Доклади на Българската академия на науките
Comptes rendus de l'Académie bulgare des Sciences

Tome 66, No 5, 2013

PHYSIQUE

Physique expérimentale

DETECTION OF CORONAL MASS EJECTIONS (CMEs) IN THE PERIOD OF MARCH–MAY 2012 AT MOUSSALA PEAK

Assen Tchorbadjieff*, Christo Angelov*, Ivo Angelov*,, Todor Arsov*, Ivo Kalapov*, Nina Nikolova*, Aneta Boyadjieva***

(*Submitted by Corresponding Member J. Stamenov on January 16, 2013*)

Abstract

A large number of geoeffective solar events were registered during the period of March–May 2012. The events were detected as Forbush effects due to Coronal Mass Ejections (CME) occurring in March–April 2012 and a rare Ground Level Enhancement (GLE) in May, produced by region NOAA 1476 moderately strong (GOES class M5.1) flare at 01:25 UT on 17 May 2012 [1]. The data from permanently operational Cherenkov-water telescope of Basic Environmental Observatory at Moussala are used for observation of those activities. The magnetic IMF disturbances and resulting Forbush decreases were registered with high level of confidence. However, the GLE event detection was not confirmed statistically. The inter-comparison between detector responses of those events is used for preliminary study of the future space weather investigations in the Basic Environmental Observatory at Moussala.

Key words: GLE, Forbush decrease, cosmic rays

Introduction. The 24th turn of solar cycle is close to its maximum in 2012 and very strong but rare solar storms are expected. The data for secondary cosmic ray fluxes, measured in the period of March–May, correspond with this prediction. Many geoeffective solar flares were associated with Earth-directed coronal mass ejections (CMEs) during the whole three-month period. The disturbances in the interplanetary magnetic field produced at this time were two consecutive Forbush events between March 8th and 13th and another two in April 2012. The most striking event was the Ground Level Enhancement registered by neutron monitor networks.

The detected Forbush decrease (FD) events are observed as density and anisotropy variation of galactic cosmic rays intensity due to disturbances in the interplanetary magnetic field (IMF) [2]. There are two types of FD according to their magnitude and origin – recurrent and non-recurrent. When FD has slow and time-dependent symmetric trend, it is assumed as recurrent. This effect is supposed to follow co-rotating high speed solar wind fluxes [2]. The non-recurrent FD is a consequence of interplanetary events short in time, caused by solar flare. The trend is sudden and sharp for less than a day, then slowly restores to normal values. Conversely, the Ground Level Enhancements (GLEs) of solar cosmic rays are the solar particle flux event caused by solar flare and could be registered by ground-based detectors as sharp increases of short duration at the cosmic ray flux intensity rates.

The differences between solar events particle accelerating mechanism that cause FD and GLE are not confirmed yet. But GLEs are quite rare events and fewer than 100 events have been observed in the last 70 years, since instruments were first able to detect them. Moreover, the event detected on May 17th was the first GLE of the current 24th solar cycle, which is of great importance for space weather study.

The March–April events were clearly registered with the muon telescope at BEO Moussala. However, the muon flux measurements during GLE were less sensitive in comparison with neutron monitors. Because of this, the detection of GLE on May 17th could not be confirmed by muon data from Moussala.

Measurements. The muon telescope measures intensity flux (IF) of the hard charged component separated in directional positions – vertical, South–North, North–South, West–East and East–West in 15 s interval. The primary nucleon energy threshold was estimated about ~ 0.5 GeV. It was specially developed and constructed for BEO Moussala observatory of the Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences. The continuous measurements began in August 2006 [3]. The telescope is constructed with 8 water Cherenkov detectors connecting 12 coincidence channels. Each of the detectors includes a mirror tank with distilled water and photomultiplier with preamplifier mounted at its housing. The dimensions of the detectors are $50 \times 50 \times 12.5$ cm, and the distilled water layer used as radiator is 10 cm. When a cosmic ray muon passes through the radiator, Cherenkov light is generated if the energy of the muon is high enough so that its speed is greater than the speed of the light in the water. Part of the Cherenkov photons reach the photocathode of the photomultiplier after multiple reflections from the mirror walls of the container.

The raw data used for research is uninterrupted time series in intervals of 15 s for different direction coincidences. The raw measurements data are available at real time and stored in specifically dedicated data server. In addition, the control of data quality is established for data verification before final data set is performed. The muon telescope produces operational control meta-data in parallel with raw measurements. Assuming any operational problems, the corresponding measurements are removed from operational data set.

In the next step, the muon data records undergo filtering for data with severe stochastic errors. This procedure removes all outliers outside the 3-sigma intervals for time series $\{y_1, y_2, \dots, y_n\}$, where n is consecutive in time index. The filtering is performed within time frames of 1 h. The statistical effect is lower data deviations with trade-off of data removal in theoretical estimation of removal of 4 records for 3 h measurements for muon data.

The data are atmosphere corrected with 10 min data series of atmosphere pressure measurements. The coefficients are calculated over all data except these during the space weather disturbances. For correction is used General Linear Models (GLM) [4]. In proposed GLM model it is assumed that every dependent variable y is generated from a particular distribution in the nonlinear family. Then the expected value $\mathrm{E}[y]$ and variation $\mathrm{Var}[y]$ are dependent on link function $g(\beta X)$ of linear predictors βX, where X is a matrix of atmosphere parameters with corresponding vector β of regression coefficient. The mean and variation for nonlinearly distributed data are optimized with solutions with scale parameter γ and $p > 0$

$$\mathrm{E}[y] = \mu = g(\beta X)^{-1}, \tag{1}$$

$$\mathrm{Var}[y] = \gamma \mu^p. \tag{2}$$

Finally, the data fluctuation and trend are fitted by 3 min two-side exponential smoothing. The newly estimated values show trend in solar events produced by weighed in time period distance $t = \tau$ with coefficients λ

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

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

With selected $\alpha = 1/3$, higher weight of the values closest in time is set.

Finally, the computed data are normalized for the whole period and the results are shown with relative values compared to mean value equal to 1. The assumption for event detection is based on values enclosed in 3-sigma error intervals. The results in the next texts are shown in type normalized value with upper and lower limit value.

Results. The first geoeffective solar flare during this period is NOAA type X1/2b and it was detected by satellites on March 5th, at 0409 UTC. The time of arrival to the earth is 0427 UTC on March 7th, 2012, with Geomagnetic Sudden Impulse (SI) with 20 nT at higher altitudes [1]. The event was detected as particles IF decrease, magnitude was very weak and outside statistical acceptance. The particle intensity flux (IF) was with higher decrease in vertical muons IF to 0.9727 (± 0.011). Those results do not confirm detection of FD event, but arrival of X5/3b flare two days later caused the largest FD for the whole two-month period. The flare was detected on March 7th at 0024 UTC. The CME arrived at the Earth on March 8th with Sudden Impulse (SI) that caused quiet to minor storm up to 59 nT at 1105 UTC. Activity increased from quiet to severe storm on March 9th due to Southward IMF Bz combined with increased Bt [1]. The SI impact on particle flux caused large FD event supposed as non-recurrent. The FD event began at Moussala at about 1130 UTC with IF of $0.992 \pm 0.0113\%$ for vertical muons. Then it lowered at 2231 UTC on the same day to 0.938 ± 0.0107 for vertical muons. The event persisted during the next day with number of IF value variations prolonged unusually long, caused probably by persisting storm.

The Earth-directed M8 class solar flare erupted on March 10th 1744 UTC. That CME reached the Earth on March 12th midday as sudden impulse of 96 nT. During the event the solar wind speed reached 775 km/s and IMF 28 nT [1]. This produced another weak FD event very short after the previous one due to those IMF storms. The measured particles began to decrease slowly about late March 12th evening and persisted until midday on the next day. The extreme attenuation was measured at 13/0138 UTC for Muon. The particle IFs were 0.9693 ± 0.011 for vertical muons. The magnitude of decrease was smaller compared to previous FD event (less than 3% in max amplitude) and trend was symmetric in decrease and followed increase. This FD was very short in time and lasted for less than 12 h. After that, the particles IF was elevated until the end of the month, except the end of March 15th, when brief Earth effective CME with sudden shock of 27 nT and wind speed up to 800 km/s were observed. This coincides with the very small decrease detected with BEO equipment, but beyond the statistical acceptance. The extreme values are $0.9816 \pm 0.011\%$ at 2139 UTC for vertical muons. The large time differences are another reason to deny the existence of FD event.

During the next weeks, the solar activity was relatively calm and produced few flares were not Earth directed. But FD event was detected on April 5th, after available active period due to sustained Southward Bz between 0900 UTC–1200 UTC [1]. The decrease began in the late afternoon of April 5th and prolonged until the early hours of April 7th. The trend was weak, symmetric with slow increase in the middle of the period. The lowest record for muons IF was registered at 2255 UTC on April 5th, with the value of 0.9789 ± 0.011. This FD is confirmed with directional measurements. For example, the NS-directed particle IF decrease is even deeper with values to 0.9707 ± 0.015 detected an hour before vertical-directed particles. The main reason for this asynchronous in time detection of lower value is longer interaction path with atmosphere of NS-directed particles.

The last FD is detected on April 25th, 2012. The event is due to arrival of C class CME, erupting on April 19th. The first event was detected by ACE spacecraft on 23/0200 UTC. The activity reached major storm levels at midlatitudes after arrival of coronal hole high speed stream (CH HSS) at 24/0200 UTC. On April 25th high latitude activity reached severe storm level and speed stream peaked to 777 km/s. Then the activity started steady decline [1]. The FD began in about the afternoon hours of 24th and coincided with the highest activity levels and persisted until late April 27th. The FD event was recurrent with symmetric trend. The amplitude of decrease was about 4%. The lowest point of vertical muons IF was registered at 26/0350 UTC with 0.9612 ± 0.0109. The event was confirmed with directional measurements too. The graphical representation for the whole period measurement data for vertical and East–West and West-East anisotropy directions is shown in Fig. 1.

The solar activity was very low at the beginning of May. There were only three weak CMEs without geoeffective impact. The solar activity ranged from low to moderate level on May 7th. The main Earth-directed activities were in region 1476. A large number C, M and optical flares was registered. The number exceeded 55 of class C and 6 of M. However, Earth-directed flares were weak and thus their impact on Earth was not significant. The only significant impact was Soutward Bz that began on May 8th at 1730 UTC and reached minimum at -13 nT. Afterwards, the magnetic field was active in high latitudes with decrease until 10th. Weak impact from not directly Earth-directed CME with speed of 500 km/s was also detected on May 13th. Those solar events were weaker compared to those in the period of March–April. Therefore, they did not produce any significant impact on regular particle intensities on the ground.

Region 1476 was less productive in the next days. It mainly produced 13 C-class flares and one M-class flare. But the M5/1f flare on 17/0147 UTC was geo-effective and produced large proton flux at geosynchronous orbit. Two radio sweeps and a radio burst were also produced almost simultaneously with the flare. The CME was detected at first by SOHO/LASCO C3 spacecraft at 17/0206 UTC with approximated speed of 1200 km/s. It was estimated that flare reached the Earth after about 20 min.

The Earth magnetic field was quiet when M5/1f flare arrived on earth orbit. But the particles in CME flux were very fast and energetic. The proton flux greater than 10 MeV began to rise at 17/0210, reached the peak (255 pfu) at 17/0430 and ended at 18/1620. The proton event greater than 100 MeV began at 17/0200 UTC, reached its maximum of 20 pfu at 17/0230 UTC and ended at 17/1725 UTC [1].

The GLE event was not statistically confirmed by muon telescope data from BEO Moussala. The shock arrival was registered with weak particle flux intensity increase in between 0200–0230 UTC, in synchronization with satellite data. But the magnitude of this increase was about 1.5%, and it was inside statistical error. The trend remained with higher intensity until midday, but the level was also only about 1% higher than the closest days and it was not enough for any statistical significance.

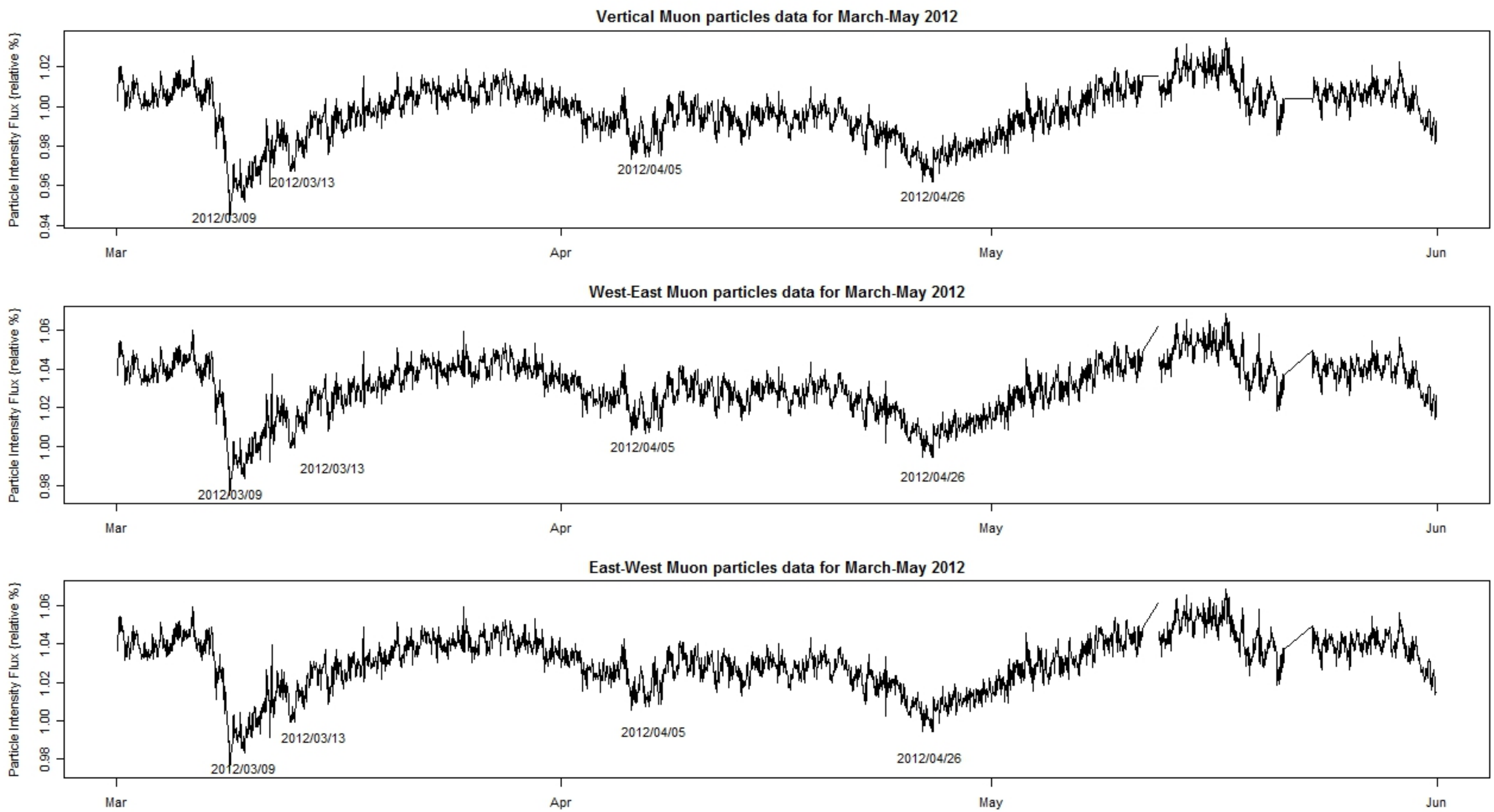

Fig. 1. Muon particle intensity flux 2012 in three directions – vertical, West–East and East–West for the period of March–May 2012. The observed FD events are shown with the text of the event date

The most likely explanation for those results is the nature of the particle processes in atmosphere. As flare is moving away from the Sun, the particles with the highest energy are moving in front of CME accelerated by shock mechanism. Thus the CME advance consists of solar energetic particles (SEP) from the ones with higher relativistic energy due to shock front [6]. When proton flux of particles with relativistic velocity enters the Earth atmosphere, they produce large showers. The protons undergo interactions with the atmosphere and produce secondaries, mainly mesons. The most commonly produced particles are pions, which occur in all three charge states – π^0, π^+, π^-. Afterwards, due to pion decay muons are produced in higher atmosphere. The probability of survival depends on primary nucleon energy, traversed path and its pitch angle of scattering through the atmosphere. Thus when SEP arrives, the secondary particle flux arises sharply. However, the probability for ground detection is atmosphere dependent because muons are significantly dependent on atmosphere perturbations. As Moussala observatory is located at 2925 m.a.s.l., 22.35E, 42.11N, with rigidity cutoff of 6.3 GEV, the flux is significantly moderated. Therefore, this is the most likely explanation for the less sensitive response of BEO muon telescope for primary particle intensity increases and leads to the conclusion that the weak proton events with NOAA classification different from X are not very likely to be confirmed. But the muon telescope produced very reliable results for detection of the magnetic disturbances caused by IMF and Soutward BZ and resulting in a galactic particles cutoff.

Conclusions. The obtained muon flux intensities are based on water Cherenkov muon telescope data registered for a period of 3 months at BEO Moussala. This period is a relatively short part of the whole 11-year-long cycle but very intense for the geoeffective solar activities. The obtained results and their comparison and joint analysis with satellite data give an excellent proof for the reliability of water Cherenkov light muon telescope of BEO Moussala for the investigation of solar-caused interplanetary disturbances and their impact on galactic cosmic rays reachinf the Earth. The obtained results could establish a good basis for investigation of the solar wind properties.

REFERENCES

[1] NOAA Space Weather, `http://www.swpc.noaa.gov/`

[2] Cane H. V. Space Science Rev., **10**, 2000, 41–62.

[3] Angelov I., E. Malamova, J. Stamenov. Sun and Geosphere, **3**, 2008, No 1, 20–25.

[4] Frees E. W. Regression Modeling with Actuarial and Financial Applications, Cambridge University Press, 2010, 362–383.

[5] Vashenyuk E. V., Y. V. Balabin, B. B. Gvozdevsky. In: Proc. 21st ecrs Kosice, Slovakia, 9–12 September, 2008.

[6] Gopalswamy N., H. Xie, S. Yashiro, S. Akiyama, P. Mäkelä, I. G. Usoskin. Properties of Ground Level Enhancement Events and the Associated Solar Eruptions during Solar Cycle 23, `arXiv:1205.0688`.

*Institute of Nuclear Research
and Nuclear Energy
Bulgarian Academy of Sciences
1784 Sofia, Bulgaria
e-mail: `assen@inrne.bas.bg`

**South-West University "Neofit Rilski"
66, Ivan Mihaylov Str.
2700 Blagoevgrad, Bulgaria