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Detection of high energy solar protons during ground level enhancements

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ABSTRACT

Registration of high energy solar protons by middle and low latitude particle monitors during ground level enhancements (GLE) is investigated. We have developed a comprehensive method, for revealing weak GLE signals. The main result of the method is estimation of probability of error for given value of observed signal amplitude. We derived, that for middle energy protons, the 99% confidence limit of GLE signal detection is determined by $\sim 4.3\sigma$ of observed signal, whereas for highest energy protons it is determined by $\sim 3.7\sigma$. Applying this method to GLE-65 at 28 October 2003, GLE-69 at 20 January 2005 and GLE-70 at 13 December 2006, we make conclusions about the maximal energy of protons during these events. We claim on the presence of >20…30 GeV protons in GLE-65 with the probability of error $\sim$7% and in the GLE-69 with the probability of error $\sim$0.4%. However, during GLE-70 maximal energy of protons was $\sim$10 GeV.

1. Introduction

Detection of GLE signal by middle and low latitude neutron and muon monitors is important research topic, it makes possible to estimate maximal energy of solar particles, which helps one better understand solar acceleration mechanisms. It is believed, that during strong solar events the protons are accelerated up to tens of GeV energies [1]. Valuable information about maximal energy of solar protons could be extracted from neutron and muon monitors, located at low latitudes. Because of high cutoff rigidity, only high energy particles can reach these locations, so only during strong solar events low latitude monitors can detect GLE signal. Such GLE signals are usually weak, and special analysis is required to prove that it is really signal rather than fluctuation of background count. Since, considered problem has statistical nature, our ultimate goal is estimation of probability of error (PE), which is determined as the probability that observed signal is caused by random fluctuations of count, rather by solar protons. The smaller is PE, the more reliable is conclusion about detecting GLE signal. If PE < 0.1, it means that GLE signal is detected with 90% confidence limit, if PE < 0.01 – with 99% confidence limit.

The amplitude of signal is measured in units of statistical significance (SS) or "sigmas", so our goal in fact is to estimate what value of observed σ reliably proves on the presence of GLE signal. Note, that in studies of high energy protons or neutrons different values of SS are derived, without any estimations of the PE (see for example [2–4]). Of course for sufficiently large SS (>5.5…6σ) there is no doubt about the presence of signal, so we do not need to apply special analysis in those cases. However, for lower values of SS it is unclear whether observed SS has caused by the flux of high energy particles or it is random fluctuation of background. Thus, it is necessary to derive a general approach to estimate the PE of observed SS during search of GLE signal.

In present paper we investigate the problem of weak GLE signal detection by low latitude detectors. For this, we have developed for the first time a comprehensive method, which estimates the PE of detected weak signals, clarifying by this, whether this signal was caused by solar protons. The Section 2 describes the method of revealing weak GLE signal and estimating the PE, in the Section 3 the analysis of data from different monitors is presented, and the Section 4 discusses the results and summarizes our conclusions.

2. Method of revealing weak GLE signal

Registration of weak GLE signal by low latitude detectors is a complicated problem. The background counts exhibits casual slow drift of mean, which is caused by daily variations due to Earth rotation, variations in temperature and pressure, and by the influence of interplanetary magnetic disturbances. This drift disturbs revealing of the GLE signal. Then, one knows neither start time of GLE signal, nor its duration. And, finally the main problem: what amount of observed SS reliably proves on the presence of signal, or more correctly, what is the probability that observed signal has caused by random fluctuation, rather than GLE. Therefore, one needs to have a general comprehensive method for deriving the PE when revealing weak GLE signal.

In this section we develop such method, which is based on multiple calculations of SS for all possible combinations of duration and onset time of GLE signal.

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To calculate PE we will need to set the maximal time interval, where weak GLE signal can appear, as well as its maximal duration. We determine these parameters on the base of observations of strong GLE signals by Aragats neutron monitor (ANM). ANM has cutoff rigidity ~7 GV, so one can assume that ANM count corresponds to 5…10 GeV protons. In 23th solar cycle ANM have detected 3 strong GLEs: GLE 60, GLE 65 and GLE 69 [5,6]. Duration of these signals were >1 h and amplitude >8σ. Since, GLE signals have typical shape; one can assume that weak GLE signals with amplitudes 3…5σ will have duration ~20…30 min. Thus we assume that weak GLE signals of 5…10 GeV protons last up to 25 min and starts ~10…50 min after the maximum of X-ray flux.

However, higher energy GLE signals have shorter duration because of weaker diffusion of solar protons in heliosphere. We have detected two weak GLE signals of 20…30 GeV protons: GLE68 (see below) and GLE 69 [4]. Durations of these signals were 3…4 min, and they started ~5 min after X-ray maximum. Hence, we assume that weak GLE signal of 20…30 GeV protons lasts up to 7 min and starts ~1…15 min after X-ray maximum.

Firstly, we choose GLE signal onset time at the moment $t_0 + 10$ min, where t_0 is time of maximum of X-ray flux and successively set signal ending time at $t_0 + 11$ min, $t_0 + 12$ min,- $t_0 + 35$ min. By this, we check 25 variants of possible signal duration from 1 min to 25 min. To remove slow drift a harmonic or polynomial trend can be applied. We used for simplicity polynomial cubic trend in ~3 h time interval. If GLE signal is too weak and it lasts few minutes, then its peak may influence the estimation of the trend. Then one should flag out the samples that belong to GLE interval and create the trend without these values.

After subtracting obtained trend, we get the "pure" fluctuating count of detector, from which the standard deviation (SD) is calculated in usual way. This value is compared to the SD obtained during quiet period and the larger of them is adopted as detector SD. The SD obtained using this method prevents us from overestimating results. Using it, the count is converted to the units of SD or σ. Summing this count in time interval of GLE signal (taking into account that SD of n-min count is equal to $n^{1/2}$) we obtain SS, corresponding to this time interval.

Then we choose next value of signal start time $t_0 + 11$ min and repeat previous procedure, deriving new 25 values of SS, then repeat the procedure for successive start times $t_1 + 12$ min, $t_0 + 13$ min, … $t_0 + 50$ min. In the result of ~25 × 40 = 1000 trials, we derive $N \sim 1000$ values of SS corresponding to different possible GLE signals, having duration 1…20 min and starting after 10…50 min after X-ray maximum. Described procedure corresponds to the protons with ~5…10 GeV energy. However, for higher (>20…30 GeV) energy protons we need about $N \sim 7 \times 15 \sim 100$ trials to count all possible variants of GLE signals.

Deriving N values of SS we search among them large examples. If no large SS is found among them, it means that there is no GLE signal. However, observed large terms can be adopted as the candidates of GLE signal. In case of there are several enhancements with large SS in different time intervals, one can conclude that GLE signal has several peaks (bumps).

For an observed large value A of SS it is necessary to estimate the PE, i.e. the probability that observed value A has originated by the chance. It is the probability that some term among N terms exceeds a given value A. Defining this probability as $P_N(A)$, note that $1 - P_N(A)$ is probability that no term among N terms exceeds A. The probability that one term is smaller than A is equal to $G(A)$, where

$$G(x) = \int_{-\infty}^{x} g(t)\mathrm{d}t \tag{1}$$

is Gaussian distribution function and $g(t)$ is Gaussian probability density function [7].

Therefore the probability that no term among N terms exceeds A is equal to $G(A)^N$. The resulting formula for probability $P_N(A)$, that some term among N terms exceeds A will be:

$$P_N(A) = 1 - G(A)^N \tag{2}$$

This is the PE for our case. Its inverse amount $1/P_N(A)$ gives us the mean number of events with SS > A, where one false event exists. Thus, in one case among ~$1/P_N(A)$ events, observed value of A originates due to random fluctuations, rather than GLE signal. For example, for $A = 4.25$ we have $P_{1000}(4.25) \sim 0.01$, which means that in ~1% of events with $A > 4.25$ one false signal can present. Therefore the value $A = 4.25$ determines 99% confidence limit of revealing GLE signal for ~5…10 GeV energy protons. Analogously $P_{1000}(3.7) \sim 0.1$, so the value $A = 3.7$ determines 90% confidence limit for that detection. However, for >20…30 GeV protons $A \sim 3.7$ determines 99% confidence limit and $A \sim 3.1$ determines 90% confidence limit of detection.

The curves of $P_N(A)$ function for $N = 100$ and 1000 are presented in Fig. 1.

3. GLE-70 at 13 December 2006

Let's consider application of this method to revealing of weak GLE-70 signal at 13 December 2006 event, associated with X3.4 class solar flare. Start time of GLE signal for different high latitude monitors is 2:40…2:50, time of maximal signal varies from ~3:00 (Moscow NM) to ~3:20 (Novosibirsk NM). Several studies devoted to this event have been carried out based on the data of high latitude NM [8–11]. In these studies the highest cutoff rigidity station that registered GLE-70 is Jungfraujoch, having $Rc \sim 4.5$ GV. Detection of GLE-70 by the NM with higher rigidity was not reported, so it was unknown maximal energy of protons during this event.

Let us investigate the count of Aragats neutron monitor (ANM) during GLE-70. In Fig. 2a there are presented 1-min count of ANM and the trend, which is calculated by excluding data in signal interval 3:27–3:43. The equation of the trend is given by

$$y(x) = 7.708 \cdot 10^5 x^3 - 3.03 \cdot 10^5 x^2 + 4.085 \cdot 10^4 x + 4.633 \cdot 10^4 \tag{3}$$

After removing the trend we derive SD ~ 340 and obtain count in units of SD, shown in Fig. 2b (note that obtained value of SD is considerably larger than Poissonian value, which is $(\text{mean})^{1/2} \sim (48500)^{1/2} \sim 220$).

After processing 1000 trials, we find the largest SS ~ 4.3 in time interval 3:27… 3:40, which is outlined in Fig. 2b by rectangle.

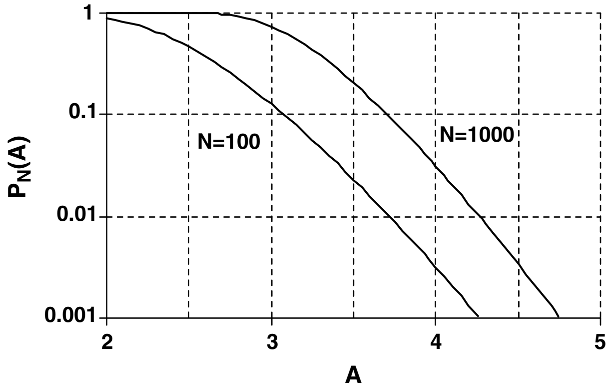

Fig. 1. Function P_N(A) at $N = 100$ and $N = 1000$.

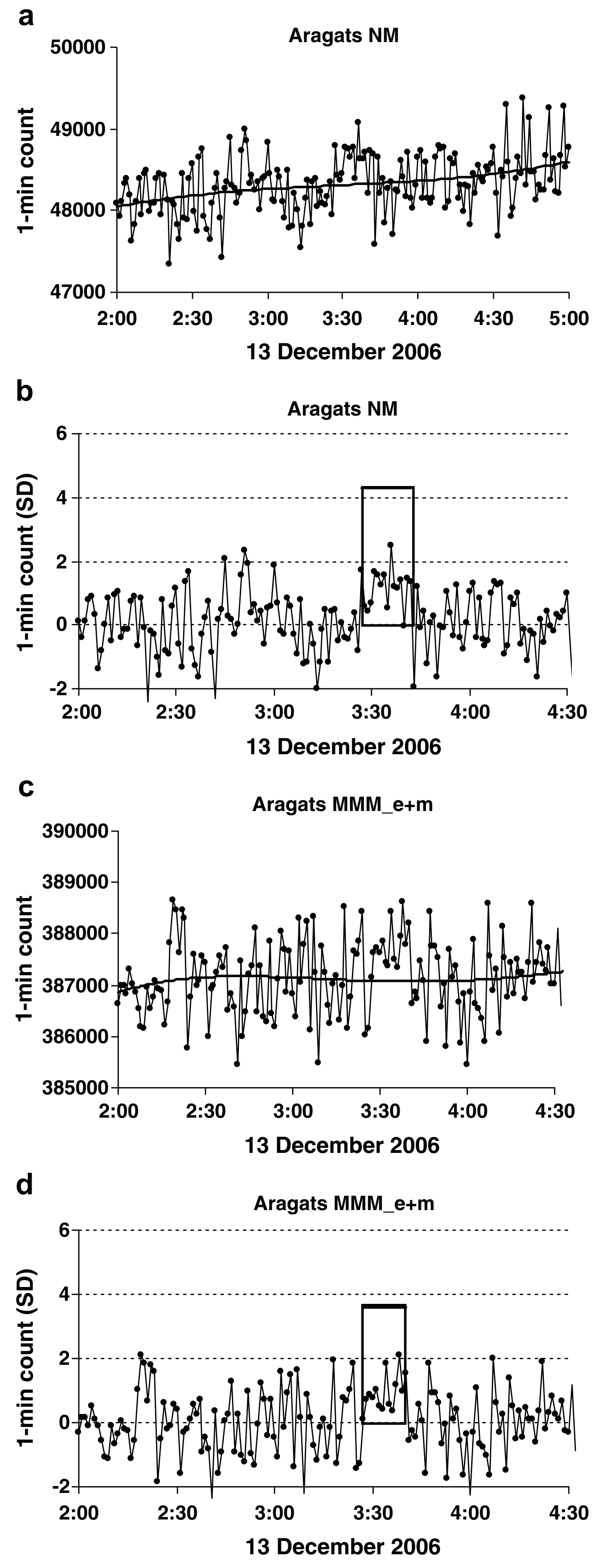

Fig. 2. ANM 1-min count with the trend (a), pure fluctuating count after trend removal in units of SD (b), AMMM 1-min count with the trend (c) and after trend removal in units of SD (d). The rectangles outline the interval 3:27–3:43 with the height ~4.3 for ANM and 3:28–3:41 with the height ~3.6 for AMMM.

The PE calculated by (2) gives $P_{1000}(4.3)$–0.0085, which is extremely small amount, reliably proving the existence of GLE signal.

Results of analogous analysis done for Aragats Multidirectional Muon Monitor (AMMM_e + m) are presented in Fig. 2c and d. AMMM_e + m registers electrons and muons, which are produced by ~10…12 GeV primary protons [12]. The SD of AMMM_e + m is 738. Maximal SS ~ 3.6 of AMMM_e + m is obtained in the interval 3:28–3:41. Corresponding PE is ~0.15. Applying this method to the data of several detectors we calculated SS for each of them and prepared the Table 1. According to this table GLE-70 was registered with >90% confidence limit by 5 monitors, having rigidity >4.5 GV: Alma-Ata NM, ANM, AMMM_e + m, Jungfraujoch NM and Hermanus NM.

The possibility of monitor to register weak GLE signal depends on its mean count, rigidity and asymptotic direction. Hence it, several monitors with high rigidity or small count rate, or both, can not detect weak GLE signals. Mean 1-min count of several monitors versus their rigidity is plotted in Fig. 3. According to Table 1 we marked by open triangles monitors detected the GLE- 70 with >90% confidence limit, and by circles – others. As a result, we plotted a dashed line, which separates two regions with >90% (upper region) and <90% confidence limit of detecting GLE-70.

Table 1
Maximal value of SS and corresponding time intervals of different monitors during GLE-70

Monitor	Rigidity (GV)	Time interval of maximal SS	Maximal SS	PE
Alma-Ata NM	6.5	3:02–3:26	5.1	1.7×10^{-4}
Aragats NM	7.1	3:27–3:43	4.3	0.0085
Aragats MMM	7.1	3:28–3:41	3.6	0.15
Hermanus NM	4.9	2:59–3:08	3.7	0.10
Hermon NM	11	3:12–3:23	3.5	0.21
Tsuneb NM	9.1	2:44–2:58	3.4	0.29
Baksan NM	5.6	2:51–2:56	3.3	0.38
Tbilisi NM	6.7	3:06–3:22	<3	
Athens NM	8.7		<2.5	

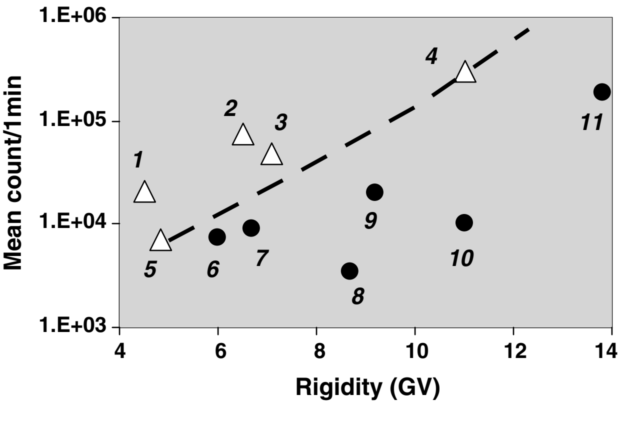

Fig. 3. Mean count of some middle and low latitude monitors versus rigidity. Open triangles show monitors, those detected the GLE-70 with >90% confidence limit: (1) Jungfraujoch, (2) Alma-Ata, (3) Aragats NM, (4) Aragats MMM(e + μ), (5) Hermanus. Black circles correspond to monitors, those did not detected GLE-70: (6) Baksan, (7) Tbilisi, (8) Athens, (9) Tsuneb, (10) Hermon and (11) Tibet.

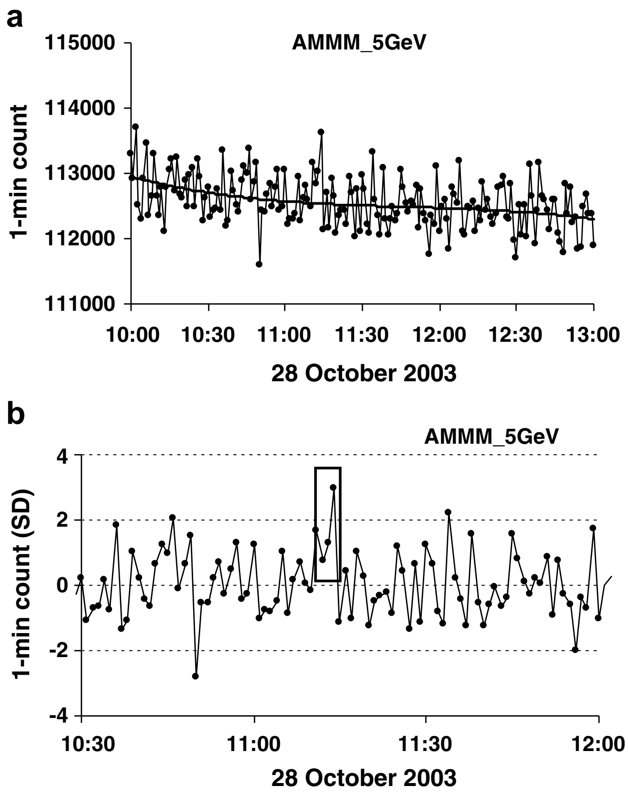

Fig. 4. AMMM_5 GeV 1-min count with the trend (a) and pure fluctuating count after trend removal in units of SD (b). The rectangle outlines the interval 11:13–11:17 with the height ~3.3.

4. High energy protons in GLE-65 at 28 October 2003 and GLE-69 at 20 January 2005

Now, let's consider the detection of higher energy protons during strong solar events by Aragats underground muon monitor AMMM_5 GeV, which registers >5 GeV muons. As it was estimated in [12] >5 GeV muons are produced by ~50 GeV protons of galactic cosmic rays, or by 20…30 GeV protons of solar events. During GLE-65 a large GLE signal was registered in several middle and low latitude monitors, which indicates on the presence of ~15 GeV protons. However, the existence of higher energy protons during this event is under question. Here we present the analysis of AMMM_5 GeV count during this GLE, on the base of our method.

On Fig. 4 there are plotted 1-min count of AMMM_5 GeV with the trend and this count after trend removal in units of SD. The rectangle outlines 4-min interval 11:11–11:15, where $SS \sim 3.2$ is observed. The PE, calculated by Eq. (2) with $N = 100$ is equal $P_{100}(3.2) \sim 0.07$. Thus, we can claim about the presence of 20…30 GeV protons in the event 28 October 2003 with the probability of error ~7%. This is sufficiently small value. It means that in 15 events with $SS > 3.2$ approximately in one case observed bump is caused by random fluctuations and in 14 cases it will be caused by GLE.

Let's consider another strong event – GLE-69 at 20 January 2005. Earlier in [4] we investigated detection of >5 GeV muons by AMMM_5 GeV during this GLE and found $SS \sim 3.93$ in 3-min interval 7:02–7:05, which was considered as GLE signal. However in [4] the PE of this detection was not estimated. Here, on the base of present method we can estimate this PE: it equal to $P_{100}(3.93) \sim 0.004$. This is extremely small quantity, which reliably excludes the possibility that observed $SS \sim 3.93$ could be originated by the chance. Thus we can claim about the presence of 20…30 GeV protons in the event 20 January 2005 with the probability of error ~0.4%.

In Table 2 there are presented all 16 GLE of 23-rd cycle, corresponding X-ray classes and maximal fluxes of >100 MeV and >50 MeV protons. There are seen 8 GLE, detected by Jungfraujoch monitors (according to http://cosray.unibe.ch) and 4 GLE which have been detected by Aragats monitors [5,6]. It turns out, that protons with energy up to ~4 GeV were presented roughly in ~50% of GLE, with energy ~10 GeV in ~25% of GLE and with energy ~20…30 GeV in 2 cases among all 16 GLE of 23-rd cycle (it should be noted that AMMM_5 GeV started to work at summer 2001, so for earlier events we don't have data).

From Table 2 it is seen particularly that several GLE having stronger X-ray emission and/or higher flux of >50 MeV protons than GLE-70, were not detected by ANM. It means, the absence of ~10 GeV particles during these GLE. Thus, GLE-70 is the weakest known event of 23-rd cycle, where ~10 GeV protons were observed. Then GLE 69 is the strongest GLE, where the huge number of 20…30 GeV protons observed.

5. Conclusions

In conclusion we investigated the possibility of detecting weak GLE signals of middle (~6…10 GeV) energy and highest (~20…30 GeV) energy protons by low latitude monitors. For this, we have developed a comprehensive method of searching weak GLE signal with drifting background of galactic cosmic rays and

Table 2
GLEs of 23rd cycle

GLE #	Data	X-ray class	Maximal flux of protons (pfu)		Detected by Jungfraujoh monitors	Detected by Aragats NM	Detected by Aragats AMMM_5 GeV
			>50 MeV	>100 MeV			
55	6 Nov 1997	X9	100	50	Yes	No	–
56	2 May 1998	X1	250	80	No	No	–
57	6 May 1998	X2	10	3	No	No	–
58	24 Aug 1998	X1	100	35	No	No	–
59	14 July 2000	X6	1500	350	Yes	No	–
60	15 Apr 2001	X14	250	180	Yes	Yes	–
61	18 Apr 2001	C2	40	10	No	No	–
62	4 Nov 2001	X1	250	55	No	No	No
63	26 Dec 2001	M7	180	50	No	No	No
64	24 Aug 2002	X3	70	28	No	No	No
65	28 Oct 2003	X17	1800	200	Yes	Yes	Yes
66	29 Oct 2003	X10	400	100	Yes	No	No
67	2 Nov 2003	X8	120	45	Yes	No	No
68	17 Jan 2005	X5	380	30	No	No	No
69	20 Jan 2005	X8	1000	650	Yes	Yes	Yes
70	13 Dec 2006	X3	200	90	Yes	Yes	No

estimating the probability of error. The method differentiates searching procedure for middle and highest energy protons due to different physical characteristics of their signals. Because of that the same values of observed SS has different probabilities of error for middle and highest energy proton GLE signals. For middle energy protons, the 99% and 90% confidence limits of GLE signal detection are determined by $SS \sim 4.3$ and $SS \sim 3.7$, whereas for highest energy protons they are determined by $SS \sim 3.7$ and $SS \sim 3.1$, respectively. On the base of this method, we analyzed the counts of different monitors and concluded that Alma-Ata NM, ANM and AMMM_e + m have detected GLE 70 with >90% confidence limit, i.e. ∼10 GeV protons were presented in this event. Note, that several other GLEs having stronger than GLE 70 X-ray emission and/or higher flux of >50 MeV protons, have not detected by Aragats monitors, which indicates the absence of ∼10 GeV protons in these events.

Investigating Aragats MMM_5 GeV data we claim on the presence of 20…30 GeV energy protons in GLE-65 at 28 October 2003 with probability of error ∼7% and in the GLE-69 at 20 January 2005 with probability of error ∼0.4%.

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