Appearance of high-energy protons at the Sun and the GLE onset

Boris Yu. Yushkov*, **Victoria G. Kurt*** and **Anatoly V. Belov**†

*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, 119991, Russia
†Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Troitsk, Moscow Region, Russia

***Abstract*. High-energy protons accelerated during large solar flares can be observed not only near the Earth but immediately at the Sun as well. This is possible through the detection of high-energy (>100 MeV) gamma-ray emission produced by pion decay. In turns neutral pions are generated in interactions of high-energy (>300 MeV) protons with the ambient solar atmosphere. Such a pion-produced gamma-ray emission was detected in 12 solar flares, and GLE particles were presented after 5 of them. Appearance of the bulk of solar protons was preceded by enhancement observed by several neutron monitors. Comparing the time of an appearance of pion-produced gamma rays with onset time of these GLE we found that accelerated protons are able to escape the Sun immediately after their acceleration without any delay.**

***Keywords*: solar flares, gamma-ray emission, GLE**

I. Introduction

Solar flare gamma-ray emissions were being detected and measured to GeV energies since 1980. These emissions are produced by the ions and electrons of highest energies accelerated at the Sun. They provide our only direct (although secondary) knowledge about the properties of the accelerators acting in a solar flare. Protons accelerated to energies >300 MeV interact with ambient solar matter and produce neutral and charged pions. In their turn neutral pions generate gamma-ray emission characterized by a special spectrum shape namely by a broad line in the 40-100 MeV range. Recognition of this spectral feature in sequentially accumulated emission spectra allows exact and unambiguous determination of both: the starting point of particle acceleration and the time behavior of these particles in the acceleration region. Accelerated particles are able to escape the Sun and can be observed as a ground level enhancement (GLE) detected mainly by neutron monitors (NM). Analysis of the 20 January 2005 event showed that the GLE onset was caused by particles which escaped the Sun immediately after their acceleration [1]. These particles belong to the same population of accelerated particles as the interacting particles do [2].

The solar flares, which have direct evidence of the pion-decay gamma-rays, were unique. Only five of them were accompanied by GLEs and will be treated in the present communication: 24 May 1990 (GLE48), 11 June 1991 (GLE51), 15 June 1991 (GLE52), 28 October 2003 (GLE65) and 20 January 2005 (GLE69).

II. The starting assumptions

Prior the analysis of individual events we shall define and discuss the starting assumptions of the method.

i) Previously in the events of 25 August 2001, of 28 October 2003, of 4 November 2003, and of 20 January 2005 [3] it was shown and will be assumed to hold here that the protons with energies above 300 MeV acquire efficient acceleration starting simultaneously with the main flare energy release.

Another type of information is based on measurements of spatial distributions of electromagnetic emissions performed in the broad wavelength range: from microwave/millimeter waves and up to 2.2 MeV gamma-rays. The measurements were made during the flares of 28 October 2003 [4] and of 20 January 2005 [2] and showed that emitting areas were concentrated within a compact closed structure above the active region on the Sun. Acceleration of the particles also took place in this area.

We therefore assume that at least first portion of the protons accelerated to high energies appeared on the Sun in the compact areas. If so, then the path length of the first portion of the particles detected at the Earth could not be shorter than 1 AU.

ii) We also assume that certain part of protons escapes the Sun immediately after their acceleration [1], [2], [5]. The time point of the escape can thus be defined by measuring the time of the onset of gamma-ray emission caused by the decay of neutral pions.

iii) We suppose that the minimum path length of particles lies between 1 AU and the Parker spiral length. This assumption is based on the fact that some magnetic field lines could be shorter than the nominal (Parker spiral) length due to a random magnetic field [6]. Thus the onset of a given SEP event can happen sooner than expectations based on the assumption that particles move along the usual Parker spiral, which is generally believed to be the shortest way. It should also be noted that major solar flares often occur in series, as for example in the events of October-November 2003, January 2005, strongly disturbing the interplanetary space and interplanetary magnetic field (IMF). It is highly unlikely that the normal Parker spirals exist under such conditions.

Suppose that GLE particles were accelerated in the flare located within the interval of the preferable heliolongitudes (W30-90). If certain portion of accelerated particles, "the lucky ones", directly access the shortest IMF lines existing in this time and if the particle transport is a simple adiabatic motion characterized by the lack of scattering then the distance covered by these particles is close to the length of smoothed spiral IMF lines. In this case a weak burst of such "lucky" particles could be detected before the arrival of the main particle bulk. This burst caused by "lucky" particles will be called a precursor.

It is possible to estimate an expected delay of this precursor relative to the appearance of gamma-ray emission caused by neutral pion decay i.e. after particle acceleration by taking into account the following considerations.

i) At the values of solar wind speed of 300-800 km/s the most probable IMF field lines lengths lie within the interval 1.08 - 1.4 AU. The low limit of the distribution of these lengths is close to 1 AU.

ii) Effective energy of particles detected by NM stations located at high latitudes has been estimated to be ~1 GeV [7], corresponding to the velocity $v = 0.875c$, (c - speed of light). It is so, because particles with higher energies are the earliest. Additionally, the number of accelerated particles considerably diminishes with their energy irrespective of the nature of the acceleration process. Due to the geomagnetic cut-off effect NM located at the middle- and low latitudes respond only to particles with higher energies.

Let us make an example. It takes 500 s for photons to propagate from the Sun to Earth. The propagation time of 1 GeV protons along the path of 1.2 AU is equal to 685 s. If photons and protons were released simultaneously then at Earth the second ones will be detected with about 3 min delay after the observation of the gamma emission.

Generally the time delay of the "lucky particles" relative to the beginning of the gamma emission from the neutral pion decay can be calculated from the particle velocity dispersion and IMF lengths spread and it ought to get into interval with duration of 1-6 min. We deliberately looked in the available for each event data set of NM network for such short increase in time interval of 1-6 min duration after time moment of pion decay line appearance on the gamma emission spectra.

III. Description of Selected events

Data obtained from selected NMs are presented in Fig.1 as histograms. Observations of high-energy gamma-rays are overlaid above as curves.

A. The Event of 24 May 1990

GLE48 was associated with the X9.3 solar flare located at N36 W76. The onset time of this event was determined as 21:02-21:03 UT [8]. A great increase caused by the solar neutron flux was detected beginning at 20:49-20:50 UT [8], [9]. Gamma-ray emission of this flare was well observed by the PHEBUS experiment onboard GRANAT and the spectral feature caused by the decay of neutral pions was detected at ~20:48:30 UT [8]. NM Mount Wellington recorded the statistically significant count rate increase of 6.6σ at 20:49-20:50 (see Fig.1) i.e. falling exactly within the expected interval of a precursor observation. It is highly unprobable that this NM could detect solar neutrons because the angle θ between the local vertical and direction to the Sun was equal 89°. Note that the asymptotic arrival direction of protons for the NM Mt. Wellington for this event corresponded to the morning sector including the Sun-Earth magnetic field line.

B. The Event of 11 June 1991

GLE51 was associated with the X12 solar flare located at N31 W17 i.e. outside the interval of preferable heliolongitudes. Gamma-ray emission of this flare was detected by the EGRET telescope onboard the Compton Gamma Ray Observatory, the spectral feature caused by neutral pion decay was observed with confidence from 02:12:56 UT [10]. The main GLE onset started later at 02:35-02:40 UT and was small [11]. NM Newark detected also a small increase (3.5σ) at 02:16-02:18 UT (see Fig.1). This burst occured in the expected interval of precursor if protons were accelerated since 02:12:56 UT.

C. The Event of 15 June 1991

GLE52 was associated with the X12 solar flare located at N33 W69 and has been widely discussed in literature, particularly in connection with the observation of gamma-ray emission with energies up to 3 GeV caused by the decay of neutral pions. The measurements were made by the GAMMA-1 detector on the Gamma satellite [12]. Unfortunately these monitoring started at 08:37 UT i.e. 20 min later than the flare impulsive phase. GLE started after 08:30 UT and was isotropic [12].

We shall assume further on, that an acceleration of high-energy protons during this flare started close to the maximum of main energy release, which happened at 08:15 UT according to observations of other emissions, and not later than the second peak of 17 GHz radioemission observed by Nobeyama station (http://solar.nro.nao.ac.jp) at 08:17 UT (see Fig.1). Credibility of such determination of the time point of acceleration of protons has been established in [13], [5], [2]. In any case protons were accelerated not later than the second peak of 17 GHz emission at 08:17 UT. NM Kiev detected a significant increase (8.5σ in the first bin) at 08:21-08:22 UT (see Fig.1). Even under the hard assumption that protons were accelerated during the first radioemission maximum the delay of NM Kiev increase does not exceed 360 s.

D. The Event of 28 October 2003

The solar cosmic ray event of 28 October 2003 (GLE65) was associated with the X17.2 flare located at S16 E08 i.e. outside the interval of preferable heliolongitudes . The earliest GLE onsets were detected at 11:12-11:13 UT by stations viewing towards the anti-Sunward

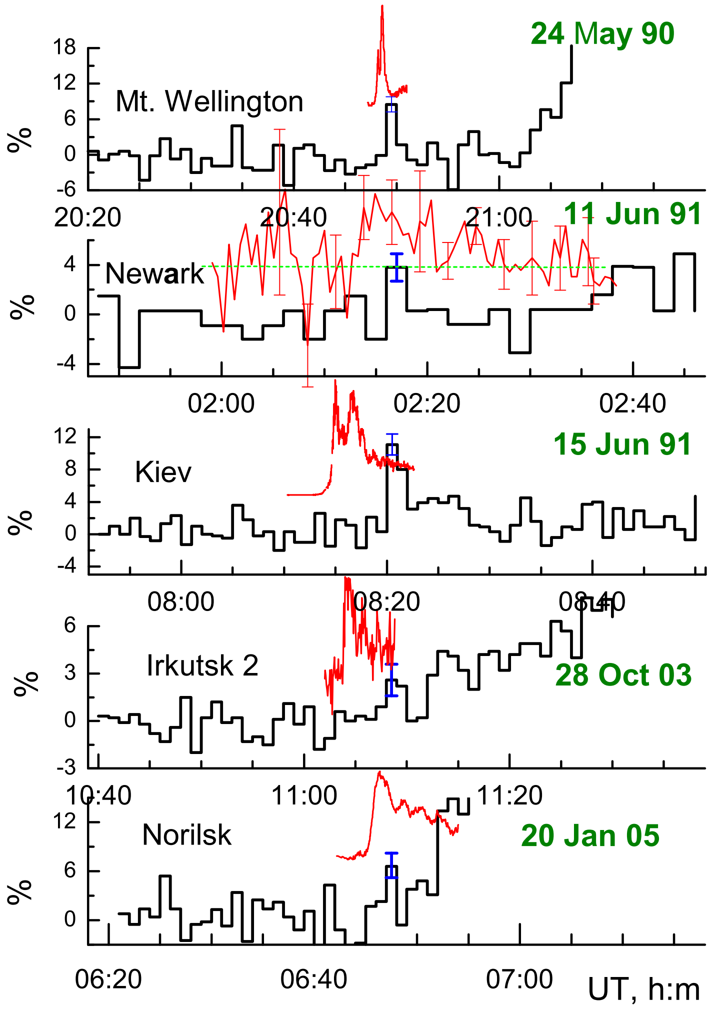

Fig. 1. Histograms present data of selected neutron monitors. Curves present data on high-energy gamma emission.

direction (e.g. [14], [15]). Alongside with protons solar neutrons with energies of hundreds MeV were also detected in this event. The near-equatorial NM Tsumeb observed a small count-rate increase beginning at 11:06 UT attributed to neutrons [14]. High-energy gamma-ray emission caused by neutral pion decay was recorded by the SONG instrument onboard the CORONAS-F satellite from 11:03:51±4 s UT [1], [3], [16].

We carefully analyzed data for the time interval before the main increase and found that NMs Cape Shmidt and Irkutsk-2 detected a small increase (above 2.5σ) in time interval 11:08-11:09. Note that these NMs could not detect solar neutrons because their θ angles exceeded 90°. In each case the time difference between the gamma-ray burst and the detected increase in the NM's count rate was within the range of the expected delay.

E. The Event of 20 January 2005

GLE69 was associated with the X7.1 flare located at N14 W61. The first GLE effect was detected by NM South Pole at 06:48-06:49 UT, the maximum icrease exceeded 3000 percents. High-energy gamma-ray emission caused by neutral pion decay was recorded by the SONG instrument onboard the CORONAS-F satellite from 06:45:34±4 s UT [1], [2], [3].

Comparison of the GLE onset with one of the gamma-ray burst lead to the conclusion that high-energy protons detected at the Earth escaped the Sun immediately after their acceleration [1]. Really, the Sun-Earth distance was equal to 0.984 AU on 20 January 2005 thus photon flight time was equal to 492 s. The speed of the solar wind varied essentially in previous days so the mean speed can not be defined unambiguously. If the length of IMF line was supposed to be the shortest one (∼1.05 AU) then the propagation time of protons having energy 1 GeV and zero pitch-angle is about 590 s. Thus particles had to arrive to the Earth later on 100 s than photons and similar delay value was observed by NM South Pole.

We, however, on close examination found that the earliest increases in the previous 1-minute bin occurred at 06:47-06:48 UT as it was detected by NMs Norilsk and Oulu. NM Norilsk detected a burst (5σ, see Fig. 1) followed by a decrease to the background level and by the next, main increase.

TABLE I
GLEs ASSOCIATED WITH HIGH-ENERGY GAMMA-RAY EMISSION

	GLE 48	GLE51	GLE52	GLE65	GLE69
Date	24.05.1990	11.06.1991	15.06.1991	28.10.2003	20.01.2005
Flare location	W76 N36	W17 N31	W69 N33	E08 S16	W61 N14
Onset time of pion-produced burst, UT	20:48:30	02:12:56	08:15 (17 GHz radioemission)	11:03:51	06:45:30
Precursor time, UT	20:49 – 20:50	2:16 – 2:18	8:20 – 8:21	11:09 – 11:10	06:47 – 6:48
$\Delta t, s$	60 ± 30	240 ± 60	330 ± 30	250 ± 60	120 ± 30
Precursor magnitude, σ	6.6 (Mt.Wellington)	3.5 (Newark)	8.5 (Kiev)	2.7 (Cape Shmidt, Irkutsk)	5.0 (Norilsk)
GLE onset time, UT	21:02 – 21:03	02:35 – 2:40	$> 8:30$	11:12 – 11:13	06:49 – 6:50

IV. Discussion

We analyzed initial stages of five GLEs for which onset times of the spectral feature caused by the neutral pion decay were defined. This feature permits in its turn to determine the time of the appearance of the protons accelerated to high energies (>300 MeV) and subjected to interactions in the solar atmosphere. We can define the escaping time of particles responsible for the GLE onset under the assumption that both interacting and escaping particles belong to the same population of accelerated particles. Table 1 contains characteristic properties of these events.

As it was found at least by one NM station the burst of gamma-ray emission was followed by the precursor spike reaching the statistic level higher than 3σ. The time delay Δt between the gamma burst and the precursor was 1-6 min.

Confidence of observation of such precursor varied from 100 percents for 15 June 1991 (GLE52) to the threshold of statistical significance for GLE51 and GLE65. We therefore have no full assertion of the proposal that these precursors really exist, only strong indications.

Data of observations shown in Fig.1 say us the following. Each spike lasts for not more than 2-4 minutes. After that count rate drops to the background level. Such behavior provides information on the origin of the spikes, which are caused by a narrow and high-anisotropic beam of escaped particles aligned along the IMF line. Such beams can be detected only by NMs with suitably oriented asymptotic cones of acceptance. Because of the orientation dependence the beams could be invisible for certain stations in certain events.

An increase produced by high-energy solar neutron has to exhibit a smoothed time profile due to their velocity dispersion and to an absence of focussing by IMF. So it can be easy distinguished.

The probability of detection of the precursor (as well of main GLE) is strongly dependent on a heloilongitude of the parent flare. Indeed, well-observed precursors were produced by flares located at 30-90 W, whereas weak precursors were produced by flares located outside this interval.

An existence of precursors is a strong argument in favor of an acceleration of high-energy protons along with the main flare energy release. Acceleration of these protons during the following flare phase contradicts with observed onset times of precursor.

V. Acknowledgement

This work was supported by the Russian Foundation for Basic Research (project 09-02-01145).

References

[1] Kuznetsov S.N., Kurt V.G., Yushkov B.Yu., Kudela K., “CORONAS-F satellite data on the delay between the proton acceleration on the Sun and their detection at 1 AU,” in *Proc. 30th Int. Cosmic Ray Conf.*, vol. 1, 2008, pp. 121–124.

[2] Grechnev V.V., Kurt V.G. et al., “An extreme solar event of 20 January 2005: properties of the flare and origin of energetic particles,” *Solar Phys.*, vol. 252, pp. 149–177, 2008.

[3] Kurt V.G. Yushkov B.Yu., Kudela K., Galkin V.I., “High-energy gamma-ray emission of solar flares as an indicator of acceleration of high-energy protons,” in *Proc. 31st Int. Cosmic Ray Conf.*, 2009 (in press).

[4] Shrijver C.J., Hudson H.S., Murphy, R.J. et al., “Gamma rays and evolving , compact structures of the 2003 October 28 X17 flare,” *Astrophys. J.*, vol. 650, pp. 1184–1192, 2006.

[5] Kuznetsov S.N., Kurt V.G., Yushkov B.Yu. et al., “28 October 2003 Flare: High-Energy Gamma Emission, Type II Radio Emission and Solar Particle Observations,” *Int. J. Modern Phys. A*, vol. 20, pp. 6705–6707, 2005.

[6] Pei C., Jokipii J.R., Giacalone J., “Effect of a random magnetic field on the onset times of solar particle events,” *Astrophys. J.*, vol. 641, pp. 1222–1226, 2006.

[7] Plainaki C., Belov A., Eroshenko E. et al., “Modeling ground level enhancements: Event of 20 January 2005 ,” *J. Geophys. Res.*, vol. 112, p. A04102, 2007.

[8] Debrunner H., Lockwood J.A., Barat C. et al., “Energetic neutrons, protons, and gamma rays during the 1990 May 24 solar cosmic-ray event,” *Astrophys. J.*, vol. 479, pp. 997–1011, 1997.

[9] Belov A. V., Livshits M. A., “Neutron burst on May 24, 1990,” *Astron. Lett.*, vol. 21, p. 37, 1995.

[10] Dunphy P.P., Chupp E.L., Bertsch D. L. et al, “Gamma-rays and neutrons as a probe of flare proton spectra: the solar flare of 11 June 1991,” *Solar Phys.*, vol. 187, pp. 45–57, 1999.

[11] Smart D.F., Shea M.A., Gentile L.C., “The relativistic solar proton event on 11 june 1991,” in *Proc. 23rd Int. Cosmic Ray Conf.*, vol. 3, 1993, pp. 55–58.

[12] Akimov V.V., Ambroz P., Belov A.V. et al., “Evidence for prolonged acceleration based on a detailed analysis of the long-duration solar gamma-ray flare of june 15, 1991,” *Solar Phys.*, vol. 166, pp. 107–134, 1996.

[13] Ramaty R., Schwartz R.A., Enome S., Nakajima H., “Gamma-ray and millimeter-wave emissions from the 2991 June X-class solar flares,” *Astrophys. J.*, vol. 436, p. 941, 1994.

[14] Bieber J. W., Clem J., Evenson P. et al., “Relativistic solar neutrons and protons on 28 October 2003,” *Geophys. Res. Lett.*, vol. 32, p. L03S02, 2005.

[15] Miroshnichenko L.I., Klein K.-L., Trottet G. et al., “Relativistic nucleon and electron production in the 2003 October 28 solar event ,” *J. Geophys. Res.*, vol. 110, p. A09S08, 2005.

[16] Kuznetsov S.N., Kurt V.G., Yushkov B.Yu. et al. , “Gamma-ray and high-energy-neutron measurements on CORONAS-F during the solar flare of 28 October 2003,” *Solar Phys.*, 2009 (in press).