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Solar Cosmic Rays: 70 Years of Ground-Based Observations

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Abstract—The main data have been summarized, and the results, achieved using data from the worldwide network during the entire period of ground-based observations of solar cosmic rays (SCRs) from February 28, 1942, when they were discovered, have been generalized. The methods and equipment for registering SCRs have been described. The physical, methodical, and applied aspects, related to the SCR generation, as well as the SCR interaction with the solar atmosphere, transport in the IMF, motion in the Earth's magnetosphere, and the affect on the Earth's atmosphere, have been discussed. It has been indicated that the fundamental results were achieved in this field of space physics during 70 years of studies. Special attention has been paid to up-to-date models and concepts of ground-level enhancement (GLE). The most promising tendencies in the development and application of this effective method of solar–terrestrial physics have been outlined.

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1. INTRODUCTION

Accelerated solar particles, which have long been known as solar cosmic rays (SCRs), have been studied for ~70 years using different methods. Many comprehensive reviews and monographs were published during this period, namely, (Elliot, 1952; Dorman, 1958; Carmichael, 1962; Dorman and Miroshnichenko, 1968; Sakura, 1974; Pomerantz and Duggal, 1974; Duggal, 1979; Dorman and Venkatesan, 1993; Reames, 1999; Ryan et al., 2000; Miroshnichenko, 2001; Miroshnichenko and Pérez-Peraza, 2008). Dorman (1957, 1963) considered in detail the SCR problem in the scope of a more general problem of cosmic ray (CR) variations. Different methodical, experimental, and general physical SCR investigation aspects, specific features of interaction between SCRs and the solar atmosphere, SCR geophysical effects, the possible SCR contribution to the problem of solar-terrestrial relations, and certain present-day applied aspects were subsequently described in the monographs (Miroshnichenko, 2001, 2003, 2011). At the turn of the 1990s (Simpson, 1990; Cliver, 2009), the international name GLE (ground-level enhancement or ground-level event) was assigned to ground-level SCR enhancements. Seven papers of foreign authors, devoted to different GLE aspects, have been recently published in a special issue of the journal *Space Science Reviews* (2012, vol. 171). Such interest in the problem undoubtedly reflects its fundamental character.

At the same time, the last Russian review on SCRs was published more than 20 years ago (Miroshnichenko, 1992). Therefore, the proposed new review and references are first of all intended for Russian-speaking readers. We first describe the informatory history of the problem (Section 2), recording equipment, and the main results of ground-based SCR observations for 70 years (Section 3). In Section 4, we briefly describe the present-day method for analyzing GLEs and try to justify a new concept of this phenomenon. Then, we discuss the fundamental physical aspects, namely, the maximal SCR energy (Section 5), as well as the relationship between SCRs and coronal mass ejections (CMEs) and the GLE registration frequency (Section 6). In Section 7, we illustrate the SCR geophysical effects and demonstrate that data of ground-based observations can be used to predict radiation hazard in space. The prospects of studying SCRs/GLEs are considered in Section 8.

2. BRIEF HISTORY OF THE PROBLEM

In the history of science, specific date can rather rarely be assigned to the origination of a new trend. However, precisely such a situation is typical of SCRs: on February 28, 1942, ground detectors for the first time registered that accelerated solar protons arrived to the Earth. A new similar event was registered on March 7, 1942 (Lange and Forbush, 1942). This was one of the greatest astrophysical discoveries of the 20th century: it turned out that charged particles can be accelerated to high energies in space. However, researchers realized this fundamental fact and its close relation to solar flares with a certain delay. Only after the registration of the third similar event on July 25, 1946, the author of this discovery (Forbush, 1946) wrote with caution that these observations "... make it possible to draw a rather unexpected conclusion that all three unusual CR intensifications can be explained by fluxes of charged particles emitted by the Sun." After the fourth ground-level increase in SCRs on November 19, 1949 (Adams, 1950; Forbush et al., 1950; Krasil'nikov et al., 1955), the relationship between the observed relativistic particles and solar flares became an unquestionable fact, which initiated a new presentable concept.

Seventy GLEs were registered from February 1942 to December 2006 (Miroshnichenko and Pérez-Peraza, 2008). From February 28, 1942 (GLE01), all events were numbered for the convenience of researchers. The last event in cycle 23 of solar activity (SA) was observed on December 13, 2006 (GLE70). In cycle 24 (started in January 2009), proton solar activity was registered with a delay: the first GLE in the new cycle occurred only on May 17, 2012 (GLE71). To all appearance, this pause not only reflects the specific properties of cycle 23 (in particular, a very long period of SA minimum) but also characterizes the unusual character of cycle 24, which is most probably a critical cycle in the SA behavior for the last 150–200 years.

On February 26–28, 1942, the British radar station for the first time registered intense radio noise in the range of meter waves (4–6 m) from the direction toward the Sun (Chupp, 1996). Later it became clear that this emission, caused by accelerated electrons, was related to the active region (AR) that crossed the central solar meridian (CSM). To all appearance, a powerful 3+ solar flare (07° N, 04° E) occurred precisely in this AR on February 28, 1942 (Pomerantz and Duggal, 1974; Duggal, 1979). Thus, in addition to the discovery of SCRs, another important event in solar studies occurred in February 1942: solar radioastronomy originated at that time, which was only reported in 1946 (Hey, 1946).

In the 1940s, observations and data on SA manifestations (e.g., as noise for radiodetection and tracking equipment) were hidden below a dense veil of secrecy between warring parties in the Second World War (Smart and Shea, 1989). Moreover, at that time, CRs were studied only in the scope of nuclear physics and results were also partially (United States) or completely (Germany and Soviet Union) made secret because nuclear weapon was being developed (Krivonosov, 2000; Gubarev, 2004). From 1941 to 1943, different European and American groups observed other increases of CR intensity that resembled solar flare effects (Chupp, 1996). However, the hypothesis that similar effects are of the solar origin was scientifically acknowledged only after the GLEs registered in 1946 and 1949. This was the first meaningful result in this field of knowledge: it was detected that protons are accelerated in space (in stellar atmospheres). This happened still before 1953, when synchrotron (or magneto-bremsstrahlung) radiation, which indicated that similar electron acceleration processes proceed in Galaxy (e.g., during Supernova bursts), was discovered in Crab Nebula. It is important to emphasize that researchers started studying SCRs by analyzing ground-based observations almost 30 years after the historical discovery of galactic cosmic rays (GCRs) in August 1912 by V. Hess.

3. WORLDWIDE NETWORK OF STATIONS AND OBSERVATIONAL DATA

Ground-based observations of the secondary components (mainly muons and neutrons) are still the most reliable source of data on primary relativistic SCRs. Ionization chambers (ICs), muon telescopes (MTs), and neutron monitors (NMs, from the mid-1950s) were the first detectors that were used to register GLEs. When SCRs are registered, these standard detectors at sea level have effective energies of ~25–35, 15–20, and 4–6 GeV, respectively (Miroshnichenko, 2001). Neutron detectors were for the first time used to register GLEs during the event of November 19, 1949 (Adams, 1950). Geomagnetic cutoff rigidity of particles (R_c) during their motion in the Earth's magnetosphere is one of the main CR station characteristics.

3.1. Worldwide Network of Stations

The worldwide network of NMs was created more than 50 years ago based on IGY-type NMs. Data acquisition and analysis systems were constantly modernized, and a new modification of such a system—a SNM-64 neutron supermonitor (Carmichael, 1968)—was designed in the early 1960s. The statistical accuracy of this device during one hour of registration is 0.24% at the Apatity latitude (67.57° N, 33.4° E, 181 m above sea level, $R_c = 0.65$ GV) at a solar activity minimum, when the GCR intensity is maximal. For the Apatity station, this is approximately three times as high as the IGY-type NM registration accuracy (0.81%). This value is ~0.18% for Moscow (55.47° N, 37.32° E, 200 m above sea level, $R_c = 2.44$ GV) and is close to 0.36% at the Mexico latitude (2274 m above sea level, 99.2° W, 19.33° N, $R_c = 8.2$ GV). The registration accuracy depends on a station's height above sea level and latitude (more exactly, R_c) and on the number of SNM-64 counters in a detector, which is not always standard. A high accuracy makes it possible to measure the fine structure of SCR flux time profiles (with a resolution reaching 1 min and even 10 s) and subsequently construct more accurate models of SCR acceleration, release, and propagation.

The present-day worldwide network for continuous CR registration includes ~50 stations equipped mainly with SNM-64 supermonitors, the data of which form the MNDB international database. Differently designed ground MTs make it possible to register SCRs arriving at large angles to the vertical. Several underground MTs are also used to register extreme events, such as the event of September 29, 1989 (GLE42) (Krymsky et al., 1990; Swinson and Shea, 1990; Miroshnichenko et al., 2000). Ground-level events often give secondary muon intensity bursts registered with non-standard instruments, which were designed in order to solve astrophysical problems and study the nuclear effects of GCRs (Karpov et al., 1998). These observations are satisfactorily completed with the network of solar neutron telescopes (SNTs) (Flückiger et al., 1998), which register the arrival of secondary neutrons generated by primary accelerated ions in the solar atmosphere.

The data of the worldwide network make it possible to estimate maximal SCR energy E_m (or particle magnetic rigidity R_m) factually at the upper limit of geomagnetic cutoff rigidity R_c (i.e., near $R_c = 17$ GV at the geomagnetic equator). Thus, standard detectors indicated that $R_m = 20.0(+10, -4)$ GV for the giant event of February 23, 1956 (GLE05). Non-standard detectors make it possible to advance into the region of energies much higher than 20 GeV (Miroshnichenko, 1994). For example, in the same event (GLE05), inclined muon telescopes in India registered relativistic solar protons with energies of 35–67.6 GeV. Observations, performed using underground detectors oriented toward the Sun, indicate that solar protons can be accelerated to energies of ~100–200 GeV (Schindler and Kearney, 1973) and even to $E_p \geq 500$ GeV (Karpov et al., 1998). The latter assumption, however, is still doubtful.

3.2. GLE Statistics

The first GLE events (before 1956) were registered at sparse stations equipped with ICs and MTs, which were mainly intended for measuring one hard (muon) component. Since the effective registration energy of NMs is lower than that of MTs and ICs, the latter detectors are less sensitive to SCRs. A special technique (Shea and Smart, 1982; Humble et al., 1991; Cramp et al., 1997; Vashenyuk et al., 2009a, 2009b), which takes into account the anisotropy of SCRs fluxes that approach the Earth, steep energy spectrum of SCRs, and the high NM sensitivity, is used to identify GLEs. At the same time, some weak GLEs (~1–10%) were registered only at high-latitude or polar stations. It is interesting that the last event in cycle 23 (GLE70; December 13, 2006) was registered not only at the worldwide NM network but also with non-standard ground detectors, specifically, with the URAGAN muon hodoscope (Timashkov et al., 2007). Moreover, this GLE was also registered with the IceTop extensive air shower (EAS) detector, which is the component of the Ice Cube neutrino telescope in Antarctica (Abbasi et al., 2008). All GLEs registered from 1942 to 2012 are listed in Table 1.

Based on Table 1, we can assume that some weak GLEs were not registered in the early years of observations due to technical and methodical difficulties. If the average occurrence rate of these GLEs is $\eta \sim 1.0$ yr^{-1}, the number of omitted events in 1942–1956 could be considerable (Miroshnichenko et al., 2012). A prolonged minimum of cycle 23 ended in December 2008; however, cycle 24 (started in January 2009) proceeds very slowly (flabbily), and sunspot formation and solar flare and proton activities are generally at a rather low level. Thus, only one GLE was registered during more than four years of the cycle (August 2013).

3.3. Near-Earth SCR Spectrum

The data on solar proton events (SPEs), which were characterized by the maximal particle intensity near the Earth's orbit, were generalized (Miroshnichenko, 1994) in order to model "the worst case" from the standpoint of radiation hazard in space (Smart and Shea, 1989; Miroshnichenko, 2003). Such events also included GLEs registered in February 1956 (GLE05), November 1960, August 1972, and September–October 1989. This generalization made it possible to construct the Upper Limit Spectrum (ULS)—integral SCR spectrum in a wide range of energies at least between $E_p \geq 1$ MeV and $E_p \geq 10$ GeV. The ULS was constructed based on the maximal $I_p(t_m)$ proton intensities at the moments t_m of maximum increase near the Earth (the so-called "time-of-maximum-method" (Miroshnichenko and Pérez-Peraza, 2008)). This spectrum can be approximated by a power function with an index dependent on the proton energy, namely, $\gamma = \gamma_0 E^a$, where a ($a = 1.0$ at $E_p \geq 1$ MeV). The main parameters of the ULS are presented in Table 2, where the intensity values are given in standard units *pfu* (1 *pfu* = 1 cm^{-2} s^{-1} sr^{-1}).

The upper limit spectrum was constructed so that the measuring errors would be exceeded and the methodical uncertainties, which originate when the spectrum is reconstructed from ground-based observations, would be eliminated. For this purpose, all spectral points on the plot (Miroshnichenko, 1994) were "lifted" by approximately an order of magnitude relative to the largest measured (estimated) $I(>E_p)$ values for each energy threshold in Table 2. Factor ~10 was selected so that the determined (assumed) uncertainties in the $I_p(t_m)$ values would be exceeded. Recently, based on the nitrate content of Greenland ice cores, McCracken et al. (2001) managed to determine the fluence of ≥30-MeV protons for the giant event of September 1–2, 1859. Our analysis (Miroshnichenko and

Table 1. Main characteristics of SCR GLEs from 1942 to 2012

GLE number	Registration date	Flare position	Onset UT	Importance Hα/X	GLE number	Registration date	Flare position	Onset UT	Importance Hα/X
1	Feb. 28, 1942	07N 04E	1228	3+	37	Nov. 26, 1982	12S 87W	0230	2B/X4
2	Mar. 7, 1942	07N 90W	N.O.	–/–	38	Dec. 7, 1982	19S 86W	2341	1B/X2.8
3	July 25, 1946	22N 15E	1615	3+	39	Feb. 16, 1984	–S ~130W	<0858	–/–
4	Nov. 19, 1949	03S 72W	1029	3+	40	July 25, 1989	26N 85W	0839	2N/X2
5	Feb. 23, 1956	23N 80W	<0334	3	41	Aug. 16, 1989	15S 85W	0058	2N/12.5
6	Aug. 31, 1956	15N 15E	1226	3	42	Sept. 29, 1989	24S ~105W	1141	1B/X9
7	July 17, 1959	16N 31W	2114	3+	43	Oct. 19, 1989	25S 09E	1229	3B/X13
8	May 4, 1960	13N 90W	1000	3	44	Oct. 22, 1989	27S 32W	1708	1N/X2.9
9	Sept. 3, 1960	18N 88E	0037	2+	45	Oct. 24, 1989	29S 57W	1738	2N/X5.7
10	Nov. 12, 1960	27N 04W	1315	3+	46	Nov. 15, 1989	11N 28W	0638	2B/X3.2
11	Jan. 15, 1960	25N 35W	0207	3+	47	May 21, 1990	34N 37W	2212	2B/X5.5
12	Nov. 20, 1960	28N ~112W	2017	2	48	May 24, 1990	36N 76W	2046	1B/X9.3
13	July 18, 1961	07S 59W	0920	3+	49	May 26, 1990	~35N,103W	2045	–/–
14	July 20, 1961	06S 90W	1553	3	50	May 28, 1990	~35N120W	<0516	–/–
15	July 7, 1966	35N 48W	0025	2B	51	June 11, 1991	32N 15W	0105	2B/X12
16	Jan. 28, 1967	22N ~150W	<0200	–/–	52	June 15, 1991	36N 70W	0633	3B/X12
17	Jan. 28, 1967	22N ~150W	<0800	–/–	53	June 25, 1992	09N 69W	1947	1B/M1.4
18	Sept. 29, 1968	17N 51W	1617	2B	54	Nov. 2, 1992	~25S~100W	0231	–/X9
19	Nov. 18, 1968	21N 87W	<1026	1B	55	Nov. 6, 1997	18S 68W	1149	2B/X9.4
20	Feb. 25, 1969	13N 37W	0900	2B/X2	56	May 2, 1998	15S 15W	1334	3B/X1.1
21	Mar. 30, 1969	19N 103W	<0332	1N	57	May 6, 1998	11S 65W	0758	1N/X2.7
22	Jan. 24, 1970	18N 49W	2215	3B/X5	58	Aug. 24, 1998	18N 09E	2148	3B/M7.1
23	Sept. 1, 1971	11S 120W	<1934	–/–	59	July 14, 2000	22N 07W	1003	3B/X5.7
24	Aug. 4, 1972	14N 08E	0617	3B/X4	60	Apr. 15, 2001	20S 85W	1319	2B/X14.4
25	Aug. 7, 1972	14N 37W	1449	3B/X4	61	Apr. 18, 2001	23S 117W	0211	–/–
26	Apr. 29, 1973	14N 73W	2056	2B/X1	62	Nov. 4, 2001	06N 18W	1603	3B/1.3
27	Apr. 30, 1976	08S 46W	2047	2B/X2	63	Dec. 26, 2001	08N 54W	0432	–/M7.1
28	Sept. 19, 1977	08N 57W	<0955	3B/X2	64	Aug. 24, 2002	02S 81W	0049	–/X3.1
29	Sept. 24, 1977	10N 120W	<0552	–/–	65	Oct. 28, 2003	16S 08E	1100	4B/X17.2
30	Nov. 22, 1977	24N 40W	0945	2B/X1	66	Oct. 29, 2003	19S 09W	2037	–/X10
31	May 7, 1978	23N 72W	0327	1N/X2	67	Nov. 2, 2003	18S 59W	1718	2B/X8.3
32	Sept. 23, 1978	35N 50W	0944	3B/X1	68	Jan. 17, 2005	15N 25W	0659	3B/X3.8
33	Aug. 21, 1979	17N 40W	0550	2B/C6	69	Jan. 20, 2005	14N 61W	0639	2B/X7.1
34	Apr. 10, 1981	07N 36W	1632	2B/X2.3	70	Dec. 13, 2006	06S 23W	0217	4B/X3.4
35	May 10, 1981	03N 75W	0715	1N/M1	71	May 17, 2012	07N 88 W	0125	1F/M5.1
36	Oct. 12, 1981	18S 31E	0615	2B/X3.1					

Nymnik, 2013) indicated that these data confirm the ULS concept with accuracy to a factor of ~7.

The upper limit spectrum is not only applied to the radiation hazard problem but also forms the reference interval of SCR fluxes used to solve the fundamental physical problem, namely, to estimate the maximal possibilities of a particle accelerator (accelerators) on the Sun or near it. This aim has not yet been achieved. At the same time, it has been confirmed with certainty that the spectrum slope tends to change ("roll-off") in the region of high energies. However, the available data in the region of extremely high energies are still insufficient for us to determine the E_m value for SCR protons. This is still a problem to be solved in spite of the fact that the statistics reached 71 GLEs (Table 1).

The spectra for the events in the last solar cycle were summarized in (Wang, 2009). After an outstanding relativistic event on September 29, 1989 (GLE42),

Table 2. Parameters of upper limit spectrum for SCR

E_p, eV	$>10^6$	$>10^7$	$>10^8$	$>10^9$	$>10^{10}$	$>10^{11}$
γ-index	1.0	1.45	1.65	2.2	3.6	>4.0
$I(>E_p)$, *pfu*	10^7	10^6	3.5×10^4	8×10^2	1.2×10^0	7×10^{-4}

their list was completed with a very large event on January 20, 2005 (GLE69), which was mainly registered with NMs. Standard MTs apparently did not register any increase, although some non-standard muon detectors registered statistically significant effects. Moreover, this GLE caused us to review the entire hierarchy of these events based on the maximal increase at relativistic energies (Miroshnichenko and Pérez-Peraza, 2008). The events were ranked now as shown in Table 3 (N.O. means that observations were absent). Event GLE69 occupies the second raw in the list according to the NM data, GLE04 (November 19, 1949; data of NMs and muon detectors) is replaced to the third raw, and GLE42 with a very hard spectrum occupies only the fourth raw. However, an outstanding GLE05 event remains the event of rank 1.

Note that the SPE hierarchy strongly depends on the key classification parameter (the interval of energies (rigidities), spectrum shape, intensity, fluence, etc.). For example, a considerable flux of relativistic particles does not mean that a powerful flux of protons will also be observed in the nonrelativistic region. Similarly, an abundant flux of nonrelativistic particles cannot unambiguously indicate that the flux of relativistic SCRs is large. As a result of this spectral peculiarity, it is very difficult to model SCR acceleration processes (Miroshnichenko and Pérez-Peraza, 2008) and construct models and methods for predicting radiation hazard (Miroshnichenko, 2003).

4. GLE ANALYSIS PROCEDURE

To determine SCR characteristics outside the Earth's atmosphere, it is necessary to calculate the coefficients characterizing the relationship between the flux of primary CRs incident on the atmospheric boundary and the response expressed in terms of the device (e.g., NM) count rate. As coupling coefficients, many researchers use the so-called NM specific yield function (Debrunner et al., 1984), which covers the range of rigidities from ~1 to ≥20 GV with an acceptable accuracy. In this context, it is important to note that the SCR spectrum is usually much steeper (softer) than the GCR spectrum. This difference was very useful for determining the SCR spectrum during large GLEs since the superposition of two CR fluxes (galactic and solar) results in a substantial change in the properties of the secondary components.

This first of all manifests itself in a path change for the absorption of secondary components in the lower atmosphere, i.e., in a change in the barometric coefficient (β), which is especially important for the neutron component. The reciprocal of the barometric coefficient ($\lambda = 1/\beta$) is called absorption length in the atmosphere (this is a path on which particle flux decreases by a factor of *e*). The procedure for taking into account the barometric effect in the presence of two components (galactic and solar) with different paths for absorption λ_g and λ_s, respectively, was developed more than 50 years ago (McCracken, 1962) and was subsequently developed in (Wilson et al., 1967; Kaminer, 1967). Specifically, Wilson et al. (1967) proposed a method used to directly measure absorption length λ_s based on data from a pair of suitable NMs. For example, on January 28, 1967, GLE17 was registered with two Canadian NMs (Calgary and Sulfur) at altitudes of 1128 and 2283 m, respectively. These two stations have very close geomagnetic cutoff rigidities and cones of acceptance, which made it possible to directly determine the λ_s value: $\lambda_s = 103 \pm 3$ g cm^{-2}. When the method of two absorption lengths is used, the following values are as a rule accepted: $\lambda_g = 140$ g cm^{-2} for neutrons produced by GCRs, and $\lambda_f = 100$ g cm^{-2} in the case of SCRs.

4.1. Basic Procedure

The NM network distributed over the globe can be considered as an integrated omnidirectional spectrometer for measuring relativistic SCR flux characteristics outside the Earth's magnetosphere. Modeling the NM response to an anisotropic SCR flux and solving the inverse problem, we can obtain the characteristics of relativistic solar protons outside the Earth's magnetosphere (Shea and Smart, 1982; Humble et al., 1991; Cramp et al., 1997; Vashenyuk et al., 2009a, 2009b). Data from 25 NM stations and a sufficient

Table 3. Amplitude of GLE events (%) during cycles 17–23

Rank	Date/Detector	IC	MT	NM
1	Feb. 23, 1956	300	280	4554 (15-min)
2	Jan. 20, 2005	N.O.	13	4527.4 (1-min)
3	Nov. 19, 1949	41	70	563
4	Sept. 29, 1989	N.O.	41	373
5	July 25, 1946	20	N.O.	N.O.
6	Feb. 28, 1942	15	N.O.	N.O.
7	Mar. 7, 1942	14	N.O.	N.O.

ground-level increase (≥10%) should be used in this basic procedure. Therefore, this procedure is as a rule used to study only rather large events. In this case, the main SCR characteristics—the energy spectrum, anisotropy, and pitch angle distribution—are determined by optimization methods when model NM responses are compared with observed responses. The SCR flux parameters determined at successive instants make it possible to trace the flux dynamics. The analysis methods include the determination of the SCR arrival asymptotic directions by calculating the trajectories of these particles in present-day geomagnetic field models. Following the newest narrative of the method (Vashenyuk et al., 2009a, 2009b), we cite below certain important details that are used to determine the SCR spectrum and anisotropy and describe other GLE properties.

A neutron monitor has a specific directional pattern. When the zenith angle increases, the particle flux weakening due to absorption is accompanied by an increase in the device spatial angle of acceptance. This results in the appearance of a pattern maximum, which is reached at zenith angles of $\theta = 20°$ and 18° for GCRs and SCRs, respectively. The CR arrival asymptotic directions are determined by integrating the motion equation for a negative test particle with the proton mass emitted upward from an altitude of 20 km above a given station (this is the average altitude of production of secondary neutrons contributing to the NM counting). Optimization methods can be used to obtain the SCR parameters based on the NM network data. The expression for the function of the NM response to an anisotropic flux of solar protons has the form (Vashenyuk et al., 2009a, 2009b)

$$\left(\frac{\Delta N}{N_g}\right)_j = \frac{1}{8}\,\frac{\sum\limits_{(\varphi,\vartheta)=1}^{8}\sum\limits_{R_{\min}}^{R_{\max}} J_{\|}(R)F(\theta(R))S(R)A_{(\varphi,\vartheta)}(R)\Delta R}{N_g}, \quad (1)$$

where $(\Delta N/N_g)_j$ is the relative increase in the NM count rate at station j; N_g is the GCR background before an increase; $J_{\|}(R) = J_0 R^{-\gamma*}$ is the rigidity differential spectrum from the direction of a source with a variable inclination; $\gamma* = \gamma + \Delta\gamma(R - 1)$ (where γ is the power spectrum index at $R = 1$ GV); $\Delta\gamma$ is the γ increment rate at 1 GV; and J_0 ($\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GV}^{-1}$) is the normalization constant. Such a representation form makes it possible to describe the spectrum with an arbitrary shape using three parameters: γ, $\Delta\gamma$, and J_0 (Cramp et al., 1997). Other parameters in expression (1) are as follows: $S(R)$ is the specific yield function (Debrunner et al., 1984); $\theta(R)$ is the pitch angle at a given rigidity (more exactly, the angle between the asymptotic direction for a given rigidity and the anisotropy calculation axis, specified by coordinates Φ and Λ, in the solar–ecliptic coordinate system GSE); $A(R) = 1$ and 0 for allowed and forbidden trajectories, respectively; and $F(\theta(R)) \sim \exp(-\theta^2/C)$ is the SCR pitch angle distribution with characteristic parameter C.

The first sum in formula (1) takes into account the contribution of all eight sectors, into which the device spatial angle of reception is divided, to the NM response (Vashenyuk et al., 2009a, 2009b). The sum also takes into account the contribution of particles obliquely incident on NMs. The second sum results from the summation of all NM response parts with respect to all rigidities varying from 1 to 20 GV at the interval $\Delta R = 0.001$ GV. In expression (1), the NM responses are calculated successively at different values of the solar proton anisotropic flux parameters outside the Earth's magnetosphere (Φ, Λ, J_0, γ, $\Delta\gamma$, C). The optimization method is subsequently used to determine the values of these parameters at each given instant by comparing the calculated responses of ground detectors with the observed ones. The following system of conditional equations for searching the function minimum is solved for this purpose:

$$F = \sum_j \left[\left(\frac{\Delta N}{N}\right)_j^{\mathrm{calc}} - \left(\frac{\Delta N}{N}\right)_j^{\mathrm{obs}}\right]^2 \Rightarrow \min, \quad (2)$$

where superscripts correspond to the jth NM responses, calculated using formula (1) and obtained from observations. The observed pitch angle distribution cannot always be described by a function close to the Gaussian function or by a combination of two oppositely directed fluxes, which is observed in the cases of the so-called bidirectional anisotropy. Vashenyuk et al. (2009a, 2009b) used the expression for the complex pitch angle distribution, which makes it possible to obtain good convergence of the optimization process:

$$F(\theta(R)) \sim \exp\left(-\theta^2/C\right)\left(1 - a\exp\left(-(\theta - \pi/2)^2\right)\right/b. \quad (3)$$

Such a function has a peculiarity when the pitch angle is close to $\pi/2$ and can theoretically take into account the pitch angle distribution peculiarities predicted by the theory of particle propagation in the IMF (Toptygin, 1983; Bazilevskaya and Golynskaya, 1989). According to its properties, expression (3) is close to the function that was used to describe complex pitch angle distribution cases (Cramp et al., 1997). When function (3) is used, two more parameters (a and b) are added to the six SCR flux parameters listed above. When a and b are zero, expression (3) is transformed into an ordinary Gaussian function.

We should note that many researchers have tried to modernize the basic GLE analysis procedure described above over the last decades (Lovell et al., 1998; Belov et al., 2005; Bombardieri et al., 2006; Krymsky et al., 2008; Firoz et al., 2010; Andriopoulou et al., 2011). However, in contrast to the complex analysis of SCR time profiles during different GLE stages (Vashenyuk et al., 2009a, 2009b), most of the indicated works were mainly aimed at analyzing the properties of only one isotropic GLE stage.

An alternative method of spectrographic global survey was proposed by Irkutsk researchers (Dvornikov and Sdobnov, 1997). The method is based on the solution of a system of nonlinear algebraic equations. These equations take into account the global amplitude distribution of variations in the integral fluxes of different secondary components, coupling function between primary and secondary variations, changes in the geomagnetic cutoff rigidity planetary system during each observation hour, and other factors. The authors used data from more than 30 CR stations, including the data of the Sayans spectrographic complex and Irkutsk MT, in order to analyze GLE42 (September 29, 1989). A comparison with the results achieved by Cramp et al. (1993) indicates that the two methods are substantially different, especially in the region of large amplitudes during the early GLE42 stages.

One of the serious common basic flaws in all above procedures consists in that the response functions of different (standard) ground detectors are known insufficiently. In particular, this is true for NMs in the region of comparatively low (≤ 2 GeV) SCR energies (Struminsky and Belov, 1997). The latter circumstance was mentioned again by the authors of the PAMELA direct space experiment (Adriani et al., 2011), when they tried to coordinate the spectral data of different detectors at energies varying from 80 MeV/nuc to 3 GeV/nuc based on the measurements performed during GLE70 (December 13, 2006). Taking into account the accuracy in estimating the absolute intensities of accelerated solar particle fluxes based on the NM data, Adriani et al. (2011) managed to reach a reasonable agreement between the fluxes measured during the PAMELA experiment and those estimated using the NM data. However, the PAMELA spectra were always harder than the spectra obtained from the NM data at low energies. This can indicate that the response functions for NMs are understated at energies of ≤700 MeV. During the second satellite pass over the polar cap, the indicated difference between the PAMELA and NM fluxes became larger, whereas the PAMELA data remained in very good agreement with the data of the IceTop ground-based experiment (Antarctica). Direct measurements of the SCR fluxes in the stratosphere also confirmed that the PAMELA data are correct.

4.2. Spectra of Prompt and Delayed Components

Using the procedure described above, Vashenyuk et al. (2009a, 2009b) analyzed 35 large GLE events that occurred from 1956 to 2006. Two components are present in each event with rare exceptions: the prompt component (PC) with an exponential energy spectrum and the delayed component (DC) with a power-law spectrum. We should note that the spectrum shape was not explicitly specified when the spectral parameters were determined, especially on the rigidity scale. The shape of the spectra, which were obtained when the inverse problem was solved, was subsequently determined based on better agreement with one of two representations: exponential or power-law ones. Table 4 presents the spectral parameters for each of 35 events (Vashenyuk et al., 2011). These are the J_0 and E_0 parameters of the exponential spectrum for the PC

$$J(E) = J_0 \exp(-E/E_0), \tag{4}$$

and the J_1 and γ parameters of the power-law spectrum for DC

$$J(E) = J_1 E^{-\gamma}, \tag{5}$$

where J_0 and J_1 are given in $\mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}^{-1}$, whereas E and E_0 are measured in GeV. The average values obtained from these data are as follows: $\langle E_0 \rangle = 0.52 \pm 0.15$ GeV, and $\langle \gamma \rangle = 4.85 \pm 0.25$. Note that it became possible to divide SCR fluxes into PC and DC and to study other fine details in an individual ground-level enhancement only because SNM-64 neutron supermonitors register GLEs very accurately (Carmichael, 1968).

4.3. Nature of DC and PC Sources

In several works (Pérez-Peraza et al., 1992, 2009; Podgorny et al., 2010), researchers tried to physically (in model) interpret the spectra for two SCR components and their solar sources. It was indicated that the PC can be generated by the acceleration by the electric field, which originates during magnetic reconnection in coronal current sheets. As a result, the spectrum of accelerated protons becomes exponential ($\sim \exp(-E/E_0)$). In this case, the characteristic energy of the spectrum (E_0) was 0.51 GeV, specifically, for the flare of July 14, 2000 (Podgorny et al., 2010) (this is close to the average E_0 value for most events in Table 4). We generally relate the PC generation to the acceleration by the electric field, which originates in the magnetic reconnection region in the solar atmosphere.

The DC is most probably caused by the stochastic acceleration by plasma turbulence in the disturbed plasma of a flare or coronal ejections (Pérez-Peraza et al., 2009). This component can also be generated by the acceleration by a shock in the solar corona (Ellison and Ramaty, 1985). However, this mechanism is effective only in the region of nonrelativistic energies. The fact that this mechanism gives a power-law spectrum with $\gamma \sim 2.5$, whereas the DC spectrum obtained from experimental data has $\gamma \sim 5$ on average, is an argument against the mechanism by which SCR particles are accelerated by a shock to relativistic energies. The same index was obtained in the model of stochastic acceleration by plasma turbulence (Pérez-Peraza et al., 2009).

Acceleration by a shock in the solar corona and interplanetary medium has serious limitations: the

Table 4. Spectra of two SCR components in GLEs from 1956 to 2006 (Vashenyuk et al., 2011a, 2011b)

GLE no.	Flare date	Radio II type	Flare importance	Flare position	Spectrum parameters			
					PC		DC	
					J_0	E_0	J_1	γ
05	Feb. 23, 1956	0336	3	N23 W80	7.4×10^5	1.37	5.5×10^5	4.6
08	May 4, 1960	1017	3+	N13 W90	2.7×10^5	0.65	1.6×10^3	4.2
10	Nov. 12, 1960	1326	3+	N27 W04	–	–	7.5×10^3	4.1
11	Nov. 15, 1960	0222	3	N25 W35	–	–	1.0×10^5	5.3
13	July 18, 1961	0947	3+	S07 W59	5.2×10^3	0.52	3.6×10^3	6.0
16	Jan. 28, 1967	0755	–	N22 W154	1.4×10^4	0.58	6.7×10^3	4.7
19	Nov. 18, 1968	1026	1B	N21 W87	1.2×10^4	0.58	2.6×10^3	5.5
20	Feb. 25, 1969	0904	2B/	N13 W37	7.7×10^4	0.38	4.7×10^3	5.0
22	Jan. 24, 1971	2316	3B	N19 W49	3.4×10^4	0.45	8.7×10^3	5.8
23	Sept. 1, 1971	1934	–	S11 W120	–	–	4.7×10^3	5.4
25	Aug. 7, 1972	1519	3B	N14 W37	6.6×10^2	1.23	4.3×10^2	5.0
29	Sept. 24, 1977	0555	–	N10 W120	6.5×10^2	1.14	9.3×10^2	3.2
30	Nov. 22, 1977	0959	2B	N24 W40	1.5×10^4	0.77	1.1×10^4	4.7
31	May 7, 1978	0327	1B/X2	N23 W82	3.5×10^4	1.11	1.3×10^4	4.0
32	Sept. 23, 1978	0958	3B/X1	N35 W50	–	–	7.0×10^2	4.7
36	Oct. 12, 1981	0624	2B/X3	S18 E31	1.7×10^3	1.21	–	–
38	Dec. 7, 1982	2344	1B/X2.8	S19W86	5.7×10^3	0.65	7.2×10^3	4.5
39	Feb. 16, 1984	0900	–	– W132	–	–	5.2×10^4	5.9
41	Aug. 16, 1989	0103	2N/X12.5	S15 W85	6.8×10^3	0.56	3.8×10^3	5.1
42	Sept. 29, 1989	1133	–/X9.8	– W105	1.5×10^4	1.74	2.5×10^4	4.1
43	Oct. 19, 1989	1249	3B/X13	S25 E09	4.0×10^4	0.53	3.0×10^4	4.8
44	Oct. 22, 1989	1744	2B/X2.9	S27 W31	7.5×10^4	0.91	1.5×10^4	6.1
45	Oct. 24, 1989	1800	2B/X5.7	S20 W57	2.4×10^4	0.72	1.1×10^5	4.9
47	May 21, 1990	2212	2B/X5.5	N35 W36	6.3×10^3	1.13	2.7×10^3	4.3
48	May 24, 1990	2100	1B/X9.3	N36 W76	2.8×10^4	0.60	9.1×10^3	4.3
51	June 11, 1991	0205	2B/X12.5	N32 W15	2.6×10^3	0.83	3.3×10^3	4.8
52	June 15, 1991	0814	3B/X12.5	N36 W70	–	–	5.8×10^3	4.6
55	Nov. 6, 1997	1153	2B/X9.4	S18 W63	8.3×10^3	0.92	8.2×10^3	4.6
59	July 14, 2000	1019	3B/X5.7	N22 W07	3.3×10^5	0.50	5.0×10^4	5.4
60	Apr. 15, 2001	1348	2B/X14.4	S20 W85	1.3×10^5	0.62	3.5×10^4	5.3
61	Apr. 18, 2001	0217	–	– W120	2.5×10^4	0.52	1.2×10^3	3.6
65	Oct. 28, 2003	1102	4B/X17.2	S16 E08	1.2×10^4	0.60	1.5×10^4	4.4
67	Nov. 2, 2003	1714	2B/X8.3	S14 W56	4.6×10^4	0.51	9.7×10^3	6.3
69	Jan. 20, 2005	0644	2B/X7.1	N14 W61	2.5×10^6	0.49	7.2×10^4	5.6
70	Dec. 13, 2006	0251	2B/X3.4	S06 W24	3.5×10^4	0.59	4.3×10^4	5.7

implementation of this acceleration requires “injection energy” (preliminary acceleration). In addition, the maximal energy of accelerated particles is only ~1 GeV in this case (Zank et al., 2000). More detailed calculations, performed with regard to the present-day semiempirical data on the plasma density vertical profile and the level of Alfvén turbulence in the corona resulted in the following formula for the SCR spectrum (Berezhko and Taneev, 2003):

$$N(E) \propto E^{-\gamma} \exp\left[-(E/E_{\max})^{\alpha}\right]. \qquad (6)$$

This expression includes the power part with $\gamma \approx 2$ (this is comparable with the value obtained by Ellison and Ramay (1985) for the shock case) and the exponential "tail" with $\alpha \approx 2.3 - \beta$, where β is the Alfvén wave spectral index in the corona. The characteristic energy ($E_{\max}$) can vary in a wide range (from 1 to 300 MeV), depending on the shock velocity. Formula (6) adequately describes the SCR spectrum in the nonrelativistic region but cannot apparently be used to describe the relativistic part of the spectrum. Anyhow, when the spectrum above 1 GeV is described for GLE42 during the late stage of the event that occurred on September 29, 1989 (i.e., essentially for the DC spectrum only), the model gives rather void results strongly dependent on the Alfvén turbulence spectral index ($\beta = 0.5$–1.5). Berezhko and Taneev (2003) did not consider the PC at all.

The theory of SCR acceleration to relativistic energies is still far from being completed. We consider here the latest results (Somov and Oreshina, 2011) achieved based on the reconnecting current sheet (RCS) concept. According to present-day observations, electrons and protons in solar flares are accelerated to high energies almost simultaneously in each "elementary flare burst" (EFB). According to observations of gamma and hard X rays, the duration of such an impulse burst is apparently no more than several seconds (Kurt et al., 2010). Somov and Oreshina (2011) considered an analytical solution of the relativistic equation of charged particle motion in a RCS with a three-component magnetic field ($B_0 \approx 100$ G, $B_\parallel \approx 0.1B_0$, $B_\perp \approx 5 \times 10^{-4} B_0$) and strong electric field E_a (up to ~30 V cm^{-1}), caused by the magnetic reconnection process. In this case, particles are accelerated to a velocity about the velocity of light along the electric field, and their kinetic energy is proportional to the time spent in the RCS. The numerical solution of the equation for parameters B and E_a presented above indicates that electrons can be accelerated during 2×10^{-7}–10^{-3} s if the acceleration region dimensions are ~7×10^2–3×10^7 cm; for protons, similar estimates will be 10^{-4}–2×10^{-2} s and ~3×10^5–7×10^8 cm, respectively. However, these estimates do not solve the problem of SCR spectrum formation on the whole, including the prompt and delayed relativistic components. We emphasize that any acceleration theory should consistently explain the main properties of the two components: the PC is observed at the event initial phase, is of a short duration and strongly anisotropic, and has an exponential energy spectrum; the DC has a smooth time profile, weak and sometimes bidirectional anisotropy, and a power energy spectrum.

4.4. New GLE Concept

The hypothesis that two relativistic SCR components exist was proposed by us in the late 1980s and has been differently discussed in literature for more than two decades (Miroshnichenko and Pérez-Peraza, 2008). For example, Shea and Smart (1996) pointed to the fact that "a double structure" of the time profiles of some GLEs was observed not only in cycle 22 but also in cycles 19–21, e.g., for the events that occurred on November 15, 1960 (GLE11), and, possibly, August 7, 1972 (GLE25). Such structures were as a rule registered at polar stations with narrow asymptotic cones of acceptance "pointed" in the direction of the first coming solar particles. In any case, the initial coherent burst (or spike) of the relativistic SCR intensity at the very beginning of a GLE can be a more general phenomenon than it was assumed previously. In particular, Shea and Smart (1997) demonstrated that two individual injections of relativistic protons from the Sun were registered at an interval of ~10–20 min during the event of October 22, 1989.

Therefore, the satellite measurements of the same event are of special interest (Nemzek et al., 1994). The authors analyzed proton intensity time profiles based on measurements on two geostationary satellites depending on the proton energy. They found that the peak, which was so distinct in the NM data, was also present in the nonrelativistic region up to energies of ~15 MeV. At the same time, a detailed analysis (Miroshnichenko et al., 2000) indicated that such a situation was not observed on GOES-7 during the event of September 29, 1989. This spacecraft registered the event in several low-energy channels, but a rather smoothed (gradual) time profile with one peak was only registered in all channels. The intensity started increasing sharply before 1200 UT and gradually reached its maximum. A peak was registered after 1300 UT, depending on the particle energy in a given channel. It is important to note that any time profile singularities were not registered in all low-energy channels, although particles with rigidities of <2 GV were measured in these channels. A gradual increase up to the maximum was registered even in the channel with the highest energies in the 640–850 MeV (1.6–2.3 GV) interval where NM observations can be performed. This single peak was observed on GOES-7 when the second peak was registered with NM. In other words, the first peak observed with NM was caused by protons with rigidities of $R > 2.3$ GV. If GOES-7 was directed oppositely, such a conclusion would be less striking; this conclusion can only indicate that the location of GOES-7 was unfavorable for the registration of the first peak in such a situation.

Completing this discussion, we refer the reader to some theoretical studies of the emission and interplanetary propagation of relativistic solar particles. Thus, based on the Boltzmann kinetic equation for particles with an anisotropic initial distribution, Fedorov et al. (1997) indicated that the amplitudes and time profiles observed during anisotropic GLEs will depend on the direction of the NM emission asymptotic reception cones with respect to the particle transfer direction in the IMF. Such an approach was applied by Fedorov et al. (1997) to GLE48 (May 24, 1990). This enhancement was strongly anisotropic at the beginning of the event and had certain indications of a double SCR injection. To describe these singularities, the authors assumed that a prolonged injection dependent on the particle energy took place in the GLE48 event. However, it seems that such an approach is insufficient for us to explain the considerable time delay between an anisotropic peak at several ground stations and a smoothed isotropic maximum at other NMs unless we assume that a second SCR injection exists. Note that the interplanetary propagation cannot substantially change the spectrum of relativistic protons. Thus, we consider the regularities, obtained above for two SCR components, as a consequence of the acceleration processes on the Sun.

5. MAXIMAL SCR ENERGY

Above, we touched briefly upon the problem of measuring and interpreting the maximal energy (E_m) that can be maintained by the particle accelerator on the Sun. In particular, bursts of secondary muon intensity caused by solar flares were registered at a nominal depth of ~200 m.w.e. (Schindler and Kearney, 1973). However, the burst value was no larger than 3σ. Subsequently, the Baksan Underground Scintillation Telescope (BUST) reliably registered the so-called Baksan effect, i.e., short-lived muon bursts (with amplitudes reaching 5.5σ), which distinctly correlate with GLE. By the end of 2005, 34 events were among muon bursts that were registered with the BUST (Karpov and Miroshnichenko, 2007).

5.1. Early Results

Many researchers illustrated the state of this problem (Karpov et al., 1998; Miroshnichenko, 2001, 2003a; Miroshnichenko and Pérez-Peraza, 2008). In spite of the experimental limitations, scarce observational data, and theoretical difficulties, researchers are still interested in the problem because of its fundamental character. The BUST results gave a new impetus to the search for the SCR energy upper limit based on the data of non-standard CR detectors (Falcone and Ryan, 1999; Ryan et al., 2000; Ding et al., 2001; Tonwar et al., 2001; Poirier and D'Andrea, 2002; Wang, 2009). Below, we present some results that have been achieved by different researchers during the last years. We mainly consider the most outstanding GLEs during cycle 23, including the events of November 6, 1997 (GLE55); July 14, 2000 (GLE59 or BDE); April 15, 2001 (GLE60); October 28, 2003 (GLE65); and January 20, 2006 (GLE69).

For example, the EAS experiment (AGASA, Japan) indicated that neutrons with energies no lower than ≥10 GeV, which corresponds to the accelerated-proton energy (at least $E_p \geq 10$ GeV), could be produced on the Sun during the flare of June 4, 1991 (Chiba et al., 1992). At the same time, measurements with GRAPES-III giant muon detectors (Ooty, India) in March 1988–January 1999 did not give statistically significant results (Kawakami et al., 1999). On the contrary, the Milagrito (water Cherenkov detector) measurements during GLE55 made it possible to detect a certain effect in a channel with a high energy threshold (Falcone and Ryan, 1999). Although the registration thresholds for this detector were not known very precisely, we can state that the energy of coming solar protons was a priori higher than 10 GeV.

5.2. Giant Detector Experiments

A group of researchers at CERN (Tonwar et al., 2001) tried to register the solar flare effects with an array of 50 EAS scintillation counter-detectors located above an L3 muon detector (the international collaboration of the L3+C experiment). Specifically, it was mentioned that the count rate of scintillation detectors pronouncedly increased on July 14, 2000, close to the instant when the ground network of NMs registered GLE59. However, this increase, as well as other 42 episodes during 353 days of EAS registration, cannot be unambiguously interpreted (purely atmospheric effects (in particular, air humidity) can contribute to this increase). Collaboration was also reported for the muon fluxes measured during the same event (Ding et al., 2001; Achard et al., 2006). The measurements were performed with a high-precision spectrometer of high-energy muons. The spectrometer made it possible to directionally register muons with energies higher than 15 GeV, which corresponds to the energy of primary protons higher than 40 GeV. The authors reported that a certain excess of muons (4.2σ) was registered simultaneously with an SCR flux enhancement peak at lower energies. The probability that the excess of muons was a random fluctuation in the background is 1%. Similar fluctuations were not observed during 1.5 h after the solar flare.

To all appearance, the flare of April 15, 2001, had to cause a much more distinct effect, which was actually observed (Poirier and D'Andrea, 2002; Karpov et al., 2005). However, the EAS detectors at CERN did not register any increase in the count rate in this case (Tonwar et al., 2001), most probably, because the solar zenith angle was large (>60°). Based on the NM data, we estimated the maximal values of the relativistic proton integral flux for the events of July 14, 2000 (BDE), and April 15, 2001. On July 14, 2000, the SCR spectrum was very soft; therefore, it is not surprising that the BDE event did not cause statistically significant effects at substandard detectors.

The event of April 15, 2001 (GLE60), had a harder spectrum ($\gamma \sim 3.0$). Solar proton effects were particularly registered with the Project GRAND Array (an increase in the muon intensity with an amplitude larger than 6.0σ) (Poirier and D'Andrea, 2002) and Andyrchi (~10σ) (Karpov et al., 2005) instruments. According to (Poirier and D'Andrea, 2002), during this event, the most probable energy of SCR primary protons was close to 100 GeV at a differential spectral index of ~2.0. We assume that such an index value is unrealistic and the E_p value is also too large. It is difficult to interpret these data mainly because reliable response functions are absent for the GRAND facility. The same difficulty is typical of the Andyrchi facility (Karpov et al., 2005) and other non-standard detectors.

Using the method and optimization parameters (Achard et al., 2006) for event selection, Wang (2009) found an excess of muons (5.7σ) in the same sky area as the authors of the experiment based on high-energy muons measured with an L3+C experiment detector. In this case, the effect duration coincided with the time when the peak flux of lower-energy protons and X and gamma rays were observed. The numerical simulation by the Monte Carlo method indicated that the burst of muon intensity was caused by primary protons with energies E_p > 40 GeV and the most probable energy about 82 GeV. Based on the simulation results, Wang (2009) estimated that the upper limit for the flux of such protons is ~2.5 × 10^{-3} *pfu*. The author assumed that protons with such high energies were accelerated during the impulsive stage of the flare that occurred on July 14, 2000, 2 min after the bursts of hard X and gamma rays.

The last giant SCR GLE was observed on January 20, 2005 (GLE69). This extreme event, which is a second-rank event (Table 3) from all 71 GLEs, made it possible to estimate once again the maximal possibilities of the solar accelerator. In particular, the Aragats neutron monitor and muon detector (3200 m above sea level, geomagnetic cutoff rigidity R_c = 7.6 GV) registered small, but pronounced, enhancements (Bostanjyan et al., 2007). Small enhancements were also registered with the Tibet NM and SNT (R_c = 14.1 GV, 4310 m above sea level) (Miysaka et al., 2005; Zhu et al., 2007) and with GRAND MT (D'Andrea and Poirier, 2005). These detectors confirmed that very small fluxes of protons with energies of >15 GeV are present. Bombardieri et al. (2008) simulated the response of sea-level NMs to this event based on yield functions (Debrunner et al., 1984). As a result, they concluded that high-rigidity SCR fluxes in the GLE69 event were small and could not cause a substantial increase in the count rate of other NMs with high geomagnetic cutoff rigidities. This is in agreement with the data on the spectra, pitch angle distribution, and SCR arrival direction obtained by the authors themselves (Bombardieri et al., 2008) for the same event.

Recently, we have managed to advance in understanding the nature of muon bursts at BUST (the Baksan effect) (Karpov and Miroshnichenko, 2007). We also estimated again the maximal intensity of primary protons (I_p(≥500 GeV) ~ (1.5 ± 0.2) × 10^{-6} *pfu*) that generated the muon burst of September 29, 1989. This value can apparently be satisfactorily coordinated with the PC spectrum for GLE42 (Miroshnichenko et al., 2000). This estimate at least agrees with the value I_p (>82 GeV) ~ 2.5 × 10^{-3} *pfu* for the BDE event (Wang, 2009), if the integral spectral index is >4.0 (Table 2).

Thus, we for the first time generalized the data of non-standard detectors on the upper limits of relativistic solar proton fluxes and maximal SCR energy. These data are fragmentary and cannot be unambiguously interpreted; nevertheless, they put forward fundamental problems: can particles be actually accelerated to energies E_p ≥ 500 GeV on the Sun or we deal with any specific effect of GCR solar modulation? These problems were also raised previously but only with respect to individual GLEs. The acceleration theory still cannot adequately describe the entire SCR spectrum, especially at E_p ≥ 100 GeV, although there are very simple maximal energy estimates (Pérez-Peraza et al., 1992) based on the current sheet model. Thus, it was found that $E_m \approx$ 250 GeV for GLE05. Meanwhile, such events that were observed on September 29, 1989; November 6, 1997; and April 15, 2001, with non-standard detectors clearly demonstrate that solar protons with energies E_p ≥ 10 GeV (and even ≥100 GeV) are available. However, the number of detectors that can register secondary muons from such protons is still insufficient. We note that information on the anisotropy of coming particles can only be obtained during single point-by-point measurements. It is difficult (although possible) to perform such measurements. However, no muon detector can measure the SCR anisotropy during GLEs. Therefore, Ryan et al. (2000) consider that several muon detectors with sufficient sensitivities in different directions could ideally be added to the worldwide network of NMs.

6. GLE SOURCE: FLARE AND/OR CME?

The GLE nature and the SCR acceleration sources and mechanisms have been discussed for several decades. The dilemma "flare or CME" is of special interest. The theoretical discussion includes the following question: what active process on the Sun—flare, CME, or their combination—is responsible for the SCR generation? It is apparently impossible to directly answer this question, and indirect arguments of adherents of any hypothesis do not yet lead to consensus. There is rather much evidence that the PC and DC of relativistic SCRs are related to a flare and CME, respectively. At the same time, some researchers consider that only CME-driven shocks accelerate high-energy solar particles. As an argument, they often use the characteristics of accelerated solar particles (SEPs) with energies lower than in the GLE case by 1–2 orders of magnitude (mainly protons with energies ≥10 MeV). Data on the solar radioemission and X and gamma rays, measurements of the SEP elemental composition and spectrum, etc., are also used. All these data are more or less thoroughly compared with the flare and/or CME characteristics. Meanwhile, it is well known that the SEP appearance at the

Earth's orbit (SPE) is related to several previous (not always known) physical processes. In particular, observed SEPs are apparently affected by the multiple and/or prolonged acceleration processes in the source (Miroshnichenko, 2003b) and by their propagation in the interplanetary medium.

One of the last discussions regarding all these problems took place at two CDAW (Coordinated Data Analysis Workshop) working meetings in the United States (2009). The results of this discussion were used to prepare a special issue of the journal *Space Science Reviews* (2012, vol. 171). The journal's editors (Gopalswamy and Nitta, 2012) note that GLE events account for only 15% of the total number of giant SPEs during a solar cycle. Therefore, it is naturally interesting what special conditions should exist on the Sun for GLE generation. Most authors of the issue first of all relate GLE generation to CMEs. A detailed analysis of all papers in this issue is beyond the scope of this review; however, we will present below the most substantial results.

6.1. Problem of the First GLE Particles

An explosive energy release on the Sun generates a flare and a CME. It is considered that X and gamma rays are related to flares. Radioemission is a characteristic of disturbances propagating through the corona and interplanetary medium. Particles can acquire energy in flares and accompanying wave processes. Therefore, it is difficult to separate the characteristics of acceleration processes from particle observations only. However, it is logical to consider that the GLE event early stage is the closest to the acceleration instant and the role of the interplanetary transfer is minimal for the first arriving particles.

Giant events make it possible to study the early phase best of all owing to a high signal-to-noise ratio, and relativistic solar protons are most applicable to the particle acceleration problem. Cliver et al. (1982) were the pioneer workers on this problem, which was subsequently considered by Kahler et al. (2003), Bazilevskaya (2009), Firoz (2010), Aschwanden (2012), and Gopalswamy et al. (2012). Bazilevskaya (2009) and Aschwanden (2012) indicated that the first relativistic particles (PC) leave the Sun at an instant close to the maximum of hard X rays and high-energy gamma rays (Kuznetsov et al., 2011). These emission types are typical of the flare explosive phase. In contrast to the first particles, a DC appears 10–30 min after a PC, when a CME develops. No correlation between particle fluxes and CME characteristics was found in this case. A shock (type II radio source) moves in front of an expanding CME. A shock can also accelerate particles, producing a power-law spectrum with $\gamma \sim 2.5$. The DC spectrum has $\gamma \sim 5$, which more corresponds to stochastic acceleration (Pérez-Peraza et al., 2009). Particles trapped in loop-shaped magnetic structures within an expanding CME are accelerated while interacting with plasma turbulence. The adiabatic losses in such traps are small as compared to the acceleration effect (Pérez-Peraza et al., 2009). Particles leave a trap when a CME appears in the high corona.

An absolutely unexpected aspect of the discussed problem of the first SCR particles was revealed by Struminsky and Zimovets (2009) when they analyzed the SCR effects in the anti-coincidence protection system ACS (the BGO scintillation detector weighing 512 kg), which shielded an SPI spectrometer onboard the INTEGRAL orbital astrophysical observatory. As is known, it is traditionally considered that the GLE onset registered by an NM at the worldwide network is the time of relativistic proton arrival. Inaccuracy and ambiguity in determining the time of solar proton arrival based on NM data is caused by the detector background (registration statistical accuracy) and variations in the geomagnetic cutoff rigidity threshold and the acceptance cone direction of arriving particles. The authors of this work paid attention to the fact that the ACS detector count rates increased evidently earlier than the ground NM count rates in some GLE events. In two cases, an ACS SPI detector was more effectively used to observe the SPE–GLE onset at the Earth's orbit than the NM network: on January 17, 2005 (GLE68), and on December 13, 2006 (GLE70). According to the enhancement amplitude, these events were rather weak. In this case, the delay of the relativistic proton arrival to the Earth relative to the burst of hard X rays was considered significant, which indicated that protons were accelerated later. Meanwhile, an increase in the ACS SPI count rate caused by the arrival of relativistic protons was observed earlier and corresponded to the SCR acceleration at the flare instant. This fact indicates that it is necessary to create spacebased detectors of solar protons and electrons with a low natural background level. Such detectors should be used to measure low-intensity CR fluxes. Indeed, in contrast to the two weak GLEs mentioned above October 8, 2003 (GLE65) and January 20, 2005 (GLE69), solar protons arrived at the ACS SPI simultaneously with the beginning of anisotropic enhancement at the NM network; i.e., this arrival coincided with that of the prompt component of SCR.

6.2. GLE and Composition of Accelerated Particles

Quite recently, Kahler et al. (2012) studied several aspects of this problem. They compared the *e*/*p* and Fe/O ratios for several GLEs with the characteristics of the corresponding flares and CMEs. The authors proceeded from the fact that GLEs represent an extreme case of gradual SEP events (SPEs), which are related to shocks driven by wide and fast CMEs. The latter are in turn related to long-duration (>1 h) bursts of soft X rays (SXRs). However, it turned out that some large gradual SPEs, including GLEs, are related to short-duration flares (<1 h), the duration of which is comparable with that of impulsive low-energy SEP events enriched in heavy elements (e.g., large Fe/O ratio), high particle (e.g., Fe ion) ionization degree, and a large *e*/*p* ratio.

To determine how the *e*/*p* and Fe/O ratios, measured in two energy intervals, depend on the characteristics of the active regions (ARs) of the corresponding flares and CMEs, Kahler et al. (2012) statistically studied 40 GLE events registered from 1976. It turned out that abundance ratios tend to smaller and stable coronal values with increasing timescales (duration) of flares and peak fluxes of soft (thermal) and hard (bremsstrahlung) X rays, as well as with increasing AR dimensions. The authors assume that these results indicate that the flare effects are insignificant in these GLEs if the wide region of "heliolongitude connections" between GLE sources with increased abundance of heavier elements is taken into account. The authors consider that SEPs accompanying GLEs are mostly accelerated at the fronts of CME-driven shocks and the relation of the flare power and time characteristics to the CME properties could explain the correlation between the SEP composition and flare properties. Even if we assume that flares mainly contribute to GLEs, in this case, it is also unclear why Fe/O-type ratios weakly tend to decrease with increasing background SEP intensities. Therefore, the authors prefer an alternative interpretation (Tylka et al., 2005): a large Fe/O ratio characterizes the acceleration by a shock, which is quasi-perpendicular near the Sun; therefore, this shock mainly accelerates "a seed population" of flare particles. Since higher injection energy is required in the case of quasi-perpendicular shocks, these shocks involve a generally smaller seed population in the acceleration process than quasi-parallel shocks. As a result, events with quasi-perpendicular shocks near the Sun will be generally characterized by smaller proton fluences at least at higher energies that were reached when a shock was closer to the Sun.

The data presented in (Miroshnichenko, 2003b) can be added to this very elegant, but rather contradictory, pattern. We tried to divide the reconstructed solar proton emission spectra, depending on the proton sources (impulsive or gradual flares and CME-driven shocks). Using several SPEs as an example (including outstanding GLE42), we found out that the number of accelerated particles, which "precipitate" in the solar atmosphere and cause gamma-ray bursts in lines, is systematically smaller than that of runaway particles registered near the Earth as SEPs. This important fact is still insufficiently studied.

Based on the consideration of the problem as a whole, we tend to assume that a physical relationship between CME flares and GLEs undoubtedly exists. However, the regularities of this relation are not rigorously deterministic and most probably correspond to the "Big Flare Syndrome," which was proposed and developed in several works (Kahler, 1982; Kahler et al., 2012). Kahler et al. (2012) also partially share this opinion: "In this scenario the trends for decreasing abundance ratios with increasing SXR and 9 GHz flux densities could be interpreted in terms of the Big Flare Syndrome (Kahler, 1982) in which all eruptive event emissions tend to scale together, in this case the SEP fluences and the associated flare peak fluxes."

6.3. GLE Registration Rate

Complete GLE statistics, accumulated during the 70 years of ground-based SCR observations, makes it possible to study some problems related to the spatial-temporal variations in solar activity and the properties of the global solar magnetic field (GSMF). It is interesting to know, e.g., the distribution of GLEs over the heliolongitude of their sources (flares). It was established that the IMF is the "guiding " factor when SCR fluxes are formed. Although relativistic particles are as a rule insignificantly scattered when moving toward the Earth (their path length can be comparable with 1.0 AU), the probability that they reach the Earth evidently strongly depends on the Parker spiral angle of the IMF. This results in a rather strong dependence of the registration rate (η) on the source heliolongitude: most sources are related to the ~30° W–90° W interval of longitudes. However, it is striking that SCRs came to the Earth even from behind-the-limb sources in 12 cases. The source distribution for giant nonrelativistic SPEs has approximately the same shape. The SPE sources that are supposedly related to the acceleration by shocks in the interplanetary space are distributed more uniformly and have a maximum at a ~30° W heliolongitude (Miroshnichenko, 2001).

Another interesting aspect, which characterizes the Sun as a star, was revealed as a result of a wavelet analysis of the GLE registration rate (η), depending on the SA level (sunspot number) and solar cycle epoch (Miroshnichenko et al., 2012). Using the dates of the events from Table 1 and the Morlet method (Pulse Width Modulation, PWM), we constructed the PWM series for parameter η, which includes the statistically significant oscillation with a period of ~11 years. In this case, η oscillations to a certain degree are coherent with the time series of the parameters of the photosphere (sunspot number S) and corona (coronal index CI). In spite of the limitations of the GLE statistics and the wavelet analysis method, these results can be interesting for understanding the periodic phenomena in the solar dynamo, solar atmosphere, interplanetary medium, and CRs.

The tendency of GLEs to group mainly on the ascending and descending branches of solar cycles is apparently caused by the specific features in the GSMF spatial-temporal structure. As is known, this field reverses its sign precisely near SA maximums. In this context, we mention the results by Nagashima et al. (1991). These authors used MT and NM data for 43 GLEs from 1942 to 1990 in order to analyze the above GLE tendency. They indicated that the flares that cause GLEs are basically forbidden during the cycle transient phase, when the GSMF reverses its sign. The absence of GLEs at an SA maximum is explained by a decrease in the particle acceleration effectiveness during the GSMF reconfiguration rather than by the suppression of SCR escape processes due to strong magnetic fields.

Since certain periodicities found in (Miroshnichenko et al., 2012) are coherent for parameters η, S, and CI; therefore, during this stage of the study, the conclusion can be made that oscillations are synchronized in different layers of the solar atmosphere: from the photosphere to the corona. This can indicate that the SCR generation (GLE) involves wide areas in the solar atmosphere rather than is a local (isolated) process.

7. GEOPHYSICAL AND APPLIED ASPECTS

Solar particles with energies about several tens and hundreds of MeV (SEPs) are substantial in many geophysical processes owing to their ionizing effect (Miroshnichenko, 2008). The following geophysical processes are most known: the effects of ozone layer depletion and disturbance in the global circuit of atmospheric electricity, variations in the Earth's atmosphere transparency, generation of nitrates and cosmogenic isotopes. There are also a number of poor-studied or still assumed (not proved reliably) phenomena. Below, we will briefly consider the contribution of relativistic solar protons to these effects. Note that the energy density and the total energy released by SCRs into the Earth's atmosphere are not comparable with any other energy that comes from the Sun to the near-Earth space. Therefore, SCRs are not the main cause of geophysical disturbances (as compared, e.g., to CMEs and geomagnetic storms). However, the SEP arrival can be an important (trigger) component of the global mechanism of solar-terrestrial relations owing to its sporadic nature.

7.1. SCR Geophysical Effects

Penetration of SEPs into the polar atmosphere should inevitably modify the composition and physical-chemical processes in the mesosphere and stratosphere (Quack et al., 2001; Kirillov et al., 2007). Quack et al. (2001) considered the SEP effect on the above processes for three GLEs, which were registered in October 1989, July 2000, and April 2001 in a wide range of energies and with regard to the time evolution of their spectra. They studied the generation of nitrogen (NO_x) and hydrogen (HO_x) oxides and variations in the ozone (O_3) content and compared the calculation results for different events. The analysis was based on a model, which took into account the penetration (precipitation) of particles into the atmosphere and the following modification of the atmospheric chemistry.

In October 1989, the ionization level in the lower stratosphere was first high, whereas the ionization in the mesosphere was lower by an order of magnitude. In due course, the ionization level in the lower stratosphere remained unchanged (since the high-energy particle intensity was almost constant); at the same time, the ionization in the mesosphere increased substantially due to the arrival of low-energy particles, the intensity of which continued increasing. The ionization variation pattern in July 2000 is more complex as compared to such a pattern in October 1989: the ionization was high in the middle mesosphere and was lower in the upper mesosphere. Since the intensity of high-energy particles starts decreasing rather early, the ionization rates in the stratosphere also decrease as an event evolves. Only in the upper mesosphere, the ionization rates increase in the course of time. In April 2001, the calculated ionization profiles are comparable in shape with the ionization profiles for the event in October 1989, although the ionization rate absolute values are smaller by a factor of ~2–3. Nevertheless, in due course, the ionization level decreases at all altitudes. The model gives identical results when the proton spectra are extrapolated to 500 or even 800 MeV.

Kirillov et al. (2007) performed studies in the same direction for GLE70 (December 13, 2006). They studied the effect of energetic solar protons on the chemistry of the middle atmosphere (20–80 km). The proton spectra were obtained based on the NM data and measurements in the stratosphere and on spacecraft. A one-dimensional model, which was previously developed by the authors with regard to its time dependence, was used to calculate the generation and loss of the content of minor atmospheric constituents during a GLE. The obtained ozone layer depletion rates were in good agreement with the measurements performed with a Microwave Limb Sounder (MLS) onboard the AURA spacecraft. The authors assumed that the ozone content in the middle atmosphere decreased when solar protons precipitated mainly due to the generation of odd HO_x components with the following recombination of ionization products.

In this section, we finally consider the known effect of cosmogenic isotope production by CRs in the Earth's atmosphere, using one of the latest works in this field (Webber et al., 2007) as an example. These authors performed new detailed calculations of the production rate of the ^{3}H, ^{7}Be, ^{10}Be, and ^{36}Cl cosmogenic isotopes, using the FLUKA (Monte Carlo code) software and taking into account recent data on the interaction cross-sections for vertically incident protons with energies varying from 10 MeV to 10 GeV. This made it possible to study the isotope production due to SCRs and GCRs in the region of low energies, where the production power is a very sensitive energy function. Based on the events in October–November 2003, it was indicated that the ^{10}Be production rate reached a maximum during these events when the energy was ~100 MeV; at the same time, the ^{7}Be and ^{36}Cl isotopes were more intensely produced at an energy of ~25 MeW with a resonance cross-section of the process. If the SCR spectrum is steeper than such a spectrum in October–November 2003, the production power maximum will shift toward lower energies. The production peak will shift to higher energies if the spectrum is less steep (as was registered on January 20, 2005). For the events in 2003, the total integral production values for the ^{7}Be and ^{36}Cl isotopes due to SCRs will be approximately three times as large as such values for the ^{10}Be isotope production. This is explained by the resonance effect, which is formed when the proton energy is ~25 MeV. Precisely such protons produce the ^{7}Be and ^{36}Cl isotopes by splitting the nuclei of atmospheric nitrogen (^{14}N) and argon (^{40}Ar), respectively.

Only the extreme event of February 23, 1956, could substantially contribute to the yearly production of the ^{10}Be isotope. For the ^{36}Cl isotope, the yearly production values are ~2–5 times larger, depending on the SCR spectrum type. Webber et al. (2007) calculated the yearly production values for the generation of the ^{10}Be, ^{36}Cl, and other isotopes at >65° geomagnetic latitude for the 1940–2006 period, including six 11-year solar cycles. The average amplitude of the 11-year variation in the yearly contents of these isotopes is ~1.77. If the latitudinal mixing is taken into account, this amplitude will decrease to 1.48 for the average global production.

7.2. SCRs in Prognostic Schemes

In the mid-1980s, researchers started to consider the idea of using ground-based CR observations, which are among numerous heliogeophysical prediction methods and schemes, in order to make short-term predictions of different phenomena. Specifically, they put forward several interesting proposals to use relativistic solar protons ($R \geq 1$ GV) as SPE predictors in the nonrelativistic region. Thus, Dorman et al. (1990) for the first time considered the possibility of diagnosing the interplanetary medium and predicting the SPE onset based on the solution of the inverse problem of SCR propagation. Based on observations up to the SCR maximum in the Earth's orbit, it was assumed, first, to restore the SCR emission function and, then, to predict the SPE development for several hours ahead. Although the methodical aspects of such an approach were sufficiently justified, it remained unclear how the proposed scheme could be verified based on observational data. One of the difficulties consisted in that a large flux of relativistic protons was not always accompanied by the same increase in the flux in the nonrelativistic region. Many researchers subsequently considered the role of relativistic SCRs in prognostic schemes (Belov and Eroshenko, 1996; Dorman and Zukerman, 2003; Mavromichalaki et al., 2009; Vashenyuk et al., 2011; Veselovsky and Yakovchuk, 2011; Pérez-Peraza et al., 2011).

Belov and Eroshenko (1996) developed an empirical approach to the determination of the solar proton spectrum near the Earth in the 10 MeV–10 GeV energy range, directly using observational data without any preliminary assumptions regarding the possible spectral shape. Their method also made it possible to reconstruct the intensity time profile for protons with any energy. Vashenyuk et al. (2011) tried to predict the form of the maximum flux spectrum (MFS) for nonrelativistic protons during SPEs using data on the DC spectrum in the corresponding GLE. In this case, the spectrum in the ≤500-MeV region was considered as a natural smooth continuation of the DC spectrum. Using the GLE47 event (May 21, 1990) as an example, these researchers indicated that the DC spectrum is in good agreement with its extrapolation into the region of low energies (≤430 MeV), where direct measurements on the Meteor spacecraft and stratospheric balloon measurements were performed. The authors proposed a reasonably limited calculation model, where data of ~20 NMs are used. This model makes it possible to obtain real-time SCR spectra with an accuracy sufficient for routine prediction and to automatically solve a number of space weather problems.

However, the next studies indicated that the scheme described above is still pilot and cannot be used to solve the problem in detail. Veselovsky and Yakovchuk (2011) verified the application of the method in (Mavromichalaki et al., 2009), which was developed in order to give early warning that solar protons with E_p ~ 10–100 MeV approached the Earth based on NMDB. A post-event analysis and comparison with the observations from 2001 to 2006 indicated that more than 50% of SPEs were omitted in the case of using such a prediction method. To increase the reliability of this method, it is necessary to use additional data on the state of solar and heliospheric activity.

Pérez-Peraza et al. (2011) used the specific features of variations in the GLE registration rate in order to develop a method for predicting such events during cycle 24. A tentative prediction indicated that the next event (GLE71) would be registered between December 12, 2011, and February 2, 2012. This event factually occurred on May 17, 2012; it was small and was only observed at high latitudes. The maximal enhancement (~23% according to 5-min NM data) was registered at the South Pole station.

Shea and Smart (2012) considered in detail the space weather aspects of practical importance in relation to an increased GLE occurrence rate in cycle 23. They presented the calculated radiation doses for aircrafts on the polar routes for each GLE event in the previous cycle. The space weather effects during large solar events in October and November 2003 are of special interest. The authors emphasize that it is important to use NM data in order to predict SPEs in the region of the most radiation hazardous SCR energies (several tens and hundreds of MeV). Such a prediction makes it possible to inform aircraft and spacecraft crews about an impending radiation hazard in advance.

8. CONCLUDING REMARKS

Our consideration indicates that all considerable GLEs, i.e., events with a developed time profile, demonstrate a clearly defined two-component structure: a PC is followed by a DC. These components visually differ in three main characteristics: (1) the shape of the time profile intensity (impulsive and smooth profiles), (2) pitch angle distributions (anisotropic and close to isotropic ones), and (3) energy spectra shape (hard exponential and soft power-law spectra). In particular, a PC is strongly anisotropic at a GLE event onset. PC particles are supposedly accelerated during magnetic reconnection in the lower coronal layers near the flare eruptive phase and the type II radio burst onset. DC particles can be stochastically accelerated in closed magnetic structures above the reconnection region; these particles can be subsequently removed into the high corona during the expansion of a CME.

We now consider again the problem that was raised in the special issue of the journal *Space Science Reviews* (2012, vol. 171): what special conditions should be formed on the Sun for the generation of GLEs? Aschwanden (2012) tends to conclude that a PC in GLE events can be generated by a flare in the lower corona, whereas a DC can be generated in two ways: by a prolonged acceleration and/or trapping of particles in the flare region or by the acceleration by coronal and interplanetary shocks. On the other hand, Gopalswamy et al. (2012) noted that a distinct correlation between the GLE amplitude and the flare or CME parameters has not yet been found. Nevertheless, there are strong arguments for the hypothesis that a shock is formed in the corona before the GLE onset precisely before a particle escapes. Particles escape when CMEs reach an average altitude of $\sim 3.09R_s$ at least for magnetically conjugate solar sources (W20–W90). Using the potential field model on the source surface (PFSS), Nitta et al. (2012) indicate that only about half of all GLEs are adequately magnetically conjugate to sources. At the same time, the CME and flare power, as well as the solar AR degree of complexity, do not provide sufficient conditions for the origination of GLEs. Moraal and McCracken (2012) indicated that GLE69 could have two sources: a flare and an accompanying CME. Mewaldt et al. (2012) indicate a very interesting GLE signature: at energies of 45–80 MeV/nuc, ~50% of GLE events have common properties with impulsive SPEs enriched in ^{3}He, including an increased content of other ions (increased Ne/O, Fe/O, and ^{22}Ne/^{20}Ne ratios) and a high charge state of Fe ions. It is assumed that such events contribute to the seed population of particles that are subsequently accelerated by shocks initiated by CMEs. Li et al. (2012) proposed a GLE generation scenario during the interaction between two CMEs, which were successively ejected from the corona above the same AR. It is assumed that the first CME is narrower and slower than the second one. When the second CME reaches the first one, their magnetic structures reconnect. Thereby, the combined effect of acceleration by shocks driven by both CMEs will be enhanced. Thus, the only conclusion, possibly consistent with the conclusions drawn by all GLE researchers, was formulated several years ago (Cliver, 2009): we deal with an intensely developing GLE concept (“evolving paradigm”).

The detailed physical pattern of the processes resulting in the two-peak GLE structure is still incompletely clear. We tend to consider that the assumption of the interplanetary origin of the two components cannot completely solve the problem. We can also rather reasonably accept the model with two solar sources as the main SCR generation model. Such an approach evidently does not contradict and most probably confirms the up-to-date concept that particles are repeatedly accelerated on the Sun. Thus, the study of SCRs is still one of the most effective instruments for studying the physics of the Sun and solar–terrestrial relations.

The possibilities of this solar–terrestrial physics direction result from the fact that many fundamental problems of particle acceleration physics (at the micro- and macrolevels) have not yet been solved during 70 years of SCR studies. The duration and power of accelerated particle injection and the relative role of particle acceleration and trapping (confinement) (prolonged events) can be among such problems. Variations in the elemental abundance and charge state of accelerated particles from event to event should be studied additionally.

The problems related to solar neutrons and solar flare gamma rays (Miroshnichenko and Pérez-Peraza, 2008; Valdes-Galicia et al., 2009; Miroshnichenko and Can, 2012) are directly related to the physics of acceleration and localization of SCR sources on the Sun, etc. However, these problems are outside the scope of this review. As an example, we only mention an unsolved problem of the gamma-ray source in the 2.223-MeV line in the GLE42 event (Miroshnichenko et al., 2000). The GLEs that were accompanied by long-duration high-energy gamma rays (e.g., GLE51 and GLE52) are still most attractive for researchers. We assume that detailed investigations of poorly studied SCR effects in the Earth’s atmosphere (with regard to the present-day possibilities of tracing its current state based on spacecraft measurements) are among important geophysical applications.

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