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Hard X-ray Radiation from Solar Flares in the Second Half of 2001: Preliminary Results of the SPR-N Experiment Onboard the Coronas-F Satellite

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Abstract—The first results of the experiment with the SPR-N hard X-ray (20–100 keV) polarimeter onboard the Coronas-F observatory (the experiment started on August 15, 2001) are presented. Hard X-ray radiation was detected from several solar flares. The spectral and temporal parameters were determined and the polarization was estimated. Comparison with the GOES observations of thermal X-ray radiation shows that hard X-ray bursts occur at the growth phase of the thermal radiation and that they are associated with the bremsstrahlung of energetic electrons precipitating into the solar atmosphere.

INTRODUCTION

Increases in the fluxes of electromagnetic radiation, in particular, in the hard X-ray range, the so-called solar X-ray bursts (Stepanov, 1982), are observed during solar flares. These bursts can be considered as one of the effects of particle acceleration in the solar atmosphere (Pikel'ner and Tsytovich, 1975).

Hard X-ray bursts are currently believed to be associated with nonthermal processes at the impulsive phase of solar flares, with coronal mass ejections (CME), with coronal shock waves, and with other forms of energy release. In particular, hard X-ray bursts can be produced by the bremsstrahlung of nonthermal electrons accelerated to energies above several tens of keV when they are injected from the acceleration source into denser and lower-lying regions of the chromosphere. In general, these electrons exhibit a power-law spectrum with an index $\gamma = 3$–7 (Stepanov, 1982). Therefore, the X-ray burst spectra generally also steeply fall off with increasing energy so that the bulk of the energy is emitted in the range below 100 keV. Only in some cases can the most intense and hard events be traced up to energies of several hundred keV (Dennis, 1985).

Investigating the properties of hard X-ray bursts from solar flares is undoubtedly of interest in understanding the particle acceleration in flares and in studying the nonflare acceleration mechanisms that have been actively discussed in recent years (Kahler *et al.*, 1986; 1988; 1994). Thus, for example, a number of observations indicate that, apart from the acceleration in flares (stochastic and/or in an electric field) and at shock waves, other acceleration processes also take place in the corona. These primarily include the processes in eruptive solar events with post-flare arches extended in space and in time with characteristic hard X-ray and radio bursts and a gamma-ray spectrum up to energies of tens and hundreds of MeV, suggesting the acceleration of particles up to relativistic energies (or at least their existence) on the Sun at a late flare stage.

The fundamental possibility of nonflare particle acceleration on the Sun was experimentally confirmed by Kahler *et al.* (1986) and Veselovskii *et al.* (1997). During CME formation, a region with open magnetic field lines and with a current sheet that separates the fields with opposite polarities is formed in the solar corona. The subsequent relaxation of the magnetic field to its original state lasts for a long period and proceeds via magnetic reconnection in the current sheet, which gives rise to a sequentially growing arcade of magnetic loops. The electric field generated inside the current sheet that separates the fields with opposite polarities by a rapidly varying magnetic field can effectively accelerate charged particles, in particular, electrons up to energies of several hundred keV.

The thermal X-ray spectra of solar flares are generally characterized by an effective temperature kT of several keV and are traceable to energies no higher than several tens of keV (Stepanov, 1982).

The detection of temporary increases in the photon fluxes with energies in the range from ~10 to several hundred keV is needed to assess the role of ohmic plasma heating and heating due to the absorption of the energy of accelerated beam electrons. Of particular importance is the possibility of observing the polarization of hard X-ray radiation, because bremsstrahlung polarization suggests the existence of energetic electron beams in the source.

INSTRUMENTATION

The SPR-N instrument has comprehensively studied the characteristics of hard X-ray bursts in an experiment onboard the unmanned Coronas-F orbiting station. This instrument is designed to measure the polarization of hard X-ray radiation from solar flares to study the mechanism of primary energy release during flares—primarily to assess the relative roles of thermal and nonthermal processes. The SPR-N instrument is used to determine the degree of polarization of X-ray radiation at energies of the order of several tens of keV, the location of the polarization plane on the solar disk with respect to characteristic magnetic structures in the flare region (together with the SRT-K XUV telescope), and the time evolution of the polarization. The instrument records X-ray radiation from solar flares with energies 20–100 keV. In addition, it can measure in detail the time profile of the intensity of X-ray radiation in the energy range 15–100 keV, to determine the flux, and to estimate the spectral hardness in this energy range. Note the first experiments on measuring the polarization of continuum line soft X-ray emission from solar flares (Tindo *et al.*, 1971, 1972; Korneev *et al.*, 1980; Zhitnik *et al.*, 1989).

The SPR-N detection unit includes a polarization detector system and a patrol detector. A general functional diagram of the detection unit is shown in Fig. 1.

The polarization detector system consists of an X-ray scatterer (a hexahedral prism composed of beryllium metal plates with a separation of 10 cm between the opposite faces and a height of 5 cm) and three pairs scintillation detectors, which measure the scattered radiation intensity. The X-ray radiation from a solar flare that passed through a filter absorbing low-energy radiation falls on the beryllium scatterer where it suffers Thomson (Compton) scattering. For a nonpolarized radiation, the probability of scattering through different angles relative to the initial direction of photon propagation is the same. When a plane-polarized radiation is recorded, most of the photons are scattered perpendicular to the polarization plane. Since the photons fall at a right angle to the surface of the scattering prism when the instrument is oriented toward the Sun, the incident radiation will clearly be scattered in the beryllium plates mainly along the plate plane (the beryllium unit of the scatterer was made of separate thin plates to attenuate the absorption of scattered radiation). The scattered X-ray radiation was recorded with six identical sensors located on the faces of the scattering prism. The pairs of oppositely located sensors correspond to the polarization planes rotated through 120° relative to one another. Since the scattered photons for a plane-polarized radiation are azimuthally anisotropic, the count rates in different pairs of sensors must be different—the pair of sensors whose optical axis is closest (within ±60°) to the direction perpendicular to the polarization plane must show the highest count rates. If, alternatively, a nonpolarized radiation is recorded, then its scattering will be azimuthally symmetric and, accordingly, the X-ray fluxes emerging from the six prism faces will be almost equal in this case.

To reduce the background attributable to the recording of an isotropic nonpolarized radiation, which can fall on the scintillation detectors, cellular collimators were placed in front of them. Each detector is a 2.0 × 4.0 × 0.3 cm^3 CsI(Na) crystal placed in an anticoincidence cap of a plastic scintillator. Both scintillators are viewed by one photoelectric multiplier (PEM) (FEU-85). The recording of charged particles is eliminated by separating the output PEM signals in pulse shape (phoswich), which reduces the background from charged particles. The detection efficiency of X-ray radiation by the detectors in the entire operating energy range 20–100 keV is ≥90%.

The signals from the oppositely located sensors are added in the electronic sections of the instrument. Thus, there are three identical pairs of scintillation detectors that can record the polarization of X-ray radiation and three channels in the electronic section that correspond to them. In each of these channels, the number of pulses is measured in a given time interval (count rate) in three amplitude ranges corresponding to the energy ranges 20–40, 40–60, and 60–100 keV. The degree of polarization and the position angle of the polarization plane are determined from the ratio of the numbers of pulses recorded in each of the three independent channels of the three pairs of scintillation detectors. The optical thickness of the scatterer τ ($\tau^{-1} = \mu\rho$), which is determined by the mass absorption coefficient μ, changes with photon energy over the range from 2.5 cm (E_γ = 20 keV) to 4.1 cm (E_γ = 100 keV), which, for given scatterer sizes, determines the detection efficiency, 70–86% of the maximum value achievable in such a configuration.

For calibrations, a light-emitting diode was placed in the lower part of each scintillation detector. To eliminate the systematic errors in polarization measurements associated with the possible channel sensitivity drift, the entire polarization detector system was mounted on a turning drive that rotates through ±60° after each exposure (the rotation duration is ~1 s), the exposure can be set by commands from the Earth in the interval from 1 to 16 s. The exposure time specifies the time resolution of the SPR-N polarization detectors. For the three pairs of these detectors, the output signals in the 20–40, 40–60, and 60–100 keV channels as well as the count rates in the anticoincidence caps of a plastic scintillator are written in the so-called polarization information-digital arrays. The drive has two modes of operation: it can switch on by the patrol detector signal

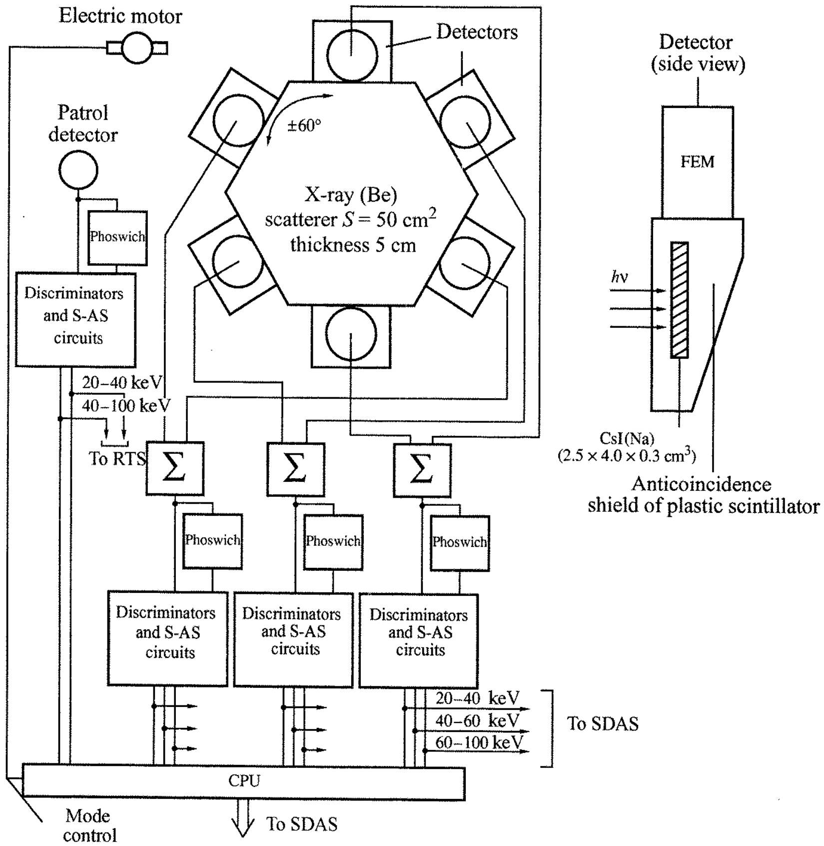

Fig. 1. The functional diagram of the SPR-N detection unit.

when a flare begins or can operate in continuous mode if the dry contacts of the light/shadow relay are closed, i.e., under light.

The patrol detector is designed for monitoring measurements of the intensity of solar X-ray radiation in the energy range 15–100 keV. X-ray radiation is recorded by a (1.5×0.3 cm^3) CsI(Na) crystal with an overlying cylindrical collimator that provides a narrow detector field of view, within $5° \times 5°$. To protect the crystal against charged particles, it was placed behind an anticoincidence shield of a plastic scintillator (phoswich). The count rates in the patrol detector channels are measured continuously and independently of the measurement cycle of the polarization detectors and the modes of SPR-N operation. The signals from the patrol detector in the 20–40 and 40–100 keV channels and the count rates of the anticoincidence cap of a plastic scintillator are written both in the polarization information-digital arrays (together with the polarization detector signals) and in separate patrol information-digital arrays with a more detailed (a factor of 2^3 shorter than the exposure time) time resolution.

TELEMETRY AND CONTROL

Telemetry data from the instrument were obtained with the scientific data acquisition system (SDAS) specially designed and constructed at the Center for Space Information Technologies (CSIT), the Institute of Terrestrial Magnetism, Ionosphere, and Radio-Wave Propagation (IZMIRAN). The main purpose of this system is to continuously collect information from the Coronas-F instruments and to store it during the absence of a radio link with the ground station; to this end, the SDAS has 128 Mbytes of solid-state memory. The system supports a complete cold backup and consists of two symmetric i486SX-based modules. The system also provides time referencing for all onboard measurements with an accuracy of 1 ms.

Accumulated information is transmitted to Earth by preloaded commands from the Earth using two 1.7-GHz transmitters, each with a power of 8 W. The total volume of transmitted information is of the order of 150 Mbyte per day. Information is received by the satellite information reception station at Neustreliz (DLR), Germany. Subsequently, the received information is sent via the Internet to the IZMIRAN, where it is processed and becomes available for users of the scien-

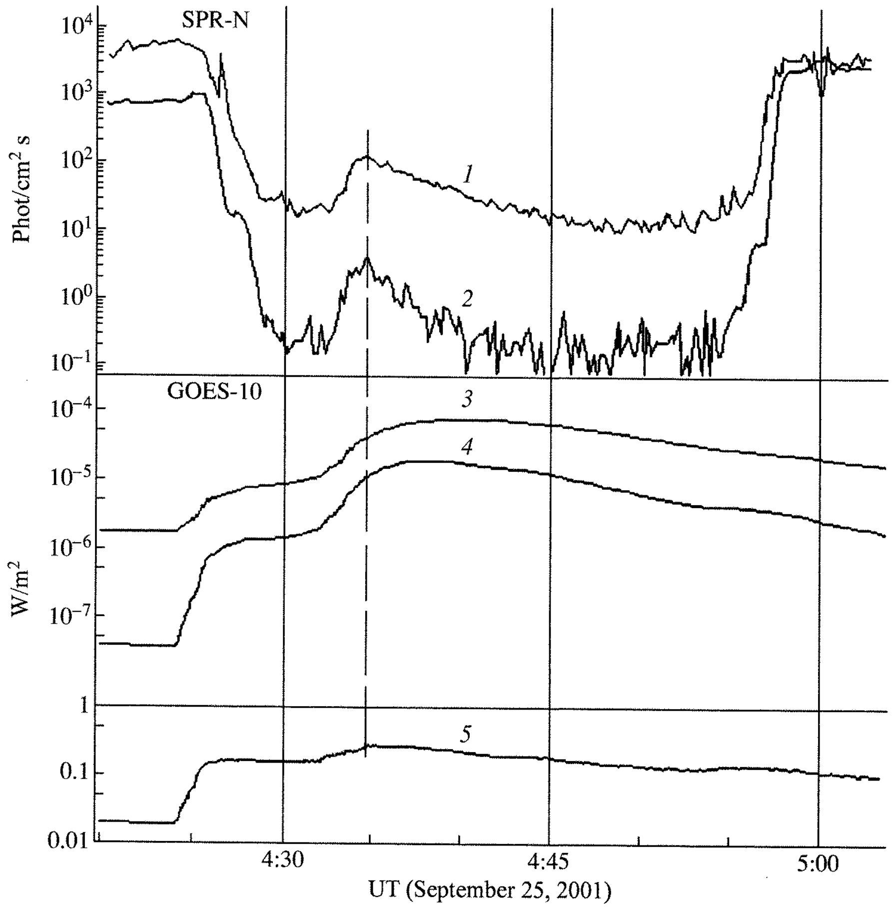

Fig. 2. Time variations in the intensity of the hard X-ray radiation recorded during the hard X-ray flare of September 25, 2001, in channels of the SPR-N patrol detector (*1*—15–40 keV; *2*—40–100 keV) and the GOES-10 X-ray monitor (*3*—1–8 Å; *4*—0.5–4.0 Å; *5*—the spectral hardness parameter defined as the ratio of intensities in the 0.5–4.0 and 1–8 Å channels).

tific instrumentation within several hours after its transmission from the satellite.

Information control of the instrumentation is carried out via a command radio link (CRL) operating at a frequency of 137 MHz directly from the CSIT, IZMIRAN. This CRL can load up to 24 kbytes of command information onboard the satellite, which is used to control the modes of operation of the instruments, including the reprogramming of onboard controllers, and to control scientific data acquisition sessions. The commands are digital arrays transmitted via a special noise-protected protocol. Commands are received onboard the spacecraft with a relatively simple transceiver; the information protocol is supported by the SDAS in software.

EXPERIMENTAL

The SPR-N experiment onboard the Coronas-F satellite began on August 15, 2001 at ~13 h 30 min UT. The instrument operates in the monitoring mode of continuous measurements. A total of ~45 Mbytes of data corresponding to ~165 observing sessions were obtained in the first four months.

The background variations in count rates are associated mainly with changes of the radiation conditions on the orbit when the satellite passes through various circumterrestrial regions. The background count rates are mainly attributable to the contribution from the local gamma-ray emission produced by the interaction of primary cosmic rays in the satellite and instrument materials. Intense increases in the background count rate correspond to the Coronas-F passage through the spurs of the outer radiation belt in the northern and southern hemispheres and the South Atlantic Anomaly (inner belt) and are attributable to the additional count rate in SPR-N channels of the bremsstrahlung of energetic belt electrons. The region of a reduced background count rate between the belt spurs corresponds to

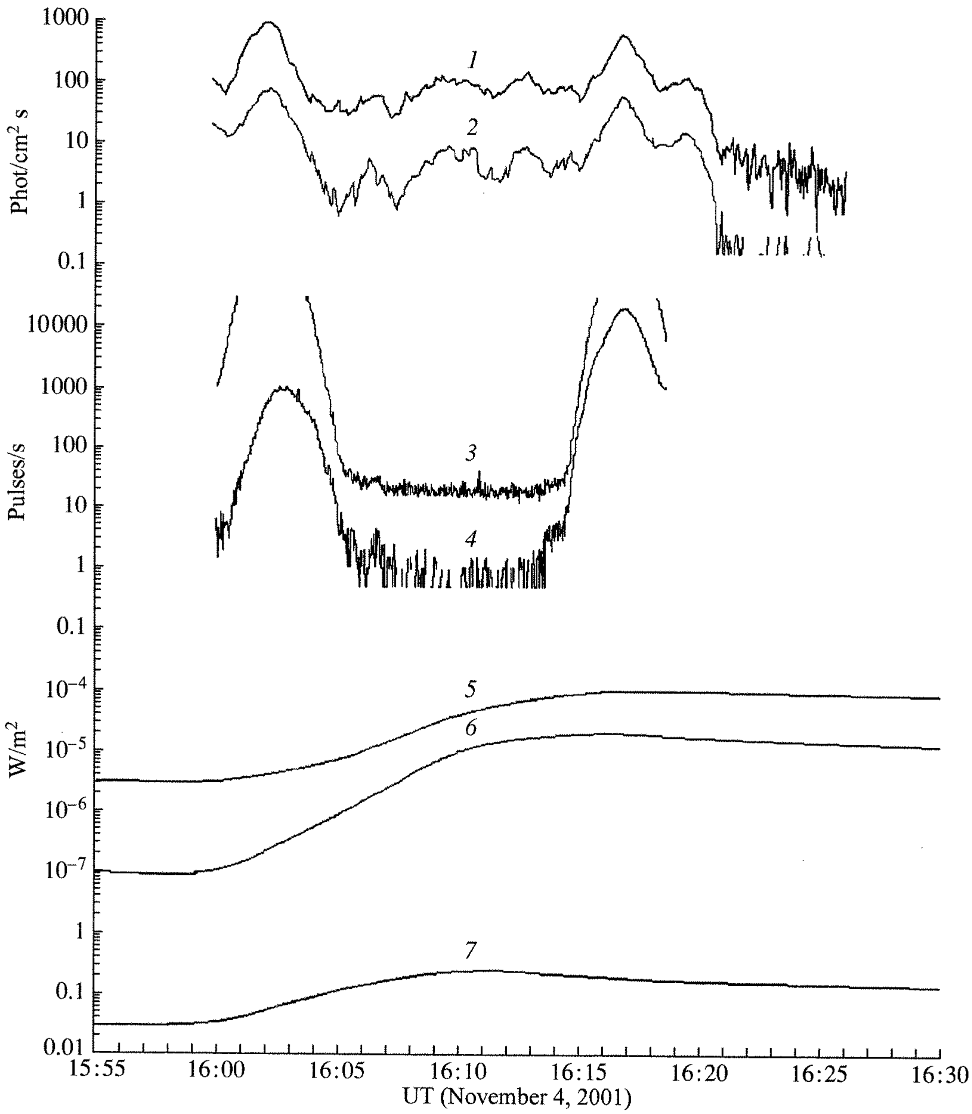

Fig. 3. (a) Time variations in the intensity of the hard radiation recorded during the hard X-ray flare of November 4, 2001 in channels of the SPR-N detector (*1*—15–40 keV; *2*—40–100 keV) and the GOES-10 X-ray monitor (*3*—1–8 Å; *4*—0.5–4.0 Å); *5*—the spectral hardness parameter defined as the ratio of intensities in the 0.5–4.0 and 1–8 Å channels). (b) Time variations of the count rate in MKL electron detection channels (*6*—0.5–1.0 MeV; *7*—0.3–0.6 MeV).

the low-latitude regions beneath the inner belt and to the polar cap regions.

The SPR-N background count rates allow the measurement sensitivity to be estimated. The background in the patrol detector channels corresponds to flares with the lowest detectable fluxes $\sim 10^{-6}$ erg/cm^2 s. Given the efficiency of the beryllium scatterer, the lowest detectable fluxes from solar hard X-ray bursts are $\sim 2 \times 10^{-7}$ erg/cm^2 s. Thus, one might expect a polarization of ~20% to be measured for typical flares accompanied by hard X-ray bursts at $> 10^{-6}$ erg/cm^2 s.

During the experiment, we performed an express analysis of the time series to select solar flares that were of interest in measuring the polarization of their hard X-ray radiation. Such events were selected by comparison with the GOES patrol measurements of soft X-ray (< 10 keV) radiation and by identifying microwave radio bursts. Examples of the intense solar X-ray events recorded with the SPR-N instrument are illustrated by the time profiles of the count rates in patrol detector channels (see Figs. 2–4). Also shown in these figures are the count rates from the GOES X-ray monitors. The

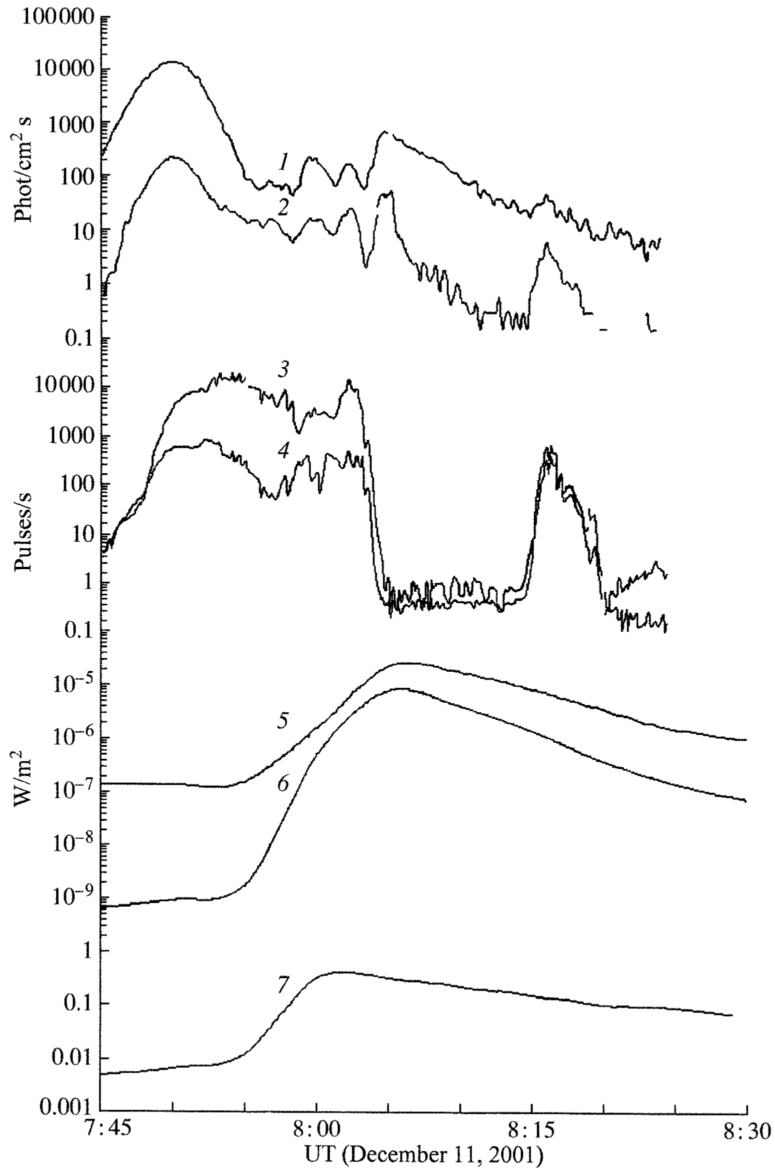

Fig. 4. Time variations in the intensity of the hard X-ray radiation recorded during the hard X-ray flare of December 11, 2001, in channels of the SPR-N patrol detector (*1*—15–40 keV; *2*—40–100 keV) and the GOES-10 X-ray monitor (*5*—1–8 Å; *6*—0.5–4.0 Å; *7*—the spectral hardness parameter defined as the ratio of intensities in the 0.5–4.0 and 1–8 Å channels) and time variations of the count rate in the MKL electron detection channels (*3*—0.5–1.0 MeV; *4*—0.3–0.6 MeV).

physical parameters of X-ray bursts determined from the SPR-N measurements are given in the table.

The duration of the increase given in the table refers to the 15–40 keV channel. The spectral hardness is defined as the index γ in the power-law energy dependence of the spectral flux density: $J = J_0E^{-\gamma}$. The values of γ were determined from the ratio of count rates in two energy ranges of the patrol detector (15–40 and 40–100 keV) at the burst peak. The values of γ determined from the ratio of the total numbers of counts in the burst (i.e., averaged over the burst) are given in parentheses. Given the detector efficiency, the peak fluxes (intensity at the burst peak) and (for a power-law spectrum) fluences were determined for these ranges. Since, as we see from Fig. 3, the flare of November 4, 2001, showed up in hard radiation as three separate increases, the table gives the corresponding quantities determined for each of these increases.

The polarization of the recorded X-ray radiation can be estimated from the maximum, I_{max}, and minimum, Parameters of the hard X-ray solar flares observed in the SPR-N experiment

Date of detection (time of maximum intensity, UT) and coordinates of corresponding flare on solar disk	Duration/ characteristic decay time, s	Spectral hardness	Peak 15–40 keV flux, phot./cm^2 s	Peak 40–100 keV flux, phot./cm^2 s	15–40 keV fluence, erg/cm^2	40–100 keV fluence, erg/cm^2
Sep. 25, 2001, $04^h34^m30^s$ S18W01	~840/325 (15–40 keV) 215 (40–100 keV)	3.7 (4.6)	~90	~4	$\sim 9.5 \times 10^{-4}$	$\sim 4.6 \times 10^{-5}$
Nov. 4, 2001, $16^h06^m30^s$ N06W18	~110	2.8 (3.1)	~40	~4.5	$\sim 1.1 \times 10^{-4}$	$\sim 2.6 \times 10^{-5}$
Nov. 4, 2001, $16^h09^m30^s$	~230	2.5 (3.4)	~55	~8	$\sim 5.5 \times 10^{-4}$	$\sim 9.8 \times 10^{-5}$
Nov. 4, 2001, $16^h12^m50^s$	~105	3.15 (3.4)	~80	~6.5	$\sim 3.5 \times 10^{-4}$	$\sim 5.6 \times 10^{-5}$
Dec. 11, 2001, $08^h05^m20^s$ N16E41	~555/160 (15–40 keV) 110 (40–100 keV)	3.4 (4.2)	~735	~50	$\sim 4.2 \times 10^{-3}$	$\sim 3.75 \times 10^{-4}$

I_{min}, count rates in the polarization detector channels. However, for all of the events under consideration (except the first increase during the flare of November 4, 2001), no statistically significant difference between the output count rates in the polarization detector channels was recorded. It should be noted, however, that when the first increase on November 4 was recorded, the satellite was near the spurs of the outer radiation belt and the MKL (this instrument was also installed on the Coronas-F satellite) electron detectors recorded an intense increase in the electron count rate with energies above 300 keV at this time (see Fig. 3). Therefore, the difference between the count rates of the SPR-N polarization detectors during this increase could result from the additional count rate of the X-ray bremsstrahlung of energetic electrons, because the individual polarization detectors have different detection efficiencies of bremsstrahlung photons. Thus, no statistically significant evidence of the polarization of hard X-ray radiation was obtained for the events under consideration.

DISCUSSION

It should be noted that during the first increase on November 4, the bremsstrahlung of precipitating electrons could also contribute to the count rate of the patrol detector. At the same time, a comparative analysis of the count rates of the SPR-N electron and patrol X-ray detectors in regions of trapped radiation indicates that the first increase on November 4 could not be entirely attributable to the bremsstrahlung of precipitating electrons and, hence, it is also associated with the detection of an hard X-ray burst. The electron flux data obtained for the events of September 25 and December 11, 2001, show that the corresponding fluxes are too low (< 1 part./cm^2 s) to provide the observed increases in X-ray channels; thus, these increases are actually associated with the detection of hard X-ray bursts.

As we see from the data in Figs. 2–4 and in the table, the events of September 25, November 4, and December 11, 2001, have a number of qualitative distinctions. The hard X-ray bursts during the flares of September 25 and December 11, 2001, exhibited a relatively fast rise in intensity and a slower quasi-exponential decay (the characteristic decay times in the 15–40 keV – τ^{15-40} and 40–100 keV –τ^{40-100} channels are given in the table). During the flare of November 4, 2001, three successive hard X-ray bursts with almost equal rise and decay times were observed against the background of a gradual increase in the X-ray flux.

During the flare of September 25, 2001, the intensity maximum of the hard X-ray radiation corresponded to the hardness maximum of the thermal X-ray radiation recorded by GOES detectors. In contrast, the intensity of the thermal X-ray radiation reached its maximum much later than the maximum of the hard radiation. It should be noted that the increase in the intensity of the thermal radiation had a two-step pattern (no adequate information is available on the hard X-ray radiation corresponding to the first step, because, as we see from Fig. 2, the satellite was in the zone of trapped radiation at this time). We can assume that a gradual heating by currents of the reconnection region took place during the flare of September 25, 2001; during this heating, conditions for electron acceleration (by sufficiently strong electric fields) arose when a maximum temperature was reached. The bremsstrahlung of electrons precipitated from the magnetic trap into denser layers of the solar atmosphere was observed in the form of a hard X-ray burst. In this case, the electron precipitation could have the pattern of strong diffusion. This assumption is supported by the fact that, as follows from the table, the ratio of characteristic decays times of the hard radiation in the 15–50 and 40–100 keV channels, $\tau^{15-40}/\tau^{40-100} \sim 1.5$, is almost equal to $\sqrt{E_e^{40-100}/E_e^{15-40}} \sim \sqrt{2}$, where E_e^{40-100} and E_e^{15-40} are the mean energies of the electrons that produced the bremsstrahlung photons recorded in the corresponding SPR-N channels. In the case of strong electron diffusion from the trap, the electron lifetime τ, which determines the characteristic bremsstrahlung decay time, is known to be defined by the relation $\tau \sim 1/v_e \sim 1/\sqrt{E_e}$. As follows from Fig. 2, the subsequent rise in the intensity of the thermal radiation as the flare was developing was not associated with any rise in temperate and, hence, it was caused by an increase in the size of the emitting region. Therefore, we can conclude that the precipitation of accelerated electrons from the trap also resulted in the heating of an increasingly large volume of matter.

As regards the flare of November 4, 2001, the hard X-ray bursts observed during this event differ from those during the flares of September 25 and December 11, 2001, on average, by harder spectra (the values of γ are, on average, larger by ~0.7). In addition, they all occur at the phase of rise in the intensity and temperature of the thermal radiation. Therefore, the hard X-ray bursts during the flare of November 4, 2001, can be assumed to be produced by the bremsstrahlung of the electrons accelerated at the initial flare stage (in this case, several acceleration cycles appear to have taken place, because at least three bursts were observed). The time profile of the count rates in SPR-N X-ray channels suggests that a quasi-monotonic increase in the intensity of the hard X-ray radiation is also traceable between the three separate impulsive increases on November 4, 2001. This increase can be interpreted as the generation of the bremsstrahlung of electrons precipitating from the magnetic trap into acceleration regions after the completion of the impulsive phase. The subsequent reconnection of magnetic field lines gives rise to a post-flare arcade of magnetic loops, which is a magnetic trap. As the flare is developing, the energy release of precipitating electrons causes the matter at the footpoints of the arcade field lines to be heated; its thermal radiation provided a soft X-ray luminosity.

As follows from Fig. 4, the time profile of the SPR-N count rates in the 15–40 and 40–100 keV channels during the flare of December 11, 2001, suggests that several increases in the intensity of the hard radiation could take place during this event. However, the first two increases were observed when the satellite crossed the zone of trapped radiation. Therefore, they cannot be attributed with confidence to the solar flare (in particular, this concerns the second increase, which coincided with the peak flux of magnetospheric electrons of the corresponding energy). The third hard X-ray burst virtually coincided with the intensity maximum of the thermal radiation. The shape of its time profile indicates that a relatively short impulsive component (which is more clearly seen in the energy range 40–100 keV) and a slowly decaying component, whose characteristic time in the 40–100 keV channel, as follows from the table, is almost a factor of 1.5 shorter than that in the 15–40 keV channel, can be distinguished during this increase. In turn, the characteristic decay time of the thermal radiation, as measured from the GOES satellite, 360 s (1–8 Å) and 256 s (0.5–4.0 Å), roughly corresponds to an inversely proportional dependence of this quantity on the mean photon energy in the soft and hard X-ray ranges. The characteristics of the hard radiation considered above suggest that the (possibly multiple) precipitation of energetic electrons from the tarp took place during the flare of December 11, 2001, at the heating phase of the acceleration region. The most powerful precipitation, which produced intense bremsstrahlung in the hard energy range (the impulsive burst component), led to an additional heating of the extensive region whose thermal radiation was so intense that it was also traceable in hard X-ray channels as a slowly decaying component of the X-ray burst. This conclusion is also confirmed by the inversely proportional dependence of the characteristic decay time on the emitted photon energy noted above.

Thus, having analyzed the SPR-N observations of hard X-ray radiation during the three solar flares, we can conclude that the energetic electrons that generated bremsstrahlung appeared in all three events at the growth phase of the thermal radiation. In this case, the electron acceleration was probably associated with the generation of strong electric fields due to the development of induction currents in the reconnection region, which heated the solar atmospheric plasma. However, each event exhibited peculiar features. In particular, the peaks of the hard X-ray bursts occurred both at the temperature (spectral hardness) maximum for the event of September 25, 2001, and at the intensity maximum (the event of December 11, 2001) of the thermal radiation. For the event of November 4, 2001, hard X-ray bursts were observed until the maximum of the hardness and intensity of the thermal radiation was reached. Comparison of the dependences in Figs. 2 and 4 indicates that, although the electron precipitation during the event of December 11, 2001, took place before a maximum temperature reached, its values were, on average, higher than those during the flare of September 25, 2001. However, a high temperature in the flare region is not the only evidence of electron acceleration and precipitation, because the spectral hardness of the thermal radiation during the event of November 4, 2001, was generally lower than that during the other two flares. Nevertheless, the generation of hard radiation and, hence, the electron acceleration took place.

That no statistically significant polarization of the hard X-ray radiation was detected during the flares under consideration can be attributed to the fact that all three flares were disk ones (see the table): the observed hard radiation was associated with the electrons precipitating deep into the solar atmosphere, i.e., the so-called thick target took place, and the radiation scattered in it was detected. A thin target is a more favorable case for the observation of polarization, because an initially polarized radiation will not suffer effective scattering, which can result in distortion of the initial polarization. Such conditions can take place for near-limb flares where some of the electrons can move perpendicular to magnetic field lines because of the broad pitch-angle distribution and the electron motion can be directed toward the observer for a certain orientation of the latter (perpendicular to the solar disk limb). Clearly, in this case, the thickness of the matter layer traversed by electrons projected onto the line of sight will definitely be smaller than the corresponding thickness when they move deep into the solar atmosphere. Therefore, when the statistics of solar flares will be further accumulated in the SPR-N experiment, one might expect a statistically significant polarization of the hard X-ray radiation to be measured at least for near-limb events.

CONCLUSION

Apart from the events considered above (September 25, 2001; November 4, 2001; and December 11, 2001), X-ray radiation was detected from more than ten solar flares, including relatively weak (M3.5) ones, during the SPR-N experiment in 2001–2002. For the most powerful events, we determined the spectral and temporal parameters and estimated the polarization. Comparison with the GOES observations of thermal X-ray radiation indicates that hard X-ray bursts occur at the growth phase of the thermal radiation and that they are associated with the bremsstrahlung of energetic electrons precipitating into the solar atmosphere.

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