A Relation between Solar Flare Manifestations and the GLE Onset

KURT, VICTORIA[1], YUSHKOV, BORIS[1], BELOV, ANATOLII[2], CHERTOK, ILYA [2], GRECHNEV, VICTOR [3]
[1] *Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia*
[2] *Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation (IZMIRAN), Troitsk, Russia*
[3] *Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia*
clef@srd.sinp.msu.ru

Abstract: Signatures of protons with energies above several hundred of MeV associated with major solar flares are observed with the neutron monitor network as ground level enhancements (GLEs). The time of proton acceleration on the Sun can be found from observations of a gamma-ray emission with spectral peculiarity around 70-100 MeV that results from the decay of neutral pions, which, in turn, are produced in interactions of high-energy protons with dense layers of the solar atmosphere. We have found previously that the pion-decay emission in these events started and peaked close to the time of the main flare energy release manifested by hard X-ray/gamma-ray continuum, narrow gamma-ray lines and high-frequency radio emission bursts as well as the maximum of the soft X-ray flux derivative. We studied data of the world neutron monitor network and GOES measurements of protons with energies above 500 MeV related to 42 GLEs since 1972 and light curves of the available electromagnetic emissions of the associated flares. Our study has revealed that the delay of the earliest arrival time of high-energy protons at 1 AU with respect to the observed peak time of the solar bursts did not exceed 8 min in 28 events. This result indicates that efficient acceleration of protons responsible for the GLE onset is close to the time of the main flare energy release.

Keywords: solar flare**,** main flare energy release, proton acceleration, ground level enhancement, world neutron monitor network.

1 Introduction

Exact determination of the proton acceleration time during solar flares is one of important problems of the solar physics. Various methods are used for this aim (e.g. analysis of the onset times of shock-induced type II radio bursts, hard X-ray emission (HXR), back-extrapolation of the particle emission time near the Sun, etc. [1-4]), but results of these methods often contradict each other. The accurate time of proton acceleration on the Sun can be found from observations of the gamma-ray emission with a spectral feature around 70-100 MeV that results from the decay of neutral pions, which, in turn, are produced in interactions of high-energy (> 300 MeV) protons with dense layers of the solar atmosphere [5,6]. However, this broad gamma-ray line was observed in seven major flares only.

Five of these events were accompanied by ground level enhancements (GLEs): 48 (24.05.1990), 51 (11.06.1991), 52 (15.06.1991), 65 (28.10.2003), and 69 (20.01.2005). Our analysis of these events revealed that the earliest arrival of particles at 1 AU lagged behind the onset time of the corresponding pion-produced gamma-ray burst by 1-5 min [7] (hereafter this time determines the arrival of an electromagnetic signal at 1 AU).

We have studied five events, in which the pion-decay emission was observed with a high temporal resolution: 24.05.1990, 25.08.2001, 28.10.2003, 4.11.2003, and 20.01.2005 [8]. We have found that the pion-decay emission in these events started and peaked close to the time of the main flare energy release manifested by the hard X-ray/gamma-ray continuum, narrow gamma-ray lines and high-frequency millimeter bursts as well as the maximum of the soft X-ray (SXR) flux derivative. From their temporal closeness we conclude that efficient proton acceleration in these events occurred during the main flare energy release and this moment can be used as a reference time for other powerful events.

In the present paper we have extended our approach to a set of major flares in which signatures of protons with energies above several hundreds MeV were observed by the neutron monitor network as GLEs. From the analysis of data from the world neutron monitor (NM) network and measurements of protons with energies above 500 MeV in 42 GLE events since 1972 we found the earliest arrival times of high-energy particles. Then we studied the light curves of the available electromagnetic emissions of solar flares associated with these GLEs and defined the main energy release time of these flares. The actual onset time of each GLE was compared with the estimated time of the main flare energy release. The difference between these times did not exceed 8 min in 28 events (i.e. in 69%) and 16 min in 35 (73%) events.

2 Method and Data

We have studied 42 GLE events since 1972 based on the data base of GLE events [9] as well as papers [1,10] which cover solar cycles 20–21. The list of events recorded by Lomnicky Stit NM [11] was also used. In addition, we used the data on fluxes of protons with energies >500 MeV from GOES/HEPAD (spidr.ngdc.noaa.gov/spidr/). We excluded from our analysis data of those NMs that were due to the solar neutrons.

Following [12] we have examined the record to identify GLEs that either show at least one neutron monitor with an ephemeral pulse preceding the main GLE, or at least show a clearly defined difference in onset times between several neutron monitors. If the first increase recorded by a single monitor exceeded 4σ above the background level, it was considered to be the GLE onset time T_{onset}. If it was weaker, then we demanded that such weak increases must be recorded simultaneously by two or more NMs and/or in HEPAD. The accuracy of estimating T_{onset} depends on the temporal resolution of NM and ranges from 5 min to 1-2 min.

In 5 events when the pion-decay gamma-ray line was recorded we estimated the initial time T_0 of high-energy proton acceleration using this line. In other cases we analyzed observations in different emissions. The initial estimate of the main flare energy release time T_0 was obtained from GOES SXR records (3-s data). The primary importance of these data is determined by the non-interrupting series of measurements since 1975. From GOES SXR records in two channels we calculated the SXR derivative, the temperature, and emission measure by means of a well-known technique [13]. Note that GOES detectors were saturated in several powerful events. Since the SXR flux is known to be nearly proportional to the total energy deposited into the flare volume by accelerated electrons (the Neupert effect [14]). This physical relation means that HXR and dI_{SXR}/dt derivative data are in a certain sense interchangeable.

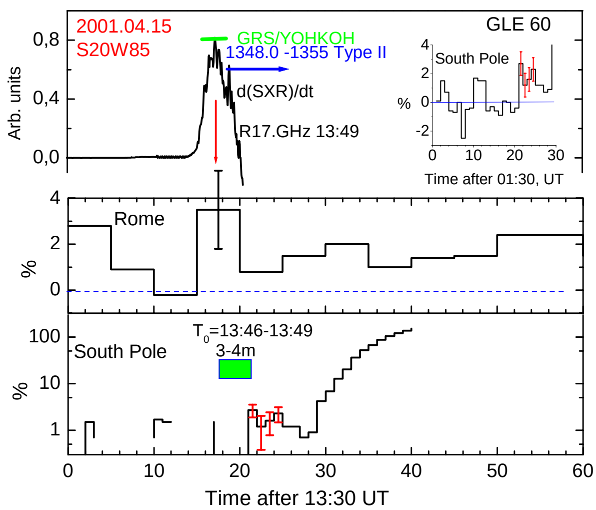

Figure 1. 15 April 2001 event.

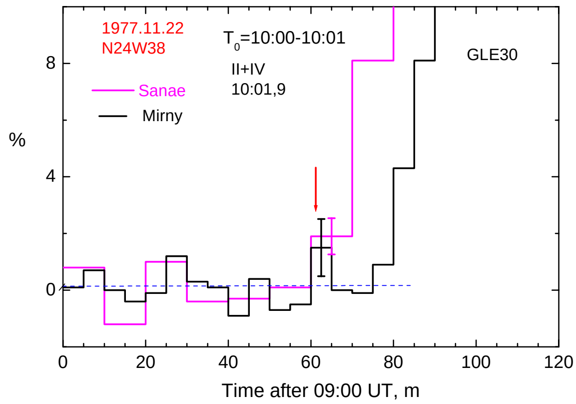

Figure 2. 22 November 1977 event.

We also involved data on bremsstrahlung up to 10 MeV recorded with Venera-13, 14, Ulysses, OSO-7, Prognoz-2, SMM, GRANAT, Yohkoh, RHESSI, CORONAS-F in several events as well as available data on narrow gamma-ray lines obtained by OSO-7, Prognoz-2, SMM, RHESSI, INTEGRAL. Measurements made by Venera-13, 14, Ulysses allowed us to define more precisely the time of the flare and maximum of energy release in events located over the west limb. We have also used all the available data on the radio emission bursts in mm-cm range.

Peak times found from different emissions coincide to within 2–4 min. This time was adopted as the moment of the main flare energy release T_0 (with a specified uncertainty).

As an illustration, Figure 1 presents data on different emissions used in determining T_0 and NM data used to find T_{onset}. In this event we adopted T_{onset} =13:51-13:52 UT. Figure 2 shows NM data on GLE30, for which we adopted T_{onset}=10:00-10:05 UT.

3 Discussion and Conclusions

We have estimated the onset times T_0 of proton acceleration up to high energies. The results for all 42 events are listed in Table 1, which contains the GLE number, the date, coordinates of the associated flare and the onset time of the II type burst according to the Solar Geophysical Data. Three columns present T_0 and T_{onset}, which we found, and the difference between them. The latter column contains the value of the onset GLE peak above background level.

Figure 3 shows a distribution of the GLE events under consideration vs. heliolongitude of associated flares. The vertical bars present maximum uncertainties of the estimated delays. Red symbols present events with a maximum enhancement of <6%. The figure does not show any significant correlation between the delay and the flare longitude.

Table 1. GLE onset and associated flares.

N	Date	Location	Type II	T_0	T_{onset}	ΔT, min	σ
25	1972.08.07	N14W37	15:19	15:19-15:22	15:25-15:31	5-6	
27	1976.04.30	S09W47	21:06	21:06-21:08	21:10-21:15	4-9	3.8
28	1977.09.19	N05W57	09:50 09:52	09:54-09:56	09:55-10:00	1-6	4.2
29	1977.09.24	N10W116	05:55.0	05:55	06:05-06:10	5-10	3
30	1977.11.22	N24W38	10:01.9	10:00-10:01	10:00-10:05	2-4	2.9
31	1978.05.07	N22W68	03:27.0	03:27-03:30	03:30-03:35	1-7	4.5
32	1978.09.23	N35W50	09:58	10:05	10:25-10:30	18-32	3
33	1979.08.21	N15W38	06:15	06:13-06:17	06:15-06:20	2-7	3.7
34	1981.04.10	N07W35	16:49.1	16:48-16:49	17:00-17:05	13-18	1.8
35	1981.05.10	N03W75	07:18.9	07:19-07:20	07:45-07:50	15-30	3
36	1981.10.12	S18E30	06:27.0	06:27-06:29	06:50-06:55	24	3.6
37	1982.11.26	S11W87	02:34.0	02:39-02:40	02:50-02:55	5-15	5
38	1982.12.07	S19W82	23:44.0	23:44-23:45	23:45-23:50	1-5	4.4
39	1984.02.16	S16W94	08:58		8:50-8:55		3
40	1989.07.25	N25W84	08:40.9	08:41-8:42	08:40-08:45	1-4	4
41	1989.08.16	S18W84	01:03.0	01:13-01:14	01:15-01:20	2-6	5
42	1989.09.29	S26W100	11:25.7	11:26	11:25-11:30	2-4	5.2
43	1989.10.19	S27E10	12:49.0	12:53-12:56	13:00-13:02	6-8	4.5
44	1989.10.22	S27W31	17:45.0	17:45-17:48	17:48-17:50	3-5	5
45	1989.10.24	S30W57	18:06	18:10-18:18	18:20-18:25	5-10	4.6
46	1989.11.15	N11W26	06:57.0	06:56-06:57	07:00-07:05	3-4	4
47	1990.05.21	N35W36	>22:14	22:14-22:15	22:20-20:25	6-11	3
48	1990.05.24	N33W78	21:00.0	20:48.4	20:48-20:50	1±0.5	6.6
49	1990.05.26	N33W104	>20:48	20:49-20:51	20:55-21:00	4-10	3.3
50	1990.05.28	N33W120	04:30.0	04:30-04:31	05:00-05:05	4-6	4.4
51	1991.06.11	N31W17	02:05	02:12:56	2:16–2:18	4±1	3.5
52	1991.06.15	N33W69	08:14.2	08:14-08:15	08:20-08:21	5.5±0.5	8.5
53	1992.06.25	N09W67	19:57.0	20:02-20:04	20:00-20:05	1-3	2.5
54	1992.11.02	S25W100	02:53.0	02:54-02:57	03:10-03:15	15-25	2.7
55	1997.11.06	S18W63	11:53.2	11:53-11:54	11:58-12:00	4-7	3.2
56	1998.05.02	S15W15	13:29:42	13:42-13:43	13:55-14:00	12-18	6
57	1998.05.06	S11W65	08:03.3	08:05-08:06	08:05-08:10	2-6	4
58	1998.08.24	N35E09	22:02.0	22:03-22:05	22:15-22:20	12-16	5.4
59	2000.07.14	N22W07	10:20.0	10:19-10:20	10:22-10:23	4±1	4
60	2001.04.15	S20W85	13:48.0	13:46-13:49	13:51-13:52	3-4	3.5
61	2001.04.18	S20W115	02:17.0	02:14	02:35-02:40	20-25	6.6
62	2001.11.04	N06W18	16:10	16:13	16:25-16:30	12-16	2.8
63	2001.12.26	N08W54	05:12	05:15-05:17	05:21-05:22	4-6	5
64	2002.08.24	S02W81	01:01.0	01:01-01:02	01:00-01:05	2-4	3.8
65	2003.10.28	S16E08	11:02	11:04:30	11:09-11:10	4±0.5	2.7
66	2003.10.29	S15W02	20:42:00	20:44:25	20:59-21:00	16	4.5
67	2003.11.02	S14W56	17:14.0	17:16-17:18	17:15-17:20	3-5	4.2
68	2005.01.17	N15W25	09:44:00	09:43.5	10:30-10:35	50	2.4
69	2005.01.20	N14W61	06:35.7	06:45:30	06:47-06:48	2±0.5	5
70	2006.12.13	S06W23	02:18.7 Re	02:26-02:28	02:35-02:40	6-14	6

Given the particle velocity dispersion and the length of the interplanetary magnetic field (IMF) lines, we can estimate the minimum possible propagation time of particles from the Sun to 1 AU. The time delay between the observed T_0 и T_{onset} for GLEs protons was evaluated as 1-6 min, since field lines of IMF with the length smaller than nominal (average) can exist [15]. In this paper we have increased this value up to 1-10 min taking into account all the possible uncertainties calculating T_0. In view of this uncertainty, less that 5 min time delay values observed in some events do not contradict the common sense.

Table 1 shows that calculated T_0 moments of the main flare energy release are in most cases close to the onset time of the II type. Figure 4 (right) shows that in 32 events these onset moments coincide with ≤ 4 min accuracy. It seems that a slight difference between T_0 and the II type onset time can not draw an unambiguous conclusion whether the high-energy protons are accelerated directly in a flare or in a shock front. Nevertheless, we believe that the method to determine the onset time of proton acceleration, based on the pion-decay gamma-ray line observation and realized in this work, supports the following conclusion: this acceleration starts at the moment of the main flare energy release.

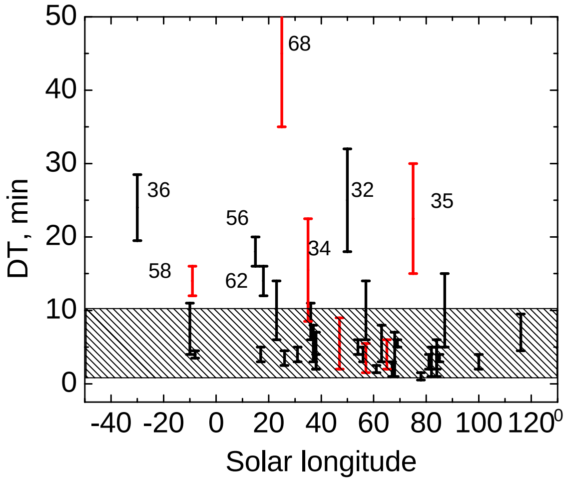

Figure 3. Time delay DT of the GLE onset vs helio-longitude of associated flare.

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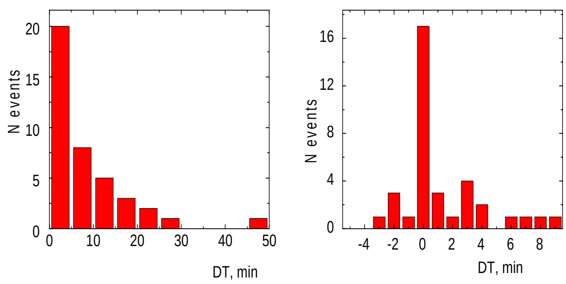

Figure 4. Left panel: distribution of time delay between T_0 и T_{onset}. Right panel: distribution of time difference between the type II onset and T_0.

Acknowledgements

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