Parameters of Thermal and Non-thermal X-ray and Gamma Ray Emission of Solar Flares, Observed onboard CORONAS-F

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Abstract.
Based on data from the SPR-N and SONG multi-channel hard electromagnetic radiation detectors onboard the CORONAS-F space observatory and the X-ray monitors onboard GOES satellites, we have distinguished the thermal and non-thermal components in the X-ray spectrum of a number of powerful flares of 23rd solar activity cycle. Temporal, spectral and energetic parameters of the flares were analyzed using the catalogs of Solar Energetic Particles and Related Phenomena (http://newserver.stil.bas.bg/SEPcatalog/).

Introduction

In the comparative analysis of flares with similar characteristics, but with different geoeffectiveness, it was shown that it may be important to take into account the conditions for the release of particles from the flare area (magnetic field topology) [Bogomolov et al., 2018]. The same conditions can affect how much of the energy of the accelerated electrons will be used to heat the solar plasma, and which will leave the flare region along with the accelerated particles.

The experiment

The CORONAS-F observatory was launched on July 31, 2001 into a quasi-circular orbit with an inclination of 82.5^o, orbital period of 94.5 min. and an altitude of 507±21 km (by the end of the flight, its orbit dropped to ~ 300 km). The spacecraft ceased to exist on December 6, 2005. The main tasks of the CORONAS-F mission are to study non-stationary processes on the Sun and their effects on the interplanetary medium and the Earth's magnetosphere.

In this work, we used the data of two devices installed on the CORONAS-F. One of them is SPR-N elaborated for studying X-ray radiation from solar flares in the range of 15-100 keV and measuring its linear polarization. In this work, only the SPR-N patrol detector was used. This is a scintillation detector based on CsI (Na) with a diameter of 1.5 cm and a thickness of 0.3 cm, above which is a cylindrical collimator providing a rather narrow field of view of the detector - within 5x5 degrees. To protect against X-rays coming from the spacecraft, lead glass 0.5 cm thick is placed under the CsI (Na) crystal. During the whole experiment with the SPR-N instrument, which began on August 15, 2001, the instrument operated in the monitor mode of continuous measurements. The output parameters of the SPR-N patrol detector are the counting rates in channels 15–40 and 40–100 keV, as well as the counting rate of the anti-coincidence shield from plastic scintillator. The time resolution for the patrol detector of the device was determined by the exposure time, which, as a rule, was equal to 4 seconds.

To obtain the parameters of the bremsstrahlung radiation from solar flares, we used data from the SONG instrument, designed to measure hard X-rays, gamma rays in lines and continuum, as well as neutron and relativistic electron fluxes. Particles are registered in SONG by scintillation detector based on a CsI(Tl) crystal with a diameter of 200 mm and a height of 100 mm, surrounded by an active anti-coincidence shield from a plastic scintillator used for protection against charged particles, as well as for the detection of relativistic electrons. The time resolution of SONG during the experiment ranged from 1 to 4 seconds.

The wide energy range from 30 keV to 200 MeV was divided into 12 channels, the first five of which at the beginning of the experiment had values: 0.03–0.06, 0.06–0.15, 0.15–0.5, 0.5–1.5 and 1.5–4 MeV. During the flight, the threshold values slowly increased, by the end of 2005 the difference was about 1.5 times. A more detailed description of the experiments with SPR-N and SONG can be found in earlier works [Bogomolov et al. 2003, Bogomolov and Myagkova 2017, Kuznetsov et al. 2006, Zhitnik et al. 2006].

Table 1 List of solar flares observed by the SPR-N instrument which can be used to separate the thermal and non-thermal components of X-ray radiation.

DATE	GOES Tbeg-Tmax-Tend			class	Lat	Lon	Backgr	Емах SONG	SEP
25.08.2001	**16:23**	**16:45**	**17:04**	**X5,3**	**-17**	**-34**	**bCbe**	**60-100**	-
05.09.2001	14:25	14:32	14:34	M6,0	15	31	E	1.3 - 4	-
11.12.2001	7:58	8:08	8:14	X2,8	16	-41	Cbe	7- 15	SEP
20.05.2002	15:21	15:27	15:31	X2,1	-21	-65	Eb	7.7-16.5	SEP
17.07.2002	6:58	7:13	7:19	M8,5	21	17	E	1.6-4.8	-
18.07.2002	3:22	3:37	3:40	M2,2	20	27	E	0.6-1.6	-
20.08.2002	8:22	8:26	8:30	M3,4	-10	38	E	4.8-8.4	SEP
21.08.2002	1:35	1:41	1:45	M1,4	-11	47	E	0.6-1.6	-
21.08.2002	5:28	5:34	5:36	X1,0	-12	51	E	4.8-8.4	-
24.08.2002	0:49	1:12	1:31	X3,1	-2	81	Ebc	4.8-8.4	SEP
30.08.2002	12:47	13:29	13:35	X1,5	15	-74	E	4.8-8.4	-
10.09.2002	14:49	14:56	15:00	M2,9	-10	-43	E	0.6-1.6	-
17.03.2003	18:50	19:05	19:16	X1,5	-14	39	Cbe	5.2-9.1	SEP
09.04.2003	23:23	23:29	23:34	M2,5	-10	78	Eb	0.6-1.6	-
26.04.2003	3:01	3:06	3:12	M2,1	20	69	Eb	1.7-5.2	-
26.04.2003	8:01	8:07	8:09	M7,0	n/d	n/d	Cb	5.2-9.1	-
27.05.2003	22:56	23:07	23:13	X1,3	-7	17	E	5.2-9.1	-
28.05.2003	0:17	0:27	0:39	X3,6	-7	17	bE	5.2-9.1	SEP
29.05.2003	0:51	1:05	1:12	X1,2	-6	37	bCb	5.2-9.1	SEP
23.10.2003	8:19	8:35	8:49	X5,4	-21	-88	bCbe	5.2-9.1	-
24.10.2003	2:27	2:54	3:14	M7,6	-19	-72	Ebc	0.65-1.7	-
28.10.2003	**9:51**	**11:10**	**11:24**	**XX17,2**	**-16**	**-8**	**ebCbe**	**80-130**	**SEP**
29.10.2003	**20:37**	**20:49**	**21:01**	**XX10,0**	**-15**	**2**	**bEb**	**5.2-9.1**	**SEP**
04.11.2003	**19:29**	**19:50**	**20:06**	**XX28,0**	**-19**	**83**	**bCbe**	**130-260**	**SEP**
17.11.2003	8:55	9:05	9:19	M4,2	-1	-33	E	1.7-5.2	-
06.01.2004	6:13	6:29	6:36	M5,8	5	-90	E	1.7-5.2	-
11.04.2004	3:54	4:19	4:35	C9.6	-16	46	E	0.22-0.73	SEP
01.01.2005	0:01	0:31	0:39	X1,7	6	-34	E	2- 6	SEP
20.01.2005	**6:36**	**7:01**	**7:26**	**X7,1**	**14**	**61**	**Ebc**	**90-150**	**SEP**

Data

During the experiment (August, 2001 – end of 2005) we obtained the following data. The X-ray emission with E>15 keV was observed by SPR-N in 159 solar flares. List of the flares observed by SONG includes 105 flares with HXR-emission >50 keV. 38 of them were observed in the energy channel >500 keV. In 4 flares gamma-emission with E>100 MeV was detected. Catalog of the flares observed in the experiment with SONG can be found in http://swx.sinp.msu.ru/apps/solar_flares_cat/. For problems of separation of thermal and non-thermal radiation, data of simultaneous measurements with the SPR-N instrument (containing both components of radiation) and SONG (bremsstrahlung, at least three channels) are required. The list of suitable flares is presented in Table 1.

First seven columns of the table are well-known data from the solar event lists: date of the flare, times (start, maximum and end) of soft X-ray emission, observed by GOES, the flare class (GOES, https://satdat.ngdc.noaa.gov/sem/goes/data/new_full/) and the solar coordinates of the active region. The next column, named ‘backgr’, shows the background conditions at the time of the flare. CORONAS-F operated on the near-Earth polar orbit, thus besides equatorial regions it crossed polar caps and Earth’s radiation belts (ERB). The conditions are shown as the sequence of the letters: e (equator), c (polar cap) and b (ERB). The capital letter indicates the moment of maximum X-ray flux. For example, a sequence ‘bCbe’ means that a flare begins when the satellite was in a ERB, the maximum of flare radiation corresponds to a polar cap, then the satellite again crosses ERB, and the end of the flare is on the equator.

For some time the satellite was in the shadow of the Earth. Flares, for which the Sun was screened by the Earth at the moment of maximum radiation, were not selected for analysis. Three flares, in which during some time (not at the moment of maximum) the satellite was in the Earth’s shadow, are marked with a gray background in the ’backgr’ cell.

The next column, labeled ‘Emax SONG’, shows the maximum energy channel in which the SONG detected gamma radiation at a level that is significant for this work, i.e. with the ability to include this channel for obtaining the spectral index, as well as for observing the dynamics of gamma radiation during the flare.

The last column (‘SEP’) indicates in which flares presented in the SOHO/ERNE proton event catalog (http://newserver.stil.bas.bg/SEPcatalog/) there was a significant flux of protons with energies 17–22 MeV. See the description of the catalog in the paper of Myagkova et al., [2019, this issue].

Results

a) Method

We take into account two components of hard X-ray emission:

1) Thermal emission from an optically thin plasma, $I(E, kT) = J_{0th} \exp(-E/kT) /E$

2) A power-law bremsstrahlung spectrum, $I(E, \gamma) = J_{0nth} E^{-\gamma}$

Other components (gamma ray lines, π^0-decay etc.) do not yield to the hard X-ray and soft gamma-ray emission.

In the SPR-N channel 40–100 keV only bremsstrahlung component presents. In the SPR-N channel 15–40 keV both thermal and non-thermal components are present. The spectral index in the channel 15-40 keV is the same as in the channel 40–100 keV.

The parameter of thermal radiation *kT* can be estimated from the ratio of values of the GOES channels 1–8 Å and 0.5–4 Å. At the same time, the contribution of thermal radiation to the SPR-N counting rate in a channel 15–40 keV cannot be estimated accurately only by GOES data. The reason is that the spectrum of thermal radiation in the energy range >15 keV is strongly incident and the error in the energy threshold values even per fraction of keV leads to a difference in counting rates by several times.

We used a different approach. First, an estimate of the bremsstrahlung index γ was made using SONG channels in which the contribution of gamma lines looks insignificant. Thermal radiation in SONG is absent. Then, knowing the γ, we determined the constant J_{0nth} from the condition that in the SPR-N channel 40–100 keV the count rates were equal to the observed ones. After this we extrapolate the obtained power-law spectrum to the SPR-N channel 15–40 keV and calculated the expected count rates in it caused only by the bremsstrahlung emission. The remaining part of the count rates (I(total) - I(bremsstrahlung)) is due to thermal component. Finally, we calculate the thermal radiation constant J_{0th} using kT, determined according to the GOES, and the condition that the SPR-N count rates in the 15–40 keV channel expected from the thermal part of the spectrum must be equal to the observed ones. As an example, Fig. 1 shows the results of the calculations described above for the flare 29.10.2003 of class X10.

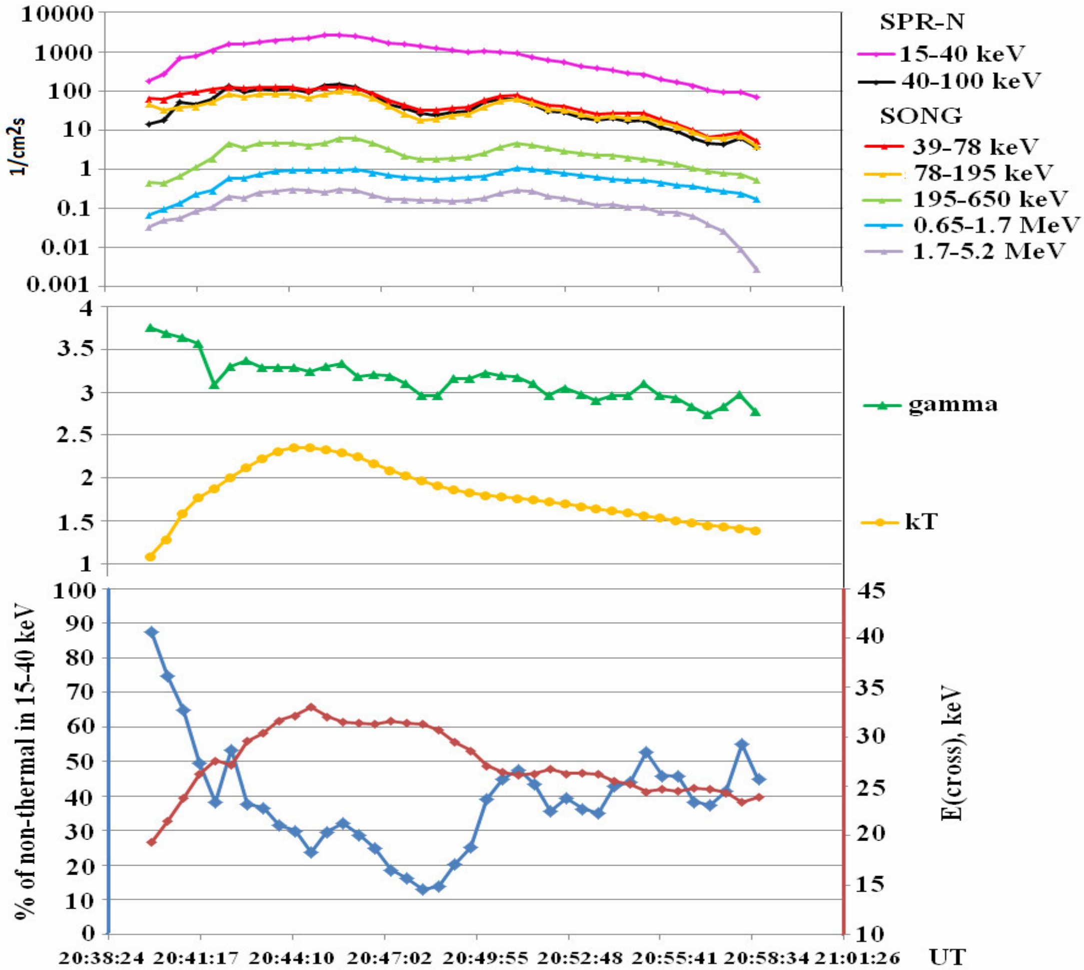

Fig. 1 The SPR-N and SONG count rates, bremsstrahlung spectral index, kT, part(%) of non-thermal emission in the SPR-N channel 15-40 keV and energy E(cross) at which thermal and non-thermal radiation fluxes become equal, obtained for the solar flare X10.0 29.10.2003.

b) Statistical analysis

To search for a possible connection between the characteristics of thermal and non-thermal components of X-ray radiation with SEP and solar wind, we chose the following parameters for the correlation analysis:

Gamma – Power index of bremsstrahlung (non-thermal radiation);

kT of thermal emission;

E (cross) – energy at which thermal and non-thermal radiation fluxes become equal;

Part (%) of non-thermal radiation, in the beginning, middle and end of a flare;

GOES class, i.e. flux in soft X-rays 1–8 Å [W/m^2];

Jp – Peak proton intensity [protons/(cm^2·s·sr·MeV)] – from SOHO/ERNE catalog;

Je – electron fluxes in three bands: 53–103, 103–175 and 175–315 keV (ACE/EPAM);

CME – linear speed [km/s].

The obtained matrix of the Pearson's correlation coefficients is presented in Table 2. Note that the correlation coefficient R only shows the strength of the linear relationship. In many cases, the relationship may be non-linear. For example, the dependence of energy E (cross) to the flare class in soft X-rays, shown in Fig. 2, is well approximated by a logarithmic line with the coefficient of determination $R^2 > 0.8$.

Table 2. Correlation matrix between the parameters of the flare X-ray emission, proton and electron fluxes and CME speed.

	Jp 17-22 MeV	Je 53-103 keV	Je 103-175 keV	Je 175-315 keV	V(CME)
GOES class	**0,59**	0,36	0,38	0,37	**0,79**
Gamma	-0,47	-0,27	-0,31	-0,44	**-0,53**
kT	**0,61**	0,40	0,41	0,34	**0,65**
Ecross	**0,55**	0,35	0,35	0,28	**0,56**
Part_start	**-0,50**	-0,11	-0,14	-0,11	**-0,61**
Part_mid	**-0,68**	-0,33	-0,32	-0,23	**-0,51**
Part_end	-0,37	-0,16	-0,16	-0,20	0,38

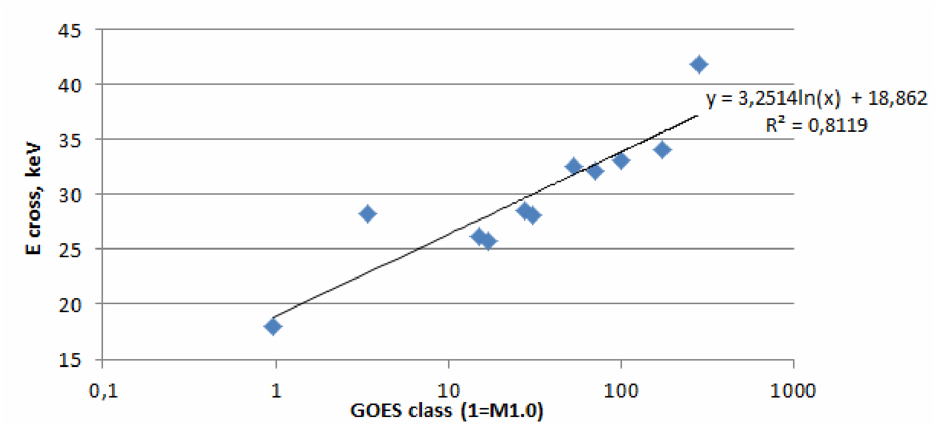

Fig. 2 The relationship of energy at which the thermal and non-thermal components of flare X-rays are equal, and the flare class in soft X-rays.

Discussion

The small statistics of solar flares used in this work allows only to note some general patterns. One of them is the absence of a significant correlation of electron fluxes with all used X-ray and gamma-ray emission parameters. Another statement is the lack of correlation of the spectral index of gamma radiation with particle fluxes.

In the future, it is planned to analyze how the energy of the accelerated electrons and the thermal energy of the flare region change during the flare. All flares from Table 1 are suitable for this analysis, if it is possible to estimate the volume of the flare area and to assume the fraction *f* of this volume filled with the emitting plasma (filling factor). In Kurt V.G. et al. [2010] these calculations are presented for one of the most powerful flares observed at CORONAS-F on January 20, 2005 (class X7.1). The calculations were carried out using the formulas from Saint-Hilaire P. and Benz A.O. [2005] assuming the passage of electrons through a dense but optically thin plasma. Some of the main results are shown in Fig. 3.

Except for the very beginning of the flare preceding the impulsive phase, the energy deposited by the electrons prevails over the thermal one and is sufficient for plasma heating in the first acceleration pulse in the time interval 06:44–06:46 UT. The kinetic energy of the electrons is close to the thermal one for a filling factor f=0.4–0.6 in the remaining time. Thus, it means that in the event 20.01.2005 the electrons accelerated in the pulsed stage of the flare brought enough energy to provide the main heating of the plasma.

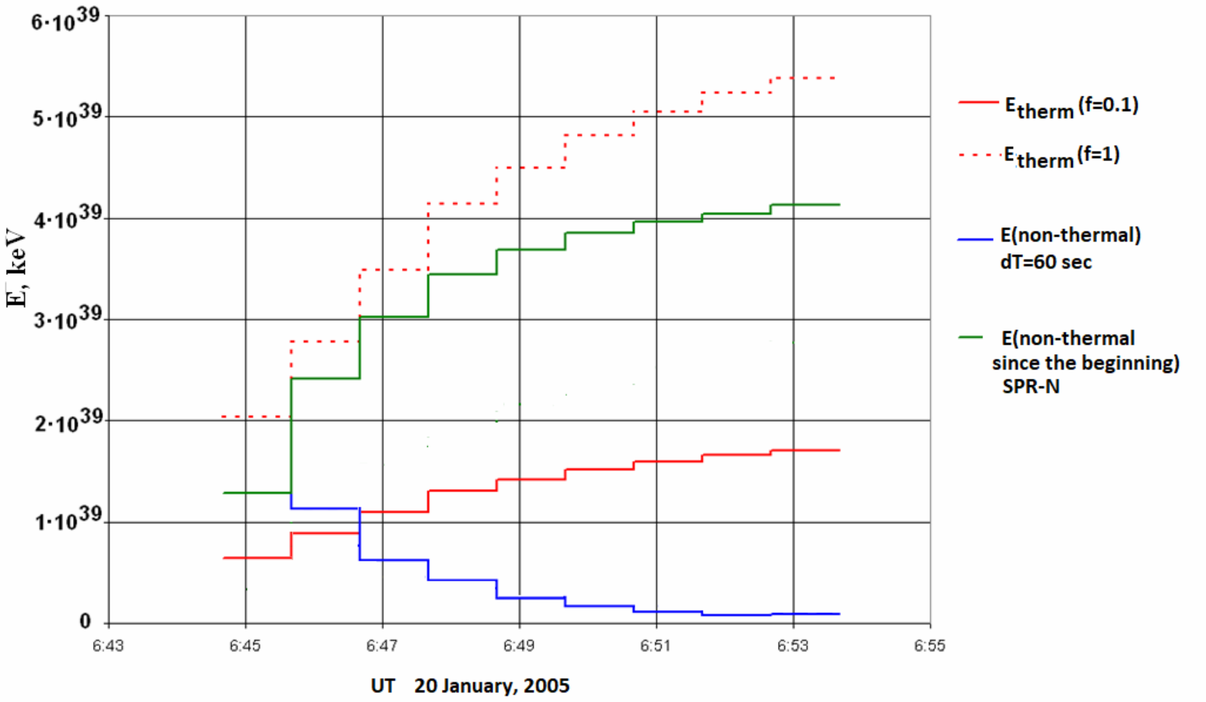

Fig. 3 Energetic parameters of the flare X7.1 20.01.2005 according to Kurt V.G. et al. [2010].

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