The Efficiency of Solar Energetic Particle Generation: CORONAS-F Mission Data Analysis

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Abstract.

We present the results of a comparative analysis on the efficiency of the solar energetic particle events (SEP) and related solar flares. Both SEP events and solar flares were detected by the CORONAS-F solar mission. We selected the SEP events based on the presence of simultaneous observations from the hard X-ray (HXR) instrument SONG (CORONAS-F satellite) with radio emission ranging from microwaves to the meter-range, as evidence of accelerated particles generated during the events and solar proton and electron data measured by MKL instrument on board CORONAS-F satellite in polar caps. The results are discussed from point of using solar flare emission features as the criteria of generation of SEP event with high proton abundance.

Introduction

Solar energetic particles (SEPs) are the observed in situ electrons, protons and heavy nuclei at energies from the keV up to the GeV range (e.g. [Desai and Giacalone, 2016]). SEPs, together with the effects caused by their solar origin, flares and coronal mass ejections (CMEs) are important space weather agents and topic of ongoing research [Jiggens et al., 2014]. While in space, humans and technological devices are exposed to different radiation effects caused by energetic particles namely ones of solar origin, cosmic rays and particles of the radiation belt of the Earth [Baker, 2000].

The main goal of this work is the comparison of the efficiency of solar energetic particle (SEP) generation in solar flare observed by CORONAS-F solar mission. In this experiment, it was possible to register simultaneously a hard neutral emission of solar flares -X-rays, gamma quanta, neutrons, and SEP particles (in polar caps), which simplified multi-wavelength observations in near-Earth space. The target of this analysis was to reveal that both, powerful and weak, SEP events are associated with the solar flares observed by SONG with high temporal resolution.

Experiments

The CORONAS-F Russian solar space observatory was launched on July 31, 2001, and operated until the end of 2005. At the beginning of its flight CORONAS-F had a quasi-circular orbit, with initial parameters: altitude 507±21 km, inclination 82.5 degrees, and period of revolution 94.5 min. The primary goal of the CORONAS-F experiment was to investigate nonstationary processes on the Sun and their impact on the interplanetary medium and the Earth's magnetosphere [Kuznetsov et al., 2014].

The development of a complex program of the studies of solar activity and its influence on the near-Earth space began in the USSR in the middle of 80s years of the 20th century. It resulted in a development of a number of satellites of CORONAS series. A set of scientific instruments Solar Cosmic Rays (SCR) was developed in order to study the relations between the radiation conditions in the near-Earth space and solar activity. This instrument was installed onboard the satellites CORONAS-I and CORONAS-F launched to orbit on March 2, 1994 and July 30, 2001, respectively. It consisted of three instruments (in this study we used two of them – SONG and MKL).

In such an orbit, the detection of neutral radiation from solar flares is possible only at low and middle latitudes outside the Earth's radiation belts, and also at the polar caps, in the absence of SEP particle flux in near-Earth space. In this case, the detector background counts are due to secondary local gamma-ray radiation produced by the interaction of primary cosmic rays with the material of the Earth's atmosphere, the spacecraft, and the detector itself. The duty cycle for the detection of solar flares on board CORONAS-F satellite was about 35% as a result of its orbit parameters, so many flares were missed. Solar energetic particles were measured by MKL in polar caps.

We used data of hard neutral radiation from solar flares obtained by the SONG (SOlar Neutrons and Gamma-rays) - multichannel gamma-ray spectrometer operated on board CORONAS-F solar space low-altitude observatory from the middle of 2001 until the end of 2005. Hard X-ray (HXR) and gamma-ray radiation are detected by the SONG instrument with the time resolution of the device was 2-4 s. SONG instrument is intended for detection of X-rays and gamma-emission within the energy range of 30 keV - 200 MeV, and neutrons with energies over 20 MeV.

MKL (Russian abbreviation for Monitor of Cosmic Rays) instrument is intended for detection of charged particles within the following energy ranges: spectra and fluxes of protons within the energy range of 1–90 MeV; spectra and fluxes of electrons within the energy range of 0.5–12 MeV; alpha-particles flux with energies of 100–140 MeV. Detector part of the instrument consists of two telescopic systems. The first scintillation detector D1 is

Table 1. Solar HXR- and gamma-ray flares detected by SONG (CORONAS-F). For abbreviations and further explanations see text.

№	dd/mm/yy	UT start-max-end of SXR, hh:mm	SXR class	AR	Coordi-nates	UT, HXR (SONG), hh:mm	Emax SONG, MeV	Jp , p/ (cm^2-s-sr)	Je, e/ (cm^2-s-sr)
1	20/08/02	08:22-08:26-08:30	M3.4	0069	S10W38	08:24-08:26	4.8-8.4	0.135	0.597
2	24/08/02	00:49-01:12-01:31	X3.4	0069	S12W51	00:58-01:07	4.8-8.4	44	6.67
3	17/03/03	18:50-19:05-19:16	X1.5	0314	S14W39	18:57-19:01	5.2-9.1	0.022	0.043
4	11/04/04	03:54-04:19-04:35	C9.6	0588	S16W46	04:13-04.18	0.18-0.7	0.51	0.243
5	17/01/05	09:59-09:52-10:07	X3.8	0720	N15W25	09:52-10:00	2-6	142.5	100
6	20/01/05	06:36-07:01-07:26	X7.1	0720	N14W61	09:44-09:56	90-150	233.5	1018

a part of spherical layer of plastic scintillator based on polystyrene inside the area enclosing a cone with a peak in the sphere's center and span angle of 140°. Semiconductor detector D2 12 mm in diameter and 2 mm thick is located in the center of the sphere. Specific ionization of the particles for their movement in the considered system is used for particles' identification and determination of their energy. Amplitude of impulse produced by the charged particle is measured by scintillator detector, for the further analysis the particles with energy release in "n-p" detector exceeding double ionization of a relativistic single-charged particle are selected. The detailed description of SONG and MKL instruments is given in [Kuznetsov et al., 2014].

In addition, data from the Radio Solar Telescope Network (RSTN) is used for investigating the behavior of the temporal profiles of the radio emission. Single frequency radio records (in eight discrete frequencies from 245 MHz to 15.4 GHz) covering heights from low corona to upper chromosphere are available. Besides that, data obtained with the Nobeyama Radioheliograph (NoRH) (http://solar.nro.nao.ac.jp/norh) and radio polarimeter, NoRP, (http://solar.nro.nao.ac.jp/norp) were also used.

Data

We analyzed the SEP events associated with the solar flares that occurred on August 20 and 24, 2002, March 17, 2003, April 11, 2004, January 17 and 20, 2005. Table 1 presents data on six solar flares detected by SONG instrument on board CORONAS-F satellite. There, the following information is listed: the date of the flares, the time of start-maximum-end, the GOES class, the number of the active region (AR) in which the flare occurred, its coordinates on the solar disk, the time of HXR emission according to SONG data, the maximum energy, Emax, of gamma-ray which were detected by SONG, proton intensity, Jp (50–90 MeV) and electron intensity Je (1.5–3 MeV) detected by MKL SONG instrument on board CORONAS-F in polar caps. All times are in UT. The energy channels of proton and electron fluxes are selected in accordance with the channels of the MKL instrument. Both for protons and for electrons we used data observed in the highest-energy channels as available for all six events.

From Table 1 it can be seen that the class of studied flares varied in a wide range, from C9 to X7, and that all of them occurred in the central or western part of the solar disk. It is also seen from the table that the fluxes of SEP (both protons and electrons) are neither proportional to the class of flares in the SXR according GOES nor to the maximum HXR energy measured by the SONG instrument.

Figure 1 shows the time profiles of all six flares in the HXR-emission according to the SONG data (solid line) and ones in the microwave according to the data of the RSTN and the NORP (dashed line).

It can be seen from Fig. 1 that for all six flares the profiles in HXR and radio emission are similar, but one can lag behind the other and the correlation of the profiles of different flares is different. It is also easy to see that the ratio of the fluxes of in situ protons and electrons is substantially different. These differences were analyzed.

Results

Figure 2 shows the dependence of the ratio of the flux of solar protons with energy of 50–90 MeV to the flux of solar electrons with an energy of 1.5–3 MeV measured by the MKL instrument in polar caps, from the coefficient of correlation of HXR and microwave emission (left panel, blue diamonds) and from the delay time of the wave radiation relative to HXR-emission (right panel, red triangles).

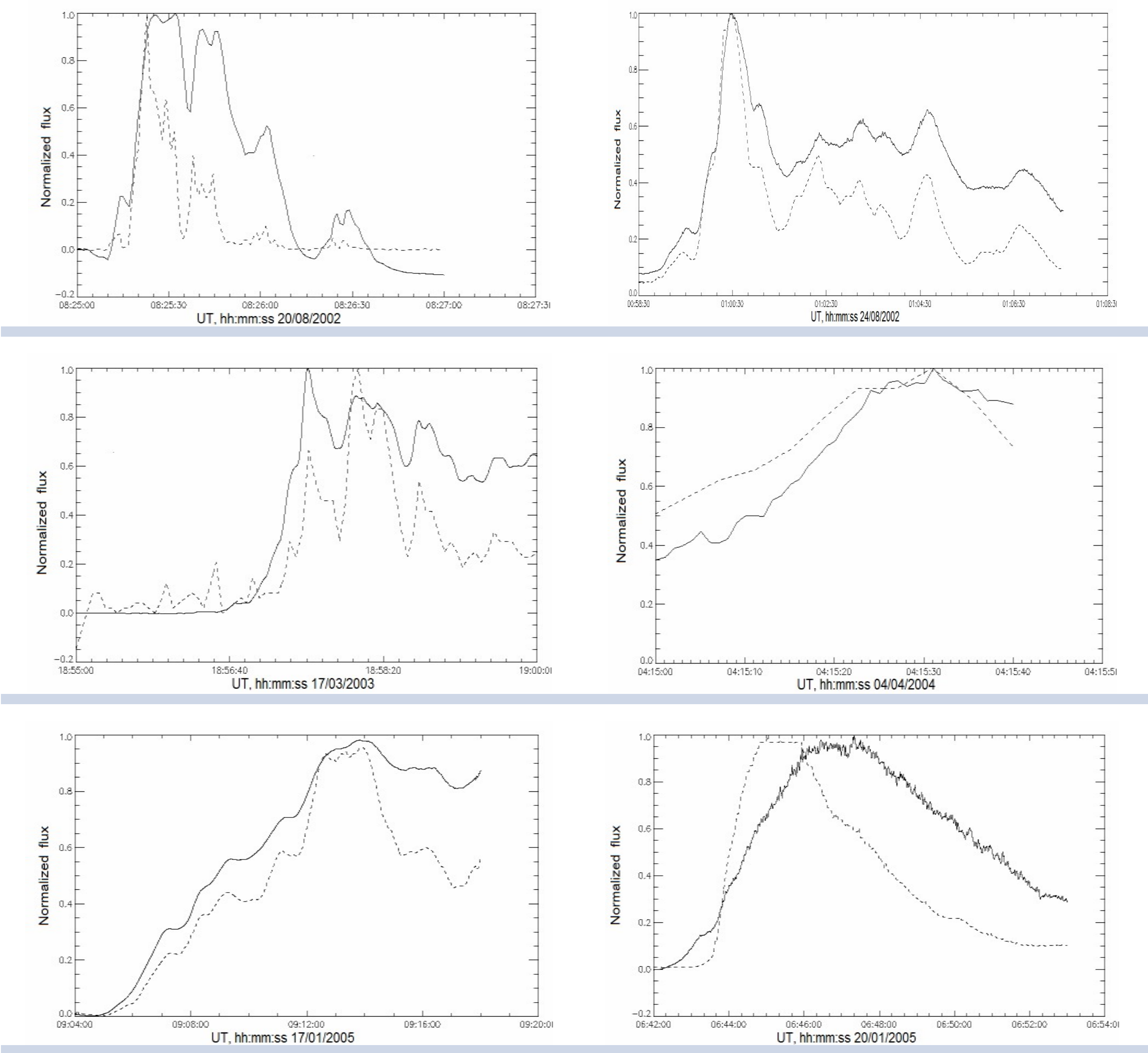

Fig. 1. The time profiles of HXR-rays (SONG), plotted in solid line, and radio (microwaves) emission, plotted in dotted line, of all six flares from Table 1. Time profiles were normalized to the maximum..

Three of the six events (August 20 2002, January 17, 2005 and January 20, 2005) have zero delays, and two of them, August 20 2002 and January 20, 2005, are characterized by a close ratio of the solar proton fluxes to the electron, so the exact dependencies of the obtained values are difficult to build. Nevertheless, both panels of Fig. 2 show a tendency to increase this ratio both with an increase in the coefficient of correlation, and with an increase in the delay time of microwave emission relative to HXR one.

The relationship of the proton to electron ratio to the correlation coefficient shows the clear dependence. Only the SOL2004-Aug-24 flare is not in good agreement with this dependence. This fact could be related with features of active regions (ARs) which were not taken into account in this study. In the paper of Bogomolov et al. [2018] to the analysis of SEP fluxes and flare plasma parameters were added also studies of the magnetic topology of the AR and its evolution before and during the solar flares. The presented results indicate that an arcade of high loops covering the AR could prevent escaping of the accelerated particles and generates a less proton-rich SEP event as it is expected by flare properties alone.

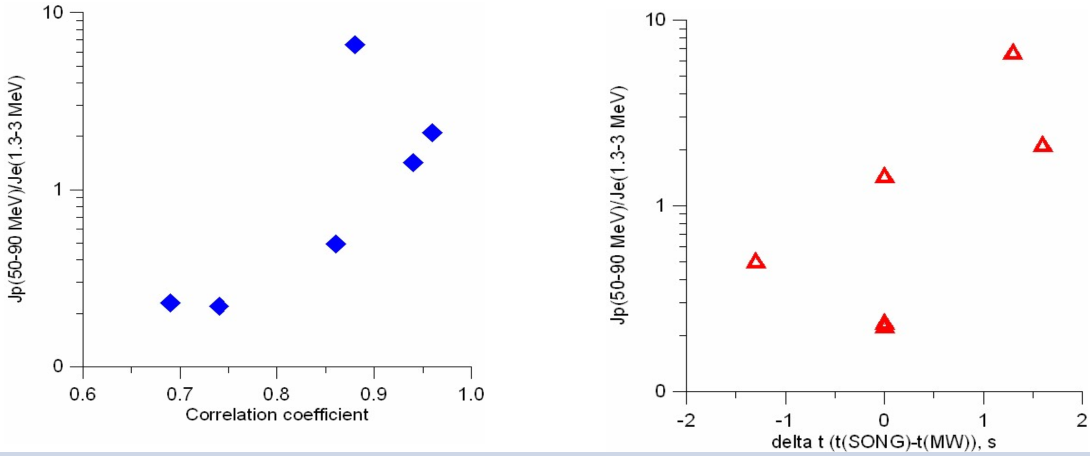

Fig. 2. The dependence of the ratio of the solar proton flux (50–90 MeV) to the solar electron one (1.5–3 MeV) on the coefficient of correlation of hard X-rays and microwave radiation (left panel) and on the delay time of the wave radiation relative to HXR-emission (right panel).

Alternatively, the flare associated with the proton-rich SEP event could occur in an AR where a fan of high loops is associated with open magnetic field lines.

Conclusions

We analyzed the SEP events detected on board the Russian solar observatory CORONAS-F simultaneously with the hard X-ray emission of flares that caused these events. The main feature of our study is that we used both HXR flare emission observations and SEP flux measurements obtained at the same spacecraft. We revealed the clear tendency of increasing the ratio of the flux of solar protons to the flux of solar electrons with rising of the correlation coefficient between HXR and microwave radiation. However, analysis of AR magnetic topology should be completed before the final conclusions. We think that these results show that the detection of energetic neutral and charged radiation on the same spacecraft could be important for the study of the relationship between the X-ray characteristics of flares and SEP events.

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