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Minor Ground Level Enhancements in the Solar Cosmic Rays in the 24th Solar Activity Cycle

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Abstract—The first (preliminary) results of a systematic search for minor ground level enhancement (GLEs) in solar cosmic rays (SCRs) in the 24th solar activity cycle are presented. The search was conducted based on the data of the global network of neutron monitors with allowance for the results of direct satellite measurements. The initial assumption is that such increases point to the possible acceleration of solar particles in shock waves, which are generated by coronal mass ejections. The shape of the integral spectrum of the accelerated particles according to observations of neutron monitors and measurements from near-Earth space vehicles could serve as a determinant for checking that hypothesis. Studying the spectra manifests an informativity of our approach to a better understanding of SCR source properties.

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1. INTRODUCTION

Many scientists have noted that the current 24th solar activity (SA) cycle differs from other cycles by a series of observational features (see e.g. [1–3]): in the behavior of sunspots, frequency, power of flares etc. In particular, the proton activity of the Sun (i.e., the frequency of solar proton events, SPEs) under standard method of SPE registration near the Earth, for example on board space vehicles of the *GOES* series, was found much lower than in the previous cycle (23rd). Thus, according to the NOAA site (https://umbra.nascom.nasa.gov/SEP/), only 42 events with a proton threshold energy of 10 MeV under the maximum intensity of 10 pfu (1 pfu = 1 proton $\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$) were registered from the beginning of the 24th cycle to September 2017 inclusively. There were 87 such events according to the same data, i.e., twice as much, in the 23rd cycle. Note that the events from the NOAA list characterize mainly the nonrelativistic region of the solar cosmic ray (SCR) spectra.

On the other hand, according to the data of the official site https://gle.oulu.fi, 16 so-called ground-based increases in SCRs, which characterize the relativistic part of their spectrum were registered in the 23rd cycle. Such events have received a name of Ground Level Enhancement (GLE) in the literature, and below for the sake of a briefness we will use this very international name. As for the 24th cycle, the global network of CR stations, mainly of neutron monitors (NMs), has observed only 2 GLEs over the entire cycle (https://gle.oulu.fi). Overall, 72 GLEs have been registered during the entire period of ground-based observations of SCRs (since February 28, 1942).

The term “hidden GLE” was proposed in 2014 [4]. It was done to define the problem of searching for weak GLEs that could be registered by the global network at the limit of NM sensitivity under some (prescribed) interval of ground-based data averaging. This problem presents an obvious interest for the obviously weak 24th cycle. The search for weak GLEs is important, first of all, for obtaining new information on the limiting (minimal and maximal) abilities of the solar accelerator (accelerators) in the conditions of decreased solar activity. In our opinion, studying weak GLEs can provide some proof of, at least, two interesting effects: acceleration of solar particles up to relativistic energies in shock waves (SWs) initiated by coronal mass ejections (CMEs) and/or efficient transportation of SCRs from the behind-the-limb sources in the interplanetary magnetic field (IMF).

The other research group proposed in July 2015 [5] to split the GLEs to three groups: the GLEs themselves, the so-called sub-GLEs, and even sub-sub-GLEs. The authors [5] think that such splitting characterizes different parts of the SCR spectrum. In particular: the relativistic events with particle energies E_p of several GeV, events with the energy of several hundred MeV, and, relatively, SPEs with a substantial increase in the proton fluxes with an energy of $E_p \geq 30$ MeV, but without protons with an energy above 300 MeV. The latter definition (sub-sub-GLEs) is very doubtful, whereas our term hidden GLE is close to the term "sub-GLE" introduced in [5]. Under the current understanding of SPEs, the event, for example on January 6, 2014 [6, 7], was a typical sub-GLE. Such diversity in the terminology, in our mind, requires returning back to the problem of GLE determination [8, 9] with allowance for the high efficiency (accuracy) of NM registration and the new experimental abilities for SCR observations [10] at mountain polar stations.

2. SELECTION OF THE DATA

It is widely known that the global network of NM stations is sensitive to primary SCRs with energy $E_p \geq$ 100 MeV (for protons). If the energy of the primary proton is $E_p < 100$ MeV (the magnetic rigidity $R < 0.44$ GV), then NMs almost do not register such protons due to the atmospheric absorption of the secondary neutrons, which are formed in the atmosphere by the primary protons of SCRs. This effect is called "atmospheric cut-off" under rigidity R_a. Due to this phenomenon, all high-latitude (polar) NMs at sea level efficiently register the secondary neutrons only under a condition that they have been formed by the primary protons with a rigidity of $R \geq 1$ GV (energy $E_p \geq 433$ MeV). This property of polar NMs does not depend on the nominal (calculated) rigidity, the "geomagnetic cut-off" R_c. It so successfully happened that rigidity $R \approx 1.0$ GV lies approximately in the middle between the rigidity of nonrelativistic particles measured on board SVs of the *GOES* type and the relativistic region [11]. Moreover, this value was found to be a convenient reference cut-off rigidity for all polar NMs.

According to recent studies [12], the cut off is completely governed by the atmospheric absorption of the secondary neutrons under the nominal cut-off rigidity $R_c \approx 0.6$ GV ($E_p \approx 200$ MeV). On the other hand, the high-mountain monitors SOPO and SOPB at the South Pole (the American station Amundsen–Scott at the Antarctic Plato, a height of 2835 m above sea level, $R_c = 0.11$ GV) has some observational advantages [12] as compared to other NMs.

Two mini-monitors [8] (DOMC and DOMB) began operation in 2015 at the southern polar dome of Earth (Central Antarctic) at the French–Italian station Concordia ($R_c < 0.01$ GV, height of 3233 m above sea level). The global network of NMs became more sensitive to SCRs due to these new instruments because the atmospheric cut-off value R_a is lower for the high-mountain monitors as compared to monitors located near sea level. As a result, high-mountain polar NMs can now register SPEs, which were "missed" by the monitors located near sea level. The threshold energy of high-mountain monitors in the Antarctic is approximately 300 MeV instead of 433 MeV due to atmospheric cut-off action.

Two Concordia mini-monitors [8] have already registered some interesting events including an SPE on October 29, 2015 (https://gle.oulu.fi, http://www.nmdb.eu). Besides the ice shield of the Antarctic Continent, there exists also a polar ice dome in the other hemisphere: the ice shield of Greenland. Its maximal height (the ice thickness) reaches 3205 m above sea level, however there are no NM stations for permanent registrations of SCRs. The only station, Thule ($R_c = 0.00$ GV), is located in the northwest of Greenland almost at sea level.

The following 15 SPEs of the 24th cycle (see Table 1) were studied at the current stage. The events were selected mainly with allowance for criteria of GLEs and sub-GLEs noted above. The data of some nonstandard ground-based detectors, which point to the possible arrival of relativistic particles from the Sun in this or other cases were also used. In some cases, additional information was used to predict GLEs. A more detailed description of Table 1 is presented in [13]. Also, a review of the history of "minor GLEs" is performed.

Now we will consider features of our selection method on the example of event no. 3 (January 27–28, 2012). While analyzing the data of polar NMs over the base period, one integer hour directly prior to the beginning of an event (the beginning of the enhancement in the flux of particles >10 MeV in Earth's orbit, or, if there were doubts, an earlier period as is shown in Fig. 1 by the thick horizontal line) was chosen for all events under study. Another choice of the base period shown by dots in Fig. 1 is possible. Then, the moments when the count rate exceeded 1% were determined based on the 5-min values of the count rate of NMs at the polar stations. It was taken as the presence of the effect of a relativistic (≥1.0 GV) or sub-relativistic (≥0.6 GV) SCR.

Figure 1 shows that the SCR effect in event no. 3 manifested at least at two Antarctic stations (South Pole (standard NM) and South Pole-B (NM without lead)), and the amplitude of the increase reached 1.8% (according to the 5-min data). Thus, the January 27–28, 2012 event was a typical "hidden GLE" (or sub-GLE).

However, we met more complicated cases in our analysis. For example, the count rate exceeded twice the level of 1% (at approximately 07.30 UT and 11.00 UT) in event no. 1 (March 7, 2011) only at one station at the South Pole. Other polar stations showed no enhancement on the background of the usual statistical fluctuations. On the other hand, there are data of the nonstandard installation CARPET [14] that consists of 240 Geiger counters located in Argentinian Andes and at a height of 2550 m above sea level at the points with coordinates of 31.8° S and 69.3° W and with geomagnetic cut-off rigidity $R_c = 9.65$ GV. Unlike NMs, the CARPET installation was more sensitive to low-energy secondary components of CRs, which are formed in the atmosphere of Earth by galactic CR or SCR particles. According to [14], increases in the

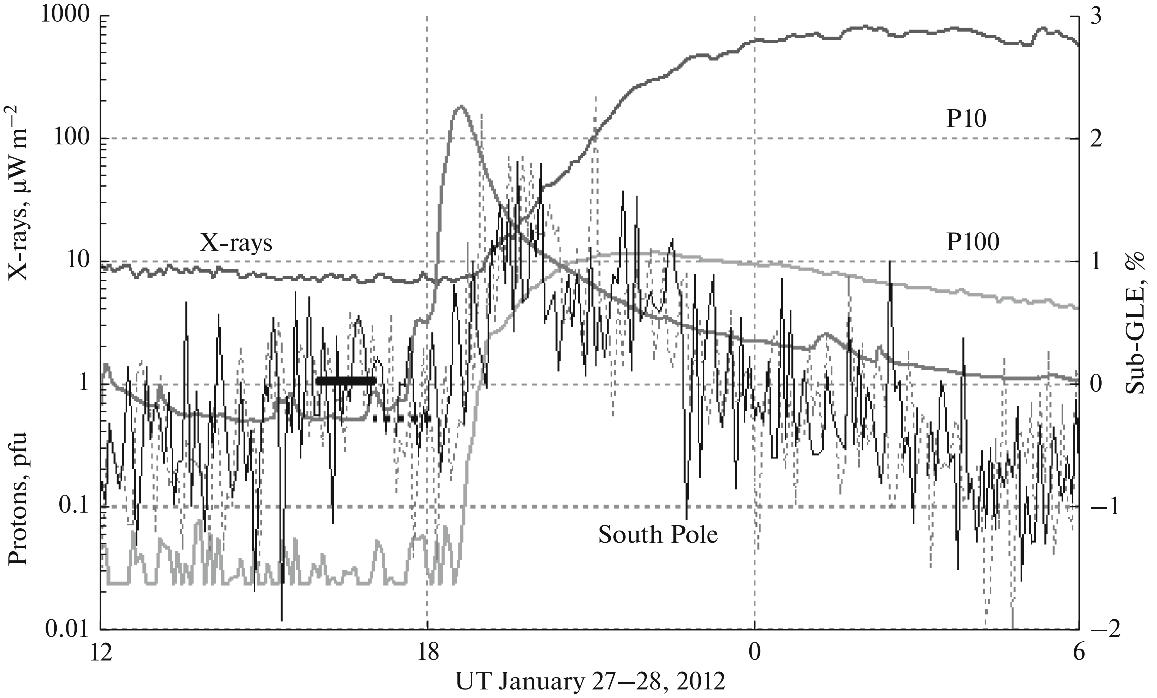

Fig. 1. Choice of the base period for the analysis of the solar proton event on January 27–28, 2012 (semi-thick horizontal line and/or dots).

count rate at a statistical level from 3σ to 10σ were observed on March 7, 2011 within the interval of 20.10–21.40 UT. That means that the solar particles spectrum was very rigid.

3. INTEGRAL SPECTRA NEAR THE GROUND

The other feature of our approach is using the method of integral spectra based on the intensities of particles of this or that energy for the interval of

Table 1. List of the studied SPEs in the 24th solar activity cycle

No.	Event Date	Intensity $I_{\max}$ (>10 MeV), pfu	Location of the source	Flare power	CME velocity, km/s	Comments
1	March 7, 2011	50	N24W59	M3.7/S	NW07/2000	Hidden GLE?
2	Jan. 23, 2012	6310	N28W36	M8.7	2175	Hidden GLE?
3	Jan. 27, 2012	796	N27W71	X1.7	2508	Sub-GLE
4	March 7, 2012	6530	N17E15	X5.4	1825	Hidden GLE?
5	March13, 2012	469	N18W62	M7.9	1884	Hidden GLE?
6	May 17, 2012	255	N12W83	M5.1	1582	GLE071
7	May 22, 2012	1660	N15W70	M5.0	1466	Hidden GLE?
8	July 23, 2012	12	Backside	Backside	Partial halo	Sub-GLE?
9	Nov. 19, 2013	No data	S70W14	No data	No data	Hidden GLE?
10	Jan. 6, 2014	42	S18W102	Backside	Partial halo	Sub-GLE
11	Jan. 6, 2014	1033	S18W11	X1.2	Partial halo	Standard SPE
12	June 7, 2015	No data	No data	No data	No data	Unusual CR increase; Sub-GLE?
13	June 22, 2015	1070	N13W00	M2.0	Full halo	Hidden GLE?
14	Oct. 29, 2015	23	S11W90	No data	No data	Sub-GLE
15	Sept 10, 2017	1490	S08W83	X8.9	Full halo	GLE72

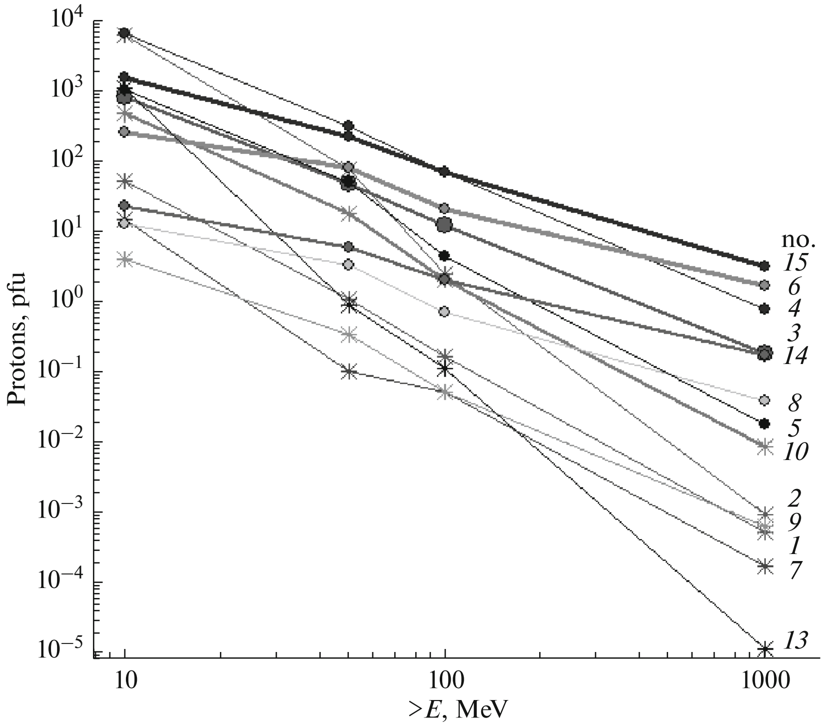

Fig. 2. Integral energy spectra in the power form (TOM-spectra) created for 13 events in Table 1.

10–1000 MeV at the moment of the maximum in the enhancement in Earth's orbit (Time-of-Maximum Method, TOM-method; see e.g., [9]). Figure 2 shows the integral TOM-spectra for 13 SPEs from 15 chosen by us. The spectra were obtained mainly using the data of the SVs of the *GOES* series (from $E_p = 10$ MeV to energies of approximately 700 MeV for protons). A power extrapolation was performed further (to energies of approximately 1000 MeV).

It follows from our preliminary analysis that the near-ground enhancements of SCRs could be observed in the polar regions of Earth only under an empirical condition that the solar particles flux with an energy above 100 MeV is not less than 0.2 pfu. Actually, no solar particles are observed in events nos. 1, 2, 7, 9, and 13. That is only a necessary but not a sufficient condition. Thus, no near-ground enhancement was observed in event no. 2, contrary to expectations. It is widely known [9] that one of the puzzles of SCR spectrum formation is that there is no stable (unambiguous) relation between the fluxes of relativistic and nonrelativistic particles: the ratio of these fluxes changes strongly from one event to another. This property is one challenge that is a deep concern in SCR physics. Moreover, it complicates modeling and calculation of the radiation hazard from SCRs.

4. ACCELERATION BY SHOCK WAVES?

As was noted above, one of the hypotheses checked in our study is the possibility of acceleration of SCRs up to relativistic energies by shock waves in the solar corona and/or in the interplanetary environment. We think that the shape of the accelerated particles spectrum is a crucial argument for and/or against such hypothesis. Unfortunately, no direct information on the SCR spectrum in the source (source spectrum) is available under observations in Earth's orbit. However, there are indirect abilities to determine the spectrum and source based on the data on the shape of the so-called TOM-spectrum near Earth (see above). As it was found long ago, the TOM-spectrum shape manifests in the form of the spectrum in the source, at least for cases when the Earth has a good magnetic relation (via IMF) to the corresponding sources: active regions on the Sun.

The idea of acceleration of particles in space by shock waves (SWs) has been proposed many years ago (see, e. g. [9]) in application to the origin of galactic cosmic rays. On the other hand, still before the discovery of SMEs and the SWs generated by them, it was found that some portion of SCRs could be related to acceleration on the fronts of numerous shock waves in the interplanetary environment. At the same time, the particles could be accelerated up to relativistic energies in specific interplanetary conditions. It was discovered in the observations of such events as those on July 17, 1959, August 4, 1972, and others (see [9]).

Study [15] became the first theoretical attempt to explain the SCR spectrum by SWs. Its authors considered a simplified (linear) version of the Fermi acceler-

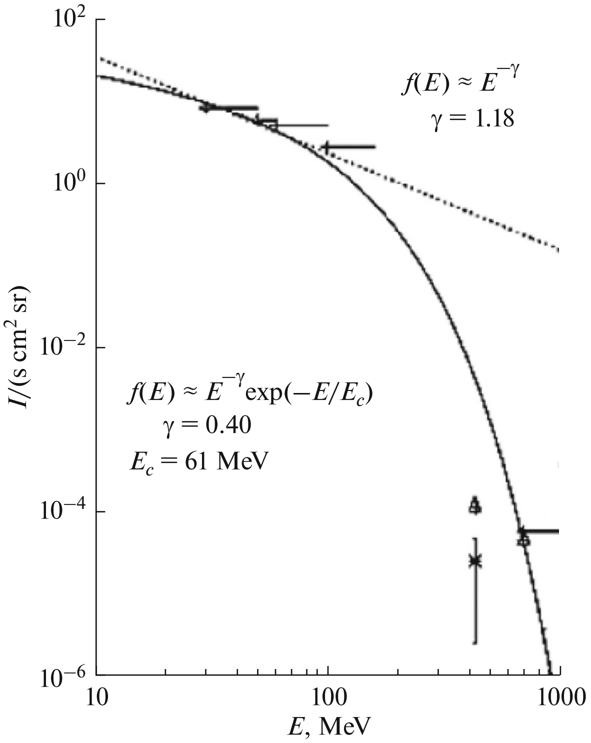

Fig. 3. Integral TOM-spectra based on the measurements on board SV *GOES-13* (left-hand side on top) and estimates [7] based on the NM observations (right-hand side at the bottom) for the sub-GLE on January 6, 2014.

ation of the first order with so-called "diffusive" acceleration during SWs (or "diffusive shock acceleration," DSA; for details see, e.g. [9]). In order to present the SCR differential spectrum, the authors [15] obtained a combination of the power and exponential functions under some simplifying assumptions:

$$dF/dE = c_0 E^{-\gamma} \exp(E/E_c) \tag{1}$$

with exponential cutting off of the spectrum at energy E_c. The following designations are taken here: F is the flux, E is the particle energy, E_c is the cut-off energy, γ is the spectrum exponent, and c_0 is the normalizing coefficient. The authors [15] took that expression (1) is acceptable for a description of the spectrum of both electrons beginning from 100 keV and protons of GLEs with an energy up to 10 GeV, and this very exponential cut-off serves as a sign of acceleration of the DSA during SWs.

In order to check formula (1), the authors [15] have chosen two typical examples: the proton events of June 7 and 21, 1980. Note that the choice of these SPEs for confirmation of the model of acceleration during SWs was, in our opinion, not very successful. Both events were very weak by the proton maximal intensity: they even were not included in the known NASA list (https://umbra.nascom.nasa.gov/SEP/), that was compiled using NOAA criterium. At the same time, the proton energy was within the limited interval of approximately 2–200 MeV. Only pairs of values of γ and E_c obtained by the authors [15], in particular 2.1 and 2.3 and 20 and 30 MeV for the events of June 7 and 21, 1980, respectively, present some interest for further discussion.

In order to base the application of expression (1) to the particle spectrum, [16] could also be mentioned where a few years prior to [15] a simple model of particle acceleration in the region of interaction of two corotating fluxes of interplanetary plasma with allowance for the adiabatic slowing down of particles in the expanding solar wind was considered. The particles are accelerated during reflection from the bow shocks. The model explains some features of the accelerated particles: their exponential spectra in Earth's orbit, the spectra behavior under change in the radial distance, the observed radial gradients of the intensity, and the observed differences in the intensities and spectra under direct and inverse interaction. The obtained solution for distribution function f, which is correct along the magnetic flux tube in the solar wind, could be written in the following form:

$$f \sim v^{-\frac{3}{1-\beta}} \exp\left(-\frac{v}{v_c}\right). \tag{2}$$

Here $\beta \cong B/B'$ is the ratio of the magnetic fields in front of the bow shock and behind it; v is the particle velocity; $v_c = V(1-\beta^2)/6k_0\beta$; V is the solar wind velocity; κ_0 is the constant that normalizes diffusion coefficient $\kappa = \kappa_0 vr$, and r is the radial distance. The form of exponential expression (2) manifests the dependence of the path length of the particle (and finally, the diffusion coefficient) on the energy that is different for particles of small energies and particles, which are usually registered in Earth's orbit as SPEs.

Transforming formula (1) for integral intensities $I(>E)$, we will apply it to the sub-GLE of January 6, 2014 (no. 10). Figure 3 shows the integral spectra of protons measured on SV *GOES-13* (up to 100 MeV), and also estimates of the absolute intensity of the relativistic particles according to NM data [7]. The asterisk shows the intensity of protons $I(>433$ MeV) that was estimated by the integral multiplicities method; the triangles show the estimates by the spectrographic global survey for proton integral intensity $I(>433$ MeV) and $I(>700$ MeV) (for details see [7]). Figure 3 shows that approximation (1) is not acceptable for description of the spectra within the entire energy interval of 10–1000 MeV (even with allowance for the measurements on board SV *GOES-13* and the scatter of estimates based on NM data). It should be specified using the data from the "intermediate" energy region of 200–300 MeV, in particular, using the new abilities for CR observations at Concordia station [8].

Figure 4 shows the observational data for event no. 14 (October 29, 2015) that was taken by the

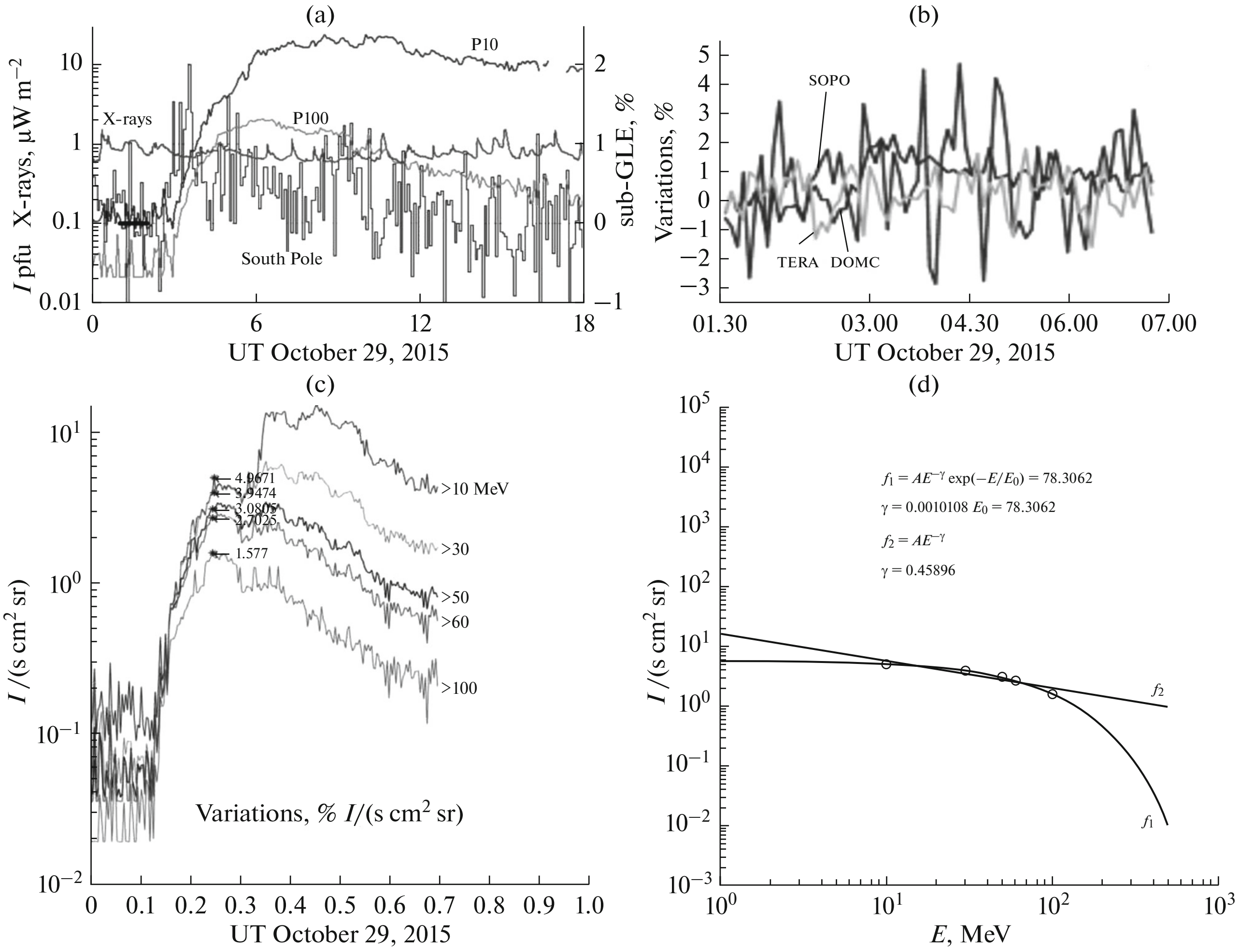

Fig. 4. (a) Time profiles of the integral count rate at the NM South Pole, (b) the data of three Antarctic stations including DOMC [18], (c) the integral intensities of the solar protons measured on board SV *GOES-15*, and (d) our approximations of the *GOES-15* data by formula (1) and power function.

authors [8] as sub-GLEs. The effect was observed at the polar NMs Apatity, McMurdo, South Pole, South Pole-B, Thule, and Tixie Bay. The panels show the following data: on top, the left-hand side (a) measurements on board of SV *GOES-15* for protons with energies $E_p \geq 10$ and ≥100 MeV, and also the 5-min data of NM South Pole; on top, the right-hand side (b), similar data of three Antarctic NMs, including the DOMC station [17, 18]; at the bottom, on the left-hand side (c), integral intensities of solar protons according to the measurements on board *GOES-15*; at the bottom, the right-hand side (d), our approximation of *GOES-15* data by formula (1) and the power function.

Figure 4 (the right-hand panel at the bottom) shows that the approximation of the TOM-spectrum by (1) during event no. 14 based on the *GOES-15* data is possible, however for final determination, the data on absolute SCR fluxes within the energy range of a few hundred MeV are needed. According to the site https://gle.oulu.fi, besides no. 10 and no. 14, the events on January 27, 2012 (no. 3), March 7, 2012 (no. 4), and June 7, 2015 (no. 12) could be considered as sub-GLEs. Thus, at least five sub-GLEs were revealed in the 24th solar activity cycle.

5. DISCUSSION AND PRELIMINARY CONCLUSIONS

The data of Table 1 are not complete, controversial, and some raise questions. For example, the results of forecasting GLEs for events no. 12 and no. 14 raise some doubts [19]. According to estimates of authors of [19], event no. 12 formally was put into the forecasting interval between February 1, 2015 and June 30, 2015, however, as far as we know, no real GLEs were observed within the indicated period. At the same time, three SPEs with maximum intensities of protons above 10 MeV (in pfu units) of 16, 1070 (no. 13 in our list), and 22 according to the NOAA criterion (https://umbra.nascom.nasa.gov/SEP/), on

June 18, 22, and 27, respectively, were registered in June 2015. Event no. 13, according to our opinion, could belong to "hidden" GLEs.

As for event no. 14, the forecasting interval was indicated in [19] as August 11–December 2, 2015. On the other hand, the authors [18] have claimed recently that two NMs (South Pole and DOMC) registered on October 29, 2015 an increase in the count rate caused by the arrival of SCRs (see Fig. 4, the right-hand top panel). At the same time, however, the maximal intensity of protons with an energy above 10 MeV was only 23 pfu according to NOAA criterion.

In spite of existing uncertainties, we think that the information presented above will be useful for further studying weak GLEs (or hidden GLEs, or sub-GLEs). It is especially true, if one considers a theoretical possibility that some portion of SCRs could be accelerated up to relativistic energies during SWs, which are generated by coronal mass ejections. Such a possibility was accepted, in particular, while analyzing GLE71 (May 17, 2012) [20]. The same assumption was used for the interpretation of the properties of a sub-GLE observed on January 6, 2014 [6, 7]. Event no. 15 (GLE72, September 10, 2017) deserves special attention: it happened at the declining phase of the 24th cycle (in the vicinity of its minimum). From the point of view of space weather, the entire disturbed period of September 4–10, 2017 presents certain interest.

An absolutely unexpected aspect of the discussed problem was revealed recently [21] while analyzing SCR effects in the anti-coinciding protection of ACS (scintillation BGO detector with a weight of 512 kg) that was screening the SPI spectrometers on board the orbital astrophysical observatory INTEGRAL. It is widely known that the beginning of the near-GLE registered by one or several NMs of the global network is taken traditionally as the arrival time of protons with relativistic energy. Uncertainty and ambiguousness in determination of the moment of solar proton arrival by the NM data is caused by both the proper background noise of the detector (the statistical accuracy of the registration) and variations in the threshold of the geomagnetic cut-off rigidity and directions of the cones of acceptance for arriving particles.

The authors [21] drew attention to the fact that in some cases of GLEs, the enhancements in the count rate in the ACS detector were observed earlier than at a ground-based NM. Two cases were found when the ACS detector SPI was a more efficient instrument for observation of the beginning of the SPE–GLE in Earth's orbit than the NM network: on January 17, 2005 (GLE68) and December 13, 2006 (GLE70). These events were rather weak in enhancement amplitude, however the delay in the arrival of the relativistic protons to the Earth relative to the burst of hard X-rays was taken as significant and manifested in later acceleration of the protons. At the same time, the enhancement in the count rate of ACS SPI caused by the arrival of the relativistic protons was observed earlier and corresponded to the acceleration of SCRs at the moment of the flare. This fact emphasizes the need for creation of solar proton and electron detectors for spacecrafts with a low level of proper background noise. Such detectors are needed for measurements of SCR fluxes of small intensity (the hidden GLEs problem). Actually, unlike in the two weak GLEs noted above [21], in two other (extremally powerful) events, on October 28, 2003 (GLE65) and January 20, 2005 (GLE69), the solar protons arrival to ACS SPI was observed simultaneously with the beginning of the anisotropic enhancement at the NM network, i.e., coincided with the arrival of the SCR rapid component (for details see [9] and the reference therein).

Thus, our preliminary results still provide no unambiguous answer to the question on the possible nature of the source (sources) of the minor near-ground enhancements in SCRs. More detailed and thorough analysis of 15 events in our list will be the subject of a separate paper.

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