The Onset Time of the Pion-Decay Gamma-Ray Emission of Major Solar Flares

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Abstract: Appearance of high-energy protons in the solar atmosphere 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. From comparison of light curves of the pion-decay emission with those observed in different energy ranges we found the onset and peak times of this gamma-ray emission to be close to the peak times of hard X-ray emission and high-frequency radio emission. This time also corresponds to the peak of the derivative of the soft X-ray emission (SXR) recorded by GOES monitors. The closeness of the peak times for of all these emissions indicates that efficient acceleration of protons up to sub-relativistic energies starts close to the time of the main flare energy release.

Keywords: solar flares, high-energy protons, pion-decay gamma-ray emission, main flare energy release.

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. [1-3]), but results of these methods often contradict each other. On the other hand there is an obvious method to determine the onset time of the proton acceleration up to high energies. We mean observations of a specific feature in a high-energy gamma-ray spectrum namely of broad gamma-ray line with a maximum near 70 MeV. This line is caused by the decay of neutral pions produced in turn by interactions of high-energies protons (> 300 MeV) with dense matter of the ambient solar atmosphere [4, 5]. Observations of the pion-decay emission during a solar flare provide undoubted evidence of protons acceleration to high energies and can be used to study the time profiles of accelerated protons and, in particular, to determine the onset time of the proton acceleration [6, 7]. Regrettably, the total number of events in which the pion-decay emission was detected is very small, only 7 cases [8]. We have studied five events observed with a high temporal resolution in order to find the time span of the pion-decay line on the temporal scale of the flare. We have found the onset and peak times of this gamma-ray emission to be close to the peak time of HXR bremsstrahlung and that of the high-frequency radio emission, as well as to the peak of the derivative dI_{SXR}/dt of the soft X-ray (SXR) emission recorded by GOES monitors. Note that the SXR emission corresponds qualitatively to an integral of the energy deposited into the flare volume by the accelerated electrons (the Neupert effect [9]). This physical relation means that HXR and dI_{SXR}/dt derivative data are in a certain sense interchangeable.

2 Experimental Data

2.1 24 May 1990 Event (X9.3)

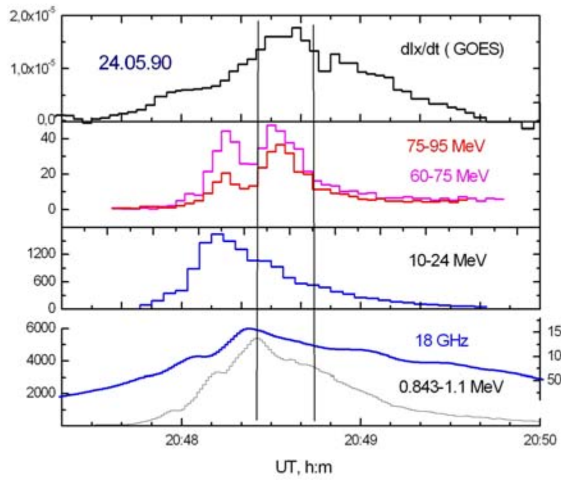

Figure 1. 24 May 1990 event.

Figure 1 presents time profiles of the gamma-ray emission measured by GRANAT/PHEBUS [10] as well as the SXR derivative and the microwave emission at 18 GHz. The second peak in the 60-95 MeV energy range at 20:48:25 UT marked by vertical lines is caused by the appearance of the pion-decay gamma-ray line [11]. The SXR derivative peaks in the same time. Microwave emission and of HXR are close to their maximum values.

2.2 25 August 2001 Event (X5.3)

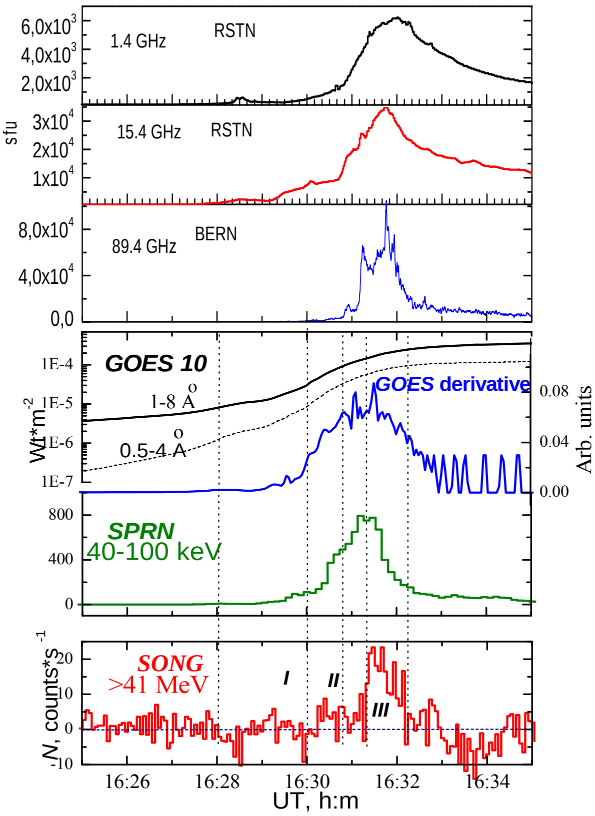

Figure 2. 25 August 2001 event.

Figure 2 presents fluxes of the radio, the SXR and its derivative at 0.5-4 Å, the HXR count rate recorded by SPRN [12] and high-energy gamma-ray emission recorded by SONG [13]. SPRN and SONG detectors operated onboard the CORONAS-F satellite. Analysis of gamma-ray spectrum [14] revealed a drastic increase of the pion-decay emission at 16:31:10 UT, i.e. close to the peak times of the radio emission, HXR and of the SXR derivative.

2.3 28 October 2003 Event (X17.2)

Figure 3 presents the fluxes of the radio emission [15], SXR derivative (1-8 Å) and count rates of the HXR and high-energy gamma-ray emission. The SONG detector

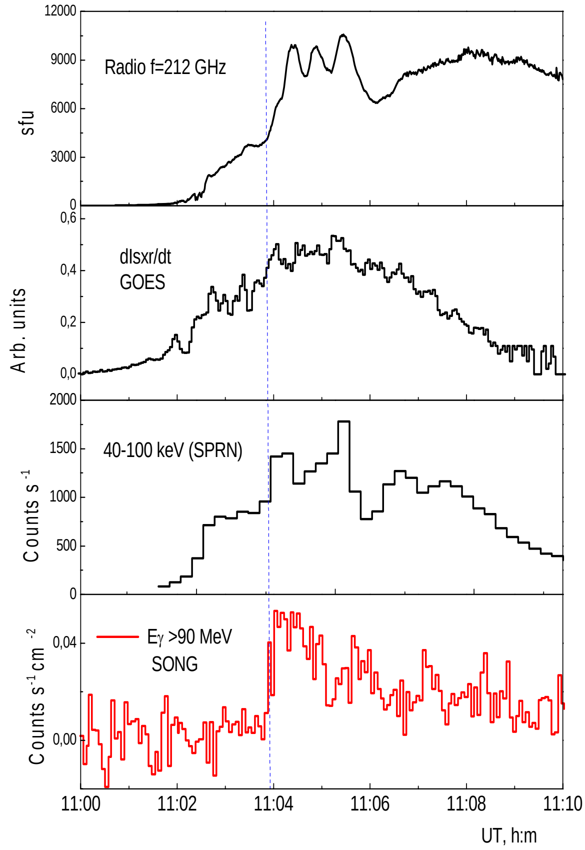

Figure 3. 28 October 2003 event.

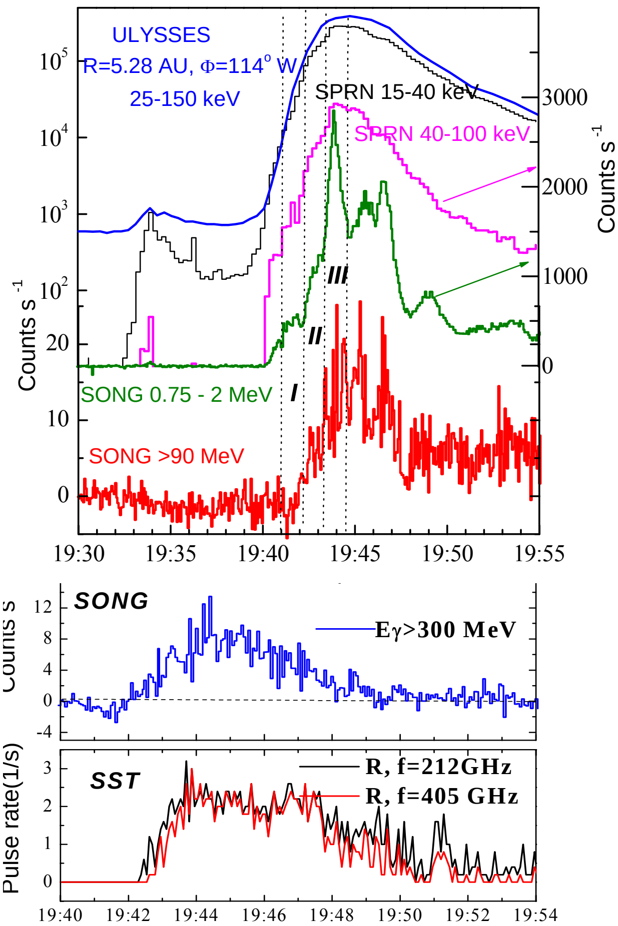

Figure 4. 4 November 2003 event.

recorded in this flare at 11:03:51 UT a sharp increase in the > 90 MeV energy range caused by the pion-decay emission that was confirmed by an analysis of the spectrum [7,14,16]. The maximum intensity in de-excitation gamma-ray lines was observed at 11:04:00-11:05:30 UT by INTEGRAL/SPI [17], i.e. simultaneously with the enhancement of the pion-decay emission. The nuclear de-excitation lines are caused by ions accelerated to 10-50 MeV/nucl. A significant increase of the magnetic flux change rate was observed starting from 11:03:20 UT [18].

2.4 4 November 2003 Event (>X28)

SXR GOES monitors were saturated during 19:43-19:58 UT in this major flare. To verify our observations we added data obtained onboard Ulysses spacecraft located outside the Sun-Earth line (these data were re-calculated for 1 AU) [18]. Figure 4 presents the time profiles of HXR, gamma-ray and radio emissions [19]. Analysis of the spectrum shows the increase of the pion-decay emission at 19:43 UT [13].

2.5 20 January 2005 Event (X7.1)

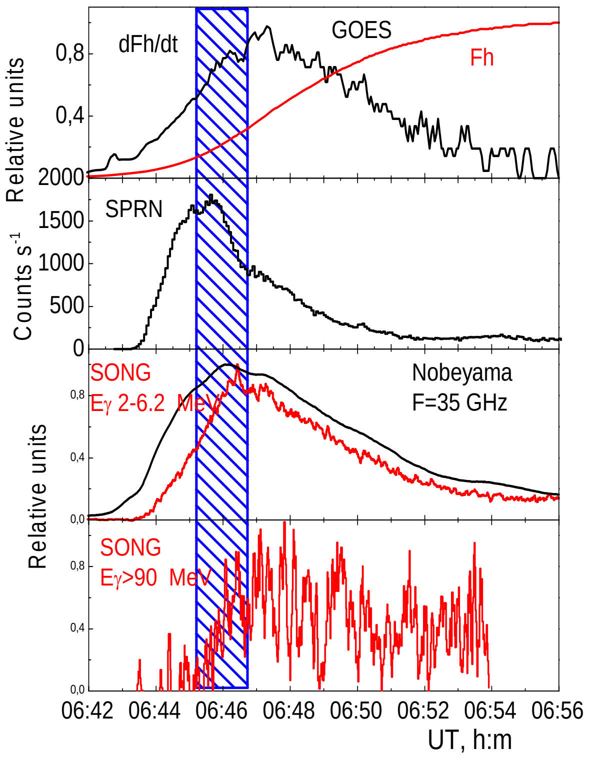

Figure 5. 20 January 2005 Event.

Figure 5 presents the SXR flux in the 0.5-4 Å range and its derivative, count rate of the HXR in 40-100 keV range (SPRN), the radio flux and gamma-ray emission count rates measured by SONG. Analysis of the gamma-ray spectrum [7,14,21] showed that the flux of pion-decay emission increased significantly at 06:45:34 UT, i.e. close to the peak times of the microwave and HXR emissions and of the SXR derivative.

3 Discussion and Conclusions

We have analyzed five events in which the pion-decay line in the gamma-ray emission spectrum had been pronounced. The analysis of gamma-emission spectra showed that the corresponding enhancement of the count rate in high-energies channels were in all cases certainly caused by the appearance of the pion-decay emission [10,13].

Generation of pions on the Sun is confirmed by observations of fluxes of high-energy neutrons and/or protons in these events. On 24 May 1990, 25 August 2001, 28 October 2003, and 4 November 2003 high-energy neutron (>200 MeV) fluxes were recorded [13,16,22-24]. Neutrons of such energies can be produced only in inelastic interactions of high-energy (>300 MeV) protons with dense matter of the ambient solar atmosphere. The same interactions produce neutral pions which in turn generate the broad gamma-line mentioned. High-energy protons were observed in three events: on 24 May 1990 (GLE 48), 28 October 2003 (GLE 65), and on 20 January 2005 (GLE69).

We have determined the moments of the appearance or a significant intensity increase of the pion-decay line as well as its peaks. The time profiles of the pion-decay emission are considerably different in the events under consideration. The duration of the rise time up to the maximum varied from several seconds to 1-2 min. A total duration of a pion-decay gamma-ray burst was also different in these flares and FWHM of the pion-decay burst in all the events did not exceed 4 min.

In all of these events the rise time of the pion-decay burst coincided with the maximum time of the high-energy bremsstrahlung, high-frequency radio emission and the peak of the SXR derivative with an accuracy of 1-2 min. In turn the peaks of the HXR and radio emissions as well as the SXR derivative are considered to be manifestations of the main energy release during the flare impulsive phase.

Thus it can be inferred that intense acceleration of protons up to sub-relativistic energies in major flares, determined from observations of the pion-decay gamma-ray emission starts temporally close to the main flare energy release. This conclusion can be used in analyses of solar particle events and GLE onset, in particular, to find the onset time of acceleration in events when the pion-decay emission was not observed.

Acknowledgements

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

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