Muon bursts at the Baksan Underground Scintillation Telescope during energetic solar phenomena

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Summary. — An extended study is performed of short-term bursts of muon intensity recorded at the Baksan Underground Scintillation Telescope (BUST) in 1981-1992. The bursts may be caused by primary protons with energy $E_p > 500$ GeV. We summarize the results of data analysis obtained during 18 Ground Level Enhancements (GLE) of solar cosmic rays (SCR). It is proved that at least three of the most significant bursts are associated, with a high probability, with the GLEs of September 29, 1989, June 15, 1991, and October 12, 1981. There are definite evidences that some of 15 other bursts seem to be also associated with energetic solar phenomena—large flares, coronal mass ejections (CME), solar proton events (SPE), etc. Otherwise, it is difficult to explain significant distinctions of their angular and temporal properties from the noise ones. The results make the very specific, strict requirements to possible particle source(s), acceleration and propagation mechanisms. The effect under discussion ("BUST effect") is suggested to be closely linked with some powerful processes at the Sun, implying possible impact of extended coronal structures, post-eruption energy release, CMEs and coronal (interplanetary) shocks on solar particle acceleration or modulation of galactic cosmic rays (GCR).

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1. – Introduction

As is well known, on September 29, 1989 a solar proton event (SPE)—the largest ground level enhancement (GLE) of solar cosmic rays (SCR) during the 22nd solar cycle—was observed by the world-wide network of neutron monitors (NM) and surface

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muon telescopes (MT) [1]). The event was also registered, for the first time, by underground muon telescopes in Yakutsk [2] and Embudo [3]. A unique increase of 43% in the total counting rate was recorded [4] by the “Carpet” detector—a central part of the Air Shower Array at the Baksan Neutrino Observatory (BNO).

In comparison with the detectors in Yakutsk and Embudo, the Baksan Underground Scintillation Telescope (BUST) has much higher threshold energies ($E_u^m > 200$ GeV for secondary muons and about $E_p > 500$ GeV for primary protons); however, its effective area (200 m^2) is ten times larger. Having the same recording area as the Carpet, the BUST provides the possibility to observe not only integral flux, but also muon intensity in any given direction. This last fact could be apparently important when studying a highly anisotropic particle flux which can be the case for ultra-relativistic SCR. So, it was not surprisingly that a research interest to high-energy SCR raised enormously due to the first reliable registration of underground effects of large flare on September 29, 1989 when solar protons, according to different estimations, have been accelerated to a maximum energy of > 20 [5], > 25 [3], > 120 [6], > 500 [7-9] and even > 900 GeV [10].

Maximum SCR energy E_m, GeV (or magnetic rigidity, R_m, GV) would evidently characterize extreme capacities of the solar accelerator(s), this parameter being a critical one in any acceleration theory. The possibilities of observational discovery of the upper rigidity boundary for SCR, of course, are limited by the galactic-cosmic-ray (GCR) background. Standard observations by the surface detectors allowed to estimate, for example, the value of $R_m = 20^{+10}_{-4}$) GV [11] by the data on the February 23, 1956 event—the largest GLE since 1942 (historical beginning of regular SCR observations). Meanwhile, by the data of non-standard surface muon telescopes [12], solar protons have been registered in the energy range of 35–67.5 GeV during the initial stage of the same event. Statistical analysis of the worldwide network data of NMs and MTs gave also some evidences that the particles with energy up to 100 GeV are produced during small solar flares and subflares [13]. These last findings, however, were not supported by similar study [14], where no effect of relativistic solar protons after comparatively small flares has been found.

The observations by underground detectors oriented towards the Sun allow to advance into an energy range of ~ 100–200 GeV. In particular, very interesting data have been obtained [15] by the narrow-angle scintillation muon telescope at a nominal depth of 200 m of water equivalent (m.w.e.) in the Experimental Mine of the Colorado School of Mines (Idaho Springs, Colorado). By the superposed epoch method (C. Chree technique), there were separated 13 and 6 bursts of muon intensity with the amplitude alteration from 120 ± 40 to $240 \pm 80\%$, respectively, within 10 min. before the beginning of the proper flare in Hα line. These evidences pointed out the possibility of particle acceleration at the Sun up to an energy of $E > 100 \pm 25$ GeV. However, they still needed to be supported by more reliable observations because the results [15], in fact, were within the limits of 3σ.

This deficiency seemed to be overcome due to the BUST observations. The paper [7] described the first (and largest) burst of muon intensity recorded at the BUST during the GLE of September 29, 1989. A search for similar bursts in the other 17 GLEs during the

BUST operation (since 1981) was undertaken, and it was shown that at least three bursts (29 September 1989, 15 June 1991, and 12 October 1981) can be considered as statistically significant ones. These short-term (< 15 min.) bursts are concentrated in a small solid angle (0.03 sr on the average) and recorded in 1-2 h after the soft X-ray maximum of a proper flare. The muon bursts during other 15 GLEs had more small amplitudes.

To clear up a connection of the above bursts with certain solar phenomena, a further analysis of the same data has been performed more recently [16-20] taking into account the angular characteristics of the bursts and the sensitivity diagram of the BUST, as well as the position and importance of the proper solar flares, nominal direction of the interplanetary magnetic field (IMF), anisotropy and spectrum hardness of relativistic solar protons. Below we summarize and carefully revise all previous findings and try to find additional arguments with the purpose to confirm a solar origin of the BUST bursts.

A short description of the BUST and its characteristics is given in sect. **2**. General features of the September 29, 1989 event, methodical problems of data analysis and comprehensive description of our main results on the proper muon burst are represented in sect. **3**. Section **4** is devoted to other two significant muon bursts (June 15, 1991 and October 12, 1981), as well as to some peculiarities of 15 more small bursts. At last, in sect. **5** we briefly discuss possible approaches to the interpretation of the BUST effect from the point of view of acceleration and propagation theory. As a summary (sect. **6**), the main properties of three most significant bursts are enumerated and several peculiarities of more small bursts are given as additional arguments in support of the first three ones.

2. – Baksan Underground Scintillation Telescope

The BUST is a part of the Large Array Complex at the Baksan Valley, located in the North Caucasus (geographical coordinates: 43.28 °N, 42.69 °E). The Telescope is at the altitude of 1700 m above sea level, in the rock excavation at the effective depth of 850 m.w.e. under the mountain Andyrchi. Geomagnetic cut-off rigidity at the BNO location is equal to $R_c = 6.4$ GV [5]. The BUST has a form of a parallelepiped with height of 11 m and base of 17×17 m^2 (see fig. 1). All its facets are covered by standard liquid scintillators $70 \times 70 \times 30$ cm^3 in size. Inside the Telescope there are two horizontal counter layers with a distance of 3.6 m between them. Besides the others, the BUST provides a single-muon detection. The precision of trajectory restoration is 3° on the average.

The BUST sensitivity diagram is shown in fig. 2 in the horizontal coordinate system. The isolines correspond to the different threshold energies of recorded muons which are limited by rock mass in given directions and display well the BUST sensitivity to cosmic rays in the same directions. The diagram is determined by the topography of the mountains at the BUST location. In searching for muon bursts during the SPEs we excluded the sky sectors where the threshold energy of muons exceeded 500 GeV. In this case, the sensitivity diagram of the BUST is the asymmetric figure making up 43% of the hemisphere. A cross-mark denotes the direction of maximum sensitivity (*i.e.* minimum rock mass and, hence, minimum value of muon threshold energy). The direction of the

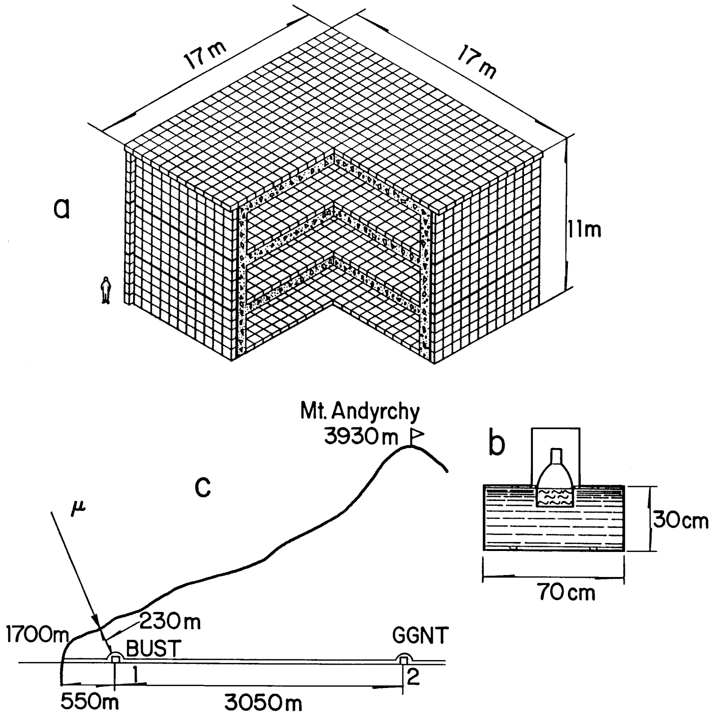

Fig. 1. – The Baksan Underground Scintillation Telescope: a) general sectional view of the BUST; b) schematic sectional view of individual particle detector filled by liquid scintillator; c) schematic profile of the mountain Andyrchi with the main underground installations of the BNO inside—the BUST (1) and gallium-germanium detector of thermonuclear solar neutrino (2) (SAGE collaboration).

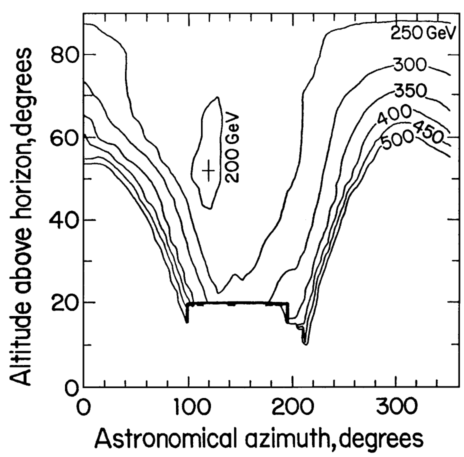

Fig. 2. – Diagram of the BUST sensitivity to cosmic rays in different directions. Isolines correspond to the threshold energies of recorded muons (in GeV), a cross-mark corresponds to the direction of maximum sensitivity, S_m, of the BUST.

maximum sensitivity bends by 38° from zenith to the North-West. Only this direction, S_m, will be named below the BUST orientation direction. An angle between S_m and the edge of sensitivity diagram changes from 30° to 85° as a function of the azimuth.

3. – The event of September 29, 1989

3˙1. *Observations.* – The solar active region NOAA 5698 is considered to be responsible for a powerful behind-the-limb flare (S25°, W105°). In spite of such a location, the flare could be observed in intense emission over a wide range of the wave spectrum—from gamma-rays to decametric wavelengths (*e.g.*, [3, 21, 22]). Since 1047 UT, the GOES-7 detectors observed a soft–X-ray event which lasted about 4 h. Maximum intensity of X9.8 (1133 UT) was accompanied by discrete radio bursts and spectacular loop structure seen in Ha line at least since 1326 UT [3]. At 8.8 GHz the commencement occurred at 1120 UT and maximum at 1137 UT. This event seems to provide the first evidence of a spatially extended component of gamma-ray line (GRL) emission [23]. Besides, there are direct observations [24] of a broad and high-speed coronal mass ejection (CME). The first Ha emission that can be confidently associated with the GRL event was a 1B flare (S24°, W90°) observed at 1141 UT from AR 5698 (see [23], cf. [3]). A picture of solar observations as a whole turned out to be very complicated, and it is not surprisingly that a large body of research led to a significant scatter in results obtained and to a broad variety of interpretations of the event physics involved.

The first relativistic protons arrived at the Earth at about 1135 UT (NM in Calgary), a maximum enhancement reached 377% at 1326 UT (NM Inuvik, 1 min data). This event, indeed, was the largest since 1956 as to total number of relativistic protons [25]. It remains also the first SPE (and, for the present, a single one) in which the signals were recorded with certainty in total counting rate at standard underground MTs, with a maximum at about 1215 UT. Notice that underground increases have been observed in the northern hemisphere only: in Yakutsk [2, 6] at the depths of 7, 20 and 60 m.w.e. with the threshold energies $E_u^p = 8.2$, 16 and 39 GeV (see subsect. **3**˙5) the amplitudes, by 1 hour data, were of $A(\%) = 12.5 \pm 0.45$, 0.94 ± 0.2 and 0.9 ± 0.4, respectively, meanwhile in Embudo (New Mexico, USA, 35 m.w.e., threshold rigidity $R_u^p = 19\,\mathrm{GV}$) the amplitude was $A(\%) = 2.2 \pm 0.2$ [3]. Underground telescopes in the southern hemisphere (Mawson and Hobart), in spite of some lower threshold rigidity ($R_u^p = 10\,\mathrm{GV}$), did not display any considerable increases [26]. This apparent discrepancy shows evidence of a northern-southern asymmetry of SCR flux with the energies of 10–20 GeV.

The surface Baksan detector Carpet has recorded a unique increase in total (T) counting rate (mainly due to secondary muons) with the amplitude $A(\mathrm{T}) = (43 \pm 0.03)\%$ by 4 min data at 1214 ± 0002 UT [4]. The same detector observed a major increase in counting rate of the low-power local showers (so-called threefold (3F) and fourfold (4F) coincidences of Carpet), with the amplitudes (%) of $A(3\,\mathrm{F}) = 14 \pm 0.5$, and $A(4\,\mathrm{F}) = 3 \pm 1$, respectively. The energies of primary protons that produced these signals were about $E_p(\mathrm{T}) = 5.4$, $E_p(3\,\mathrm{F}) = 10$ and $E_p(4\,\mathrm{F}) = 20$ GeV [5]. The maximum of all increases at the Carpet was fixed at 1214 UT. A signal at the BUST in total counting rate, however, was not recorded; it was revealed only in the narrow solid angle at 1330 UT (see subsect. **3**˙2).

3˙2. *Method of the BUST data analysis.* – The 15 min data of only single muons with a trajectory length more than 7 m were used to search for the muon intensity bursts at the BUST [7-9]. Such a selection gives the total counting rate of muons of 7.5 s^{-1}. It should be emphasized that no increase in total counting rate was found for any GLE including the September 29, 1989, event (see fig. 3a).

To search for increases of the particle flux with a strong anisotropy, the sensitivity diagram was divided into 680 inter-overlapping rectangular cells by $10° \times 15°$ in size on zenith and azimuthal angles, respectively. A behaviour of muon counting rate for each angular cell was analyzed with the 15 min BUST data during 3 hour interval (in all 12 intervals of 15 min duration); 1 h before the maximum of soft–X-ray burst (as an indicator of the flare) and 2 h after one. The biggest burst within 3 hour interval was regarded as a possible signal. This procedure was adjusted when analyzing the September 29, 1989 event and repeated without any changes for 17 other GLEs.

To estimate statistical significance of the certain burst, a full number of angular cells and time bins used in the search $n = 680 \times 12 = 8160$ [8, 9] was taken into account. Then the probability to observe a given increase during 3-hour interval in any cell in assumption of the Poissonian counting rate distribution was calculated as

$$p(3\ \mathrm{h}) = 1 - e^{-n\omega}, \tag{1}$$

where ω is the Poissonian probability to find the observed or bigger increase in a given angular cell during a given 15 min interval. Notice, however, that due to such a procedure we overestimate the number of angular cells, because they are inter-overlapping. Therefore, a value of $p(3\ \mathrm{h})$ gives only the upper limit of the expected probability (1). The overestimation coefficient changes from 2 to 1 for the bursts with different amplitude changing from 2.5 to 6σ, respectively.

But is the counting rate distribution for individual cells Poissonian? To answer this question, we investigated specially the angular cell with the burst of September 29, 1989. No deviation from the Poisson law has been found in this case till 4σ. For all cells the total statistics enabled us to look at the region till ~ 6 standard deviations, and again no deviation was found.

3˙3. *Muon burst of September* 29, 1989. – The muon intensity burst with magnitude of 5.5σ (fig. 3b) was found during September 29, 1989 GLE by the above technique. This excess above the average GCR noise corresponds to only 0.8% above the total counting rate of the BUST, $N(\mathrm{T}) = 6300$ muons/15 min, that is less than one standard deviation ($\sigma = 1.3\%$). So, we cannot expect a confirmation of the burst from total counting rate see (fig. 3a). The Poissonian probability of the 5.5σ fluctuation is $2.2 \cdot 10^{-7}$. However, the probability to observe a given increase during 3 h in any cell is only $p(3\ \mathrm{h}) < 1.8 \cdot 10^{-3}$. It corresponds to an average occurrence rate of about 1 burst per 2.3 months. But the frequency of the chance coincidence of such burst with any GLE in the 3 hour interval will be about 1 per 560 years.

The most intriguing and strange features of the burst to be explained are: a

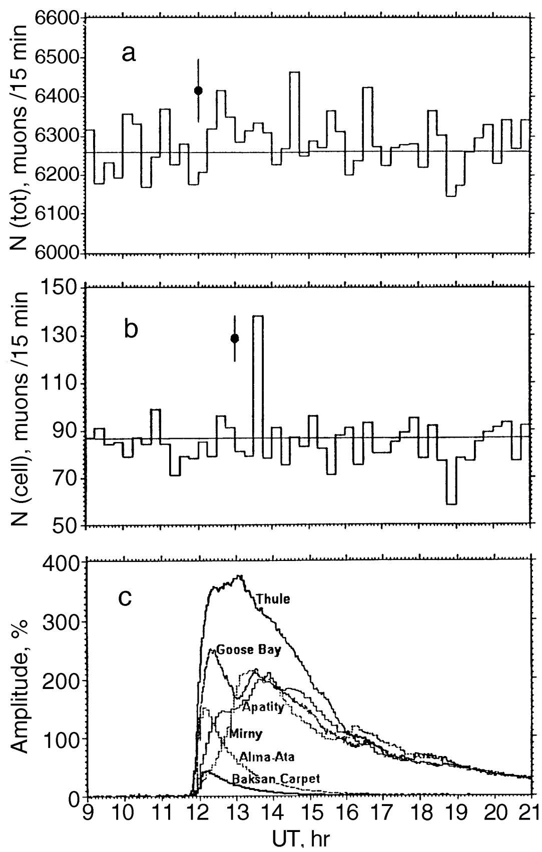

Fig. 3. – Intensity-time profiles of September 29, 1989 GLE at different detectors: a) absence of statistically significant signal in the total counting rate of the BUST; b) short-term, narrow solid-angle burst with magnitude 5.5σ at the BUST; c) time profiles at the Baksan Carpet Array (BNO) and at neutron monitors of Apatity, Alma-Ata, Goose Bay, Mirny and Thule.

narrowness of the burst both in space (solid angle = 0.03 sr) and in time (duration not more than 15 min); a time shift relatively to the Carpet, NM and MT data onset (see fig. 3c); and, of course, very high energy of primary protons, $E_p > 500$ GeV.

The intensity-time profiles observed by NMs in this event turned out to be very complicated (fig. 3c). Some NMs had fixed two maxima, for instance, Goose Bay; at Alma-Ata station and Carpet array only first maximum was recorded; at the same time, the NMs in Thule, Apatity and Mirny have registered only second maximum. The second (and biggest) maximum was observed at 1315-1330 UT by the NMs with a cut-off rigidity of $R_c < 5$ GV [1], meanwhile the NMs with $R_c > 5$ GV, as well as surface and underground muon detectors did not reveal any additional increases (standard MT has a threshold of atmospheric cut-off of about 4-5 GV). To our surprise, the very hard muon burst at the BUST coincides in time with second maximum (see figs. 3b and 3c). The delay of the BUST burst from the soft–X-ray maximum is about 1.95 h, and from the maximum of Carpet, MT and first NM maximum 1.3 h.

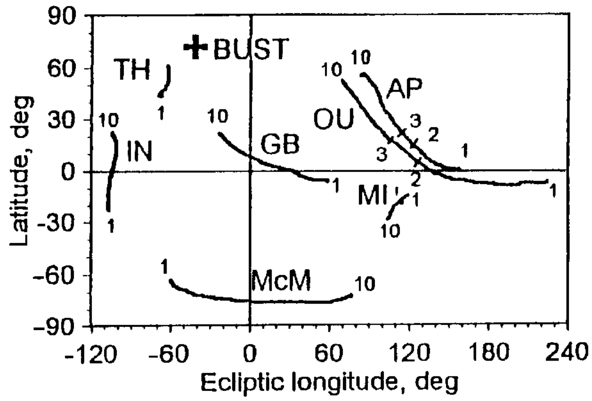

Fig. 4. – Asymptotic cones for a number of neutron monitors (TH-Thule, IN-Inuvik, McM-Mc Murdo, GB-Goose Bay, OU-Oulu; and AP-Apatity) at 1300 UT of September 29, 1989. A cross-mark denotes the direction of entry of the BUST particles; the figures at the curves correspond to the characteristic rigidities of incoming particles.

Is there a direct contradiction with the data of the Carpet array located at the same geographical point and showing a strong decrease of SCR intensity at the moment of the BUST burst? The absence of the second increase at the Carpet can be provided only for a very flat spectrum of primary protons in the range of several hundred GeV. For example, if there were a monochromatic (monoenergetic) beam of the 500 GeV protons, or a similar one corresponding to the GCR spectrum, it could provoke the recorded increase at the BUST and no discernible signal at the Carpet.

In space, the BUST burst direction is near to that of SCR maximum flux which passes through the Thule NM asymptotic cone. The burst direction deviates from the last above not more than by 25° (fig. 4). The GSE longitude of the burst may be considered as coinciding with a nominal IMF one, a difference between them being $\Delta\lambda = 3°$. Both directions—of SCR maximum flux and BUST burst—rise very high above the ecliptic plane (the burst GSE latitude is 72°). To complete this "geometric picture" of the event, note that the direction of SCR maximum flux was significantly changing during the event: if during the first increase (1200-1230 UT) the apparent particle source could be placed to the north of the ecliptic, then past 1330 UT it began to move to the south of the ecliptic [1]. A single spacecraft (IMP-J satellite), which could be able to measure the IMF directly, was inside the Earth's magnetosphere (in its tail) at the time of the event. Indirect information (in particular, about the level of geomagnetic disturbances) indicates that the IMF on September 29, 1989 was fairly quiet ($K_p = 3$-4).

3·4. *Origin of the muon burst.* – Had the BUST protons a solar origin, it is easy to show (see subsubsect. **4**·3.2) that they could not be trapped and contained so long ($>$ 1 h) in the magnetic loops of the solar corona. As a possible alternative, there is a model of two SCR sources [27] separated in time and space. In application to the NM intensity profiles, the model has led to satisfactory results [25]. New evidences of probable

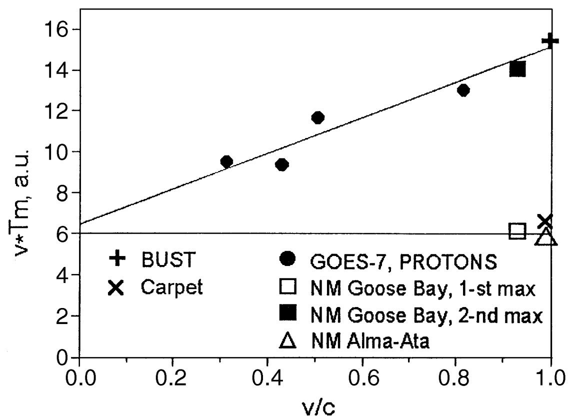

Fig. 5. – The vT_m diagram for the September 29, 1989 GLE [28]. A cross corresponds to the BUST burst. It belongs to the point population of the delayed component (DC). It implies the simultaneous ejection from the Sun of both the DC and the BUST particles.

existence of two sources have been recently obtained by using the so-called vT_m-technique [28] and relying upon some peculiarities of SCR anisotropy [29] during the event. It has been argued that there were two populations (components) of relativistic particles in the September 29, 1989 event—prompt (PC) and delayed (DC) ones (fig. 5). These two populations were ejected in different moments, and they formed two maxima in the NM data. From fig. 5 one can see that the Alma-Ata, Carpet and first Goose Bay maxima belong to the hard PC. On the contrary, the BUST burst belongs to the soft DC, together with the GOES-7 protons and second maximum of NM Goose Bay. It implies the simultaneous ejection from the Sun both of the DC and BUST particles.

On the other hand, it has been found [30] that the peaks of the 470 MeV and 4 GeV ejection profiles of the GLE occurred when CME height reached > 5 solar radii. It is argued that particle ejection appears to result only from a single CME-driven shock and not from the flare impulsive phase or from separate coronal/interplanetary shocks. Notice, however, that extensive analysis [21, 22] of optical, radio, and other relevant data suggests two phases of energy release in this event. After an impulsive phase, a prolonged post-eruption (PE) energy release occurred in an extended region of the corona following the eruption of a large CME. This phase is responsible for numerous coronal and interplanetary phenomena including observed GLE. The PE energy release can create spatially extended sources of broad-band emission covering large areas on the solar disk. In particular, the gamma-ray event [23] may be due to particle precipitation through large-scale magnetic-field loops that connect the source of the PE energy release above the AR 5698 behind the limb with the AR 5703 located at the disk (S24°, W62°). This interpretation seems to be more likely than the suggestion [31] that a CME-driven coronal shock is a plausible source of the energetic protons producing gamma-rays on the visible disk.

In the light of more recent findings, a general scenario of the event [32, 33] based on all available data, may be also compatible with the two-source model of SCR acceleration in extended coronal structures [27]. This model does not exclude twofold ejection of relativistic protons [34]. In subsect. **3**˙6 we represent additional arguments to the above approach when reconstructing a probable spectrum of SCR in this event.

3˙5. *Estimation of primary-proton intensity.* – The BUST allows to measure the intensity of secondary muons. Using the muon excess in burst above GCR counting rate, real solid angle for a proper cell, effective cross-area of the BUST at given direction and net time of data accumulation, we obtain that integral intensity of muons caused the observed burst. For the GLE of September 29, 1989 the intensity is estimated to be of $J_m(>E_u^m) = (1.5 \pm 0.2) \cdot 10^{-6}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$.

Calculation of the corresponding primary-proton intensity $J_p(>E_u^p)$ is a more difficult task. Standard direct calculation by using the muon intensity and multiplicity function of the muon production by primary protons is faced with considerable difficulties. The result of the calculation depends heavily on the shape of SCR spectrum and on the kind of theoretical multiplicity function, both of them having significant uncertainties. The SCR spectrum in the energy range of several hundred GeV is unknown (the proper observation data are absent). And, moreover, there are many evidences that it is impossible to extrapolate the power-law function with unchanging spectrum slope from the 1–10 GeV range to the higher energies [35]. Indeed, it is easy to show that the values of proton intensities differ from one another up to 100 times at the same muon intensity, depending on various muon production functions and probable kinds of primary spectrum.

Therefore, another method using the amplitude $A_m(\%)$ of the muon counting rate increase was applied. The proton amplitude $A_p(\%)$ may be connected with the muon amplitude $A_m(\%)$ by the expression

$$A_p(\%) = \mathbf{k} A_m(\%)\,, \tag{2}$$

where a coefficient $\mathbf{k}$ slightly depends on the primary-spectrum shape within the energy range of interest. It should be changed from 1.4 at the δ-function spectrum up to 0.8 at the power-law integral spectrum with the exponent $\gamma = 7.0$ ($\mathbf{k} \sim 1$ at $\gamma = 1.7$). Uncertainty of the BUST threshold energy will be the main source of errors in this case. The uncertainties of the muon production function and unknown primary spectrum shape lead to large errors in the BUST threshold energy $E_u^p = 500^{+300}_{-200}$ GeV. In reality, however, the value of E_u^p cannot be less than 400 GeV, otherwise a direct discrepancy evidently appears between the data of the BUST and Carpet detector located at the same point.

Proton intensity corresponding to the BUST burst can be easily calculated by using (2) and well-known GCR spectrum (*e.g.*, [36]). We get a value of $J_p(>E_u^p) = (1.2 \pm 0.2^{+2.1}_{-0.8}) \cdot 10^{-5}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$ (statistical errors are indicated first, possible systematic uncertainties due to the threshold energy E_u^p and coefficient $\mathbf{k}$ are shown second). It should be noted that upper systematic limit of intensity corresponds to the lowest permissible proton energy (400 GeV) and to the highest value of $\mathbf{k} = 1.4$, and lower limit to the contrary case.

3·6. *Reconstruction of solar proton spectrum.* – To compare the above result with the data of other detectors we have attempted to reconstruct a probable spectrum of relativistic solar protons in the September 29, 1989 event relying upon the data of NMs and standard surface and underground MTs in the very high-energy range. Following standard procedure [35], only maximum values of integral intensity near the Earth were used. To simplify this task and to avoid the dependence on any theoretical models, we used maximum percentage increases at each detector. In other words, we ignored a difference in the responses of various detectors to SCR and GCR (due to their different spectra). Of course, this way gives no hope to obtain precise approximation of the spectrum; however, it seems to be good enough for tentative comparison of the BUST data with the other ones. The results are given in fig. 6, as follows: 1) percentage increases (the left scale) at NMs *vs.* a geomagnetic cut-off E_c; 2) the same, at surface MTs [1, 37, 38] in dependence on geomagnetic or atmospheric cut-off ($E_a \sim 4$ GeV); 3) Carpet Array data *vs.* the threshold energies E_p [5]; 4) underground MTs data at the Yakutsk Array Complex [2, 6] and Embudo [3].

It is time to mention that the threshold energies of MTs in Yakutsk, namely, $E_u^p \sim 5$, 15, 35 and 85 GeV [6], in our opinion, were overestimated by the Yakutsk research group in 1966: that time the researchers could not carefully take into account the fluctuations of the first collision of GCR protons in the atmosphere. Therefore, we accomplished our own estimations of E_u^p by the empirical formula [39]

$$E_u^p \text{ GeV} = 0.41 d_1 + 0.58 d_2 , \tag{3}$$

where d_1 and d_2 are the atmospheric and underground depths (in m.w.e.), respectively. This formula gives the following E_u^p magnitudes for MTs at the Yakutsk Complex:

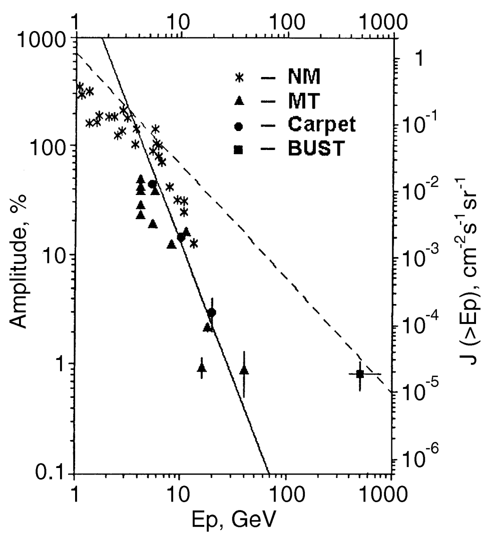

Fig. 6. – Integral energy spectrum of solar protons near the Earth for September 29, 1989 GLE in a wide range of relativistic energies. The solid line is an approximation of the neutron monitor and telescope data above 4 GeV (prompt component). The dashed line is an extrapolation of the GOES-7 [43], Meteor [44] and GMS-3 [45] data (delayed component) up to relativistic energies.

MT1 (0 m.w.e.) = 4.1; MT2 (7 m.w.e.) = 8.2; MT3 (20 m.w.e.) = 16; and MT4 (60 m.w.e.) = 39 GeV. These values do not contradict to other estimations by the same authors [40] with taking into account the first-collision fluctuations. For the other underground MTs (Embudo, Mawson and Hobart) we obtained the E_u^p values close to the authors' estimations.

In the range from 1 to 4 GeV, the spectrum slope in fig. 6 becomes steadily steeper with increasing energy, which is similar, in general, to the results obtained by the other researchers (*e.g.*, [41, 42]) for various time intervals during the event. However, above 4 GeV the SCR spectrum is quite satisfactorily fitted by the power law with the invariable exponent, $A(\%) = 4000\, E_p^{-2.5}$. Absolute intensity spectrum can be obtained by multiplying the above dependence and GCR spectrum [36]. After all, the following spectrum was found: $J_p(>E_p) = 20 \cdot E_p^{-4.1 \pm 0.3}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$. This intensity law is represented by the solid line, with the right scale in fig. 6. The dispersion of the data points around the fitting line seems to be explained by neglecting the difference between amplitudes at the detector and in space and ignoring the SCR anisotropy, atmospheric and geomagnetic effects, rather than by statistical errors of measurements. A good agreement between the above results and spectrum estimations [6, 37] obtained by different approach and in different energy ranges indicates that our simplifications led to no blunders.

In the same fig. 6 the BUST burst of September 29, 1989 is also shown. The enhancement in the narrow solid angle makes up $A_b = (0.82 \pm 0.24)$ % to the BUST total counting rate. This amplitude is seen to correspond to proton intensity $J_p(>E_p) = (1.8^{+0.9}_{-0.8} \cdot 10^{-5}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$, which coincides, within error boxes, with intensity obtained in the previous subsect. **3**·4 by different technique. Thus, both methods gave agreeable results.

Proton intensity estimated by the BUST data for the event of September 29, 1989 obviously does not agree with SCR spectrum obtained by the NM and MT data approximation (solid line in fig. 6). The dashed line in fig. 6 is an extrapolation of the GOES-7 [43], Meteor [44] and GMS-3 [45] data in the power-law form $J(>E_p) = 1.2 \cdot E_p^{-1.7}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ (E_p in GeV) up to the very high energies. One can see that the BUST point and some NM data (delayed component) are near to that dashed line. Taking into account this fact, as well as the 2-hour delay of the BUST burst and results of vT_m-technique (see fig. 5), we may assume that the BUST effect, most probably, is not connected with the main stage of the proper flare and acceleration of the bulk of relativistic protons, but it can be associated with post-eruptive processes in the solar corona.

4. – Search for bursts during other GLEs

After finding and studying of the BUST burst of September 29, 1989, a search was undertaken, with the same technique, for similar bursts in the other 17 GLEs since 1981. During two events (June 15, 1991 and October 12, 1981) the muon bursts with magnitudes of 5.0σ were found and they may be regarded as statistically significant increases. The bursts during the other 15 GLEs are smaller. All three significant bursts are similar to each other, lasting over short time (< 15 min), being concentrated in a small solid angle (0.03 sr on the average), being recorded in 1-2 h after soft–X-ray maximum and probably corresponding to the same energies of primary protons within a narrow range around 500 GeV. Meaning to go deeply into the data and to extend a base for their interpretation, we describe below the main features of additional events in some detail, together with the results of previous studies.

4˙1. *The event of June* 15, 1991. – A source of the June 15, 1991 GLE was a very powerful flare (X12, 3B) at heliographic coordinates N33°, W69°, with the onset at 0810 UT in NOAA region 6659. The GLE maximum of $20 \pm 4\%$, by 15 min data of NMs, occurred at about 0930 UT [46]. This flare was the source of a number of energetic solar phenomena, but its main peculiarity turned out to be a very hard gamma-ray emission ($E_\gamma > 1$ GeV) lasted at least 2 h [47]. Based on this fact, some researchers have proposed either continuous acceleration of protons to the energies of $E_p > 10$ GeV [48], or their trapping in magnetic loops of the corona [49] after impulsive phase of the flare. Originally, a trapping model was applied [50] to the GLE of June 11, 1991 when the longest-duration gamma-ray flare (8 h) occurred (No. 17 in our list, see below table I). However, taking into account a wider set of solar data on this event, it has been concluded subsequently [51] that pure trapping cannot account for the observations during at least the first 3 h after the beginning of the flare.

The muon burst at the BUST of 5.0σ was recorded during this event at 1000 UT, about 99 min after the soft–X-ray burst maximum. The muon intensity and corresponding intensity of primary protons (calculated by the same technique as in subsect. **3**˙4) were $J_m(> E_u^m) = (1.3 \pm 0.2) \cdot 10^{-6}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$, and $J_p(> E_u^p) = (1.1 \pm 0.2^{+1.9}_{-0.7}) \cdot 10^{-5}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}$, respectively. The surface detectors of relativistic protons in this GLE provide data, unfortunately, only up to 6 GV [46] so we could not reconstruct SCR spectrum at the very high energies.

An angle between the IMF and burst directions was $\alpha = 30°$, the burst direction being deflected from IMF towards the Sun ($\Delta\lambda = 15°$) and upwards ($\Delta\varphi = 28°$). Unfortunately, at the moment of muon registration at the BUST the data on IMF are absent, but there are proper data at the moment of flare onset and about 5 h later [46]. By these data it may be concluded that IMF direction at 0900 UT corresponded to the GSE latitude $-23°$ and longitude 145°, this direction being changed very slightly during the GLE. A total duration of the event in relativistic particles at the Earth's orbit did not exceed 12 h, whereas large-scale state of the IMF changes with characteristic time of > 1 day. So, we used above the IMF data at the beginning of the flare. As to the possible existence of CME associated with the event, direct observational data are absent. However, there are indirect evidences [52] to believe that observed prolonged energy release following the CME may be a source of particle acceleration up to high energies at the late stage of this phenomenon.

4˙2. *The event of October* 12, 1981. – The GLE was due to the flare of moderate importance (2B, X3.1) with the onset at 0615 UT at heliographic coordinates S18°, E31°. The maximum increase of SCR flux (11% on 5 min NM data) was observed in Goose Bay at 0910 UT. This GLE had rather large duration (over 15 h) and prolonged anisotropy lasting for ~ 6 h [53]. Its spectrum in the energy range of 10 MeV–5 GeV was very hard [54], with an integral power law index of 2.1.

Significant muon burst was recorded at the BUST at 0745 UT, *i.e.* 69 min after soft–X-ray burst maximum, and coincided in time with a maximum of significant increase at the Baksan Carpet Array. The muons intensity in the burst and corresponding primary-proton intensity have been estimated as $J_m(>E_u^m) = (1.1 \pm 0.2)\cdot 10^{-6}\,cm^{-2}\,s^{-1}\,sr^{-1}$, and $J_p(>E_u^p) = (1.3 \pm 0.3^{+2.3}_{-0.9})\cdot 10^{-5}\,cm^{-2}\,s^{-1}\,sr^{-1}$, respectively. In this case, again, we could not reconstruct SCR spectrum in the wide range of relativistic energies because of lack of surface detector data above 5 GeV.

The BUST burst was recorded from the direction close to the nominal IMF one: only 14° to the West from it, and 10° above the ecliptic plane. However, real IMF vector at this time was oriented almost vertically under the ecliptic plane, and just that hour its direction overturned almost to 180°. At the same time, IMF magnitude and solar wind velocity at the Earth's orbit reached their minimum values, and plasma density its maximum value [55]. It may imply that on October 12, 1981 the Earth was inside or near a heliospheric current sheet (HCS). Such a position considerably facilitates SCR transport from the Sun to the Earth. Unsteady behaviour and small IMF magnitude seemed to make for great angular difference between the IMF vector and direction of muon burst.

Notice that the originating flare occurred at the eastern part of the solar disk, so it prevents a prompt (direct) arrival of accelerated particles along the IMF lines of force. Therefore, it is to assume that either an effective mechanism of relativistic particle transport in the western direction operates in the corona, or another acceleration source exists—far from the flare site, but close to the foot point of the IMF line of force connecting the Sun with the Earth. In this context, it should be noted that some evidences of bi-directional flow of relativistic protons have been found [56] during the intermediate periods of the event. Such a result agrees with the IMF loop model [57] proposed earlier to explain prompt arrival of non-relativistic protons in the same event. To complete this controversial picture, note that according to the data compiled in CME list [58], about 0913 UT on October 12 a CME was observed at the distance >10 solar radii.

4·3. *Small bursts during other* GLEs. – As was mentioned above, among all 18 studied SPEs, three events (September 29, 1989, June 15, 1991 and October 12, 1981) are manifestly distinguished by the most significant muon bursts at the BUST. Preliminary analysis [8, 9] showed that at least these three bursts could not be explained by statistical fluctuations. The rest of 15 bursts should not be considered as significant, because their amplitudes are comparable with background ones. If this is the case, their properties must be the same as those of background (noise) fluctuations. To our surprise, however, it turned out not to be like that. As is shown in the following, their properties significantly differ from noise ones and are similar to the properties of the three major bursts. Therefore, we consider that one needs to adduce together the main properties of the biggest bursts registered during every individual event from 18 GLEs, including three significant bursts and other 15 small ones as well. The results are summarized in table I.

Table I contains in columns: 1, the burst number in a significance decreasing order; 2, the date of the event; 3, the time of the burst onset (the beginning of 15 min interval in

TABLE I. – *The BUST muon bursts related to GLEs of 1981-1992.*

No.	Date	Onset UT	Counts/15 min		Significance		Delay min	λ deg.	φ deg.	α deg.
			mean	burst	st. dev.	P(3 h)				
1	2	3	4	5	6	7	8	9	10	11
1	29/09/89	13.30	86.6	138	5.5	0.0018	117	318	72	72
2	15/06/91	10.00	92.1	140	5.0	0.017	99	340	51	55
3	12/10/81	07.45	62.6	102	5.0	0.024	69	301	10	17
4	25/06/92	20.15	133.5	186	4.5	0,080	4	49	45	93
5	16/02/84	10.00	20.5	42	4.8	0.15	62	28	31	76
6	08/12/82	01.45	29.7	54	4.4	0.28	111	353	73	77
7	16/08/89	01.15	20.0	40	4.5	0.35	− 3	266	32	56
8	26/11/82	04.30	92.1	132	4.2	0.36	97	219	47	94
9	10/05/81	08.00	69.5	104	4.1	0.42	29	297	35	39
10	25/07/89	10.15	68.9	103	4.1	0.45	91	15	71	81
11	24/05/90	21.30	54.2	84	4.0	0.58	39	316	61	61
12	22/05/90	00.15	72.6	106	3.9	0.68	116	28	40	77
13	19/10/89	12.45	131.1	175	3.8	0.70	− 13	302	50	51
14	26/05/90	21.00	48.5	76	4.0	0.71	2	267	89	89
15	28/05/90	05.30	114.1	155	3.8	0.73	57	269	54	66
16	24/10/89	20.15	14.3	30	4.2	0.79	104	220	15	95
17	11/06/89	03.45	108.6	148	3.8	0.79	96	213	55	97
18	22/10/89	18.45	83.5	118	3.8	0.83	40	215	69	94

which the biggest burst was found); 4, the average counts per 15 min inside the angular cell; 5, the number of muons in the burst; 6, the burst magnitude (standard deviations); 7, the upper limit of the chance imitation probability P(3 h) of such increase in any angular cell during 3 h; real probability, for certain, is less than this limit (see subsect. **3**˙2); 8, a time difference (minutes) between the soft–X-ray burst maximum (as an indicator of the flare) and the BUST burst onset; 9 and 10, the geocentric solar-ecliptic (GSE) longitude, λ, and latitude, φ, respectively, of the burst direction; 11, the angular distance, α, between the burst direction and direction of nominal IMF (its GSE longitude is $\lambda \sim 315°$ and GSE latitude is $\varphi \sim 0°$).

4˙3.1. Statistics of muon bursts. The probability to observe the burst of September 29, 1989 by chance is less than $1.8 \cdot 10^{-3}$ (see table I). A combined probability W_{18} of the chance joint realization of all 18 events of table I was calculated in the form

$$W_{18} = P(1 + x + x^2/2 + \ldots + x^{17}/17!)\,, \tag{4}$$

where $P = p_1 p_2 \ldots p_{18}$, and $x = -\ln P$. This formula for the combined probability W_c is used in the case when the probability of each event p_i is a chance value rather than a simple number. Then for all bursts we got $W_{18} = 0.036$. The same procedure applied to the random chosen time intervals (far away from the GLE) gave $W'_{18} = 0.92$. It should be noted that the W_c value is strongly affected by the overestimation of a number of "effective" angular cells. As mentioned above, the coefficient of overestimation is changed from 2 to 1 for the burst amplitudes from 2.5σ to 6σ, respectively (see subsect. **3**.2). Such a correction is not very important for each burst, but the combined probability becomes too small, $W_{18}^{c} = 0.009$, that is only 5 times more than for the September 29, 1989 burst alone. Besides, if to add the 17 biggest bursts, observed during the random chosen time intervals, to the September 29, 1989 burst, then combined probability becomes of $W_{18}'' = 0.36$, that is 10 times more than W_{18}. All the above evidences of the series of bursts during GLEs certainly differed from the noise ones. It also points out that some of the other muon bursts (first of all, of June 15, 1991 and October 12, 1981) have probabilities smaller than it may be expected for the background. For three most significant bursts a combined probability of their chance joint realization W_3 is less than $7\cdot 10^{-5}$. Therefore, a series of those three bursts may be considered as more statistically significant than the single September 29, 1989 burst.

4.3.2. Spatial properties of bursts. Three significant bursts (September 29, 1989, June 15, 1991 and October 12, 1981) were recorded by the BUST from the directions which are considerably deflected from the direction to the Sun: 42°, 20°, and 59° to the West from the Sun and 72°, 51°, and 10° above ecliptic plane, respectively. Besides, the other 15 bursts having magnitudes comparable with a background, are not uniformly distributed as it must be for the noise fluctuations.

Figure 7a) shows that the wide-angle region ($\Delta\lambda \sim 160°$, shaded area) opposite to the nominal IMF does not contain BUST bursts. They are concentrated above the ecliptic plane in the region which looks towards the IMF, and they are symmetric

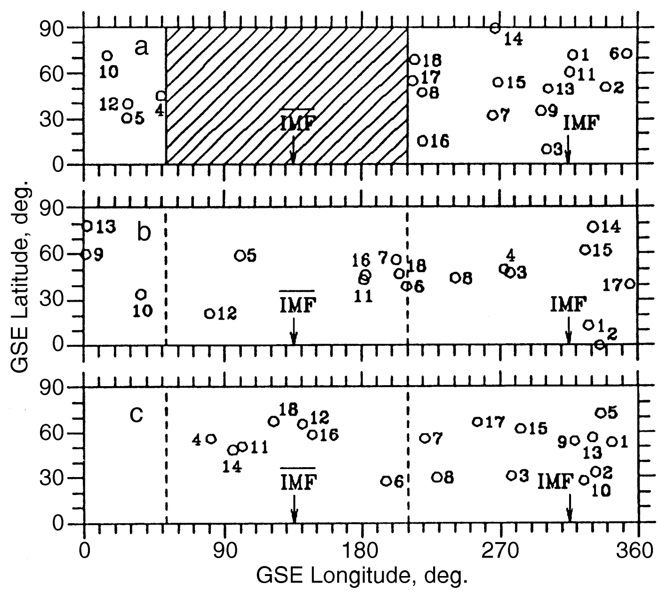

Fig. 7. – Spatial properties of the BUST bursts: a) the registration directions in geocentric solar-ecliptic (GSE) coordinates for the bursts correlating with GLEs; b) the same, for the background bursts; c) the orientation directions, S_m, of the BUST sensitivity maximum.

dispersed around the nominal IMF direction. Should it be connected with any peculiarities of the selection method or with non-uniform orientation of the BUST sensitivity diagram during GLEs? To answer this question, the noise bursts were selected with the same method within 3-hour intervals which were distanced in 24 h before or after the GLE. They do not have the above structure ((fig. 7b)), their angle distribution being close to the uniform one. The BUST orientation directions S_m during each GLE are shown in fig. 7c). Their angle distribution does not almost differ from the uniform one, too. Thus, the observed asymmetry of angle distribution of the BUST bursts cannot be conditioned by any peculiarity of the selection method or by the choice of preferential BUST orientation. The probability to find by chance all the 18 bursts within the unshaded part in fig. 7a is equal to $2.5 \cdot 10^{-5}$.

How to explain the above-observed peculiarity? A gyroradius of the 500 GeV protons in magnetic field with a magnitude $B = 5 \cdot 10^{-5}$ G is about 2 AU. It denotes that a turning angle will be of 30° at 1 AU, if the particles move in homogeneous magnetic field of above magnitude. In principle, only 4 times strong field ($2 \cdot 10^{-4}$ G) is required to turn the 500 GeV protons on 180°. Note that the above value of B is characteristic at the Earth orbit. In the Sun-Earth space the IMF is inhomogeneous, and in quiet state it decreases as $1/r^2$ from several G at the Sun to the B value near the Earth. Hence, an average IMF in space between the Sun and Earth is rather strong, $\langle B \rangle = 10^{-2}$ G, and the region of strong enough IMF to turn the 500 GeV particles is stretched up to 0.5 AU, or up to angular distance of 30° from the Sun (for a terrestrial observer).

In reality, however, the situation is more complicated. Near the ecliptic plane the IMF is bent as Archimedean spiral. By our estimation, the deviation angle of 500 GeV protons in the idealistic (Parker) IMF is about 20° on the average. It does not contradict to the Tibet Air Shower Array data at the GCR energy of 10 TeV [59], where the Sun "shadow", due to IMF influence, is shifted for $\sim 1°$ from the Sun direction. Obviously, such influence will be stronger for the BUST 500 GeV protons. Moreover, real trajectories of particles will depend on their angle distribution near the source and on its location, as well as on real configuration of the IMF and a role of SCR drifts and scattering on large-scale perturbations. For more detailed estimations, there are not enough data about the real IMF configuration and the presence of large-scale perturbations during the GLEs under study. Nevertheless, the IMF seems to be strong enough to bend considerably the 500 GeV proton trajectory; the IMF direction is distinguished in space for such particles, too.

From this point of view, it is also interesting to consider a burst frequency as a function of the angle α between the nominal IMF direction and directions of the bursts recorded during GLEs (fig. 8a)), noise bursts (fig. 8b)), and the BUST orientation (fig. 8c)). The solid lines in fig. 8 correspond to observations; a forecast for uniform distribution of bursts over the hemisphere above the ecliptic plane is shown by dotted lines, and the dashed line demonstrates a forecast for the uniform distribution of bursts in the angle range $0° < \alpha < 100°$. It is easy to see that the bursts recorded during GLEs are almost uniformly spread within the angle sector $0° < a < 100°$. The probability to find by chance all the 18 bursts in this sector is about $6.8 \cdot 10^{-5}$. The

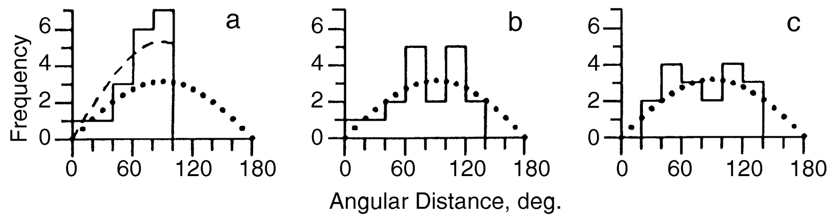

Fig. 8. – Frequency of the BUST bursts as a function of the angle distance between the direction of nominal IMF and the directions of the bursts correlating with GLEs (a), background bursts (b), and the BUST sensitivity maximum orientation (c).

noise burst distribution is similar to that for the BUST orientation direction, and it is close to uniform distribution over the hemisphere ($0° < \alpha < 180°$).

The above features allows us to affirm that spatial properties of the bursts during GLEs differ from the noise ones and are similar to properties of three significant bursts.

4.3.3. Temporal properties of bursts. One of the embarrassing features of three significant bursts (as well as other 15 under study) is their time delay relatively to soft–X-ray maximum (as a zero time). To make this feature clear in fig. 9 we present the time distributions of the bursts occurred within 3 h observation intervals related and not related with GLEs. In the first case (fig. 9a)) one can see that the above peculiarity is very likely to be not a chance because of evident surplus of bursts in the time interval from 1.5 to 2 h. Moreover, the bursts before X-ray maximum are practically absent, since two "preceding" bursts (August 16 and October 19, 1989, see table I), in fact, may be considered by 15 min data as coincident with soft–X-ray maximum. The probability to find by chance > 8 bursts in one bin (0.5 h) on condition that any another bin will not have bursts is equal $6.1 \cdot 10^{-4}$. The noise burst distribution (fig. 9b)) corresponds evidently to the uniform one.

Thus, the asymmetry in angular and temporal distributions of the BUST bursts cannot be explained by any peculiarity of the selection method and/or by the existence of any preferential orientation direction of the BUST sensitivity diagram, as well as by chance fluctuations of galactic background. Therefore, we are inclined to consider 15 small bursts as a mixture (superposition) of background Poissonian fluctuations with the bursts correlating with certain solar phenomena. The share of these last bursts

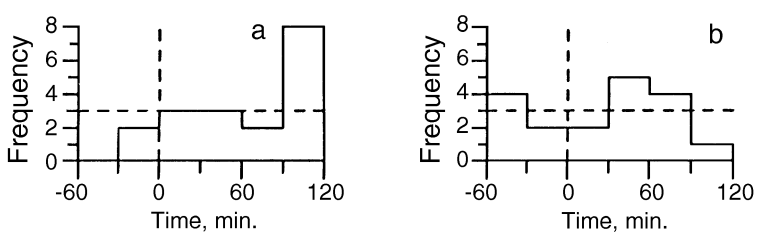

Fig. 9. – Frequency of the BUST bursts correlating with GLEs (a) and background bursts (b) as a function of their time delay relatively to soft–X-ray maximum of a proper flare.

must be noticeable to provide for significant difference of the spatial and temporal distributions from noise ones.

5. – Discussion

As shown above, our results give convincing evidences of statistical correlation between the BUST bursts and some energetic solar phenomena. Moreover, they provide also for certain proofs of causal connection between them. Nevertheless, it is still difficult to explain them unequivocally in the framework of traditional ideas about the sources and mechanisms of particle acceleration at the Sun and their transport in the heliosphere. Several alternative explanations may be proposed.

The first is that the BUST bursts are usual background fluctuations. However, it seems very unlikely to find reliable correlation of random fluctuations with much more random GLEs. Besides, the obvious difference between the properties of GLE-related and non-related (noise) bursts is difficult to explain.

The second alternative does not exclude that some kind of large-scale disturbance arises in the heliosphere (near the Earth's orbit) producing a weak short-term anisotropy of GCR with the energy of $E_p \sim 1$ TeV within a limited spatial region. Such a variation of GCR flux in disturbed IMF may be recorded as the BUST muon burst. But how the above disturbance can correlate with a certain solar flare? We would not suggest any reasonable mechanism for the realization of such phenomenon. A single possibility is that such a modulation of GCR originates near the Sun. The connection with certain solar processes is inevitable in this case.

At last, short-term, anisotropic proton flux (beam) with the energy > 500 GeV may be either produced in the source (at/near the Sun), or focused in divergent magnetic fields near the Sun. Theoretical estimations (*e.g.*, [60, 61]) indicate a magnetic focusing of charged particles in the IMF to be very important. To obtain a perceptible probability that such a flux hits the Earth one has to assume the existence of rather large number of the beams. More probably, however, that near the Sun the proton flux must have rather wide-angle distribution not excluding close to the uniform one. But only a small part of protons concentrating at any narrow solid angle can arrive at the Earth. In the absence of the IMF these particles are expected to be detected from the source (Sun) direction. The presence of IMF has to cause a displacement of the "visible source" direction, as was discussed in subsect. **4**˙3.2. For the > 500 GeV protons in the real IMF, there is, in principle, a possibility of the "visible source" displacement at angular distances of 20°-30° and more.

As to the significant delay of ultra-relativistic beams, it is obviously impossible to accept a hypothesis about trapping and prolonged containment of relativistic protons in the coronal magnetic loops. The presence of a second source [25, 27] or twofold ejection [34] would be a possible explanation of the above delay in some events. For example, the evidence presented [62] on the 22 October 1989 GLE (No. 18 in table I) indicates that there were two distinct injections of relativistic protons into the interplanetary medium. On the other hand, a bi-directional anisotropy of SCR was discovered in the same event [63]. The most logical explanation of these features is suggested [63] to be an impulsive particle injection followed by continuous shock acceleration over an extended period of time. On the contrary, we are inclined to think that the effect under consideration is closely linked with the particle acceleration in extended coronal structures (>0.5 solar radii), side by side with CME generation at the late (post-eruption) phase of complex flares. Speaking to the point, during the event of June 25, 1992 (a fourth candidate to be a significant BUST burst) a post-flare loop system was observed 10–12 h after the X3.9 class flare which had a maximum at 2011 UT [64].

Of course, a question of fundamental interest is: how to accelerate solar particles up to the energy of $E_{\rm m} > 500$ GeV? Obviously, many modeling efforts are required to combine different groups of observational data and reconcile various interpretations of the event of September 29, 1989 type. Available acceleration models do not exclude large values of $E_{\rm m}$. For example, the two-source model [27] gives a value of $E_{\rm m}^{\rm p} \sim 250$ GeV for the flare of February 23, 1956 type. In the electromagnetic model of solar flare [65] the maximum proton energy may be as large as 10^6 GeV. As the most suitable concept for the interpretation of observed phenomenon, at this moment, we regard a post-eruption process with acceleration due to magnetic-field reconnection [66] in the configuration with a vertical current sheet in the corona [67].

A reconnecting current sheet (RCS) arises between leaving and post-flare loops. An electric field appearing due to reconnection process, at the typical plasma parameters in the RCS is about 10 $\rm V \cdot cm^{-1}$ [66]. The maximum energy of accelerated protons will be then of $E_{\rm m}^{\rm p} \sim 100$ GeV, this value being in agreement with the BUST proton energy in order of magnitude. Post-eruption acceleration allows also to explain, in principle, some other properties of the BUST bursts. Consequently, the problem reduces to the search for adequate magnetic configurations (structures) at or near the Sun. Apparently, GCR modulation due to scattering on the post-eruption coronal structures or on CMEs (as on similitude of magnetic lens) cannot be excluded as well. But we do not know any model which describes similar processes.

6. – Summary

Summing up our results, we enumerate below the main features of the muon bursts observed at the Baksan Underground Scintillation Telescope in correlation with a series of 18 GLEs of solar cosmic rays in 1981-1992 (“BUST effect”). The biggest one associated with the September 29, 1989 flare was a very short-term (< 15 min) burst with magnitude 5.5σ concentrated in a small solid angle (0.03 sr), being recorded about 2 h after the soft–X-ray maximum and probably corresponding to the energy of primary protons within a narrow range around 500 GeV.

The coincidence in time of the BUST burst and second maximum of the NMs profiles of September 29, 1989 GLE, in our opinion, is not chance, being connected with the presence of powerful post-eruption processes and, as a result, with a twofold ejection or two-source production of relativistic solar particles. Changing direction of SCR maximum flux during the event of September 29, 1989 may also indicate rather the existence of two sources, than large-scale disturbance of the IMF. The comparison of the intensity estimation by the BUST data with the reconstructed integral spectrum of SCR near the Earth suggests also that the observed particles could not be accelerated in a proper flare together with the first portion of relativistic protons. The BUST particles could be connected in this case with the second, post-eruption stage of the event. At any rate, a drastic difference in spectral and anisotropy characteristics of relativistic protons belonging to the prompt and delayed components points to different mechanisms of their generation and release.

In space, the BUST burst is near to the direction of SCR maximum flux, and it is displaced as far as $\sim 75°$ from the Sun direction. The burst registration direction bends to the West from the Sun (aside the nominal IMF) and to the ecliptic plane upwards. At least two other muon bursts (during the GLEs of June 15, 1991 and October 12, 1981) are statistically significant and with a high probability can also be associated with powerful processes at the Sun. In the whole, they have similar properties as the burst of September 29, 1989.

Our analysis proved that the bursts recorded during other 15 GLEs, with amplitudes close to noise ones, have spatial and temporal properties considerably different from the noise burst ones and similar to the features of three significant bursts. These differences cannot be explained by any peculiarities of the burst selection method. Therefore, the noticeable share of the 15 small bursts might also be connected with certain solar phenomena. Although in this case signal bursts could not be separated from the background, however, they give additional support to three significant bursts.

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