Solar proton event on January 23, 2012

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Abstract: In this paper we focus on the signature of the solar proton event on January 23, 2012, as observed with the CARPET (KOVER) cosmic ray detector. This instrument was developed within an international cooperation between the Lebedev Physical Institute RAS (LPI; Russia), the Centro de Radio Astronomia e Astrofisica Mackenzie (CRAAM; Brazil) and the Complejo Astronomico el Leoncito (CASLEO; Argentina). The CARPET (KOVER) cosmic ray detector was installed on April 2006 at CASLEO at the Argentinean Andes (31.8S, 69.3W, h=2550 m, Rc=9.65 GV). We have analyzed cosmic ray variations observed by the GOES satellite instruments and by ground-based neutron monitor network (NMDB) during this event, as well as available solar and interplanetary medium observational data. We present and discuss the low ionosphere behavior under the impact of solar flare that occurred on January 23, 2012 and was followed by solar particles event. The ionosphere response to this solar phenomenon was detected using riometers (30 and 38.2 MHz) and VLF systems operating at the Comandante Ferraz Brazilian Station in Antarctica and at the Itapetinga Radio Observatory in São Paulo (Brazil). The results show that the low ionosphere was affected by this solar particles event, as evidenced by absorption observed in the cosmic noise and very low frequencies amplitude variation.

Keywords: solar flare, solar proton event, energy spectra, cosmic noise absorption, riometer, VLF propagation.

1 Introduction

In this paper we discuss the results of the analysis of cosmic ray variations observed by the CARPET (KOVER) cosmic ray detector on January 23, 2012. We concentrate on the possible solar flare effects observed by the CARPET on 23 January, 2012. This instrument was developed within an international cooperation between the Lebedev Physical Institute RAS (LPI; Russia), the Centro de Radio Astronomia e Astrofisica Mackenzie (CRAAM; Brazil) and the Complejo Astronomico el Leoncito (CASLEO; Argentina). The CARPET (KOVER) cosmic ray detector was installed in April 2006 at CASLEO at the Argentinean Andes (31.8S, 69.3W, 2550 m, Rc=9.65 GV). The CARPET records include data of 3 channels 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 X-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 [1-3]. In contrast to the Neutron Monitor (NM) measurements 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. During solar proton events (SPEs), high-energy particles can penetrate deep in the Earth's atmosphere, depending on the local vertical geomagnetic cutoff rigidity [4]. Particles with energies of several MeV can reach top of the atmosphere only at higher (polar) latitudes, while the few GeV particles can do it even at mid-latitude and equatorial region. Effects of solar proton events (SPEs) in the lower ionosphere at the polar region have been detected using riometers [5-8], as well as very low frequency (VLF) radio signals receivers [9-12]. During a SPE there is a lowering of the effective height of the low ionosphere due to the enhanced ionization at lower altitudes. The changes in ionization affect the radio wave propagation, which can be detected as absorption of the cosmic noise by riometers, and as amplitude and phase variations of VLF signals. The protons during SPEs can penetrate to lower altitudes and affect the lower D-region boundary [13].

In this study we evaluate the lower ionosphere behavior under the impact of energetic protons produced during SPE that occurred on 23 January 2012. The ionosphere behaviour is estimated from the measurements of the cosmic noise absorption (CNA) provided by riometers operating at Comandante Ferraz Brazilian Antarctic Station (EACF, 62.1S, 58.3W, Rc$\approx$2 GV) and at Itapetinga Radio Observatory (ROI; coordinates 23.2S, 46.6W, Rc$\approx$10 GV), São Paulo (Brazil). We also use VLF signals record from transmitter in Hawaii (NPM; 21.4N, 158.2W, 21.4 kHz, Rc$\approx$13 GV) and received at EACF and ROI stations.

2 Solar flare on 23 January 2012

Three successive (and partially overlapping in time) solar flares (C2.5/SF, M1.1/1N and M8.7) have occurred in active region NOAA 11402 (located at $\sim$N25W20) on January 23, 2012 [14]. The bottom panel of Fig. 1 shows the time profile of the GOES X-ray solar emission (0.5-4 Å band) during 00-08 UT time interval on 23 January, 2012. Maximum phase of the first flare (C2.5) was observed around 01:50 UT, for the second flare (M1.1)- around 03:15 UT and the third one peaked around $\sim$03:59 UT.

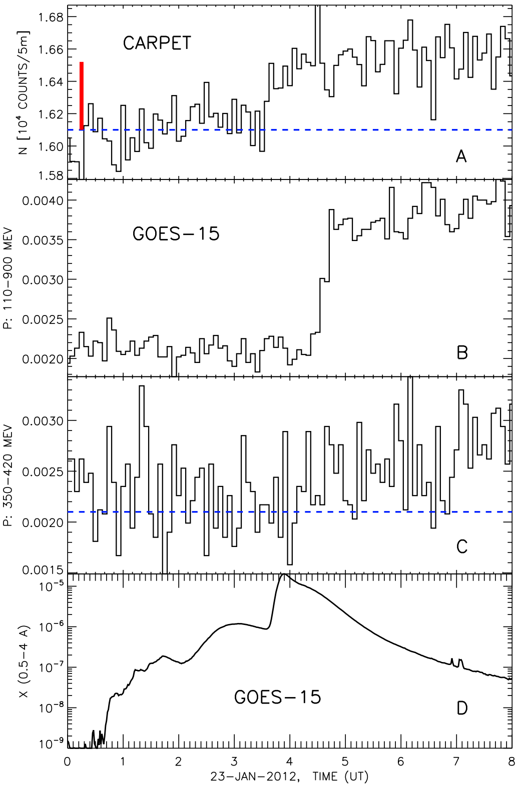

Figure 1: Solar particle event on January 23, 2012. Panel A: 5 min TEL channel records of the CARPET cosmic ray detector [3]. Vertical red bar at left shows 3 r.m.s of the data during preflare period 0-3 UT. Panel B and C: time profiles of proton flux (p/cm^2·s·sr·MeV) in energy channels 110-900 MeV and 350-420 MeV, recorded onboard GOES-15 [14]. Panel D presents X-ray solar flux (W/m^2) variations detected onboard GOES-15 [14].

Last event was associated with a M8.7 solar flare which started at ~03:30 UT on 23 January 2012 in active region NOAA 11402. The M1.1 and M8.7 flares were associated with two fast Coronal Mass Ejections.

Also we note,

- the Fermi-LAT (Large Area Telescope) instrument detected increased gamma-ray emission (E>100 MeV) from the Sun between 00 UT and 19 UT on January 23, 2012 [15]. This indicates a gradual phase of the high-energy processes in the solar flare.

- the FIB detector on board the International Space Station observed solar neutron event on January 23, 2012 associated with the M8.7 solar flare [16].

- the solar charge particle flux $<$ 1 GeV was recorded by PAMELA instruments after 08 UT on 23 January 2012 UT [17].

2.1 CARPET observations

Figure 1 presents several experimental time profiles for the solar flare event on 23 January 2012. Panel A shows 5 min cosmic ray records in TEL channel of the CARPET. Using results presented in paper [18] the CARPET data were corrected by pressure and temperature variations. We note a significant increase (~3-7 r.m.s) of TEL counts between 03:40 and 08:00 UT. Panels B and C show 110-900 MeV and 350-420 MeV proton flux variations observed by GOES-15 [14], respectively. This event was recorded in 8 particle channels of the GOES-15 sensors (total energy range E=15-900 MeV). These experimental data allow to determine a solar proton energy spectrum with a power law form as

$$J(E) = 3{\cdot}10^7{\cdot}\mathrm{E}^{-3.9\pm0.3}(\mathrm{p}/(\mathrm{cm}^2{\cdot}\mathrm{s}{\cdot}\mathrm{sr}{\cdot}\mathrm{MeV}))\ (1)$$

in the 100-900 MeV energy range for time interval between 5 and 8 UT. To evaluate the expected flux of secondaries at the CARPET device location, we have simulated solar proton transport through the Earth's atmosphere as follow,

(a) the simulations were based on PLANETOCOSMICS/Geant4 code [19, 20].

(b) as a first step of iteration we used the spectral form (1) to determine the solar proton spectrum in the energy range from 9 GeV up to E_{max}.

(c) calculations were carried out for the set of E_{max} (15 GeV, 20 GeV and 30 GeV) and proton spectrum index γ=(-3.9) - (-1.5) range.

As a result of Geant4 simulations, we deduced an energy spectrum of solar protons at the top of the Earth‘s atmosphere as

$$J(E) = 1.5{\cdot}10^4{\cdot}\mathrm{E}^{-2.8\pm0.3}(\mathrm{p}/(\mathrm{cm}^2{\cdot}\mathrm{s}{\cdot}\mathrm{sr}{\cdot}\mathrm{MeV}))\ (2)$$

in the energy range 9-15 GeV. This spectrum of incident primary solar flare protons fits well the particle flux increase detected by the CARPET during the time period 05-06 UT on January 23, 2012.

To determine an expected relative count rate increase produced by these incident protons in the ground-based neutron monitor records, we have used a well-known equation,

$$N = \int_{Rc}^{Rmax} m(R,x)\cdot J(R)\cdot dR(3),$$

where N is a count rate of NM at selected geomagnetic location characterized by certain geomagnetic cuttoff rigidity Rc, m(R,x) is a specific yield functions for protons. J(R)

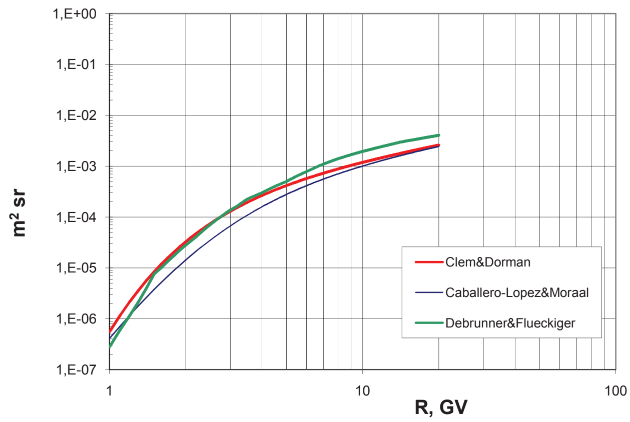

Figure 2: The specific yield functions presented in [21]. We used in calculations a set of m(R,x) determined in [22]
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is a rigidity spectrum of incident solar proton flux at the top of the atmosphere in the proton rigidity range from Rc up to Rmax. There are a few estimations of the m(R,x) and some of them are presented in Figure 2 [21]. We used the set of m(R,x) given in the paper [22] to estimate relative increases of NM counting rates caused by proton fluxes described by (1) and (2) with intermediate spectrum in between. Results of such calculations based on equation 3 are presented in Table 1.

Rc, GV	0.5	2.4	9.6
dN/N_b, %	5.5±0.5	4.5±0.5	1.6±0.5

Table 1: Expected increase of NM counts produced by the incident solar proton flux characterized by energy spectra in the form $J(E) = 3{\cdot}10^7{\cdot}E^{-3.9}$ for 5 - 900 MeV range, $J(E) = 1.6{\cdot}10^3{\cdot}E^{-2.5}$ for 0.9 - 9 GeV and $J(E) = 1.5{\cdot}10^4{\cdot}E^{-2.7}$ for 9 - 15 GeV energy range.

We have analysed the Neutron Monitors data (NMDB) [23] in order to determine a possible GLE effect in the NM records.

As a result of this analysis we note,

(1) "classical" impulsive GLE effect related to the M8.7 solar flare was not found in this dataset

(2) cosmic ray measurements by neutron monitors Irkutsk, Nain and Jungfrauoch (NM64) allow to suggest slow and small amplitude increase of NMs count rates during ~03:50-08 UT. Fig.3 (upper panel) shows a time profile of the dN/N_b (%) parameter determined as mean values for the records of NM Irkutsk, Nain and Jungfrauoch (NM64). Bottom panel of the Fig.3 presents the CARPET device count rate variations relative to the preflare background N_b. The values of N_b were calculated for each station for 0-3 UT time interval on 23 January 2012. Vertical red arrows are indications of onset time of the M8.7 solar flare in NOAA 11402 active region.

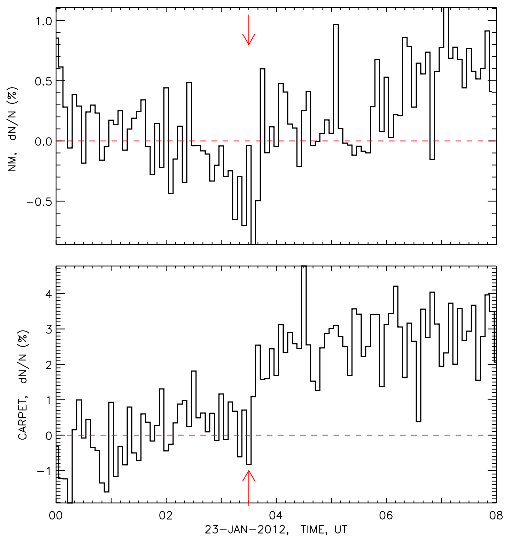

Figure 3: 5-min histograms of the dN/N % parameter determined as mean values from the measurements of NM Irkutsk, Nain and Jungfrauoch-NM64 (upper panel) and for the CARPET device records (bottom). The preflare count rate N_b was calculated for each station for 0-3 UT time interval on 23 January 2012. Vertical red arrows are indications of onset time of the M8.7 solar flare in NOAA 11402 active region.

2.2 Very low frequency and cosmic noise absorption records

As mentioned above, the SPE on January 23 followed a M8.7 GOES class solar flare originated in the active region NOAA 11402. The X-ray emission of the solar flare and the observed ionosphere behavior are shown in Fig. 4. Two lower panels of Fig.4 show the cosmic noise absorption at 30 and 38.2 MHz signals and VLF amplitude variations at EACF. This event started during the night hours at EACF (00:00 to 07:05 UT) and ROI (00:00 to 09:00 UT) [24] sites, which means that the CNA absorption was produced by an additional ionization, e.g. due to energetic solar protons. But the ionosphere behavior obtained from the VLF amplitude data includes the combined influence of X-ray radiation plus particle precipitation till 04:18 UT, the sunset time at NPM transmitter location. The CNA analysis shows that the SPE events affected the ionosphere at both observational sites but in a different way. At EACF the CNA started at ~3:00 UT at 38 MHz and almost one hour after at 30 MHz. The CNA reached the maximum absorption level at 10:00 UT, with 1.0 dB and 0.5 dB, at 38 and 30 MHz respectively. The CNA at 38 MHz also presents peaks of absorption at 03:30, 05:00 and 08:00 UT, the first one appeared almost one hour before the beginning of the >100 MeV proton event detected by GOES. At ROI, the CNA has the same time evolution from 03:00 to 10:00 UT, with the difference that the absorption was only present at 30 MHz, but at this site the CNA at 38 MHz only started at ~11:00 UT. Then afterwards the absorption shows a similar variation with the same attenuations at both frequencies suggesting a slow behavior similar to that one observed at EACF.

Significant ionospheric absorption effects were also suggested in the VLF amplitude analysis. But in this case, the amplitude variations till 04:18 UT are due to a combination of solar radiation and particle precipitation effects, where the amplitude increases occur in close association with the X-ray flux enhancements. The VLF amplitude shows a significant (>3σ) decrease from ~03:30 UT to ~10:00 UT at EACF and ROI ([24], not shown in Fig.4), as showed by the decrease of VLF amplitude compared with a quiet day curve. The amplitude decrease is clearly seen at NPM-EACF radio signal path, which maximum of ~10 dB is achieved at ~04:20 UT at EACF. At ROI the VLF amplitude decrease is ~5 dB [24].

3 Conclusions

As a preliminary result of the analysis of the CARPET cosmic ray detector records on 23 January 2012, we conclude:

(1) significant increase (3-7σ) of the CARPET count rate was detected during ~03:30-08:00 UT on 23 January 2012. We suggest this increases is the indication of the long-lasting presence of high-energy solar protons (E>9 GeV) entering the Earth's atmosphere.

(2) independent results of the analysis of VLF propagation data and riometer records during these events support this conclusion [24].

(3) the study of the low ionosphere behavior during the

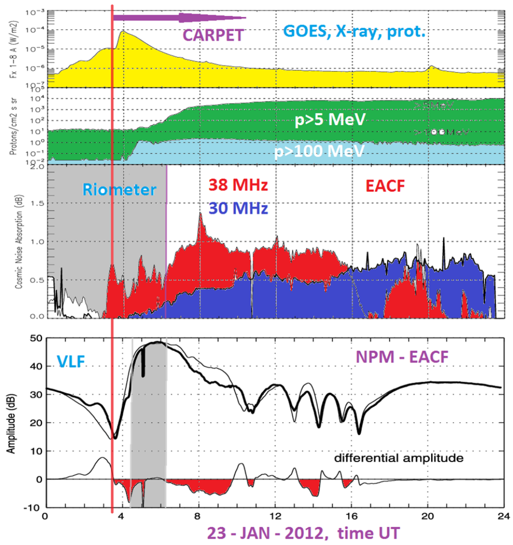

Figure 4: Solar flare event on January 23, 2012. From top to bottom: time profiles of solar X-ray (1-8 Å) and proton fluxes (>5 MeV and >100 MeV) observed by GOES. Middle: the CNA amplitude variations observed at EACF. Bottom: VLF amplitude variations observed at EACF.

SPEs that occurred on 23 January 2012, strongly suggests that it was disturbed by few GeV protons in Antarctica and at lower latitudes in the South America region.

(4) the ionospheric absorptions detected with the riometer and VLF propagation measurements done at two different sites with high geomagnetic cutoff rigidity is an evidence of >10 GeV protons penetrating into the Earth's atmosphere. The long-duration of the absorption effects on 23 January (from ∼03:30 to 10:00 UT) also suggests long-lasting presence of higher-energy protons in the Earth's atmosphere. This suggestion is supported by significant increases of cosmic rays detected with CARPET cosmic ray device. A similar case was observed early during the solar flare event detected by the CARPET instrument on March 7, 2011 [4].

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