CORONAS-F OBSERVATIONS OF ACTIVE PHENOMENA ON THE SUN

V.N.Oraevsky[1] , I.I.Sobelman[2], I.A.Zitnik[2], V.D.Kuznetsov[1], A.I.Stepanov[1],G.M.Polishuk[3], P.N.Kovilin[3], A.A.Negoda[4], V.I.Dranovsky[5], Ya.S.Yatskiv[6]

[1] *Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation, Russian Academy of Sciences, 142190, Moscow Region, Troitsk, IZMIRAN, Russia*
[2]*Lebedev Physical Institute, 119991, Moscow, Leninsky prospekt 53, Russia*
[3]*Russian Aviation and Space Agency, 107996, Moscow, Shepkina str.,42, Russia*
[4]*Design Office "Yuzhnoye", 49008, Dnepropetrovsk , Krivorozhskaya str., 3, Ukraine*
[5]*National Space Agency of Ukraine,03022 Bozhenko str., 11, Kyiv,Ukraine*
[6]*Main Astronomical Observatory of the National Academy of Sciences of Ukraine, 27 Akademika Zabolotnoho St.,03680 Kyiv, Ukraine*

ABSTRACT

Complex observations in the framework of the CORONAS-F Mission aimed at the study of active phenomena in the solar corona are described. The main features are given for the following experiments: (1) XUV-imaging spectroscopy with high temporal and spatial resolution, (2) X-ray spectroscopy, (3) X-ray and gamma-ray photometer/spectrometer, and (4) solar cosmic rays. Some new observational data on the structure and dynamics of flares and transient events are discussed along with their analysis.

CORONAS Program and CORONAS-F Mission

The international CORONAS Program (Complex Orbital near-Earth Observations of Solar Activity), which incorporates the Orbital Solar Observatory CORONAS-F, is aimed at investigating the Sun in different phases of the 11-year cycle. The previous mission CORONAS-I (launched in 1994) observed the Sun near the epoch of minimum activity. CORONAS-F will provide observations of solar activity in the vicinity of the maximum of the current cycle 23. On July 31, 2001, the satellite was launched into orbit with the following parameters: inclination 82,49°, minimum distance to the Earth 500,9 km, maximum distance to the Earth 548,5 km, and period 94,859 min. Such an orbit ensures repeated 20-day periods of continuous observations of the Sun, which are particularly important for helioseismologic studies and monitoring of solar flares. The effective stabilization of the spacecraft orientation is about 5 arc.sec per second. It will significantly improve the spatial resolution of solar observations.

Scientific Objectives of the CORONAS-F Mission

The main scientific objectives of the mission are as follows: observation of global oscillations of the Sun, seismologic and interior studies; a complex study of powerful dynamic phenomena of solar activity, such as active regions, flares, and mass ejections in a broad wavelength range from optical to gamma-radiation; acceleration of cosmic rays in active solar events, their outflow, propagation in interplanetary magnetic field, and impact on the Earth's magnetosphere.

SCIENTIFIC PAYLOAD AND OBSERVATIONAL RESULTS

Scientific Payload

The scientific payload of the mission comprises four main groups of instruments: Helioseismology - Spectrophotometer DIFOS (PI – V.N.Oraevsky); Monochromatic Imaging with a High Angular Resolution - Solar X-Ray Telescope SRT-K (PIs - I.I.Sobelman and I.A.Zitnik), X-Ray Spectroheliograph RES-K (PIs - I.I.Sobelman and I.A.Zitnik), Spectrophotometer DIOGENESS (PI – J.Sylwester); Electromagnetic Fluxes and Polarization Measurements (from UV to γ-) - X-Ray Spectrometer RESIK (PI – J.Sylwester), Solar Spectropolarimeter SPR-N (PIs – I.I.Sobelman, I.P.Tindo, and S.I.Svertilov), Flare Spectrometer IRIS (PI – G.E.Kocharov), Gamma Spectrometer HELIKON (PI – E.P.Mazets), X-Ray Spectrometer RPS (PIs - V.M.Pankov and Yu.D.Kotov), Amplitude-Time Spectrometer AVS (PI – Yu.D.Kotov), Solar UV Radiometer SUFR-Sp-K (PI – T.V.Kazachevskaya), Solar UV Spectrophotometer VUSS-L (PI – A.A.Nusinov); Study of Solar Corpuscular Fluxes - SCR Complex (PI – S.N.Kuznetsov) (Gamma-Ray and Neutron Spectrometer SONG, Cosmic Ray Monitor MKL, and X-Ray Spectrometer SKI-3). Measurements of electromagnetic emissions in a broad wavelength range and of solar particles, including neutral (neutrons) and charged ones (electrons, protons, and nuclei) provide a full pattern of the physical processes in solar active regions.

Spectrophotometer DIFOS

The Spectrophotometer DIFOS is used to measure intensity fluctuations of the solar white-light emission and to provide the inherent oscillation spectrum. The intensities are measured simultaneously in six optical spectral ranges (350, 500, 650, 850, 1100, and 1500 nm) with a bandwidth of 10% of the central frequency. The results of the DIFOS experiment are submitted to *"Adv. Space Res."* for publication.

The SPIRIT experiment, Full Sun imaging XUV spectroscopy

The scientific goals of the experiment are the following: investigation of the active-Sun dynamics from high resolution X and XUV spectral images in the 1,85-304 Å band; study of dynamics of non-stationary solar events (flares, jets, Coronal Mass Ejections, etc.) over a time scale from ~1 sec to months; diagnostics of the fine structure of solar plasma in flares, active regions, and coronal holes with T = 0,05-50 MK; and study of distribution of the Fe- and He-ions over the solar disk and corona up to 5 solar radii.

The SPIRIT instrument includes the SRT-C telescope and RES-C Spectroheliograph assemblies. The former comprises a Ritchey-Chretien telescope for 171, 195, 284, and 304 Å bands with multilayer optics similar to the SOHO EIT telescope, FOV of 42', and angular scale of 2,4"/pix and a Herschel telescope-coronagraph for 175, 304 Å bands with off-axis paraboloids with Mo-Si coating, FOW 45', and angular scale of 2,6"/pix. In the coronagraphic mode, the device has the instant FOV of 45" at 2-5 R and two optical sensors to control pointing to the Sun by stars. The RES-C Spectroheliograph assembly comprises a FeXXV full Sun bragg crystal spectroheliograph with λ=1,85–1,87 Å, angular scale of 1'/pix, and spectral resolution of $1{,}5.10^{-4}$ Å; two MgXII full Sun bragg crystal spectroheliographs with λ = 8,418-8,423 Å, orthogonal dispersion planes, FOV of $1{,}3^0$, angular scale of 4,1"/pix, and spectral resolution of 3.10^{-3} Å; and two XUV diffraction grating slitless spectroheliographs, each giving full Sun spectral images in two selectable spectral bands of 177-207 Å and 285 – 335 Å, angular scale of 6"x1'/pix, and spectral resolution of 3.10^{-2} Å /pix.

The main characteristics of the measuring channels are given in Table 1.

Table 1. Spectral bands of the SPIRIT instrument and excitation temperatures of ions in solar plasma

Spectral band	Basic ions	T, 10^6 K
1.85 - 1.87 Å	FeXXIV – FeXXV	20 – 50
8.418 - 8.423 Å	MgXII	10
177 – 207 Å	OIV, FeIX-XXIV, CaXIV-CaXVII	0.3 – 16
285 – 335 Å	HeII, SiXI, FeXV-FeXVI, MgVIII, NiXVII, CaXVII	0.05 – 5
171±3 Å	FeIX – FeX	1.3
175±5 Å	FeX – FeXI	1.3
195±6 Å	FeXII	1.6
284±8 Å	FeXV	2
304±8 Å	HeII, SiXI	0.05, 1.6

The first results of the SPIRIT experiment can be summarized as follows. During the first year of flight, the CORONAS-F SPIRIT instrument provided more than 130 thousand solar XUV images and spectra in 10 spectral channels. Monochromatic full Sun images in MgXII resonance line 8.42 Å were obtained for the first time. High-temperature structures (3-20 MK, 1MK = 10^6 K) associated with active regions were first observed on the solar disk and above the limb (up to 0,3 R). For the first time, full-Sun images in the spectral bands of 8.42 Å (MgXII), 175 Å (FeIX-XI), and 304 Å (HeII) were recorded simultaneously, which is important to study the spatial structure and dynamics of the solar corona. The time series of solar XUV images in several bands of the 8,42–304 Å spectral range were recorded by the SPIRIT telescopes and spectroheliographs over the time scales from seconds to months. Full Sun spectral images in more than 200 monochromatic lines of various ions with the excitation temperatures from 0.05 to 16 MK were observed by the SPIRIT XUV spectroheliographs in the XUV spectral bands of 177-207 Å and 285-335 Å. These spectra enable the temperature and density diagnostics of different solar structures from flares to coronal holes.

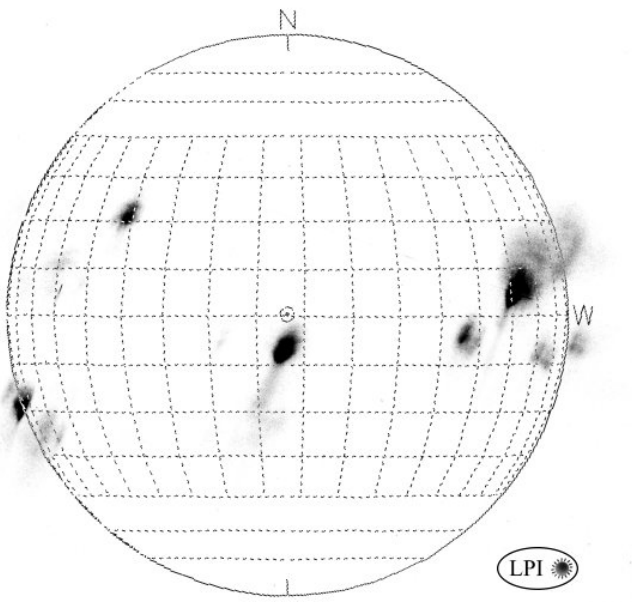

Fig. 1. The distribution of plasma with T~10 MK (MgXII line) over the solar disk (SPIRIT telescope/ specroheliometer on Dec., 04, 2001, at 04:07 UT).

Figure 1 shows the distribution of plasma with T~10 MK (MgXII line) over the solar disk. The image was obtained with SPIRIT telescope/specroheliometer on Dec. 04, 2001, at 04:07 UT.

The colour images of the Sun and spectroheliograms obtained within the frames of the SPIRIT experiment are available on the web-sites http://www.xras.lebedev.ru/ and http://coronas.izmiran.rssi.ru

Spectrophotometer DIOGENESS and X-Ray Spectrometer RESIK

The DIOGENESS and RESIK instruments measure the solar radiation spectra in the wavelength range of 3-7 Å and are intended for the study of X-ray emission from active regions and flares with a high spectral resolution. The X-ray spectra obtained are comparable by their spectral and time resolution with the world's best-known measurements. Owing to the polar orbit of CORONAS-F and the full coverage of a broad spectral range, these spectra are complementary of those obtained on Yohkoh.

Figure 2 illustrates the spectra in CaXIX measured with high spatial resolution (~5″) in the growth, intermediate, and decay phases of the most intensive flare in the current solar cycle (August 25, 2001). The temperature of the emitting plasma decreases from 25 MK in the growth phase to 12 MK in the decay phase. One can readily see the changing widths of the spectral lines, which indicate the role of plasma turbulence in the flare evolution. It is the first time that the spectra with so high spatial resolution have been obtained in the given spectral range (3-7 Å) for an X-class flare. DIOGENESS has provided about 2600 solar spectra, including the spectra of several major flares. The spectra obtained reveal a lot of the emission lines formed as a result of collisional excitation of atoms, excitation of the atomic inner shells, and dielectron recombination. These spectra allow a detailed diagnostics of the flare-generated plasma. The relative line emission intensities bear information on the energy balance in solar flares and provide a deeper insight into the role of non-Maxwellian and non-equilibrium processes in the plasma volumes close to the primary energy deposition sites. Temperature variations in the flare-generated plasma have been analyzed, and the effects associated with electron transitions in the Ar XVIII (Lyb) and Si XIV ions have been revealed for the first time.

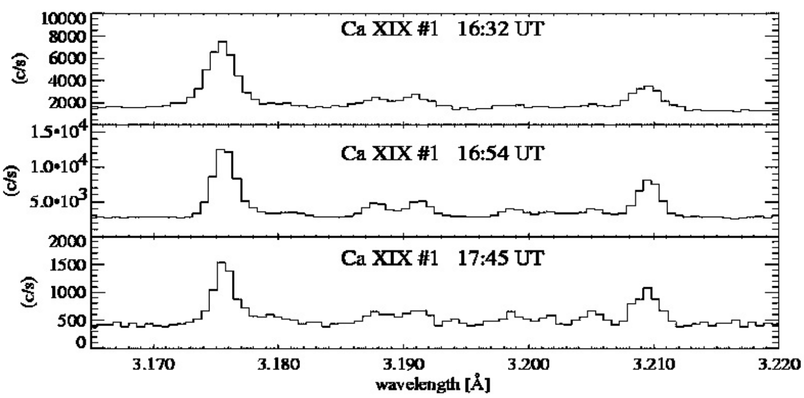

Fig. 2. CaXIX spectra obtained with a high spatial resolution (~5″) in the growth, intermediate, and decay phases of the current cycle most powerful flare (August 25, 2001, DIOGENESS Spectrophotometer data).

Figure 3 illustrates spectra in the four RESIK channels obtained near the peak of the X1.5 class flare on April 21, 2002. The four wavelength ranges of spectral bands #1, #2, #3 and #4

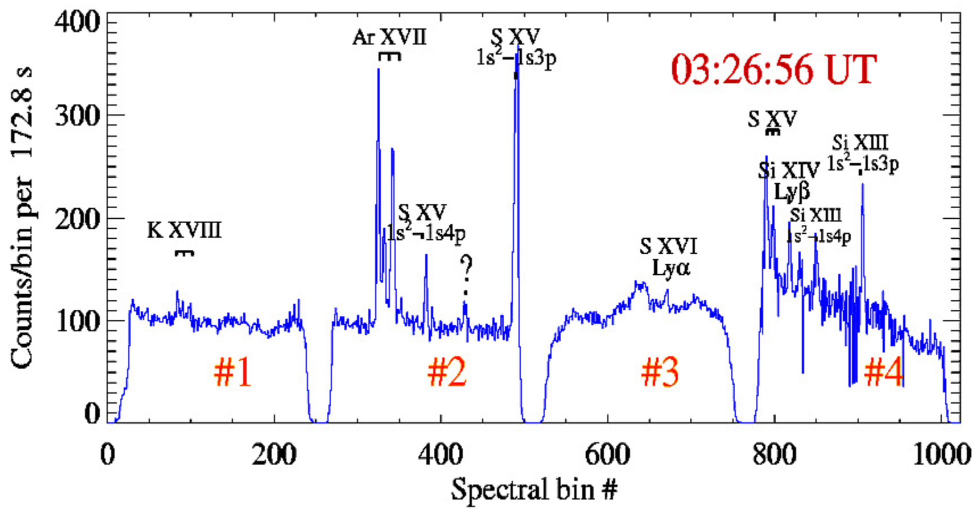

Fig. 3. Spectra in the four RESIK channels obtained near the peak of the X1.5 class flare on April 21, 2002.

correspond to 3.37 Å - 3.88 Å, 3.82 Å– 4.33 Å, 4.31 Å – 4.89 Å, and 4.96 Å– 6.09 Å, respectively. The RESIK spectrometer has provided about a million solar X-ray spectra in the wavelength range of 3.2-6.1 Å, which so far has been poorly investigated. Several spectral lines not observed earlier have been revealed. Time variations of the physical parameters of hot solar plasma have been observed, and the plasma emission measure of solar flares has been studied. The X-ray spectra recorded with the RESIK spectrometer are available on the web sites http://www.cbk.pan.wroc.pl/2002.htm and http://surfwww.mssl.ucl.ac.uk/surf/data_request.html.

Flare Spectrometer IRIS

The instrument is designed for the study of X-ray flare activity in the Sun in the spectral range of 2-200 keV. In the patrol operation mode, it has 12 energy channels ensuring the time resolution of 2.5 s. In the burst-registration mode, there are 64 energy channels ensuring 1 s time resolution and 4 channels ensuring 10 ms resolution. Spectral measurements with such a high time resolution have never been obtained before in the solar X-ray studies. Observations of the temporal fine structure of hard X-ray fluxes provide direct information on the evolution of energy release processes in the flare explosive phase and allow a deeper insight in their physical mechanisms.

Figure 4 shows the structure of the time profile for hard X-rays of the December 19, 2001 solar flare with impulsive energy release in different energy channels. In the burst of 90-s total duration, one can see five peaks of 1-3 s following one another at about 20-s intervals. Therefore, the recorded hard X-ray profile is, probably, due to generation of individual overlapping pulses with a relatively small modulation depth.

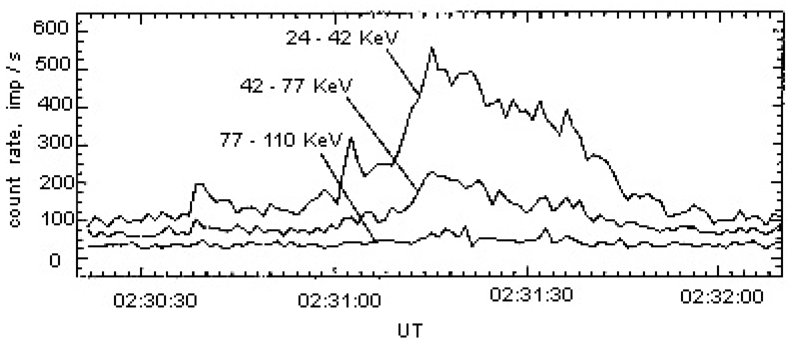

Fig. 4. Time profile for hard X rays of the December 19, 2001 solar flare with impulsive energy release in different energy channels (Flare Spectrometer IRIS).

As shown by the spectral analysis of the X-ray time profile of the solar flare of December 19, 2001, carried out by Kocharov et al. (2002) and Dmitriev et al. (2002), intensive oscillations with a period of 36 s and a few weaker components with periods of 4, 13, 23, and 26 s can be identified in the soft X-ray range (3.6-5.0 keV) in the pre-flare phase. For detailed study of the time structure, the data series from the 3,6 – 5,0 keV and 24 – 42 keV energy channels have been treated using the methods of the spectral analysis that take into account the specific character of the series itself (Jenkins and Watts, 1969). In the course of the flare (onset and further evolution), the spectral structure of the emission changes: oscillations with a period of 18 s become most intensive, new components with 6- and 8-second periods appear, oscillations with a period of 4 s continue, and all other oscillations vanish. In the hard X-ray range (24-42 keV), oscillations with a period of 31 s are most intensive in the pre-flare phase. One can also identify oscillations with the periods 5, 15, 22, and 37 seconds. All these oscillations coincide with those recorded in soft X-rays to an accuracy of the recording discreteness equal to 1 second. As in the case of soft X-ray emission, intensive oscillations with a 17-s period and a weaker component with a period of 4 s can be revealed in the course of the flare. In the post-flare phase, one can see powerful oscillations with periods of 6 and 15 s, the latter being most intensive, and also oscillations with periods of 11, 20, 45, and 54 s.

Thus, the spectral analysis of data from the flare spectrometer IRIS shows that the flare energy release is a periodic process with a period of 18 s. The periodicity was revealed both in the soft and hard X-ray range, but was not observed in the pre-flare phase. This is an evidence of the impulsive nature of electron acceleration in flares and a significant contribution of the non-thermal component to the soft X-ray intensity.

Analysis of the general pattern of formation and evolution of oscillations at different stages of the flare evolution allows their interpretation as a system of related oscillators, which can insignificantly change the oscillation frequency and (above all) amplitude. This means that the pumping of energy from some structures to the others takes place during the flare evolution and continues in the post-flare period.

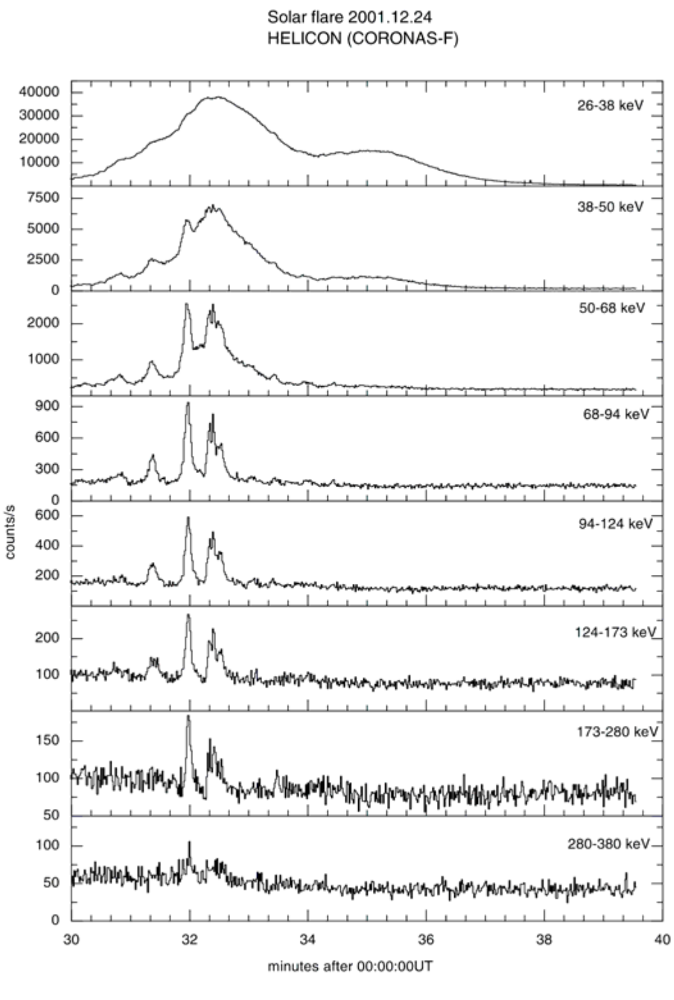

Fig. 5. Emission time profile for the major flare of December 24, 2001 (T_0=0 h 31 m 41.895 s UT) as recorded in the explosive phase in eight energy channels (HELIKON Gamma Spectrometer data).

Gamma Spectrometer HELIKON

The instrument measures the temporal and spectral parameters of the flare-generated hard electromagnetic emission in a broad energy range from X-rays to gamma radiation (10 keV – 10 MeV). It enables monitoring of the radiation conditions in the near-Earth space environment and soft solar flares, detection and recording of hard ($E\gamma >$ 50 keV) flares and gamma bursts. Several hundred solar flares and some tens gamma bursts were recorded during the interval from August 15, 2001. Most of the flares had soft spectra and were recorded in the background operation mode with 1 s time resolution in eight adjacent energy ranges from 26 to 380 keV. One of the major solar flares was recorded in the explosive phase on December 24, 2001 at T_0=0 h 31 m 41.895 s UT. Figure 5 demonstrates the dynamics of that flare in eight energy channels and the sequence of the energy spectra obtained in different phases of the event.

Solar Cosmic Ray Complex

The complex of instruments for SCR studies comprises a Gamma Ray and Neutron Spectrometer SONG, Cosmic Ray Monitor MKL, and X-Ray Spectrometer SKI-3. The complex is intended for combined investigations of solar cosmic rays and their manifestations in the Earth's space environment. The SONG device provides records of X- and gamma-ray spectra in the range of 0.03-100 MeV, detailed spectra of gamma lines in the range of 0.3-20 MeV, >20 MeV neutrons, and charged SCR particles - >70 MeV protons and >50 MeV electrons. The MKL device is used to measure the fluxes and spectra of the 1-200 MeV protons and 0.5-12 MeV electrons. The CKI-3 device determines the chemical composition and ion spectra within Z=1-10 for He in the energy range of 1.5-20 MeV/nucleon and Ne in the energy range of 4-40 MeV/nucleon. As distinct from the SOHO and Yohkoh instruments, the SONG spectrometer is able to measure high-energy (up to 100 MeV) gamma quanta, including those, which result from the decay of π-0 mesons produced in high-energy proton interactions. As shown by the CORONAS-F onboard measurements of solar neutrons, the SONG spectrometer has a background at least 5-7 times as low as the SMM GRS device - the only one recording solar neutrons in the same energy range.

The SONG instrument recorded dozens of solar flares. In most cases, it measured the bremsstrahlung gamma-quanta with energies <150 keV, however some records are also available of the >7 MeV bremsstrahlung gamma-quanta. The events associated with the flare observed on November 4, 2001 at 16^h16^m have been analyzed in detail. As follows from the GOES data, the phase of plasma heating in the flare lasted about 10 min. During that period, SONG recorded three bursts of gamma-quanta with the energy <500 keV. In the intervals between the bursts, the bremsstrahlung background increased monotonically, while the charged particle background along the satellite trajectory did not change. It was, probably, due to precipitation of trapped electrons over the flare region. The high-energy particle flux recorded after the flare was, obviously, generated at the CME shock front (velocity of about 1800 km/s near the Sun) in the corona or interplanetary space. This conclusion is inferred from the 30-50 min delay of the first 10-500 MeV protons detected at the Earth's orbit and the characteristics of the particle flux before the arrival of the shock wave. Acceleration at the CME shock front was also the main source of high-energy particles after the flares of September 24 and November 22, 2001. The flares of November 4 and 22, 2001 were followed by strong magnetic storms due to the arrival CME to the Earth. During magnetic storms, the boundary of trapped particles in the Earth's magnetosphere moved up to L~3.5-4 and the outer radiation belt virtually vanished. After the storm, it was restored, the electron fluxes with E~0.3-0.6 and 0.6-1.5 MeV increasing by half an order compared to the pre-storm values. The flux of high-energy electrons was increasing several days. The cosmic-ray electron flux could be used to monitor the polar caps. Under quiet geomagnetic conditions, the polar cap boundary was observed at geomagnetic latitudes $\Lambda \cong 75 - 78°$ during 06:00-11:00 MLT and at $\Lambda \cong 68°$ during 15:00-22:00 MLT. Under disturbed conditions, it became quasi-circular and moved to $\Lambda \cong 58°$. This analysis allows us to verify the existing magnetospheric models and to develop new dynamic models.

Table 2 gives the content of various elements (nuclei with energies of 11.4–23 MeV/nucleon) in percent of the oxygen content for four time intervals during the flare of November 4-7, 2001 (CKI-3 device). Time variations of the ions from C to Si are similar to those obtained for protons and electrons. The ion composition remained practically unchanged during the burst of high-energy particles.

Table 2. The content of various elements during the flare of November 4-7, 2001.

Time	C	N	O	Ne	Mg	Si
22 h 04 Nov – 15 h 05 Nov	39.0 ± 3.9	11.9 ± 1.7	100	14.4 ± 2.3	17.9 ± 2.4	17.4 ± 2.2
22 h 05 Nov – 07 h 06 Nov	45.5 ± 3.4	10.4 ± 1.3	100	12.0 ± 1.4	20.6 ± 2.0	16.8 ± 1.8
07 h 06 Nov – 19 h 06 Nov	42.4 ± 6.5	11.2 ± 2.7	100	12.4 ± 2.7	16.8 ± 3.4	10.4 ± 2.6
19 h 06 Nov – 20 h 07 Nov	54.7 ± 12.6	8.5 ± 2.0	100	12.2 ± 4.6	21.6 ± 6.7	18.9 ± 6.0

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E-mail address of V.D. Kuznetsov: kvd@izmiran.rssi.ru
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