lambda_1 \Delta x_{\tau-1} + ... \tag{3}$$

$$\lambda_i = \alpha(1-\alpha)^i; \quad where \quad 0 < \alpha < 1 \tag{4}$$

The selected $\alpha = 1/3$ is closer to 0 than 1 for the purpose for higher weight of the closest in time interval values, than the distant. In final computation data is normalized for the whole period. Finally we normalyzed data with average value for whole period. In this way we present general comparison of intensity flux levels.

The data stability differs for devices. The Muon telescope is measuring on 15 seconds and data is filtered with this time resolution. The smaller intervals and larger in size time series reduce error with magnitude of $\propto \frac{1}{\sqrt{(n)}}$. The results for vertical muons and SEVAN neutrons are confirmed by larger 3σ confidence intervals. According to this we used 3σ intervals to estimate levels of acceptance. But the magnitude of intensity variation for directional muons is lower compared to vertical ones. All data is presented by value and lower and upper intervals for normalized data.

4. Overview of NOAA observations and CME events

Below brief satellite information for CME events is provided. The source for this information is Space Weather Center of NOAA [6]. According to satellite information the solar CMEs begun in very early hours of March 5th. The first largest solar event started on 0230 UTC, peaked at 0409 UTC and decayed at 0433 UTC. It was classified as X1/2B solar flare and its direction was towards Earth. Then there was another 15 large solar flares with classification M or X during the periods of March 5-7 and March 9-10. But only 3 of them were directed to earth - X5/3B March 7, peaked at 0024UTC; M6 March 9 peaked 0353UTC; M8 March 10, peaked at 1444 UTC [6].

The X1/2B CME arrived at March 7th following sudden geomagnetic impulse.The following X5/3B CME arrived at the Earth on March 8 and impacted geomagnetic field on 1105 UTC. The CME persisted with strong storms caused by Interplanetary magnetic field (IMF) during March 9. The weather started to calm in next two days. The M8 event from March 10 reached Earth on March 12 midday with high solar wind speed (775 km/s). The IMF also increased to 28 nT during CME arrival. Another geoeffective CME was observed after sudden shock of 27nT on March 15th. This storm was brief, but with very high wind speed of about 800 km/s. The probable date of source is any of M class events of March 14th [6].

5. Results and discussion

The X5/3B CME solar event is registered with high statistical significance by Forbush decrease. The registered Forbush decrease was non-recurrent with very large magnitude larger that 8%. The first sign was detected as short weak decrease after 0830UTC followed by quick resume after 30 minutes. The event begun shortly after CME arrival at about 1130 UTC for both - neutrons and muons. The particle flux intensities started to decrease afterwards until 2100UTC when Forbush decrease turned to significant and permanent. The extreme low values due to Forbush decrease were registered at level of $((0.9158 \pm 0.0246)$ at 2240UTC for neutron and (0.9377 ± 0.0102) for muons) at 2231UTC for muon flux intensity. Then the flux intensities varied in next 24 hours, fluctuating with lower than normal magnitudes of flux intensities. Second very short sharp particle fall was registered at 0403UTC for neutrons and 0341UTC for muons. The measured intensities are (0.9562 ± 0.0104) for muons and (0.9158 ± 0.0248) for neutrons. The intensity continues to vary reaching another three significant steep extreme decreases in next 18 hours. Four significantly deep low extreme values were registered at 0635UTC,1727UTC, 1949UTC and 2056UTC for neutrons and 0640UTC, 1726UTC,1937UTC 2117UTC for muons. Afterwards the particles flux intensity started to increase to normal values at the end of March 09. All significant flux intensity decreases are shown in Table 1 1.

Table 1. The largest measured intensity steep decrease (Normalized)

Date	Time[UTC]	Neutron [%]	Muon [%]
2012-03-08	2235	0.9158 ± 0.0246	0.9377 ± 0.0102
2012-03-09	0400	0.9158 ± 0.0248	0.9562 ± 0.0104
2012-03-09	0635	0.9285 ± 0.025	0.9584 ± 0.0103
2012-03-09	1735	0.90385 ± 0.0243	0.9504 ± 0.0103
2012-03-09	1940	0.933 ± 0.0252	0.9511 ± 0.0103
2012-03-09	2100	0.9231 ± 0.0248	0.9504 ± 0.0102

The flux intensity was elevate to normal with coincidence with space weather until arrival of M8 solar flare. The measured particles started to decrease slowly about late midnight on March 12 and persisted until midday on next day, March 13th. The extreme attenuation was measured in 13/0138UTC for Muon and 13/0133UTC for neutron component. The geoeffective CME amplitude was smaller compared to the X5/3B CME. There was only (0.96 ± 0.0103) decrease for muon and (0.925 ± 0.024) for neutrons. The FD was recurrent with sudden quick attenuation. The total attenuation was less than 3% . It was very short in time and lasted less than 12 hours. This explains the very low error.

The CME from march 15th produced very brief event with small attenuation less than 2% with lower amplitude change to (0.9738 ± 0.0106) for muons and (0.9575 ± 0.0258) for neutrons. The event was very short and lasted about an 6 hours and fell to lower intensity at 2008 UTC for muon detector and 1854UTC for SEVAN data. The low magnitude and error intervals do not give serious confirmation for reality of registered CME event. Another reason for this is asynchronous in time of 2 hours in the lowest intensities registration for muon and SEVAN. The data with 30 minutes averages for vertical muon and SEVAN neutron flux intensities for observed period are shown in Fig.4.

The possible effect when Earth directed CMEs solar wind travels is galactic cosmic rays cut-off due to IMF disturbances. This magnitude of cosmic ray solar modulation variations depend on direction and speed of solar wind which consists of plasma of low energy protons and electrons. As a result the particles entered to the Earth are with lower density with energy sufficient to reach ground level. The Forbush event followed X5/3B flare lasted for more that 2 days, decrease was deep but slow and has two significant plateau on

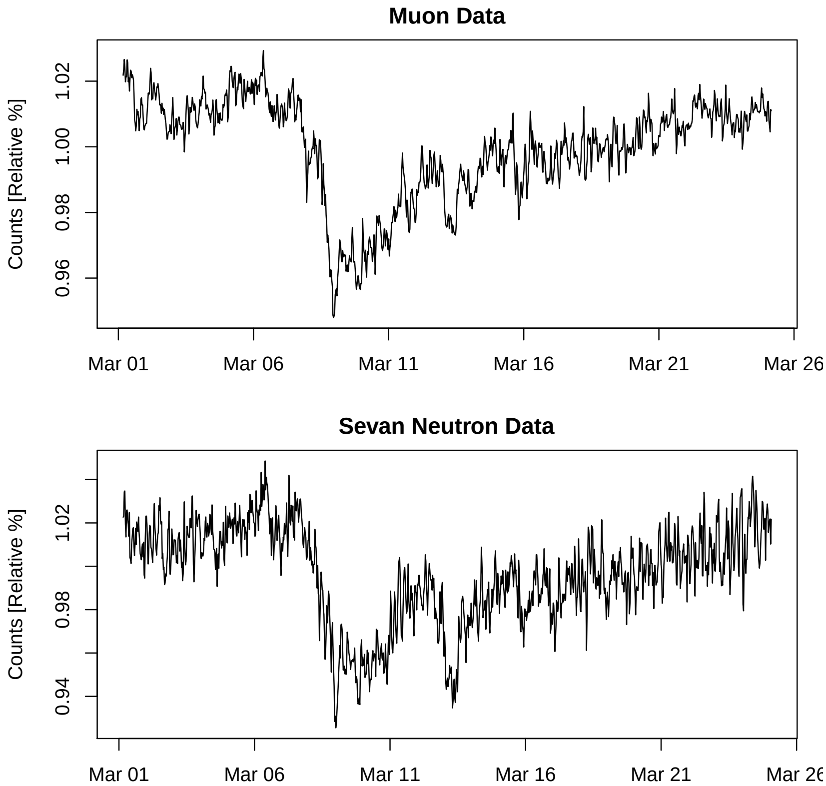

Fig. 4. 30 minute averages for neutrons and muons measured at Moussala. The neutrons are measured by SEVAN equipment for period March 1 0000UTC until March 25 2359UTC. The data from muon telescope is for period 0000UTC until March 30 2359UTC

March 8 and March 9th. We assume this FD as recurrent due to CME shock waves. The next M8 flare event registered on March 13th has quick sharp decrease and follows significant solar wind. It is assumed as recurrent event. The last event on March 15th is connected to very high wind speed.

The anisotropy is investigated with east-west effect during the X5/2B CME, registered on late March 8. The Forbush decrease was registered in east-west(EW) directions with different magnitude. East-west coincidences lowered at 2124UTC to $(0.9438 \pm 0.0133)\%$ conversely to lower West-East(WE) magnitude $(0.9851 \pm 0.0139)\%$ at 2119UTC. The first important notice on directional measurements is that FD decrease amplitudes are lower than 5% for EW directed and less 4% for WE. This is because longer path of traverse of charged particles in directional measurements compare to vertical. This results to measurements of secondaries of cosmic particles with higher energy which are less dependent on magnetic field disturbances.

Another important notice is that measured lower values for directional measurements are asynchronous in time with vertical directed particles. There is only one coincidence in time between extreme low values between vertical direction and EW and WE measurements. This is steep decline at 1739UTC for WE and at 1744UTC for EW directions. The magnitudes are $(0.9346 \pm 0.0132)\%$ for EW and $(0.9489 \pm 0.0132)\%$ for WE directions. There are two significant falls in WE direction at March 9th and three for EW direction. The possible reason for asynchronous in time registering the extreme low values are large period when CME persisted and possible statistical fluctuations due to diurnal circles and atmosphere perturbation through particle traverse. All of them are shown in 2.

Table 2. Directional intensity steep decreases (Normalized)

Date	Time[UTC]	Direction	Muon [%]
2012-03-09	0128	EW	0.9138 ± 0.0133
2012-03-09	0003	WE	0.9488 ± 0.0132
2012-03-09	0259	WE	0.9244 ± 0.013
2012-03-09	1201	EW	0.9401 ± 0.0135
2012-03-09	1529	EW	0.944 ± 0.0134

The M8 solar flare was detected with lower statistical significance due to lower decrease magnitude. The trend was symmetric and the lowest values are registered with more than 1 hour advance in EW direction at March 13th 0530UTC with magnitude (0.953 ± 0.0135). The lowest value for WE particle fluxes is measured at 0752 UTC with $(0.9488 \pm 0.0132)\%$. For the supposed event on March 15th there was detected faint attenuation at WE direction with amplitude $(0.9758 \pm 0.0138)\%$ at 1900UTC. The EW decline was inside the statistical error and is at (0.9755 ± 0.0138) at 1906 UTC. The decline for both directions lasted very shortly to about 90 minutes and were very close in time. The WE and EW data series are shown in Fig. 5.

6.Conclusion

This paper reported in brief the registered solar flare events at BEO Moussala. The results managed to generate statistically significant results for solar flares in the period 5-10 March 2012. In addition it pointed out supposed FD decrease after strong space wind in March 15th 2012. This paper shows, that the analysis of FD overview could be performed very soon after event ground detection with quite significant precision. The development of data treatment and filtering procedures are good basis for practical systematic real-time research of space weather events.

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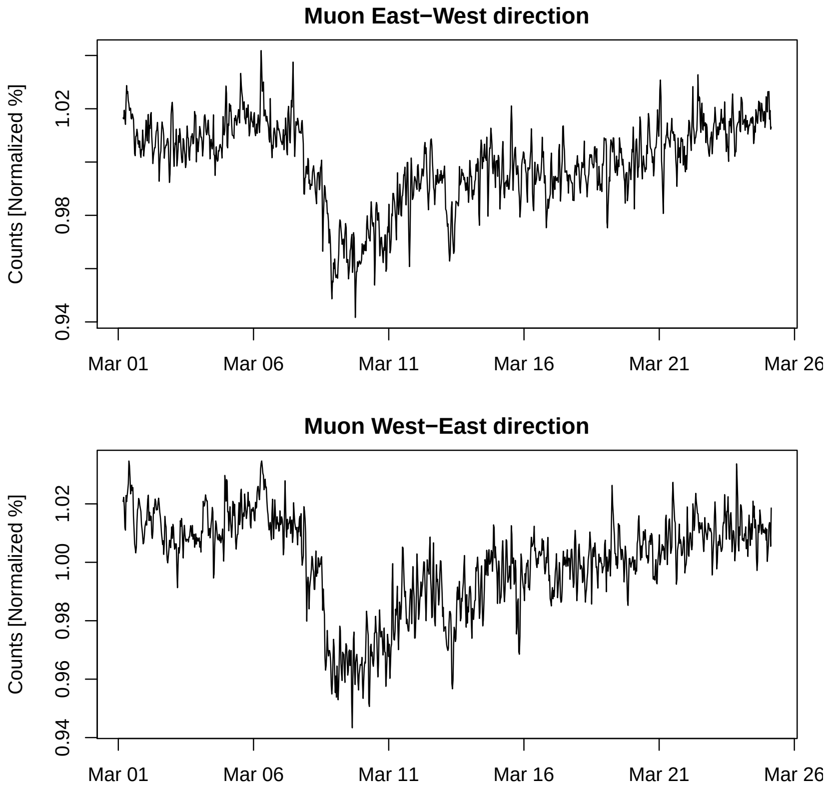

Fig. 5. 30 minute averages for East-West directed muon fluxes measured in Moussala. The data from muon telescope are for period 0000UTC until March 30 2359UTC

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