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2013 J. Phys.: Conf. Ser. 409 012151

(http://iopscience.iop.org/1742-6596/409/1/012151)

Determination of Acceleration Time of Protons Responsible for the GLE Onset

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Abstract. Appearance in the solar atmosphere of high-energy protons during major solar flares can be identified from the observation of a broad gamma-ray line in the 70–100 MeV range of the flare emission spectrum. This emission line 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. We considered 12 events with clear observations of the pion-decay gamma emission and compared the light curves of this emission with time profiles of different emissions. In 9 events out of 12 we found the onset and peak times of high-energy gamma-rays to be close to the peak times of other electromagnetic emissions and the derivative of the soft X-ray emission. This closeness indicates that efficient acceleration of protons up to sub-relativistic energies starts typically close to the time of the main flare energy release. The further study dealt with the data recorded since 1972 by the world neutron monitor network related to 44 Ground level enhancements (GLEs) and light curves of neutral emissions of the associated flares. The study revealed that a 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 10 min in 30 events. This result indicates that in the majority of events, efficient acceleration of protons responsible for the GLE onset should be close to the time of the main energy release in flares.

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1. Introduction

Correct determination of the proton acceleration time during solar flares is one of open questions 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,

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are produced in interactions of high-energy (>300 MeV) protons with a matter of the solar atmosphere [5,6]. However, the pion-decay gamma-ray emission was clearly observed in several 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].

We have studied events, in which the pion-decay emission was observed, and found that the pion-decay emission in these events typically 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 radio bursts as well as the maximum of the derivative of the soft X-rays. From this temporal closeness we conclude that efficient proton acceleration to high energies starts typically during the main flare energy release, and this moment can be used as a reference time for other powerful events.

Then 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 determined the main energy release time in 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 45 GLE events since 1972 based on the data base of GLE events [8] as well as papers [1, 9] which cover solar cycles 20–21. The list of events recorded by Lomnicky Stit NM [10] 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 solar neutrons.

We examined data following [11]. 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 1-2 min to 5 min.

For events when the pion-decay gamma-rays were recorded, we estimated the initial time T_0 of high-energy proton acceleration using this emission. In other cases we analyzed observations of different emissions. The initial estimate of the main flare energy release time T_0 was obtained from the GOES SXR records (3 sec data). The primary importance of these data is determined by the non-interrupting series of measurements since 1975. We calculated the SXR derivative and the temperature from the GOES SXR records in two channels by means of a well-known technique [12]. 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 [13]). This physical relation means that HXR and dI_{SXR}/dt derivative data are in a certain sense interchangeable.

We also involved data on bremsstrahlung up to 10 MeV recorded with Venera-13, Venera-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 with OSO-7, Prognoz-2, SMM, RHESSI, INTEGRAL. These lines are emitted by nuclei excited by protons accelerated up to 10-50 MeV. Measurements made by Venera-13, 14, Ulysses allowed us to determine more precisely the time of the flare and maximum of energy release in events located behind the west limb. We have also used all available data on the radio emission bursts in the 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 . An example of T_0 and T_{onset} determination is presented in Figure 1.

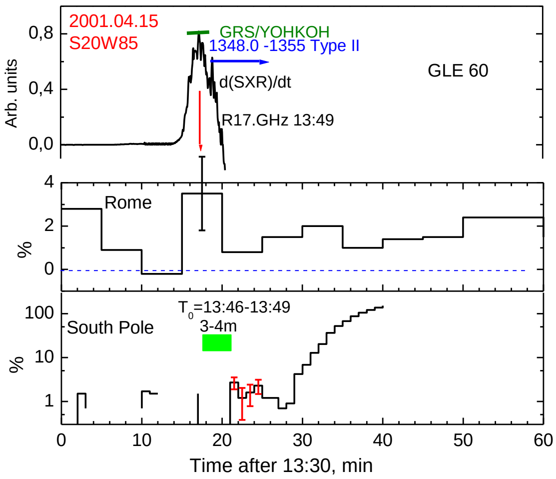

Figure 1. The event on 2001 April 15.

3. Discussion and Conclusions

We have estimated the onset times T_0 of proton acceleration up to high energies and arrival times of high-energy protons in events under consideration. Figure 2 shows a total distribution of time delay between T_0 and T_{onset}. One can see that this delay does not exceed 10 minutes in 28 cases. 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 and 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 [14]. In this paper we have increased this value up to 1-10 min taking into account all possible uncertainties in calculations of T_0. In view of this uncertainty, the less than 5 min delays observed in some events do not defy common sense. Therefore, the delay between the observation moment of the main flare energy release T_0 and T_{onset} of first accelerated particles is comparable with the shortest propagation time.

Figure 3 shows the distribution of the delay for the GLE events under consideration versus the heliolongitude of associated flares. The vertical bars present maximum uncertainties of the estimated

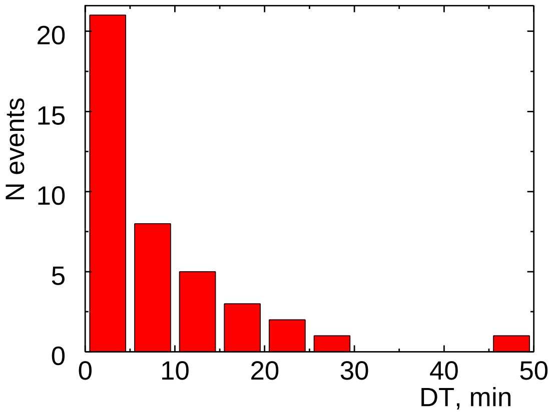

Figure 2. Distribution of time delay between T_0 and T_{onset}

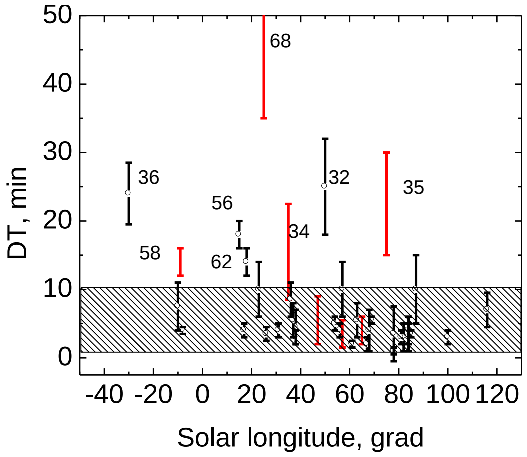

Figure 3. Time delay DT of the GLE onset versus the heliolongitude of associated flare

delays. Red bars present events with a maximum enhancement of <6%. The figure does not show any significant correlation between the delay and the flare longitude.

The determined T_0 moments of the main flare energy release are in most cases close to the onset time of II type bursts. In 32 events their onset times coincide with $\leq$ 4 min accuracy. It seems that a slight difference between the T_0 and the II type burst onset times can not be used to draw an unambiguous conclusion whether high-energy protons are accelerated directly in a flare or in a shock front. Nevertheless, the method to determine the onset time of proton acceleration based on the pion-decay gamma-ray line observation and realized in our study supports the conclusion that the proton acceleration starts typically close to the main flare energy release.

This work was supported by the Russian Foundation of Basic Research under (grants 09-02-00115, 11-02-00757, 12-02-00037) and the Russian Ministry of Education and Science under State Contract 16.518.11.7065. the Integration Project of the Russian Academy of Sciences (RAS) SD No. 4, the Programs of basic research of the RAS Presidium No. 10 and 22, and the grant of the Federal Agency for Science and Innovation, State Contract 02.740.11.0576

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