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Cosmic Ray Variations Recorded by the CARPET Facility on March 7, 2011

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Abstract—The CARPET cosmic ray detector was installed in 2006 in the Argentinean Andes at an altitude of 2550 m at the El Leoncito Astronomical Complex (CASLEO) in San Juan, Argentina (S31.8, W69.3; R_c = 9.659.65 GV). This instrument was developed at the Lebedev Physical Institute (LPI) in Russia as part of an international collaboration between the LPI, Brazil's Mackenzie Center for Radioastronomy and Astrophysics (CRAAM), and the CASLEO. This work presents the results from analyzing variations in cosmic ray intensity recorded by the CARPET facility during the solar proton event of March 7, 2011. Also used in our analysis were the experimental data obtained by the GOES, FERMI, and ISS spacecraft during this solar event.

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INTRODUCTION

The CARPET cosmic ray detector was installed in the Argentinean Andes at an altitude of 2550 m at the El Leoncito Astronomical Complex (CASLEO) in San Juan, Argentina (S31.8, W69.3; R_c = 9.65 GV). This instrument was developed at the Lebedev Physical Institute (LPI) in Russia as part of an international collaboration between the LPI, the Mackenzie Center for Radioastronomy and Astrophysics (CRAAM; Sao Paulo, Brazil), and the CASLEO. A description of this instrument and its characteristics can be found in [1, 2] and briefly below:

The instrument consists of 240 gas-discharge Geiger counters (Type CTC-6) integrated in 24 blocks. Each block consists of 10 counters arranged in two groups of five counters each in two horizontal planes. The upper layer of counters is separated from the lower by a 7-mm thick aluminum absorber plate. Experimental data are read every 0.5 s by three channels: UP and LOW correspond to the total count of the charged particles (electrons and positrons with an energy of $E > 200$ keV, protons with $E > 5$ MeV, and muons with $E > 1.5$ MeV; also recorded are photons with $E >$ 20 keV at an efficiency below 1%) that penetrate all of the upper (UP) and lower (LOW) counters. Signals simultaneously recorded in the upper and lower counters of each block are summed in the coincidence channel (TEL) of the CARPET detector and correspond to more energetic particles: electrons with $E >$ 5 MeV, protons with $E > 30$ MeV, and muons with $E >$ 15.5 MeV.

As distinct from ground-based neutron monitors, the CARPET detector is sensitive to the low-energy charged secondary cosmic ray component produced by the primary galactic cosmic rays and the solar cosmic rays in the Earth's atmosphere.

Over a period of more than 6 years, the CARPET facility detected several substantial Forbush decreases of cosmic rays and more than 170 increases in the cosmic ray count associated with thunderstorm activity in the near-ground atmosphere [1, 2]. This work presents the results from cosmic ray observations made by the CARPET detector during the solar proton event of March 7, 2011.

OBSERVATIONAL DATA OF MARCH 7, 2011

The solar proton event of March 7, 2011, was associated with an M3.7 solar flare observed emerging from active region NOAA 1164 at N23, W50. Figure 1 presents the measurement data obtained by the three channels of the CARPET detector over the period of 18:00 to 23:00 UT on March 7, 2011. The count rate in all three channels (UP, LOW, and TEL; count rates N1, N2, and N12, respectively) can be seen to grow between 20:10 and 21:30 UT. The maximum increase in these channels was 5–6%. The vertical arrow in the bottom panel indicates the time of X-ray flare event onset (0.5–4 Å) from NOA 1164, recorded by the GOES-13 satellite at around 19:40 UT on March 7 [3].

Figure 2 presents individual experimental data obtained during this event. The X-ray flare event (0.5–

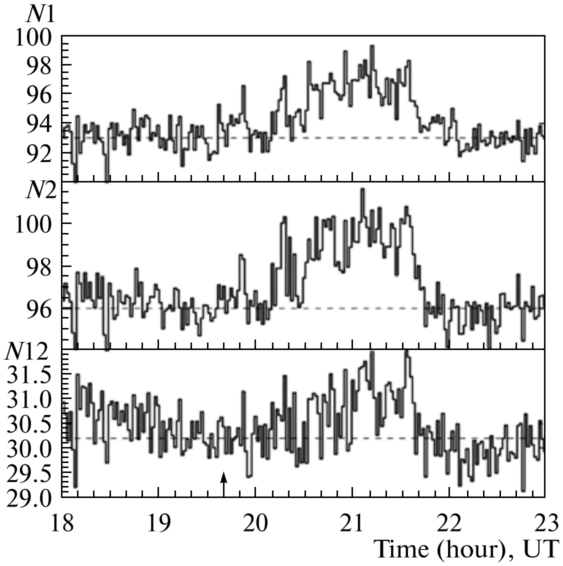

Fig. 1. Particle count rates in the three channels of the CARPET detector on March 7, 2011, between 18:00 and 23:00 UT. From top to bottom: channels UP, LOW, and TEL. Presented are the half-second particle count rates N1, N2, and N12 averaged over every 90 seconds. The count rate in all three channels can be seen to increase during the period from ~20:10 to ~21:30 UT. The vertical arrow in the bottom panel indicates the time of solar flare X-ray emission (0.5–4 Å) from the active region NOAA 1164 (on March 7 at ~19:40 UT), recorded aboard the GOES-13 satellite [3].

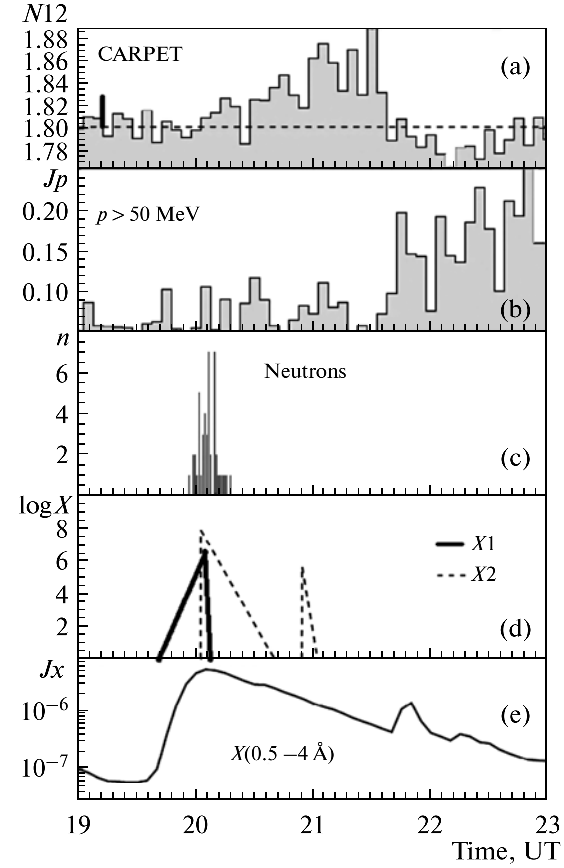

Fig. 2. Solar proton event of March 7, 2011. (a) Five-minute particle count rate in the TEL channel of the CARPET detector (N12 × 10^4). The vertical black line segment on the left corresponds to the 3σ error determined prior to the flare (19:00–20:00 UT). (b) Intensity of the flux of protons with $E > 50$ MeV (Jp, $cm^{-2} s^{-1} sr^{-1}$) according to the measurement data obtained aboard the GOES-13 satellite [3]. (c) Observations of solar neutrons by the NEM-FIB instrument aboard the ISS [6]. (d) Data on the solar X-ray flux records made aboard the FERMI (GBM: X2, 12–25 keV) and RHESSI (X1, 100–300 keV) spacecraft. (e) Variation in the solar X-ray flux (0.5–4Å; Jx, W m^{-2}) according to the measurement data obtained aboard the GOES-13 satellite [3].

4 Å) started at around 19:40 UT on 7 March [3] and attained its maximum at around 20:12 UT (GOES-13 data, Fig. 2e). Several hard X-ray bursts were recorded at the same time by the FERMI (quantum energy, 12–25 keV; ground-based monitor (GBM) data; X2 in Fig. 2d) and RHESSI (X-ray radiation; E = 100–300 keV; X1 in Fig. 2d) spacecraft. These data are represented by the corresponding triangles indicating the start–maximum–finish instants of the X-ray burst observations. The height of the triangles corresponds to the logarithm of the total count of photons of the above energies during the burst.

An important feature of this event is the prolonged (>10 hours) observation of high-energy solar gamma-ray emissions with E >100 MeV [5] and solar neutron fluxes (E = 44 MeV). The time distribution of the instants these neutrons emerged, based on measurements by the NEM-FIB detector aboard the International Space Station (ISS) [6], is shown in Fig. 2c. The very observation of solar neutrons is an indication of the presence of high-energy protons in the particle acceleration region. Some of these protons will interact with the solar atmosphere to produce electromagnetic radiation and neutron fluxes, while others can leave the flare region and escape into interplanetary space. It is the latter protons that can be detected aboard spacecraft and by ground-based cosmic-ray detectors.

Figure 2a presents measurements of the particle count rate in the TEL channel of the CARPET detector, while Fig. 2b shows the fluxes of protons with $E >$ 50 MeV measured aboard the GOES-13 satellite [3].

Analysis of the data presented in Figs. 1 and 2 allows us to draw the following conclusions.

The increase in the count rate in the TEL channel of the CARPET instrument was observed to occur between 20:10 and 21:30 UT on March 7, 2011. A substantial increase in the count rate was simultaneously observed in the UP and LOW channels as well. The increase in the TEL channel was (3–10)σ (up to 6%) of the pre-flare level recorded at 19:00–20:00 UT.

The increase in the intensity of low-energy protons with $E >$ 50 MeV was recorded aboard the GOES-13 satellite only at 21:30 UT. This lag behind the time of the increase in the count rate at the CARPET detector (around 20:10 UT) was apparently due to the effect at the CARPET detector being caused by more energetic protons than aboard the GOES-13 satellite. There was no effect from the increased intensity of protons with $E > 100$ MeV aboard the GOES-13 spacecraft [3].

Note that according to the measurement data provided by ground-based neutron monitors (the NMDB data base) [7], no ground-level enhancement (GLE) of cosmic rays was recorded during this flare event. One of the factors responsible for this could be the strong anisotropy and/or weak intensity of the flux of primary high-energy solar protons at the magnetospheric boundary at this time (20:10–21:30 UT).

We already noted that the geomagnetic cutoff rigidity at the location of the CARPET detector was $R_c =$ 9.65 GV, and so the increase of the instrument's count rate can be assumed to be due to the cascade of secondary particles generated in Earth's atmosphere by solar protons with $E > 9$ GeV. This possibility is supported by observations of very low-frequency (VLF) radio emissions and those of ground-based riometers during this time. These indicate increased atmospheric ionization levels in areas with the geomagnetic cutoff rigidities ranging from 2.5 GV to 9 GV.

CONCLUSIONS

Analysis of variations in the cosmic rays recorded by the CARPET detector and ground-based neutron monitors during the solar proton event of March 7, 2011, associated with an M3.7 solar flare from the active region NOAA 1164 (N23, W50), and of solar flare data acquired by various instruments aboard the GOES-13, FERMI, and ISS spacecraft, allow us to draw the following conclusions.

(1) The particle count rate in the three channels of the CARPET cosmic ray detector was observed to increase on March 7, 2011, between 20:10 and 21:30 UT. The magnitude of the increase was $(3–10)\sigma$ (up to 6%).

(2) Considering that the geomagnetic cutoff rigidity at the location of the CARPET facility is $R_c = 9.65$ GV, we may assume that the increase in its particle count rate during the flare was caused by a cascade of secondary particles produced by primary solar protons with $E > 9$ GeV in Earth's atmosphere. This assumption is supported by the results from independent observations of VLF radio emissions and those of ground-based riometers indicating increased atmospheric ionization levels over an extended region with geomagnetic cutoff rigidities ranging from ~2.5 to ~10 GV.

(3) An important feature of this event is the prolonged (>10 hours) observation of high-energy solar gamma-radiation with $E > 100$ MeV and fluxes of solar neutrons ($E = 44$ MeV). This is a direct indication of the presence of highly energetic protons in the particle acceleration region. Some of these protons interact with the solar atmosphere to generate a neutron flux, while others can leave the flare region and propagate in interstellar space to be recorded by space- and ground-based cosmic ray detectors. At the same time, several hard X-ray bursts were recorded by the instruments aboard the FERMI (GBM, quantum energies of up to 300 keV) and RHESSI (up to 300 keV) spacecraft.

Note that the above hypothesis that fluxes of solar protons with $E > 9$ GeV were present in Earth's atmosphere during the solar proton event of March 7, 2011, requires further investigation with a thorough analysis of all the data available on ground-based NM and muon telescope measurements.

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REFERENCES

1. De Mendonca, R.R.S., Raulin, J.-P., Makhmutov, V.S., et al., *Bull. Russ. Acad. Sci. Phys.*, 2009, vol. 73, no. 3, p. 404.
2. De Mendonca, R., Raulin, J.-P., Bertoni, F., et al., *J. Atmos. Solar Terr. Phys.*, 2011, vol. 73, p. 1410.
3. www.swpc.noaa.gov/
4. http://hesperia.gsfc.nasa.gov/fermisolar/
5. Allafort, A., Giglietto, N., Omodei, N., et al., *Proc. 32nd ICRC*, Beijing, 2011, vol. 10, p. 113.
6. Koga, K., Goka, T., Matsumoto, H., Obara, T., et al., *Proc. 32nd ICRC*, Beijing, 2011, vol. 10, p. 166.
7. www.nmdb.eu/