Possible ground level enhancements at the beginning of the maximum of Solar Cycle 24

A Belov\textsuperscript{1}, E Eroshenko\textsuperscript{1}, O Kryakunova\textsuperscript{2}, N Nikolayevskiy\textsuperscript{2}, A Malimbayev\textsuperscript{2}, I Tsepakina\textsuperscript{2}, V Yanke\textsuperscript{1}

\textsuperscript{1} Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), Moscow, Troitsk, 142190, Russia
\textsuperscript{2} Institute of Ionosphere, Kamenskoe Plato, Almaty, 050020, Kazakhstan

E-mail: krolganik@yandex.ru

\textbf{Abstract.} Three solar energetic proton events in the beginning of 2012 (January and March) revealed significant increases of the integral proton fluxes with energies \textgreater 100 MeV were analyzed by the data from subpolar neutron monitors (>500 MeV). As it was found the event on January 27, 2012 was followed by cosmic ray enhancement of about 2\% at several subpolar and high latitude neutron monitors which coincided with the onset of the intensity increase in the GOES channels. This was also confirmed with the GOES/HEPAD data that allow us to consider the event on January 27, 2012 as a Ground Level Enhancement. The events in March 2012 (7.03 and 13.03) occurred under very complicated situation in the interplanetary space and a more detailed analysis is needed. Nevertheless, these events may contain some contribution of solar cosmic rays in the ground level observations.

\section{1. Introduction}

Proton events (enhancement of the flux of accelerated charged particles – protons and nuclei – in the Earth’s atmosphere and near Sun space environment) are one of the most important and most dangerous phenomena of space weather, which needs careful studying (www.swpc.noaa.gov). Time distribution of proton events is very inhomogeneous (figure 1) with the majority of them occurring during the maximum of the solar cycle as well as within its descending phase. In order to study proton increases it is useful to unite data of the Geostationary Operational Environmental Satellite (GOES) in which uniform and full information on X-ray flares and protons fluxes at various energy ranges are accumulated, with data of the world neutron monitor (NM) network.

Currently, it is considered that in the 24th cycle of solar activity only 2 ground level enhancements (GLEs) of solar cosmic rays (SCR) are registered: on May 17, 2012 [1, 2, 3, 4] and on January 6, 2014 [5]. Both in quantity and in power of GLEs and in solar activity as well the current cycle concedes to the previous [6, 7, 8]. The number of solar proton events (SPEs) registered on satellites are much higher than the number of GLEs recorded on the ground; however, as a rule, GLEs tend to occur more frequently in higher level storms and thus have a considerable radiation impact. In 2012 around 30 SPEs were marked. We decided to analyze the behaviour of the cosmic ray (CR) intensity recorded by the world wide NM network during the events of the 24th solar activity cycle when a significant increase of the integral proton flux with energy > 100 MeV was recorded by satellite experiments. This turned out to be directly in the events on January 27, March 7, and March 13 of 2012. As GLE should be considered an event in which at least on one NM at sea level
statistically significant increase of count rate coinciding on time with increase in the satellite data would be observed. Perhaps, the decisive word here is in modeling of increase on a network of stations. This criterion is satisfied by the event in January 2012. And other events considered in this work in March 2012 need to be studied and analyzed more detailed with using some modeling approach. It was not noticed earlier because nobody paid attention to so small events. The aim of our work is to show that all above mentioned events may be considered as candidate GLEs. Apparently, in 24th cycle more GLEs than it is widely recognized were observed.

The aim of our work is to show that all above mentioned events may be considered as candidate GLEs. Apparently, in 24th cycle more GLEs than it is widely recognized were observed.

Figure 1. Proton increases in 1976-2013 on the background smoothed numbers of solar spots. Small red circles mark the time of increase of the protons of >10 MeV energy higher 10 pfu, large yellow circles mark the time of GLEs of SCR.

2. Data and method
For this analysis, data of the neutron component of CRs recorded at subpolar and high latitude NMs with time resolution of 1-, 5-, and 30 minutes have been used. Those were taken from the NMDB database (www.nmdb.eu) for January and March 2012. These data were compared with measurements of soft X-Ray (GOES15) and integral fluxes of protons of different energies (>10, >50 and >100 MeV) obtained onboard GOES13. Data from High Energy Proton and Alpha Detector (HEPAD) on the high energy channels was also involved in the analysis. Parameters of the solar activity and the interplanetary space were accessible by http://www.swpc.noaa.gov/ and OMNI data base – (http://nssdc.gsfc.nasa.gov/omniweb/ow.html).

3. Event on January 27, 2012
The first large proton event in 2012 started on January 23, after the flare of M8.7 class from the region AR11402 (N27W71), located at western side of solar disk. The particle flux with energies of >100 MeV was 2.3 pfu. On January 24 the flux of particles of >10 MeV reached 3400 pfu (radiation storm of 3 level), on the 25 January – 6300 pfu (radiation storm of 2 level). On January 26 proton enhancement continued in the level 1 of radiation storm. This proton increase did not come to the end as on January 27, after the first 2012 flare of the highest class (X1.7), the next enhancement had begun. The source of this flare was in the same active region AR11402 (N27W71) which by this time came to the western limb of the visible solar disk. At 17:27 UT on January 27 UT in this area the flare of the X1.7 class occurred and reached maximum at about 18:37 UT (peak time). Time of the CME lift-off was 18:28 UT, type II radio burst started at 18:30 UT. At this time a large proton increase for particles >10 MeV (800 pfu), >50 MeV and >100 MeV (11.9 pfu) occurred. For particles of >100 MeV, the event was close to background on the next day 28 January 2012. For particles with energies >10 MeV the event lasted much longer and finished on the 1st of February, 2012.

In figure 2 the data from the NMs South Pole B (SOPB), South Pole (SOPO) and sea level station Mirny (MRNY) with a time resolution of 30 minutes (baseline time interval is 17 – 18 UT) are
plotted together with 5-minute GOES 13 data for protons with energies >10 MeV, >50 MeV, >100 MeV.

\[ \text{Figure 2. CR variations (right scale) recorded at NMs South Pole B (SOPB), South Pole (SOPO) and Mirny (MRNY) with 30-minute resolution and 5-minute data of proton fluxes recorded at GOES 13 on 27 January 2012, 1500 UT – 28 January 2012, 0900 UT.} \]

A small increase of count rate (about 1%) with the onset around 18:25 UT was also observed at other high latitude ground level NMs: Thule (THUL), Inuvik (INVK), McMurdo (MCMU), Terre Adelie (TERA), Fort Smith (FSMT) (see figure 3 for FSMT and INVK). At all these stations an increase of NM count rates in percentages relatively base line reaches about 1-2% that corresponds to 8-10 standard sigma, so, this enhancement is statistically provided. Duration of GLE may be ranged from one hour to about 48 hours. In our case we see a significant difference in duration for southern NMs (figure 2) and northern ones (figure 3) that may tell about large north-south anisotropy in this event. It is not clear what is the reason of this north-south anisotropy and so long enhancement at the northern stations. This needs further investigations. But we can suppose that the signal that is seen by the NMs Fort Smith and Inuvik, may be caused by solar cosmic rays only during the initial phase.

\[ \text{Figure 3. CR variations (right scale) recorded at NMs Fort Smith (FSMT) and Inuvik (INVK) with 30-minute resolution and 5-minute data of protons by the data of GOES 13 on 27 January 2012, 1500 UT – 28 January 2012, 0900 UT.} \]

In figure 4 data from HEPAD for proton fluxes averaged by the energies within each HEPAD channel: Proton P8 (350 to 420 MeV), Proton P9 (420 to 510 MeV), Proton P10 (510 to 700 MeV) are presented with 10 minute resolution. For simplicity sake these channels are marked as 375, 465 and 605 MeV in figures 4, 6, 9. A coincidence in the onset of enhancements in both groups of data is evident. This completely satisfies criteria for GLE and allows us to consider the event on 27.01.2012 as a GLE one. However, it is worthy further studying and modeling [9, 10]: definition of asymptotic
directions, integral and differential spectra and so on. Modeling by different groups of scientists carried, combine data of all ground level detectors and allows one to define spectra and angular distribution of SCR. In result, more definite conclusions may be obtained than those derived from the analysis of data from separate detectors. Unfortunately, nobody carries modeling of such small GLEs, since usually more powerful events are preferred.

Figure 4. Average fluxes of 375, 465 and 605 MeV protons recorded on HEPAD on 27 January 2012, 1500 UT – 28 January 2012, 0900 UT.

4. Event on March 7, 2012
Next the powerful burst of the solar activity occurred in March 2012 when AR 11429 appeared on the visible side of solar disk, having complicated magnetic configuration and extending over a large area (www.swpc.noaa.gov). During the period from March 2 to March 8, 2012 this group produced 11 flares of class M and 2 flares of the highest class X. The peak of the flare activity fell on March 7, 2012. On this day there were two flares of class X: the first one, of X5.4 importance, began at 00:02 UT in AR11429 (N17E27) with peak time 0:24 UT. The second flare began at 01:05 UT in AR 11430 (N22E12) and ended at 01:30 UT. This X1.3 flare was associated to a fast CME of 1825 km/s velocity at 01:30 UT. The first solar flare (X5.4) was associated to an even faster CME at 00:24 UT (with a speed of 2684 km/s). As it was shown by Richardson et al. [11] the SEP (Solar Energetic Particle) event of March 7, 2012 is the result of the first flare-CME pair (e.g. X5.4 and 2684 km/s velocity of CME) and that the possible interaction among the two CMEs is excluded. A large and fast CME was observed starting from 0:24 UT and radio bursts of II and IV type started at 0:17 UT. As a result, on March 7 the new, more powerful proton event was associated with solar flare of X5.4 from AR 11429. Proton flux with energy >10 MeV started to grow at about 4:24 UT and reached 6000 pfu, and for energy >100 MeV - 70 pfu. For protons with energy >100 MeV, the event ended on March 11, 2012, for protons with energy >10 MeV, it proceeded much more long, gradually weakening. In figures 5 and 6 the behaviour of proton fluxes by the GOES data shows at the beginning the profile characteristics for an eastern source. The fluxes of low energy protons firstly increased very gradually (from 4:30 to 10:00 UT) and from 10:00 UT rapid growth of the proton fluxes is clearly visible. It coincides with the time interval between the arrival of two disturbances: the first one was a shock wave (defined by SSC) registered at 4:20 UT and associated with CME from March 4, 2012, and second one – a substantial increase of solar wind velocity (from 400 to 600 km/s in 10:00 – 16:00 UT interval) and associated with CME on March 5, 2012.

In figure 5 the NM data are presented from the stations: Tixie Bay (TXBY), Fort Smith (FSMT), South Pole B (SOPB), South Pole (SOPO) and Thule (THUL) at 30-minute resolution (baseline time interval is 23 – 24 UT). Also 5-minute proton data with the energies >10 MeV, >50 MeV, >100 MeV recorded at GOES 13, are shown. Small increase of CR intensity (about 2%), registered by ground level stations SOPO and SOPB at 8:00 -10:00 UT, is coincided with the increase of the protons at GOES13 and in the average fluxes of 375, 465 and 605 MeV protons from HEPAD. One can see that the behavior of count rate at subpolar NMs repeats the behavior of the high energy particle fluxes on HEPAD that confirms a contribution of solar CR in the ground level observations.
But still we cannot definitely refer this event to the GLE because of very complicated interplanetary situation at that time, as it seen in figure 7.

**Figure 5.** CR intensity recorded at NMs Tixie Bay (TXBY), Fort Smith (FSMT), South Pole B (SOPB), South Pole (SOPO) and Thule (THUL) with 30-minute resolution and 5-minute data of protons by the data of GOES 13 on 6 March 2012, 2000 UT – 8 March 2012, 0200 UT.

**Figure 6.** Average fluxes of 375, 465 and 605 MeV protons recorded on HEPAD on 6 March 2012, 1800 UT – 8 March 2012, 0200 UT.

These complications arose due to the solar ejections (halo CMEs) occurred on 4 – 5 of March in those AR that generated later the flares of X importance.

**Figure 7.** Behaviour of 10 GV CR density (A0) and equatorial component $A_{xy}$ of the vector CR anisotropy (middle panel), relevant parameters of the interplanetary magnetic field (IMF): IMF intensity and solar wind velocity (upper panel), Kp-index and Dst of geomagnetic field (lower panel) during the period March 5-12, 2012. Vertical line means the shock arrival (SSC).
At the beginning of March 7 (4:20 UT) the SSC assumingly associated with halo CME observed on March 4, arrived at Earth. After this the IMF intensity increased significantly (up to 20 nT) but solar wind velocity remained at not high level some time. It started to grow after 10:00 UT and reached value of 600 km/s in some hours. Perhaps this increase of velocity was caused by arrival of the other interplanetary disturbance associated with the halo CME on March 5 from the same AR11429. Speed of this CME was higher, than the speed of the previous one, and near Earth the second front caught up with the first that could favor to additional acceleration of energetic charged particles which were already observed near the Earth at this time. The possible enhancements of the solar particles of ~1 GeV is very difficult to select on the background of the strong CR modulation. At the same time geomagnetic storm also occurred. It should not be expected that this magnetospheric effect causes large variations of cutoff rigidities at high latitude stations, but asymptotic directions may be strongly changed, that creates additional problem for modeling of this event. Specific situation arose with two approaching fronts of interplanetary disturbances. It was difficult for particles to go out from this region between two fronts, but they could be accelerated and accumulated there.

We suggest that a contribution of SCR to the increase of count rate at some sea level NMs on March 7 exists, however model calculations are necessary for more certain conclusions.

5. Event on March 13, 2012

The situation on March 13 is much simpler than on March 7. The flare M7.9 was registered on March 13 at 17:12 UT in the AR11429 (N19W59) and reached peak time at 17:41 UT. The start of CME observations was at 17:36 UT, radio burst type II started at 17:15 UT and type IV – at 17:17 UT. Initial CME velocity was 1884 km/s.

Figure 8. CR intensity recorded at NMs South Pole B (SOPB) and South Pole (SOPO) with 10-minute resolution and 5-minute data on the protons with the energy >10 MeV, >50 MeV, >100 MeV by the data on satellite GOES 13, for the time interval 13 March 2012, 1400 UT – 14 March 2012, 1000 UT.

Figure 9. Average fluxes of 375, 465 and 605 MeV protons recorded on HEPAD on 13 March 2012, 1400UT – 14 March 2012, 1000 UT.
In figure 8 data of NMs at the stations (SOPB) and (SOPO) with 10-minute resolution (baseline time interval is 16 – 17 UT) and 5-minute data of protons with the energies >10 MeV, >50 MeV, >100 MeV from GOES 13 are plotted. One can see that growth of CR intensity at ground level stations began close to increase of particle fluxes on the GOES 13 that makes possible a contribution of SCR to the observed effect. A small increase was recorded also at sea level stations Terre Adelie (TERA) and Thule (THUL) with the onset time identical to the enhancement recorded in GOES 13. In figure 9 data of average fluxes of 375, 465 and 605 MeV protons on HEPAD are presented for this event. It is seen that the onset of SCR enhancement 17 UT is not in contradiction by observations of all detectors (GOES 13, HEPAD, NMs). But after the time of maximum proton fluxes we do not see a decrease in the count rate of the NMs.

Some difficulties of analysis for this event are caused by its occurrence in the recovery phase of Forbush effect (FE) which started on March 12. In figure 10 parameters of interplanetary space (IMF intensity and solar wind velocity) are plotted together with CR characteristics derived by GSM [12] and index of geomagnetic activity Kp. It is seen that after the disturbance arrival the solar wind velocity increased up to 800 km/s and planetary Kp index reached 7 (the level of strong magnetic storm). After the shock arrival a long and large (~5%) Forbush effect began which lasted about 2 days. At the same SSC moment a strong increasing of the equatorial anisotropy (up to ~3%) was observed, that occurs seldom and is a characteristic feature of this event. Apparently, because of the recovery phase of FE the CR intensity at polar stations continue to grow (figure 8) after the clear enhancement simultaneously with protons measured at GOES 13 and HEPAD.

![Figure 10. Behaviour of 10 GV CR density (A0) and equatorial component Axy of the vector CR anisotropy (middle panel), IMF intensity and solar wind velocity (upper panel), and Kp-index and Dst of geomagnetic activity (lower panel) during the March 10-17, 2012.](image)

![Figure 11. CR intensity recorded at NMs Alma-Ata B (AATB), Jungfraujoch (JUNG), South Pole B (SOPB) and South Pole (SOPO) on 13 March 2012, 1200 UT – 14 March 2012, 1500 UT.](image)
If compare the CR intensity at South Pole (SOPO), South Pole B (SOPB) and mid latitude stations Alma-Ata B (AATB) and Jungfraujoch (JUNG), then, directly at the moment of the onset of proton enhancement the CR intensity at polar stations increases as compared with mid latitude stations (figure 9). Such discordance between data of two groups of NMs might be explained by the presence of low energy (solar) CR which are registered at polar stations.

6. Conclusions
All three events at the beginning of 2012 may be considered as candidate GLEs of SCR.
On January 27, 2012 an increase of the counting rate of ~2%, coincides in time with a proton increase at the integral intensity recorded onboard the GOES satellite (E>100 MeV) and also with increases of the average fluxes of 375, 465 and 605 MeV protons recorded on HEPAD. Such an increase is also registered on several sea level NMs that allow one to speak about GLE for this event.
On March 13, 2012 an increase at the counting rate similar in size to the event on January 27 is observed on several high-latitude NMs at the same time that an increase in GOES high energy protons, is presented. A GLE, possibly, was observed here. If there was no Forbush decrease at this time the situation, most probably, would been clearer.
The most difficult and most interesting situation that deserves a detailed analysis, modeling and further investigation, took place on March 7. In this event, the arrival of SCR to Earth coincided in time with large modulation effects in galactic CRs and with significant magnetospheric disturbance. Our analysis shows that in this event there is a possible influence of SCR on the counting rate of subpolar NMs.

Acknowledgments
Authors wish to acknowledge to all teams providing continued ground level CR monitoring (http://cr0.izmiran.rssi.ru/ThankYou/) and acknowledge the NMDB database (www.nmdb.eu), founded under the European Union's FP7 programme (contract no. 213007) for providing data. (www.nmdb.eu). This work was supported also by Kazakhstan Aerospace Committee under program 076 and under grant N0014/GFZ.

References
[1] Papaioannou A, Souvatzoglou G, Paschalis P, Gerontidou M, Mavromichalaki H 2014 Solar Phys. 289 423 DOI 10.1007/s11207-013-0336-2
[2] Takao K, Bieber J, Clem1 J, Evenson P, Gaisser T, Pyle R, Tilav S 2013 Proc. 33nd Int. Cosmic Ray Conf. (Rio de Janeiro) SH21A-2183
[3] Augusto C R A, Kopenkin V, Navia C E , Tsui K H, Feliciano A C, Pinto A C , de Oliveira M N et al. 2013 Proc.33nd Int. Cosmic Ray Conf. (Rio de Janeiro)
[4] Li C, Firoz Kazi A, Sun Ling P, Miroshnichenko I. 2013 Astrophys. J. 770 34
[5] Thakur N, Gopalswamy N, Xie H, Mäkelä P, Yashiro S, Akiyama S, and Davila J M 2014 Astrophys. J. Lett. 790 1
[6] Gopalswamy N, Xie H, Akiyama S, Pertti A, Mäkelä P and Yashiro S 2014 Earth, Planets and Space 66 104
[7] Sharma A, Verma S R 2013 International J. of Astronomy and Astrophys. 3 212
[8] Chapman G A, de Toma G, Cookson A M 2013 Solar Phys. 289 3961
[9] Plainaki C, Belov A, Eroshenko E, Mavromichalaki H, Yanke V 2007 J. Geophys. Res. 112 No A4 CiteID A04102
[10] Plainaki C, Belov A, Eroshenko E, Mavromichalaki H, Yanke V 2008 Adv. Space Res. 41 doi:10.1016/j.asr.2008.07.011
[11] Richardson I G et al. 2014 Solar Phys. 289 3059
[12] Belov A et al. 2005 J. Geophys. Res. 110 A09S20 doi:10.1029/2005JA011067