Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 1 (SH), pages 7–10

ID 188

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

Time Scales of Hard X-ray and Radio Emissions of Large Proton Flares

ALEXEI STRUMINSKY[1, 2], IVAN ZIMOVETS[1]
[1] *Plasma Department, Space Research Institute, Profsoyuznaya st., 84/32, Moscow 117997, Russia*
[2] *Cosmic Ray Department, IZMIRAN, Troitsk, Moscow Region 142092, Russia*
astrum@iki.rssi.ru

Abstract: The hard X-ray emission (>150 keV) observed by Anti Coincidence System of Spectrometer on *INTEGRAL(*ACS SPI) during the X-class solar flares on 2006 December 5, 6 and 13 provides evidences that a flash phase of these three flares is formed by several acts of impulsive energy release and particle acceleration. The largest proton flux observed in the interplanetary space after the December 6 solar flare corresponds to the hard X-ray emission delayed by 5 minutes relatively to beginning of the flash phase and lasted about 20 minutes. This observational fact supports our interpretation of the 2003 October 28 and 2005 September 7 events (Struminsky and Zimovets, 2007) that the delayed hard X-ray emission might be considered as a feature of effective proton acceleration. The flare of 2006 December 14 is an elementary impulsive event, when a single statistically significant peak of the hard X-ray emission was observed. The event of December 14 allows putting the limit on association between solar events and protons in the interplanetary space in a case of good magnetic connection.

Introduction

Each of the last tree solar cycles provides us clear examples of solar flares showing that a proposed single loop model is not viable. Such flares are characterized by several acts of energy release and particle acceleration (bursts of high-energy emissions). Here we should mention well-known flares on 1982 June 3 [1], 1991 June 4, 9 and 15, 2002 July 23[2, 3], 2003 October 28 [4, 5] 2005 September 7 [6,7]. It is of interest to extend such multiwavelength studies to as many other flares. The X-class flares of December 2006 provide this possibility. The analysis of the 1982 June 3 flare in [1] shows that the first and second bursts of energetic photon emissions are associated with the evolving morphology of the active region and are due to different particle accelerations. Moreover, for the authors [1] it seems unlikely that particle acceleration during the flash phase may serve as a seed population for shock acceleration during the extended phase.

The first and great success of *RHESSI* are observations of the solar flare of 2002 July 23 [2]. Its intense impulsive phase with continuum and gamma-line emission extending up to greater than ~7 MeV lasted 16 min from ~00:27 to ~00:43 UT. The authors of [2] integrated over this time interval obtaining the gamma-ray spectrum and did not study a temporal evolution of the gamma-spectrum. The high sensitivity of the SPI allowed to study a temporal evolution of gamma-spectrum during impulsive phase, which also lasted about 16 min, of the flare on 2003 October 28[4]. Three phases (A – 11:02:13 UT, dominant continuum; B – 11:03:28 UT; dominant line emission; and C – 11:06:43 UT, decay) were distinguished. Note that all RHESSI results correspond only to the C phase of this flare [4, 5]. The authors of [5] summarized multiwavelength observations of the 2003 October 28 event and found the reversion of magnetic polarity in different points of the flare region accompanied by acoustic peaks: P1 (11:02:30-11:04:30UT, acoustic peak 11:04±4

UT), P2 (11:10:30-11:20:30UT, acoustic peak 11:07±4 UT), P3 (11:06:30-11:19:30UT, acoustic peak 11:07±4 UT). These facts give a physical base for the A, B and C phases that each phase corresponds to new energy release and particle acceleration [6]. We investigated from this point of view the largest proton flares of 2005 January 20 and September 7 [6] and concluded that the delayed hard X-ray emission (during the C phase and later) might be considered as a feature of effective proton acceleration in the flare region. In this work we use the approach developed in [6] for investigation of the December 2006 events.

Data

The ACS SPI registers integral flux of primary and secondary hard X-rays with energy >150 keV. During large solar flares and before arrival of SEP this is mainly primary solar X-rays. Figure 1 shows time profiles of the ACS SPI count rate during the X-class solar flares in December 2006. A background level reflects different radiation conditions in the interplanetary space. For instance, a slow increase of the green curve after 15 minute is caused by SEP. Zero time corresponds to start of microwave burst at 15.4 GHz for each event.

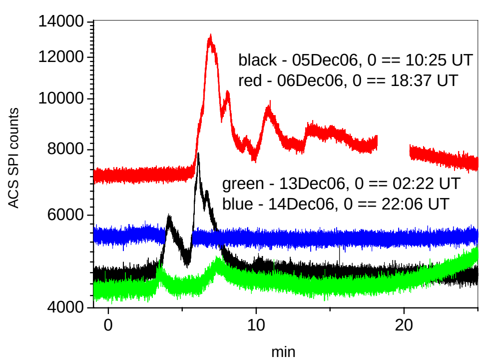


Figure 1: Time profiles of the ACS SPI count rate (background is not subtracted) during the X-class flares in December 2006.

Below we compare hard X-ray time profiles with time profiles of radio emission 1-sec intensity (ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_RADIO/) at 245 MHz and 8.8 GHz. The solar radio emission at 245 MHz is the plasma emission at plasma frequency and its harmonics initiated by electron beams, but the emission at 8.8 GHz might be both plasma and gyro-synchrotron emission.

Observations

An unexpected rise of the solar activity close to its minimum in December 2006 resulted in four X-class flares and four SEP events. The first events of this series happened just after appearance of the AR 10930 on the solar disk.

2006 December 5 (X9.0: 10:18, 10:35, 10:45 UT;S07E79; radio 15.4 GHz, 10:25, max 11000 SFU at 10:30; 10:58 UT).

In Fig. 2 we see a signature of relativistic electrons (two peaks of the hard X-ray emission) during the B and C phases. The maximum intensity is delayed (C). The 8.8 GHz emission started near the zero time, but the 245 MHz emission showed a sharp peak during the A phase (like on 2002 July 23 and 2003 October 28.

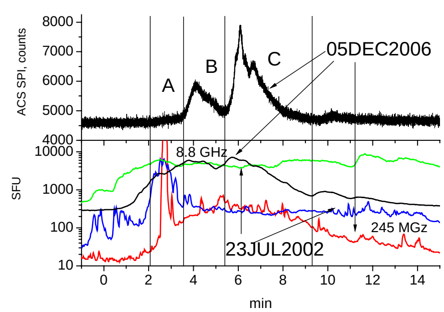
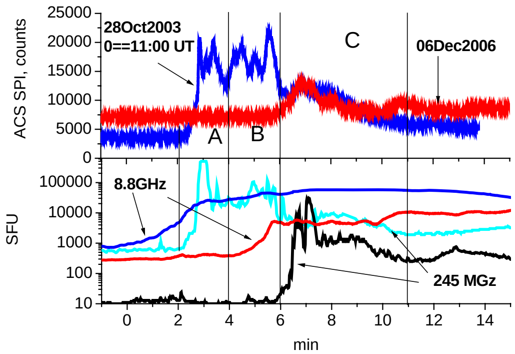


Figure 2: The time profile of ACS SPI count rate; the radio emission at 245 MHz and 8.8 GHz (in comparison with the 2002 July 23 event) of the December 5 event.

2006 December 6 (X6.5: 18:29, 18:47, 19:00; S06E63; 15.4 GHz, 18:38, max 12000 SFU at 1847, 1937 UT)

The hard X-ray emission had a maximum during the C phase, but it was depressed in A, B. This event reminds the C phase of the 2003 October 28 and 2005 September 7 events (Fig. 3). Note that sources of soft and hard X-ray emission were widely separated in space according to the *RHESSI* observations during the C phase.



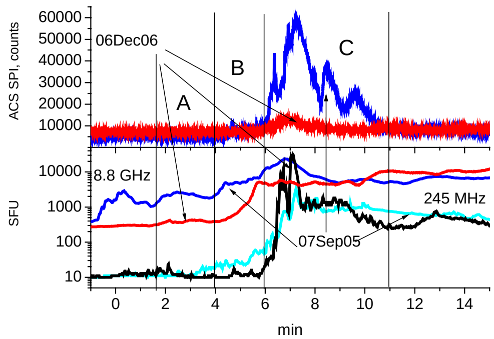


Figure 3: Time profiles of ACS SPI count rate and radio emission intensity at 245 MHz and 8.8 GHz of the December 6 event (red and black) in comparison with those of the 2003 October 28 and 2005 September 7 events (blue and cyan).

2006 December 13 (X3.4; 02:14, 02:40, 02:57 UT; S06W23; 15.4 GHz, 02:22, max 9900 SFU at 02:29 , 03:25 UT)

In Fig. 4 we see two humps of the hard X-ray emission of the 2006 December 13 event. These humps coincide in time with similar peaks of the December 5 event, but differ by absolute intensities. The 8.8 GHz microwave emission was nearly equal during about 8 minutes in different events (Fig. 4 and Fig. 5). The time profile of 245 MHz emission has three maximums in contrast to events of 2006 December 5 (Fig. 4) and 2002 July 23 (Fig. 5), which possibly reflect changes in local plasma conditions.

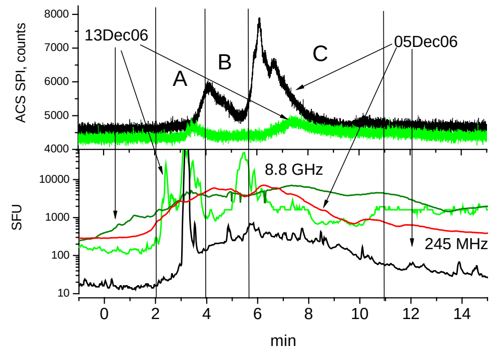


Figure 4: The time profile of ACS SPI count rate and radio emission intensity at 245 MHz and 8.8 GHz of the December 13 event in comparison with those of the December 5 event.

2006 December 14 (X1.5; 21:07, 22:15, 22:26 UT; S06W46; 15.4 GHz, 22:07, max 1300 SFU at 22:09, ??:?? UT)

Discussion

Figures 4 and 5 demonstrate a quantitative agreement between microwave intensities at 8.8 GHz during 4-8 minutes of different solar flares. Since simultaneous hard X-ray intensities are different, this 8.8 GHz emission should be radiated by plasma occupying equal volumes under similar conditions during different flares, but not by the gyrosynchrotron mechanism.

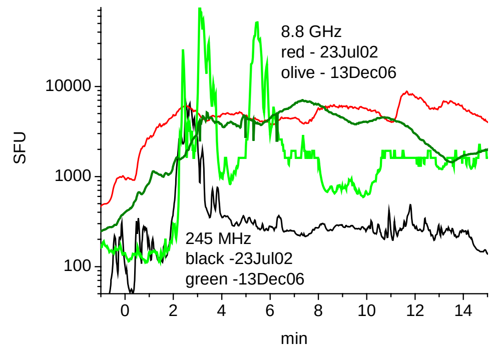


Figure 5: The time profile of radio emission intensity at 245 MHz and 8.8 GHz of the December 13 event in comparison with those of the 2002 July 23 event.

The 2002 July 23 event produced an intense complex type III-like burst with onset at 00:27 UT, that extended from the highest observing frequency of 13.825 MHz to the local plasma frequency near 20 kHz at the Wind spacecraft [3]. We should expect a long type III-like emission for all events of December 2006. The Chacaltaya and Mexico NM registered solar neutrons produced during the C phase on 2005 September 7 [8]. The solar neutron from the 2006 December 6 event also might be registered by these NM's. However, the expected neutron enhancement would be below background, if we assume the same relation between hard X-ray intensity and neutron production at the Sun. The largest proton flux observed in the interplanetary space after the 2006 December 6 corresponds to the hard X-ray emission during the C phase. Therefore, the delayed hard X-ray emission might be considered as a feature of effective proton acceleration. The event of 2006 December 14 might be considered as an elementary event with short hard X-ray emission during the A phase and puts the limits on association between solar signatures and protons in the interplanetary space.

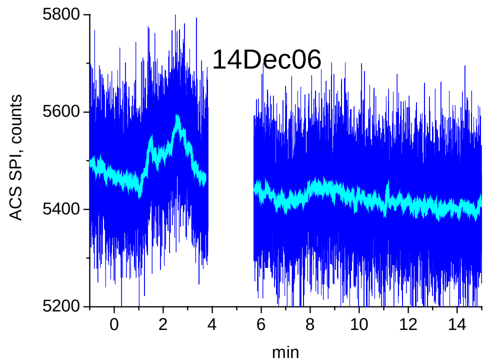


Figure 6: The ACS SPI count rate (cyan – running average) during the 2006 December 14 event.

Conclusions

- The hard X-ray emission of the December 2006 flares provides evidences of several acts of energy release and particle acceleration. The concept of A, B and C phases [6] fit well these flares.
- One loop evaporation model doesn't work in large X-ray flares of December 2006.
- Protons are accelerated during each phase, but the maximum energy is different. The most effective acceleration up to hundred MeV energies occurs during the C phase.

Acknowledgements

The authors thank Alexandr Lutovinov (the Russian INTEGRAL Data Center) for his help getting the ACS SPI data. This work is partially supported by the grants (RFBR 07-02-08367, 05-02-17105, 05-02-17251; NSh-5359.2006.2). AS thanks the LOC for the local hospitality.

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