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Possible Ground Level Enhancements of Solar Cosmic Rays in 2012

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Abstract—It is commonly accepted that two ground level enhancements of solar cosmic rays (GLEs) have so far been recorded in solar cycle 24: one on May 17, 2012, and one on January 6, 2014. The current solar activity cycle is considered to lag behind previous cycles in both quantity and magnitude of GLEs. Considerably more (around 30) solar proton events have been recorded from satellites. In this work, we analyze the patterns of cosmic ray intensity over the worldwide neutron monitor network during those events of 2012 in which considerable increases in the integral proton fluxes with energies of >100 MeV were observed, i.e., the events of January 27, March 7, and March 13, 2012. All of these events may be considered possible GLEs. More GLEs have apparently been observed during solar cycle 24 than is widely recognized.

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INTRODUCTION

Proton events (increases in the flux of accelerated charged particles (i.e., protons and nuclei) in the Earth's atmosphere and in circumsolar space) are among the most important and dangerous phenomena of space weather and require intense study. The ground level enhancement (GLE) of solar cosmic rays is of special importance, since it is the strongest of the increases in protons. GLE is one of the clearest manifestations of sporadic solar activity, and it is always observed in combination with other sporadic events. To study such increases in protons, it is useful to combine GOES data (which include uniform and complete information on X-ray flares and proton fluxes in different energy ranges) and data from the worldwide neutron monitor network. Large-scale events are usually the focus of researchers' attention [1–6]. Events with weak increases in cosmic ray intensity can be ignored, though studying these events could contribute to our understanding of this complex class of phenomena.

The aim of this work was to analyze patterns of cosmic ray intensity over the worldwide neutron monitor network during those events of 2012 in which substantial increases in the integral fluxes of protons with energies of >100 MeV were observed. Three such events were observed in 2012, on January 27 and March 7 and 13.

EVENT OF JANUARY 27, 2012

The first large proton event began on January 23, 2012, after a M8.7 flare from active region 11402 (N27W21) located at the west edge of the solar disk. The flux of particles with energies of >100 MeV was 2.3 pfu; it reached 3400 pfu on January 24 and 6300 pfu on January 25. The proton increase continued at the level of a Class 1 radiation storm on January 26. The event was still under way when a large-scale proton increase for particles with energies of >100 MeV (11.9 pfu) started on January 27, the first extreme (Class X1.7) flare of 2012. The flux of particles with energies of >10 MeV was as high as 800 pfu. For particles with energies of >100 MeV, the event ceased the next day, January 28, 2012. For particles with energies of >10 MeV, the event lasted longer, ending on February 1, 2012.

Figure 1a shows variations in the cosmic ray intensity at the neutron monitors of the South Pole B (SOPB), South Pole (SOPO), and Mirny (MRNY) stations with 30-min resolution and the 5-min GOES-13 data on protons with energies of >10 MeV, >50 MeV, and >100 MeV. As can be seen, the increase in cosmic ray intensity recorded by the ground-based stations began almost at the same time as the one recorded by the GOES-13 satellite. It has the classical form of a GLE event, with a sharp increase and a smooth decline in intensity.

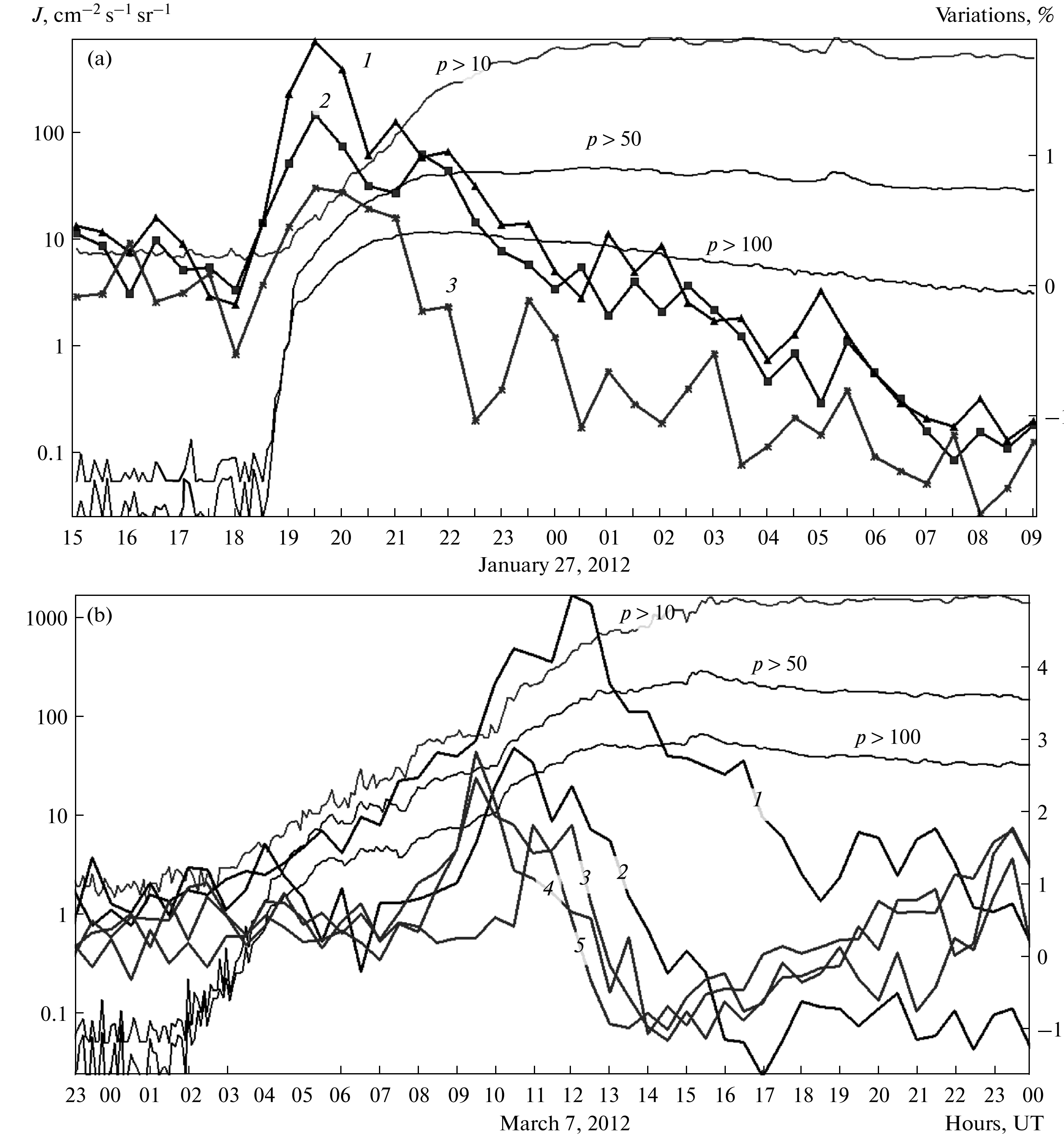

Fig. 1. Variations in cosmic ray intensity at neutron monitors during (a) the event of January 27, 2012, at the SOPB (*1*), SOPO (*2*), and MRNY (*3*) stations with 30-min resolution and the 5-min GOES data on protons with energies of >10 MeV, >50 MeV, and >100 MeV; (b) the event of March 7, 2012 at the TXBY (*1*), SOPB (*2*), INVK (*3*), FSMT (*4*), and THUL (*5*) stations with 30-min resolution and the 5-min GOES data on protons with energies of >10 MeV, >50 MeV, and >100 MeV.

A weak increase was also observed at other polar neutron monitors (the Tule THUL, McMurdo MCMU, and Terre Adelie TERA stations). We believe this event may be considered a minor GLE, but it still merits further study and simulation.

EVENT OF MARCH 7, 2012

The next high-power burst in solar activity started in March, when active region 11429 with a complicated magnetic configuration appeared on the visible disk side. M-class flares were observed from the first hours of its appearance. The region produced 38 solar flares, including 25 C-class flares, 11 M-class flares, and 2 X-class flares, along with 3 large mass ejections between March 2 and 8, 2012. The peak of flare activity in the region fell on March 7, 2012, when two X-class flares occurred. The first, X5.4 in active region 11429 (N17E27), started at 00:00 UT and ended at 03:49 UT; the second, X1.5 in active region 11430 (N22E12), started at 01:05 UT and ended at 01:30 UT. Both active regions were located in the northeastern part of the solar disk and had the very complicated configuration α-β-γ.

Due to the increased solar activity, a minor proton event for a flux of particles with energies of >10 MeV (4 pfu) began at the altitude of the geostationary orbit on March 4–5, 2012. It was joined by new high-power proton event on March 7, 2012, that was caused by X-class solar flares from active regions 11429 and 11430. The proton fluxes with energies of >10 MeV reached an amplitude of 6000 pfu, while the amplitude of those with energies of >100 MeV was as high as 70 pfu. The event ended on March 11, 2012, for protons with energies of >100 MeV, but continued with a gradual decline for protons with energies of >10 MeV.

Figure 1b shows variations in the cosmic ray intensity at the neutron monitors of the Tiksi (TXBY), Fort Smith (FSMT), SOPB, SOPO, THUL, and Inuvik (INVK) stations with 30-min resolution and the 5-min GOES-13 data on protons with energies of >10 MeV, >50 MeV, and >100 MeV. A weak rise can be seen in the intensity recorded at these ground-based stations, coinciding with the second increase in particles recorded by the GOES-13 satellite.

To study this event, we must analyze the conditions in near-Earth space. The arrival of the SSC shock wave front at 04:21 UT coincided with the start of the increase in cosmic ray intensity at the SOPO and SOPB stations. It is possible that only low-energy particles were additionally accelerated at the front of this shock wave [7], since no enhancement of particles was observed at this time at the neutron monitors of the TXBY, FSMT, THUL, and INVK stations. The sharp increase in the velocity of the solar wind at 08:00 UT could have accelerated low-energy particles, leading to the second enhancement of cosmic rays that was recorded at the neutron monitors of the SOPB and SOPO stations in the 10:00–13:00 UT interval. The event of interest was anisotropic, with a possible contribution from the magnetospheric effect. The arrival of ejections from two events of filament disappearance induced a magnetic storm in near-Earth space that lasted 18 hours. The daily mean A_p index was 64 on March 7.

Solar cosmic rays probably contributed to the increase in cosmic ray intensity recorded by the monitors on March 7. Magnetospheric effects and the modulation of galactic cosmic rays likely contributed to this increase as well. The event was extremely complicated, and more detailed analysis and model calculations are needed before we can draw any firm conclusions.

EVENT OF MARCH 13, 2012

The flare activity of region 11429 did not cease in the early March: an M6.3 flare occurred on March 9, 2012; an M8.4 flare and two C-class flares were observed on March 10, 2012; a C-class flare occurred on March 11; finally, after a brief period of calm, a long M7.9 flare (from 16:35 UT to 20:46 UT) and a C-class flare were observed on March 13. A new GLE started on March 13, 2012, during which fluxes with energies of >10 MeV reached 500 pfu, while those with energies of >100 MeV went as high as 2 pfu. Attenuation of the proton flux with energies of >100 MeV (2 pfu) began the next day.

Figure 2a shows variations in cosmic ray intensity at the neutron monitors of the SOPB and SOPO stations with 10-min resolution and the 5-min GOES-13 data on protons with energies of >10 MeV, >50 MeV, and >100 MeV. It can be seen that the increase in cosmic ray intensity recorded at the ground-based stations began near the particle enhancement on the GOES-13 satellite, making it likely that solar cosmic rays contributed to the observed effect. A weak enhancement was also observed at the monitors of the TERA and THUL stations.

Conditions during the event of March 13 were much simpler than those of the event of March 7. Some of the difficulties in analyzing this event are due to it occurring against the recovery phase of a Forbush effect that began on March 12. Figure 2b shows variations in density A_0 of galactic cosmic rays with a rigidity of 10 GV and the A_{xy} equatorial anisotropy component, calculated using the global survey method [8] with data from the worldwide neutron monitor network, along with variations in IMF strength and the velocity of the solar wind before and after the M7.9 flare of March 13, 2012. It can be seen that the arrival of the disturbance raised the velocity of the solar wind to 800 km s^{-1} and in planetary K index to 7 (the level of a strong magnetic storm). After the arrival of the shock wave, a long (more than 2 days) and deep (~5%) Forbush effect began, and an extremely strong increase in the A_{xy} of galactic cosmic rays (up to ~3%) was observed. This is very rare and is a characteristic feature of such events. The two periods of the magnetic storm coincided in time with sharp increases in IMF strength during the arrival of the shock wave. A comparison of the cosmic ray intensities at the SOPO and SOPB and midlatitude

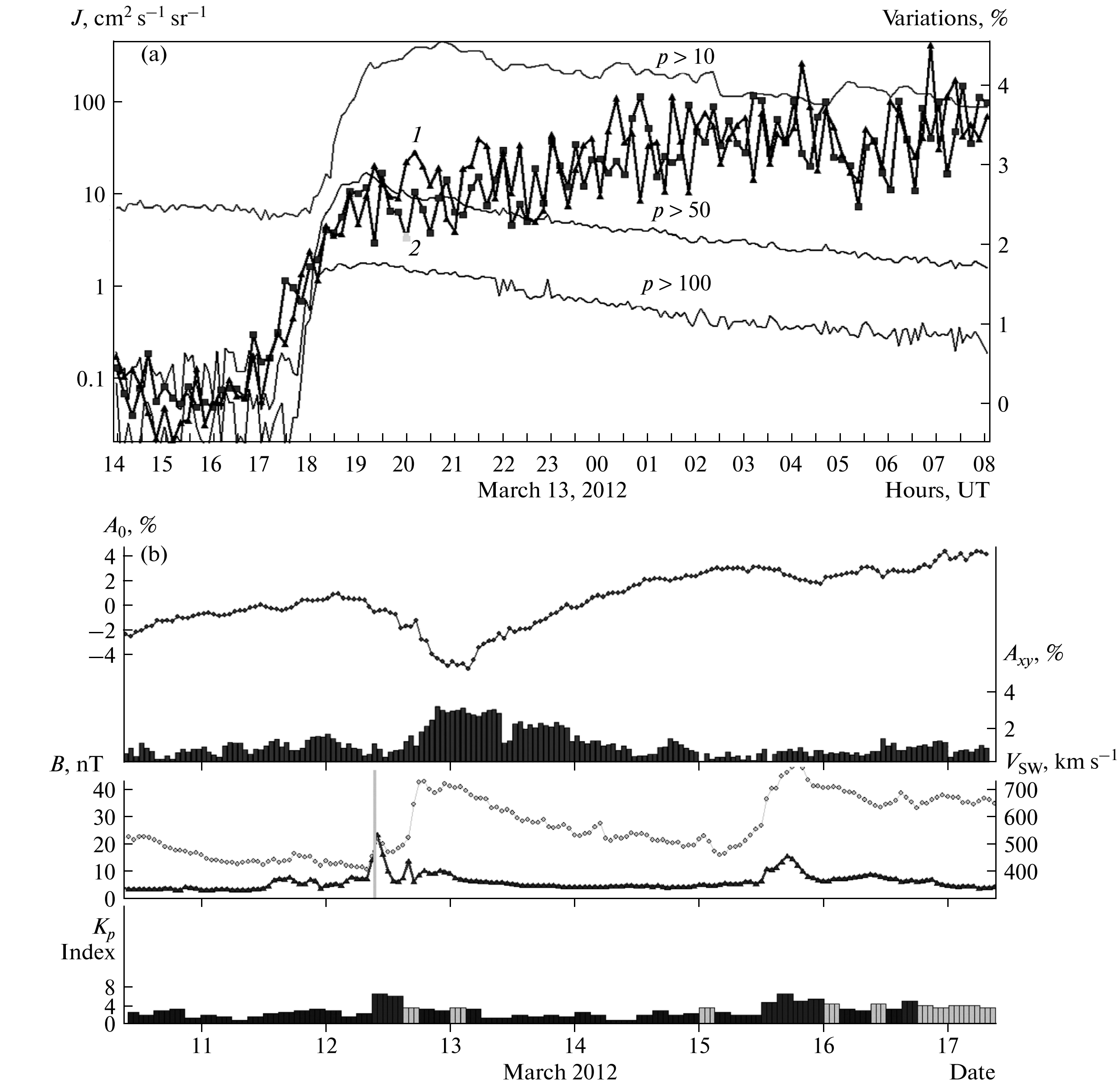

Fig. 2. Event of March 13, 2012: (a) variations in cosmic ray intensity at the neutron monitors of the SOPB (*1*) and SOPO (*2*) stations with 10-min resolution and the 5-min GOES data on protons with energies of >10 MeV, >50 MeV, and >100 MeV; (b) variations in the density of cosmic rays with a rigidity of 10 GV A_0 (dots), the equatorial anisotropy component A_{xy} (top histogram), the solar wind velocity V_{SW} (white diamonds), IMF strength B (black triangles), and the geomagnetic field index K_p (bottom histogram) after the M7.9 flare in near-Earth space during the period March 10–17, 2012. The vertical line shows the moment of the shock wave's arrival.

AATB and JUNG stations shows that at the moment the GLE began, the values at the polar stations grew relative to those at the midlatitude stations.

CONCLUSIONS

All three of the events at the beginning of 2012 can be considered possible GLE. An up to ~2% increase in the count rate concurrent with the proton enhancement on the GOES satellites was recorded at several neutron monitors on January 27, 2012, allowing us to identify it as a GLE.

A similar increase in the count rate on March 13, 2012, was simultaneously observed on the GOES satellites and at several polar neutron monitors. It is highly probable that this was a GLE as well. It could have been recognized earlier if there had been no Forbush decrease at the time.

The most complicated and interesting situation meriting detailed analysis and simulation was the one on March 7, 2012. The arrival of solar cosmic rays on Earth during this event coincided in time with strong modulation effects in galactic cosmic rays and considerable magnetospheric effects. However, we believe solar cosmic rays also affected the count rate of near-polar neutron monitors during this event.

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