On Estimate of First Solar Proton Arrival to Earth

Alexei B. Struminsky and Ivan V. Zimovets

Abstract—**The anticoincidence system of the spectrometer on INTEGRAL (ACS SPI) is sensitive to primary and secondary γ-rays with energy >150 keV and effectively responses to arrival of solar protons and electrons. If a flux of primary γ-rays is small, then ACS SPI registers an arrival of solar protons much earlier in comparison with neutron monitors (NM). For example, on 2006 December 13 the solar proton onset was observed by ACS SPI only about 3 min later the hard X-ray flare, that is 10 min earlier than the ground level enhancement (GLE). However if a flux of primary solar γ-rays is large enough, then a solar proton onset is observed by ACS SPI simultaneously (2005 January 20) or later (2003 October 28) in comparison with NM. Obtained times of solar relativistic proton arrival to the Earth do not contradict to their acceleration during γ-ray flares.**

I. Introduction

For analyzing of solar proton events it's very important to know a time moment of first relativistic proton arrival to the Earth (see [1,2] and references therein). A GLE onset observed by one of NM's is arbitrary considered as this time moment. A typical temporal resolution of NM with reasonable statistics is about +/- one minute. Such accuracy might be satisfactory for estimates of release time of solar protons into the interplanetary space taking into account free parameters of propagation models like a length of interplanetary magnetic field (IMF) line and mean free path. Depending on solar wind velocity a length of IMF line might be varied by several tenth of AU and a mean free path is within the Palmer consensus range [3] that gives a comparable error for the release time. However this definition of solar relativistic proton onset does not account a intrinsic background of the detector and a rate of solar proton intensity increasing. These unaccounted factors may create a larger error of proton arrival time, which will lead to incorrect estimate of solar proton release into the interplanetary medium and, therefore, moment of their acceleration.

In this work we underline a unique ability of ACS SPI to register solar energetic particle (SEP) arrival in some cases much earlier than the NM network owing to data high statistic accuracy and temporal resolution.

We can't quantitatively estimate fluxes of SEP measured by ACS SPI, since we don't know its response functions to SEP with unknown composition, spectra and angular distribution. However there are indirect evidences that ACS SPI is an effective detector of relativistic solar protons. In this case becomes evident that we need reconsidering the current views on solar proton release into the interplanetary and propagation their. For example, the solar proton onset, registered by ACS SPI on December 13, 2006, corresponds to their injection into the interplanetary medium during the solar γ-burst that is inconsistent with conclusions obtained from data of ground based detectors [4-6].

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II. Results of observations and their analisys

We consider four SEP events of the 23rd solar cycle, which have showed an enhancement of ACS SPI count rate both due to primary and secondary γ-rays. Some characteristics of parent solar flares are presented in Table 1, for each event the pre-flare background caused by galactic cosmic rays was subtracted from ACS SPI data and the intensity-time profiles of running average are depicted in Fig. 1 relatively zero-time (Table 1). These time moments might be considered as a beginning of high energetic processes during these solar flares [7-8]. About first 10-minutes the enhancements above background are definitely caused by primary solar γ-rays, but later a considerable (in some cases – dominant contribution) from secondary γ-rays has been observed.

TABLE I
Some characteristics of solar flares discussed.

Date	*Zero (UT)*	*Coord.*	*X-ray event*			
			Imp.	Start	Maximum	End
13.12.2006	02:22	S06W23	X3.4	-8	+18	+35
14.12.2006	22:07	S06W46	X1.5	-60	+8	+19
20.01.2005	06:40	N12W58	X7.1	-4	+20	+45
28.10.2003	11:00	S16E08	X17.2	-59	+10	+24

One can normalize count rates of the ACS SPI and Kiel NM during the GLE event of 2006 December 13 beginning from 27 min and conclude that both instruments proportionally response to relativistic solar protons, but have a different background level. Possibly, due to statistical errors and high level of the NM background the GLE onset is delayed relatively an arrival of first relativistic protons, which is observed by ACS SPI.

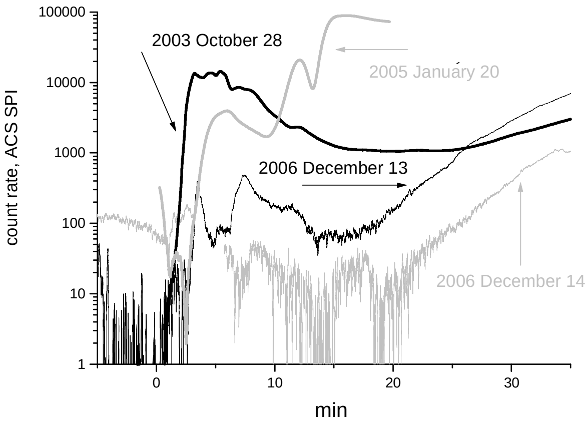

Fig. 1. Running average count rate of ACS SPI (background subtracted) during the considered events (Table 1).

In Fig. 2 we see two distinct enhancements of the ACS SPI count rate (maxima are out of scale) caused by primary γ-rays. The ACS count rate increase due to secondary γ-rays began between 16-17 minutes at a rather high background, so a possible onset of relativistic solar protons might be even 2 min earlier than marked in Fig. 2. Note, we may not separate an impact of primary and secondary γ-rays between 12 and 20 min

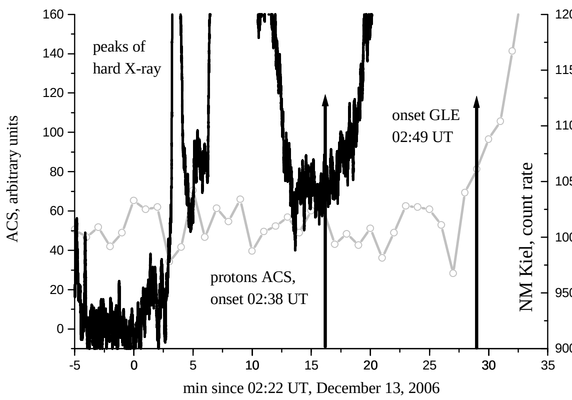

Fig. 2. The GLE event of 2006 December 13: count rates of ACS SPI (blue) and the Kiel NM (red). Arrows mark proton onsets.

The event of 2005 January 20 (Fig. 3) is distinguishable from other GLE events by anomalously quick arrival of solar protons to the Earth (see [9-10] and references therein). Observations of this event by ACS SPI occurred at a high pre-flare background created by the previous proton event [9]. The anisotropic GLE phase, observed best of all by the South Pole and McMurdo NM's, started about 9-10 min after the zero-time and its beginning practically coincided with the second peak of the ACS SPI count raste. We can not normalized counts rates of ACS SPI and NM's as in previous case, because they are considerably different. This might be caused by as variable angular distribution and spectrum of solar protons well as possible impact of primary γ-rays to the ACS SPI count rate [9]. Therefore the solar proton onset was simultaneously observed on 2005 January 20 by ACS SPI and NM's.

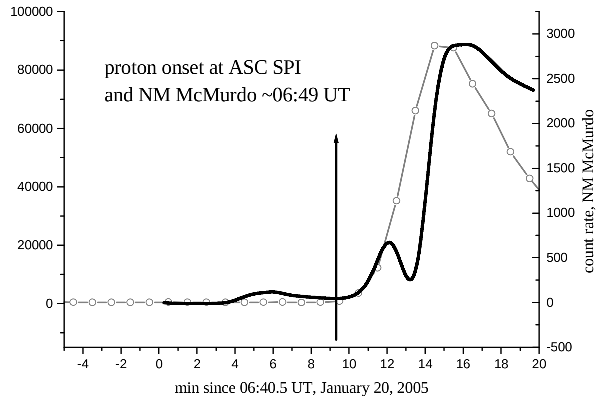

Fig. 3 The GLE event of 2005 January 20: count rates of ACS SPI (black) and the McMurdo NM (red). A vertical arrow marks the proton onset.

The event of 2003 October 28 (Fig. 4) is an example of other case. является примером другого рода. The anisotropic GLE phase with duration of about 15 min coincided in time with high plateau of the ACS SPI count rate observed after very large solar γ-burst. An intensity level at the plateau is considerably higher than the peak intensities of primary γ-rays observed on 2006 December 13. A gradual increase of the ACS count rate started on ~25 min and corresponded to the GLE isotropic phase, i.e. the ACS proton onset was delayed in comparison with NM's observations.

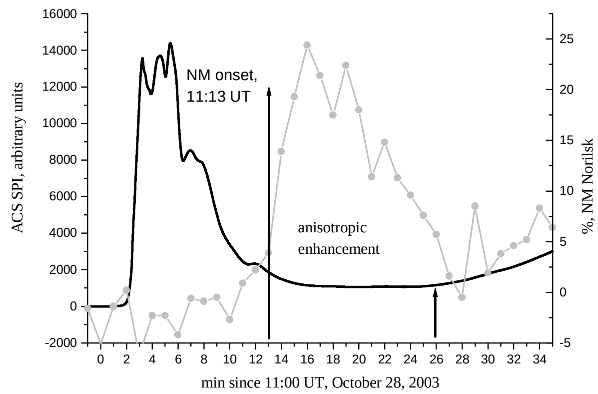

Fig. 4 The GLE event of 2003 October 28: count rates of ACS SPI (red) and the Norilsk NM (blue). Vertical arrow mark a proton onset as observed by different instruments.

At present an origin of this plateau is unknown. Possibly, this plateau as well as a broken time-profile around 11-12 min (that is 2-3 min earlier than the anisotropic GLE phase) are associated with additional impact of secondary γ-rays from interactions of relativistic solar protons. From another hand it was supposed in [11] that a time interval of the plateau corresponds to the second episode of neutron production and, therefore, γ-rays. Note that according to estimates [12] for fitting of the GLE event a gradual (about 40 min) injection of protons into the interplanetary space was necessary beginning from 11:11±2 UT.

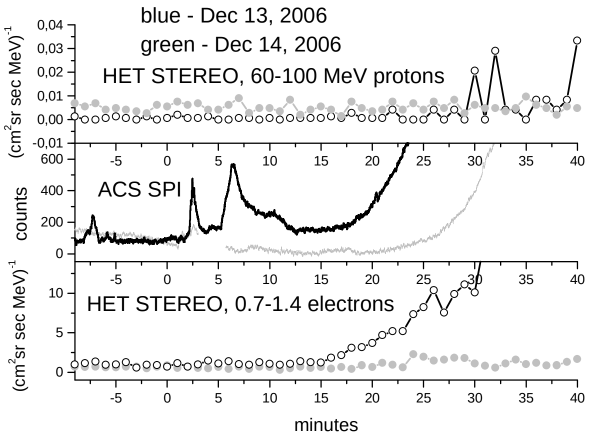

Fig. 5 The proton and electron intensities observed by HET STEREO on 2006 December 13 and 14 (upper and lower panels) and the ACS SPI running average count rate.

III. Discussion

Relativistic solar electrons might be considered as a source of secondary γ-rays on 2006 December 13. Indeed the HET instrument aboard STEREO shows a clear onset with gradual increase around the 15-th minute (lower panel in Fig. 5). Observations of the 2006 December 14 event exclude such a possibility. As seen in Fig. 5 a gradual increase of the ACS SPI count rate on December 14 is not accompanied by any electron enhancement. Besides proton intensity within 60-100 MeV was at the background level more than 30 min. Therefore we conclude that gradual increase of ACS SPI count rate is associated with relativistic protons, which intensity is below the NM threshold.

The proton event of 2006 December 13 by data of ACS SPI started at 02:39 UT (<17 min), of the NM network at 02:50 UT (28 min) [4-5] and of the MEPhI muon hodoscope at 02:54 UT (32 min) [6]. These detectors are listed by increasing of their threshold energy. Is an onset time of protons is caused by a difference of background level or by a difference of threshold energies? The effect of threshold energy assumes that particles with higher energies have been released considerably later. This later release was not observed in other considered events. We suppose that the most natural explanation is an influence of a detector background (a signal/background ratio) since the background level was different in the considered events. A rate of proton intensity increase would determine in this case an error of proton arrival time.

A clear anisotropic phase of GLE on 2003 October 28 and 2005 January 20 was observed during 10-15 min practically after solar γ-emission, but not on 2006 December 13, when no one operating ground based detector had a right pointing or a collimated proton flux did not heat the Earth. The anisotropic GLE phase was registered only once on 2005 January 20 with large fluctuations of the count rate (Fig. 3). The gradual increase of proton intensity observed by ACS SPI on 2006 December 13, apparently, does not correspond to the anisotropic GLE phase.

The solar flare of 2006 December 13 is a unique considering a relationship between hard X-ray and microwave emission [8], its hard X-ray intensity in the main peak was depressed by about one order in comparison with other cases for comparable microwave intensities. This is an evidence of dominant acceleration and interaction of electrons in a optically thin target and a small fraction of electron energy consuming for plasma heating, i.e a classical impulsive phase of the flare was not observed. Possibly, we deal with a coronal source of high energy particles, which arbitrary is not associated with GLE anisotropic phase.

IV. Conclusion

- An onset of anisotropic GLE phase does not correspond always to arrival of first solar protons to the Earth. Determining a moment of first solar proton arrival one needs to consider a detector background and a rate of proton intensity increase. An error caused by these factors may be greater than a detector time resolution. The GLE onset not always corresponds to a moment of first relativistic proton arrival to Earth.
- During the 2006 December 13 event, when the intensity of primary gamma-rays was rather low, a massive gamma-ray space born detector (ACS SPI) appeared to be a more effective instrument for observations of the proton event onset than the NM network. The proton event onset was observed by the ACS SPI about 11 min earlier than the GLE onset.
- For two other considered GLE events, when a level of primary gamma-rays was rather high, an arrival of first solar protons was observed by ACS SPI simultaneously with NM’s (2005 January 20) and later (2003 October 2003).

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