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Analysis of cosmic ray variations observed by the CARPET in association with solar flares in 2011-2012

V Makhmutov[1,2], J-P Raulin[2], R R S De Mendonca[3], G A Bazilevskaya[1], E Correia[2,3], P Kaufmann[2], A Marun[4], G Fernandez[4] and E Echer[3]

[1] Lebedev Physical Institute RAS, Moscow, Russia
[2] Universidade Presbiteriana Mackenzie, EE, CRAAM, Sao Paulo, Brazil
[3] National Institute for Space Research, INPE, Brazil
[4] Complejo Astronmico el Leoncito, CASLEO, Argentina

E-mail: makhmutv@sci.lebedev.ru

Abstract. The CARPET cosmic ray detector was installed on April 2006 at CASLEO (Complejo Astronmico El Leoncito) at the Argentinean Andes (31.8S, 69.3W, 2550 m, Rc=9.65 GV). This instrument was developed within an international cooperation between the Lebedev Physical Institute RAS (LPI; Russia), the Centro de Radio Astronomia e Astrofsica Mackenzie (CRAAM; Brazil) and the Complejo Astronmico el Leoncito (CASLEO; Argentina). In this paper we present results of analysis of cosmic ray variations recorded by the CARPET during increased solar flare activity in 2011-2012. Available solar and interplanetary medium observational data obtained onboard GOES, FERMI, ISS, as well as cosmic ray measurements by ground-based neutron monitor network were also used in the present analysis.

1. Introduction

The CARPET cosmic ray detector was installed on April 2006 at Complejo Astronomico El Leoncito (CASLEO) in the Argentinean Andes at an altitude of 2550 m (31.8S, 69.3W). The CARPET instrument (based on 240 Geiger tubes) was developed within an international cooperation between the CRAAM, the CASLEO and the LPI RAS [1]. Description of the CARPET cosmic ray detector is reported in [1,2]. Its main features are:

(1) the CARPET records include 3 channels data with 0.5 s time resolution. The UP and LOW channels data are records of the total fluxes of >200 keV electrons and positrons, >5 MeV protons, >1.5 MeV muons and >20 keV γ-rays (the latter with an efficiency <1 %). The telescope channel (TEL) counts number of particles crossing through both UP and LOW layers of counters: >5 MeV electrons, >30 MeV protons and >15.5 MeV muons.

(2) in contrast to the Neutron Monitor (NM) mesurements our detector is sensitive to the low energy secondary component of cosmic rays produced by primary galactic or solar cosmic ray flux in the Earth's atmosphere.

To calculate vertical geomagnetic cutoff rigidity (Rc) at the CARPET location we used a method proposed by Nymmik et al. [3]. We obtained Rc=9.65 GV for quiet geomagnetic conditions and Rc=9.0 GV during geomagnetic disturbances (for Kp=4).

During over six years of observations a large number of cosmic ray variations related to rain precipitations and surface atmospheric electric field changes were recorded [1,2]. In previous studies atmospheric effects in the CARPET detector records were analyzed. As a result the barometric and temperature correction coefficients were estimated [2].

Solar flare activity has increased in 2010-2012 which corresponds to the rising phase of the 24th solar activity cycle. Several significant solar flares were detected during this period, which produced 11 Solar Energetic Particle events detected onboard GOES satellites [4]. Only one GLE was observed in the current solar cycle (17 May 2012).

In this paper we discuss the results of the analysis of cosmic ray variations observed by the CARPET detector on March 2011 and on January 2012. We concentrate on the possible solar flare effects observed by the CARPET on 7 March, 2011 and on 23 January, 2012.

2. Experimental data and discussion

2.1. Solar flare on 7 March 2011

The solar proton event on 7 March 2011 was associated with a M3.7 flare from active region NOAA 11164 located at N23W50 [4]. Figure 1 shows several dynamic features of this event. Panel A and B compare cosmic ray records in TEL channel of the CARPET and >50 MeV proton flux variations observed onboard GOES-13. High-energy solar neutron bursts were also recorded by NEM-FIB detector onboard International Space Station (ISS), and their arrival time distribution is shown in panel C [6]. Panel D shows 12-25 keV X-ray solar bursts recorded by FERMI-GBM monitor and 100-300 keV X-ray solar burst observed by RHESSI [4,7]. Triangles show Start-Maximum-End time of the bursts originated from NOAA 11164. Heights of triangles correspond to the logarithm of total counts detected during these bursts. And finally, the solar 0.5-4 Å X-ray flux recorded on board GOES-13 is presented on panel E [4].

From the analysis of available experimental data which are presented in Figure 1 we point out that:

(1) the solar flare 0.5-4Å X-ray emission on 7 March 2011 started at 19:40 UT and reached its peak flux around 20:12 UT (panel E). During this time few hard X-ray bursts were also detected by the Fermi-GBM and RHESSI instruments (panel D). Finally, long-lasting >100 MeV γ-ray emission was observed for more than 12 hours [8]. Appearance of energetic solar neutrons was detected around maximum of X-ray emission (panel C). This is a direct indication of the presence of high-energy solar protons at the flare site. Some of these protons can interact within solar atmosphere producing neutrons, while other protons can be ejected into interplanetary space and detected by available cosmic ray instruments in space and at ground level.

(2) the CARPET's count incerase in TEL channel was observed during $\sim$20:10-21:40 UT at a statistically significant level of 3-10 r.m.s. Also, we point out that simultaneously statistically significant increase of counts was detected in UP and LOW channels of the CARPET.

(3) the GOES-13 records only show an increase of proton flux in low energy channels (<100 MeV), which starts on $\sim$21:30 UT. Evidently, there is a delay in arrival time of these low energy protons in comparison to high-energy protons detected by the CARPET after $\sim$20:10 UT.

Bearing in mind that geomagnetic cutoff rigidity at the CARPET location is Rc=9.6 GV it means that the observed CARPET count rate increases may be produced by cascade of secondary particles originated from high-energy solar protons (E$\geq$9 GeV) in the Earth‘s atmosphere. We understand that this hypothesis needs a careful and accurate verification, i.e. estimation of possible proton fluxes, energy spectra and expected response of the CARPET and NMs.

4) we note, by using the NM Data Base facilities (NMDB, [9]), that the network records on 7 March 2011 do not show any clear increase associated with the present flare. No ground based NM increase (GLE) was reported yet in association to this solar flare [5].

2.2. Solar flare on 23 January 2012

This event was associated with a M8.7 solar flare which started at $\sim$03:30 UT on 23 January 2012 in active region NOAA 11402 (N28W20).

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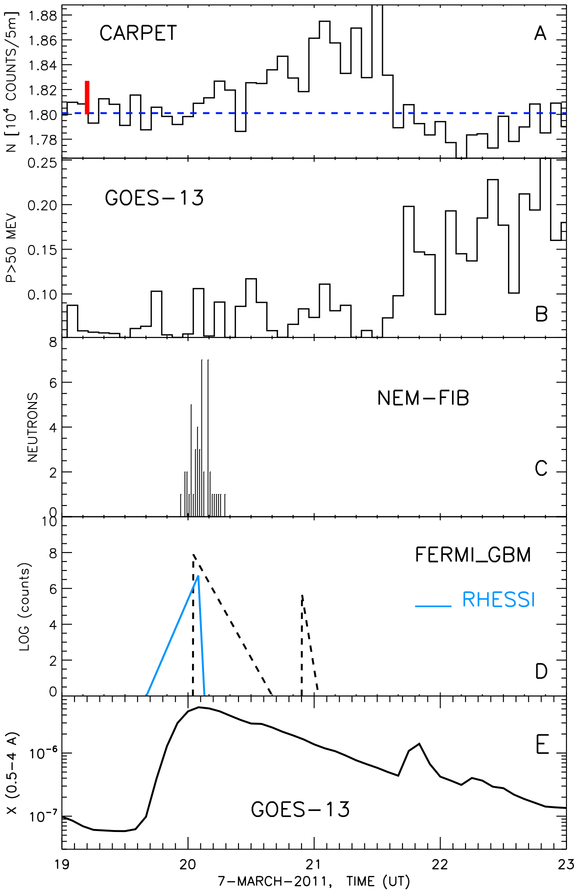

Figure 1. Solar flare event on March 7, 2011. Panel A: 5 min TEL channel records of the CARPET. Vertical red bar at left shows 3 r.m.s of the data during preflare period (19-20 UT). B: time profile of $>$ 50 MeV proton flux (p/cm^2·s·sr) as recorded onboard GOES-13 [4]. C: solar neutron observations by NEM-FIB detector onboard ISS [6]; D: FERMI-GBM (12-25 keV) and RHESSI (100-300 keV) solar burst observations [7]. E: solar X-ray flux (W/m^2) recorded on board GOES-13 [4].

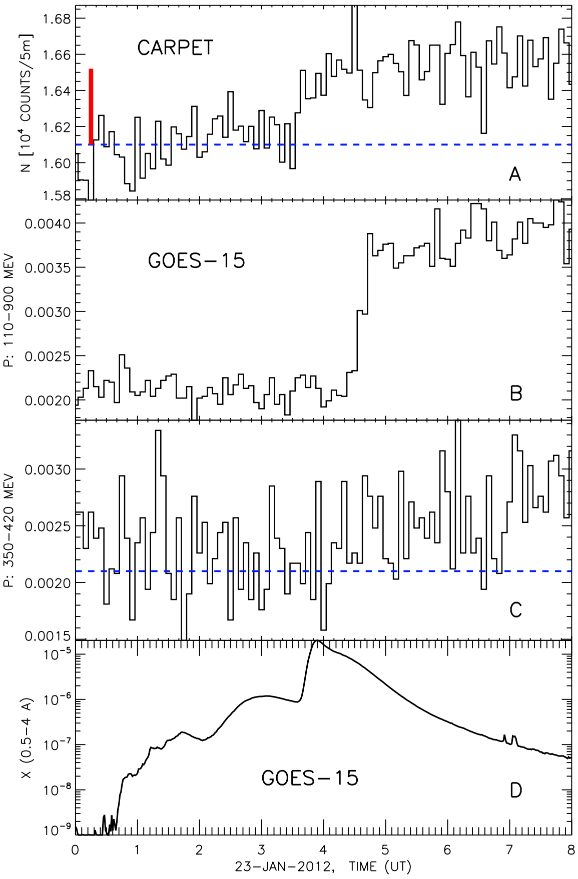

Figure 2. Solar flare event on January 23, 2012. Panel A: 5 min TEL channel records of the CARPET. Vertical red bar at left shows 3 r.m.s of the data during preflare period 0-3 UT. Panel B and C: time profiles of proton flux (p/cm^2·s·sr·MeV) in energy channels 110-900 MeV and 350-420 MeV, recorded onboard GOES-15 [4]. Panel D presents X-ray solar flux (W/m^2) variations detected onboard GOES-15 [4].

Figure 2 presents several experimental time profiles for the 23 January 2012 event. Panel A shows 5 min cosmic ray records in TEL channel of the CARPET. We note a very significant increase (∼3-7 r.m.s) of TEL counts between 03:40 and 08:00 UT. Panel B and C show 110-900 MeV and 350-420 MeV proton flux variations observed by GOES-15. Also, the Fermi-LAT instrument, detected increased γ-ray emission (E>100 MeV) from the Sun between 00:00 UT and 18:37 UT [10].

This event was recorded in 8 particle channels (energy range E=15-900 MeV) by GOES-15 sensors. Then we can estimate a solar proton energy spectrum between 5 and 8 UT with a power law form as J(E)= $3{\cdot}10^7{\cdot}E^{-3.9}(p/(cm^2{\cdot}s{\cdot}sr{\cdot}MeV))$ (1) in the 100-900 MeV energy range. To evaluate the expected flux of secondaries at the CARPET device location, we have simulated solar proton transport through the Earth's atmosphere. The simalations were based on PLANETOCOSMICS/Geant4 code [11-13]. In the present simulations we used the spectral form (1), extended up to 15 GeV, as the first iteration step. Finally, we deduced a proton spectrum at the top of the Earth's atmosphere as J(E)=$1.5 \cdot 10^4 \cdot E^{-2.7\pm0.5}(p/(cm^2 \cdot s \cdot sr \cdot MeV))$ in the energy range 9-15 GeV, which fits well the increase detected by the CARPET. This spectrum is unusually hard for this energy range and may be indicative of special conditions in the acceleration region.

3. Summary

As a peliminary result of the analysis of the CARPET cosmic ray detector records on March, 2011 and January, 2012, we conclude: (1) statistically significant increases were detected during ~20:10-21:30 UT on 7 March 2011 and during ~03:30-08:00 UT on 23 January 2012. (2) these increases are indications of the long-lasting presence of high-energy solar protons (E$\geq$9 GeV) with unusually hard spectrum entering into the Earth's atmosphere. Independent results of the analysis of VLF propagation characterstics data and riometer records during these events support this conclusion (see paper [14] for details).

The observed CARPET excesses are therefore indicative of high-energy processes occurring on the Sun in magnetized environment, initiated by energetic protons, and producing subsequent products as high-energy electrons, positrons, pions and photons. Therefore, comparison with the Submillimeter Solar Telescope (SST) records at 212 and 405 GHz during solar flares, will be crucial to better understand these processes. Unfortunately, during the 07 March 2011 and 23 January 2012 solar events, no SST data are available because of calibration tasks and nighttime hours, respectively.

Finally, we note that a more careful analysis of the NMDB records is needed in order to get a final conclusion on the presence or not of solar flare effects in the form of GLEs during these events.

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