From the geophysical to heliophysical year: The results of the CORONAS-F project

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Received 20 October 2007; accepted 15 November 2007; published 27 December 2007.

[1] The main and most significant results of the CORONAS-F space project are presented. In the scope of this project observations of solar activity and its impact on the Earth were carried out from July 2001 to December 2005. The remote observation devices studied the localization and morphology of solar activity in the second half of the 23rd solar cycle. High-temperature plasma formations are found and studied in the solar corona, eruptive phenomena, processes of particle acceleration, and atomic and nuclear processes in solar flares are investigated. The devices of the "Solar Cosmic Ray" complex studied manifestations of solar activity in the near-Earth environment, dynamics of the radiation belts of the Earth, and rebuilding of the magnetosphere structure in the periods of magnetic storms caused by active events on the Sun. Results related to the upper atmosphere of the Earth and helioseismology are also presented. *INDEX TERMS:* 2162 Interplanetary Physics: Solar cycle variations; 2164 Interplanetary Physics: Solar wind plasma; 2194 Interplanetary Physics: Instruments and techniques; *KEYWORDS:* heliophysical year, CORONAS-F project, near-Earth environment, helioseismology.

Citation: Kuznetsov, V. D. (2007), From the geophysical to heliophysical year: The results of the CORONAS-F project, *Russ. J. Earth. Sci., 9,* ES3004, doi:10.2205/2007ES000276.

1. Introduction

[2] During 50 years of the space era, the Russian space science passed in studies of solar activity and its influence on the Earth a way from the first artificial satellite to the CORONAS-F satellite, a multifunctional solar space laboratory. The space researches were the very activity that provided the most important input in the knowledge and ideas on solar activity and solar-terrestrial relations what we currently have. Currently it is impossible to consider the very concept of geophysics without a relation to heliophysics, the science studying the Sun and heliosphere filled by the solar wind. The fact that 2007 was claimed as Heliophysical Year once more emphasizes not only the importance of researches in this region for the Humanity, but the broadening of the frames and deepening of our knowledge from geophysics to heliophysics during the passed years of studies. Actually, a lot of new information was obtained concerning space, Sun, and its impact on the Earth and various spheres of human activity both, on the Earth and in space. The state of our knowledge reached the level when we are able to predict with a significant probability solar activity and its influence on the Earth and characterize all this by the term space weather which more and more enters our everyday life.

[3] The CORONAS-F is the second satellite of the CORONAS Program (Complex Orbital Near-Earth Observations) which has been developed by the Physical Science Division of the Russian Academy of Sciences and is realized in the frame of the Federal Space Program. During the period of observations from July 2001 to December 2005, broad-scale durable continuous observations of solar activity and registration of its manifestations in the near-Earth environment were performed. The scientific payload of the satellite including 15 scientific devices registered electromagnetic and corpuscular radiation of the Sun within a wide spectral range (from optical to gamma emission) and within the energy range from a few keV to hundreds of MeV. The initial altitude and the inclination of the satellite orbit were approximately 500 km and 86°, respectively. The observational period fell on the phases of the maximum and decay of the 23rd cycle of solar activity, when a whole series of extreme events (powerful flares and ejections what provided obtaining the most detailed information on these events and study their manifestations in the near-Earth environment: in the dynamics of the Earth's radiation belts and structural rebuilding of the magnetosphere) occurred on the Sun.

ISSN: 1681–1208 (online)

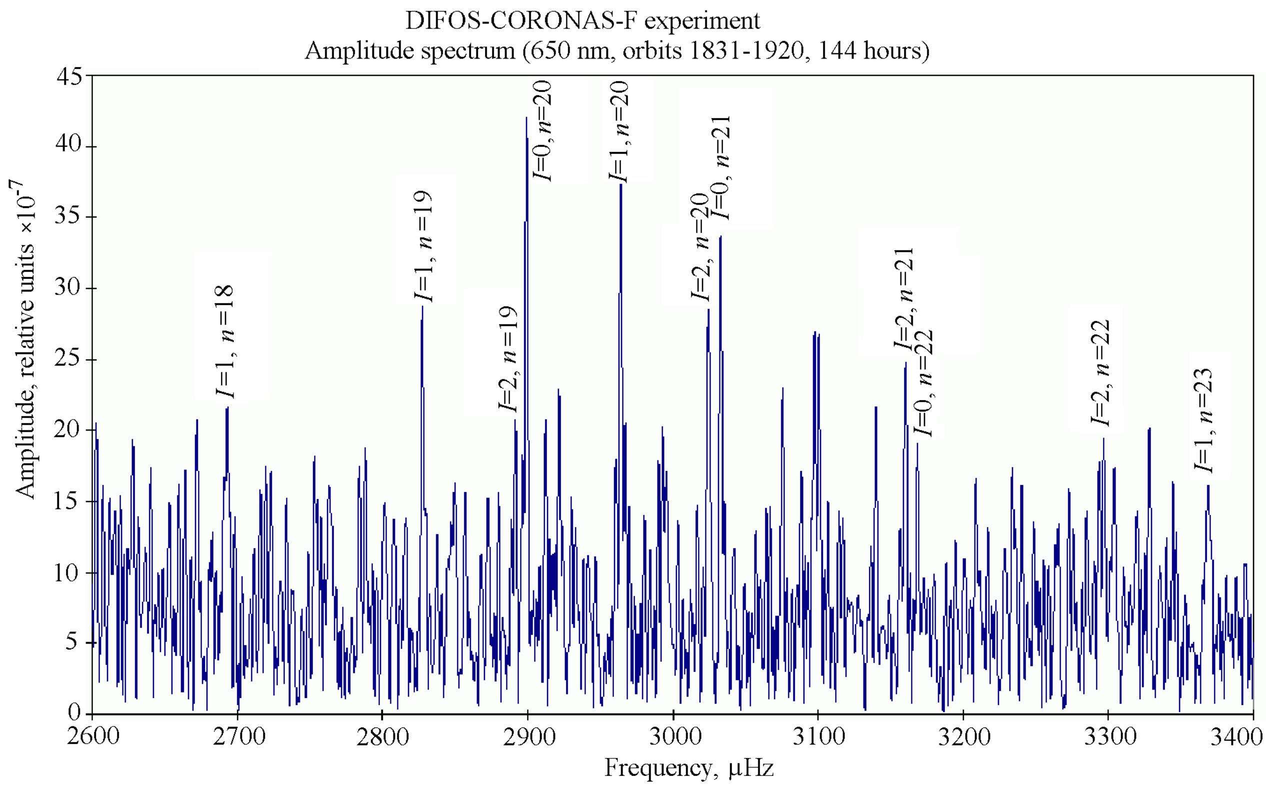

Figure 1. The power spectrum of the global oscillations of the Sun. The DIFOS experiment.

2. Observations of the Sun and Its Activity

2.1. Global Oscillations of the Sun

[4] Global oscillations of the Sun registered by methods of the helioseismology make it possible to diagnose the inner solar layers. The DIFOS device on board the CORONAS-F satellite registered low (l = 0, 1, and 2) eigenmodes of the global oscillations of the Sun (oscillations of an acoustic type called p-modes and having a period of about 5 min) within the broad wavelength range (350–1500 nm). Very small changes (10^{-5}–10^{-6}) of the total solar radiation flux related to these oscillations (*Lebedev et al.* [2004]) were measured. Establishing of principal possibility of helioseismological studies in observations at near-Earth satellites (when the light reflected from the Earth's surface reduces the measurement accuracy) was an important result of these observations. In the power spectrum (Figure 1), the peaks corresponding to harmonic global oscillations (p-modes) with a particular period and the values of l and n numbers (the number of oscillation meshes in azimuth and solar radius, respectively) are distinctly pronounced. From 10 to 15 separate harmonics which in the coarse of time were changing and substituted by other harmonics were registered simultaneously, the latter fact manifesting the dynamics of the inner layers of the Sun caused by the interaction of the outer convective shell having a broad noise spectrum to eigen oscillations of the Sun.

2.2. X-ray Solar Images

[5] The entire complex of unique studies was carried out [*Zhitnik et al.,* 2005] using the multi-channel X-ray telescope. Numerous images of the Sun with high spatial resolution in various spectral lines corresponding to different temperature layers of the solar atmosphere made it possible to localize and study the morphology of various active phenomena.

[6] Solar activity level unusually high for a few recent decades was observed on the Sun in the period of October–November 2003. The whole series of flares was prominent by

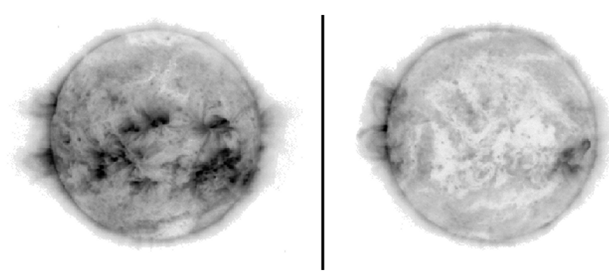

Figure 2. The state of two solar hemispheres in the period of October–November 2003, when the most powerful events of a few recent decades occurred on the Sun. The longitudinal (hemispheric) asymmetry of the location of active regions over the solar surface is seen. The solar X-ray telescope of the SPIRIT experiment.

their power. The flares were accompanied by powerful ejections with velocities up to a few hundreds of km s^{-1}. The sun was covered by active regions, numerous magnetic loops, and strongly heated regions. The global longitudinal (almost hemispherical) asymmetry of the location of active regions on the solar surface was the case of the very powerful flares and ejections. The images of the Sun (see Figure 2) obtained with the interval of a half of solar rotation show that there is almost no active regions on one hemisphere, whereas on the other hemisphere there are more than 30 such regions. Strong gradients of the magnetic field were the very factor what provided such powerful flares what caused strong magnetic storms on the Earth and enhanced cosmic ray fluxes in space.

[7] The morphology and dynamics of development of these flares, ejections, and related to them dimmings (darkening) (see Figure 3) were studied in these events on the basis of the X-ray observations [*Chertok et al.,* 2005; *Slemzin et al.,* 2005]. As a results, it is found that the observed dimmings were mainly formed as a result of a complete or partial opening of magnetic fields in the process of coronal mass ejections and (related to this process) flowing of the matter out of the large-scale magnetic structures of the intermediate layer and corona and corresponding lowering of the emission measure. It is found also that the global character of the dimmings in these and other events means that a considerable part of the solar atmosphere mass was involved into the process of eruption of coronal mass ejection. A repeatability of eruptive events and the dimming picture was observed from one event to another, and each time the coronal ejections eruption involved approximately the same structures which succeeded in recovering their magnetic field and luminosity during the time interval between the events.

[8] On the basis of observations by the spectroheliograph RES-K (the SPIRIT experiment) in the resonance MgXII (8.42 Å) line in the solar corona, a complete class of new events (rapid-dynamic plasma formations with the temperatures up to 20 millions of degrees [*Grechnev et al.,* 2006; *Zhitnik et al.,* 2003]) was discovered. Images and dynamics of these high-temperature formations are studied for the first time. They are formed, apparently, when the hot plasma formed during solar flares fill in the magnetic configuration in the corona, and the emission of this hot plasma contours it. As a result the formations have a variable form (see Figure 4) in a shape of “hot clouds”, “spiders”, loops, propagating wave fronts, and igniting in sequence magnetic arches. The hot plasma formations registered in the corona present a manifestation of one of the heating mechanisms of the solar corona as a result of energy release in magnetic configurations and its transformation into the plasma energy. It is found that the mass ejections from the solar atmosphere often observed by the coronagraph on board the SOHO European satellite are often related to the found hot plasma formations in the corona.

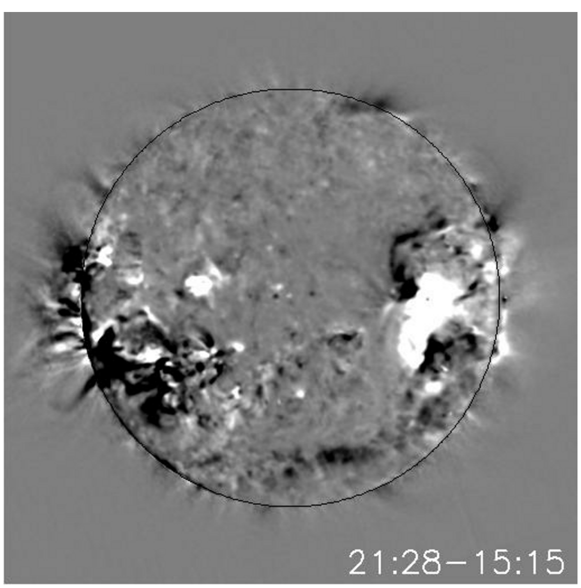

Figure 3. Powerful flares and ejections on the Sun on 26 October 2003. The SPRINT experiment, the wavelength was 175 Å.

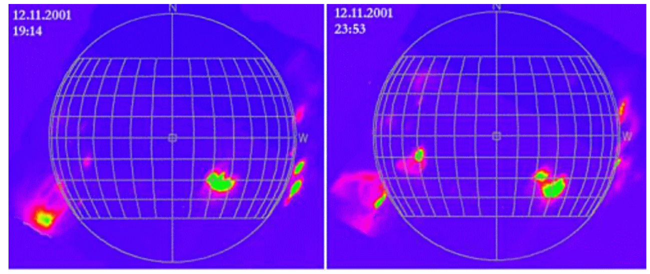

Figure 4. Images of hot (up to 20 millions of degrees) plasma formations in the solar corona observed in the MgXII (8.42 Å) line. The SPIRIT experiment.

[9] Observations by the X-ray telescope operating in the coronagraph regime made it possible for the first time to obtain data on the solar corona dynamics at distances up to three solar radii. This region is important for understanding of the nature of many phenomena, but is not observed by other devices, because it is an intermediate region between the near-limb region observed by telescopes and the far corona observed in the white light by coronagraphs. It this region of the corona, loops and magnetic field arches, aligned streamers, and jets of the elapsing solar wind are distinctly seen, whereas mass ejections and eruptive filaments at these altitudes were observed for the first time. The X-ray coronagraph obtained also for the first time maps of the distribution of the hard X-ray radiation for quiet and disturbed corona in the presence at the limb of bright active regions which illustrate visually the magnetic heating of the corona over active regions.

[10] The magnetic heating of the corona was confirmed also by the spectra of the solar X-ray radiation obtained by the X-ray spectrometer RPS-1 for various numbers of sunspots: the more sunspots, the more hard spectrum of the X-ray radiation was registered (see Figure 5) and, respectively, the stronger was the impact on the Earth’s atmosphere.

[11] In the period 6–17 September 2005, a series of ex-

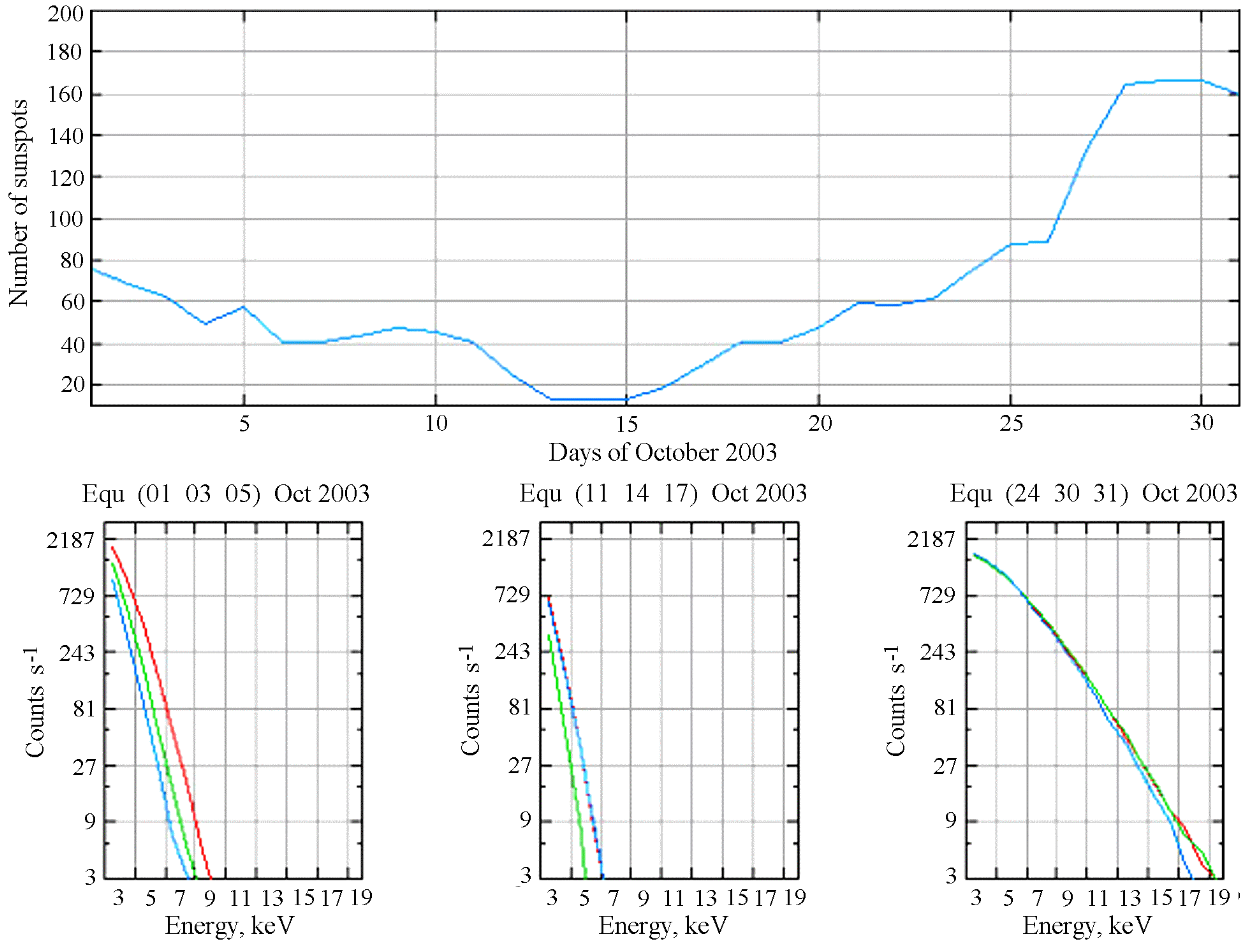

Figure 5. The dependence of the background (without flares) X-ray radiation spectra of active regions on the sunspot number illustrating the magnetic heating of the solar atmosphere in October 2003, correspondingly at the beginning (1, 3, and 5 October), in the middle (11, 14, and 17 October), and at the end (24, 30, and 31 October). The X-ray spectrometer RPS-1.

treme events occurred on the Sun related to the passage over the disk of the AR10808 active region. The series included 10 X-ray flares of the X class and 27 flares of the M class accompanied by powerful ejections of the coronal substance and strong geomagnetic storms. During that period, the SPIRIT/CORONAS-F equipment registered 13 flares. The analysis of the images in the coronal lines in the 175 Å range with the temperature of 1.2 MK showed that during all flare events there occurred a strong restructurization of the magnetic field in the region of the flare (see Figure 6). The AR10808 active region had an area of >1400 m. p. of the visible hemisphere and numerous delta-structures. Åseries of flares within this active region caused on the Earth an increased magnetic activity during a durable time interval. The magnetic storm started on 10 September 2005 passed its maximum on 11 September 2005. Magnetic storms and considerable disturbances were observed 6 days in a row (10–15 September 2005) and 8 days in a row (9–16 September 2005), respectively. On the night from 10 to 11 September 2005, a Forbush effect with a value of 13% for the 10 GeV energy was registered. It was one of the largest (the forth by its magnitude) Forbush effect in the current solar cycle. Later, after 19 September 2005, the AR10808 group

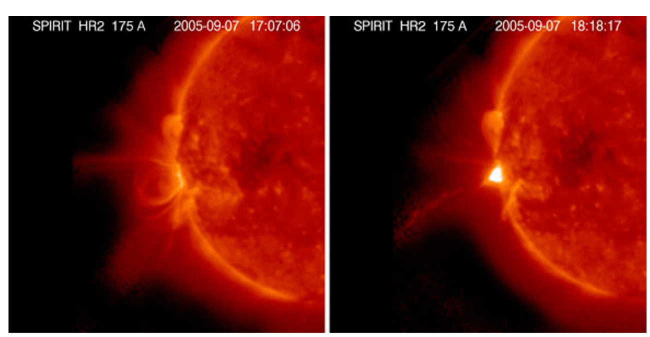

Figure 6. Rebuilding of the magnetic field structure in the solar corona during the strong limb flare of X17 importance on 7 September 2005. (left-hand and right-hand images show the pre-flare state and the flare maximum phase, respectively). The SPIRIT experiment.

decreased considerably and was simplified, but still had a delta-configuration.

2.3. Solar Flares

[12] During the period of the observations by the CORONAS-F devices with high time and spectral resolution in the broad energy range, a vast amount of new information on various physical processes in flares was obtained. The information concerns spectral, energetic, polarization, and dynamical characteristics of flare emissions, spectra of accelerated particles, gamma lines etc.

[13] On the basis of the observations with high time resolution in the X-ray range (3–40 keV) using the flare spectrometer IRIS and spectral analysis, characteristic periods of plasma oscillations in active regions before the flare, during the flare, and after the flare were determined [*Dmitriev et al.,* 2002, 2006]. These periods differ considerably (from a few seconds to tens of seconds), this fact manifesting changes in the resonant properties of the magnetic configuration of active regions. Such signs could be used for forecasting of solar flares on the basis of the observed X-ray emission and for creation of a model of the flare process.

2.4. Impulsive Phase of a Flare

[14] The impulsive phase of a flare is characterized by an energy release which (as we see it in the X-ray radiation) has an oscillation (saw-like) character [*Dmitriev et al.,* 2002]. The beams of charged particles accelerated in the flare inject into the dense layers of the solar atmosphere and form peaks of the X-ray emission with characteristic intervals of 20 s. Quite similar picture of the energy release in the form of saw-like oscillations is observed also in tokomaks during an instability break related to reconnection of magnetic field lines [*Prist and Forbes,* 2000].

[15] The hard X-ray emission generated at the interaction of directed beams of accelerated particles with the dense solar atmosphere should be linearly polarized. Attempts to measure this polarization for a long time were failing. A considerable linear polarization in the flare maximum was for the first time measured by the SPR-N specropolarimeter at the CORONAS-F satellite for one of the most powerful flares on 29 November 2003 (class X-10) [*Zhitnik et al.,* 2006]. This is a direct proof not only of the existence of the accelerated particle beams themselves, but a confirmation of the fact that these particles are accelerated by the pulse electric field during the magnetic reconnection, but not by some stochastic mechanism.

[16] The impulsive character of the energy release and particle acceleration was registered also in the time profiles and dynamic spectra of the hard X-ray emission of flares in 8 energetic channels (26–380 keV) of the HELICON gamma spectrometer. On the basis of these observations, the dynamics of hard emission spectrum (characteristic times and values of the spectrum slope change) was determined. The most hard spectrum is realized in the flare maximum.

2.5. Atomic Processes in Flares

[17] The detailed spectroscopic diagnostics of the flare plasma and atomic processes in the flares were performed with the help of DIAGENESS spectrophotometer and RESIK X-ray spectrometer [*Sylwester et al.,* 2005a, 2005b]. For the first time the absolute Doppler shifts of the X-ray spectral lines in solar flares and the absolute content of K (potassium) and CL (chlorine) in the solar corona were determined, and spectral lines of solar plasma ions for high values of the quantum numbers n (see Figure 7) opening new possibilities for a new method of the temperature diagnostics of the coronal plasma were detected. New spectral lines were also detected and their identification was performed, hundreds of spectra of helium-like ions Ca XIX, S XV, and Si XIII were measured. More than one million of linear spectra were obtained during the period of observations, a catalog was created <http://www.cbk.pan.wroc.pl/resik_catalogue.htm>, and an atlas of spectral lines of the Sun in the range 3.4 Å –6.1 Å was prepared.

2.6. Nuclear Processes in Flares

[18] In powerful flares, the accelerated protons and nuclei with an energy above a few MeV cause numerous nuclear reactions at collisions with nuclei of the medium. The gamma radiation, gamma lines of excited nuclei, annihilation electron–positron lines, and neutrons formed in the reactions bring important diagnostic information on the acceleration process and the composition of the solar atmosphere. These processes were registered by the devices of the gamma range: the amplitude–time spectrometer AVS-F and the spectrometer of solar neutrons and gamma radiation, SONG.

[19] Figure 8 presents an example of registration of the gamma lines in the flare on 29 October 2003 showing the presence in the solar atmosphere of various chemical elements and their isotopes [*Arkhangel'skaya et al.,* 2006]. In this case they are iron, magnesium, silicon, neon, oxygen, and carbon. A peculiarity in the spectrum corresponding to the line caused by the capture of the neutrons born in the flare is also seen. As far as the gamma radiation of the flare presents a sum of separate gamma lines excited by the accelerated protons, the presented gamma radiation spectrum simultaneously characterize the initial spectrum of the protons accelerated in the flare, this spectrum being one of the most important characteristics of the acceleration process.

[20] The line of the annihilation of electrons and positrons was observed in the energy range of 0.5 MeV in the spectrum of the gamma radiation of the flare by the amplitude–time spectrometer AVS-F. The line appears only in powerful flares when sufficient number of positrons is formed from the radioactive nuclei born in the flare.

[21] At the near-Earth orbit, the neutrons born in solar flares could be registered only at high energies (higher than 30 MeV), because at lower energies they decay to proton, electron, and electron antineutrino (it is the beta-decay of a neutron, the decay time of neutrons in vacuum being 16 min), not reaching the Earth. The gamma radiation and

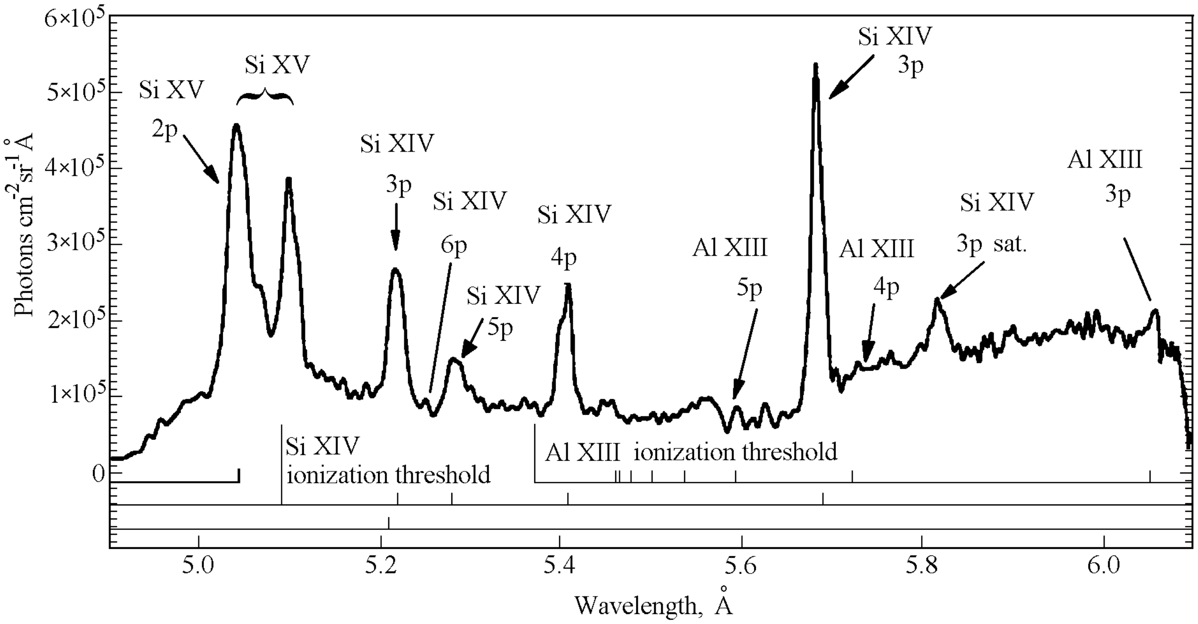

Figure 7. Spectral triplet of Si XV ion and lines of the helium-like ions Si XIV and Al XIII corresponding to the atomic transitions with high values of the n quantum number: from $n = 3$ to the ionization threshold. The X-ray spectrometer RESIK.

neutron flux for powerful flares of October 2003 registered by the SONG device are shown in Figure 9 [*Kuznetsov et al.,* 2006]. This data compared with other observations make it possible to determine the moment of the exit of accelerated protons and energetic neutrons from the solar corona.

2.7. Ultraviolet Emission of Solar Flares

[22] On the basis of the observations by the solar ultraviolet radiometer SUFR-Sp-K and ultraviolet solar spectrophotometer VUSS-L, the fluxes of ultraviolet emission from solar flares were measured by T. V. Kazachevskaya et al. (in press, 2008) and *Nusinov et al.,* [2005]. Figure 10 shows an example of such measurements in the $L\alpha$ line (in the wavelength range shorter than 130 nm) by the VUSS device for the 21 January 2003 flare. The typical value of the changes of the ultraviolet emission in the band in the vicinity of the $L\alpha$ line for the flares of the X-ray class C9-M1 is approximately 0.5%. For the most powerful flares, the increase in the ultraviolet emission in the 130 nm band does not exceed a few percents.

3. Registration of Solar Activity Manifestations in the Near-Earth Space Environment

3.1. Magnetosphere and Radiation Belts

[23] Conducting measurements of solar cosmic rays along the orbit of the CORONAS-F satellite by the SCR (Solar Cosmic Ray) equipment, a continuous series of the data on the fluxes of energetic solar particles was obtained, the data on the fluxes of solar electrons with energies above 300 keV being unique, because no other measurements has been conducted in this period.

[24] The conducted measurements of solar cosmic rays made it possible to study the dynamics of the magnetosphere and radiation belts of the Earth and also changes in the boundaries of penetration of energetic solar particles

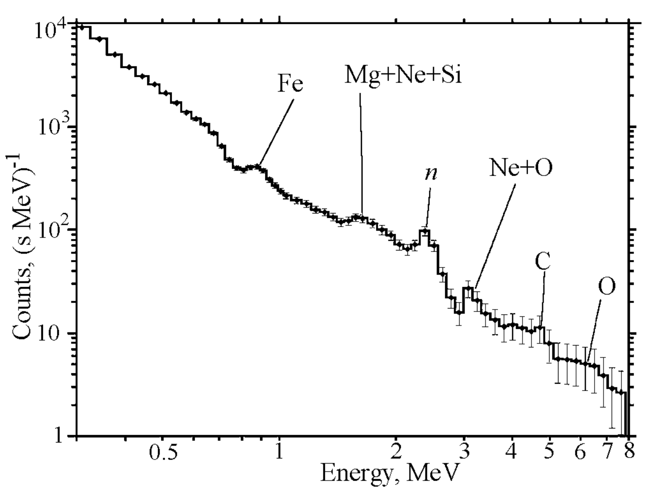

Figure 8. Gamma lines from the flare on 29 October 2003 showing the presence in the solar atmosphere of various chemical elements and their isotopes.

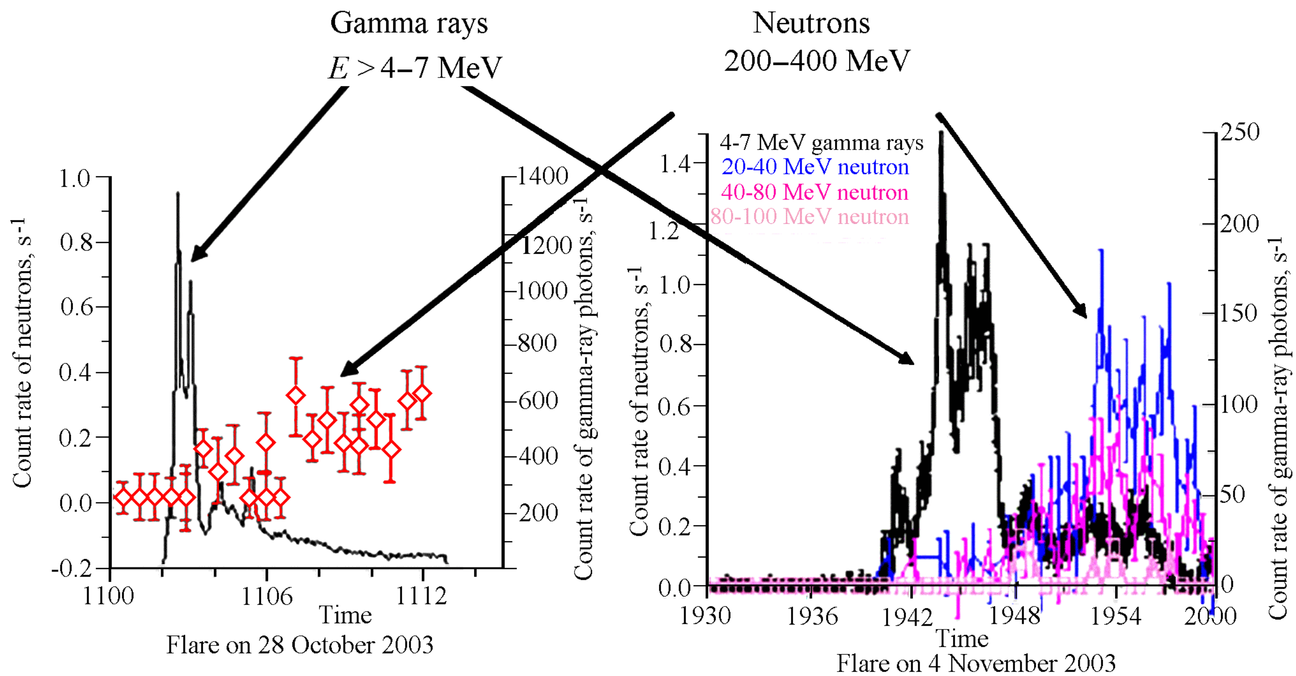

Figure 9. Fluxes of the gamma radiation of neutrons from the solar flares on 28 October 2003 and 4 November 2003. The spectrometer SONG of solar neutrons and gamma radiation.

into the magnetosphere in the periods of strong geomagnetic disturbances [*Kuznetsov et al.,* 2007a, 2007b].

[25] The periods of extreme events on the Sun, in particular events in October–November 2003, when powerful flares on the Sun caused two very strong magnetic storms, were especially favorable for studying of effects of the solar-terrestrial relations. Figure 11 shows for this period an example of deformation of the magnetosphere and dynamics of the radiation belts accompanied by penetration of energetic particles to low L-shells.

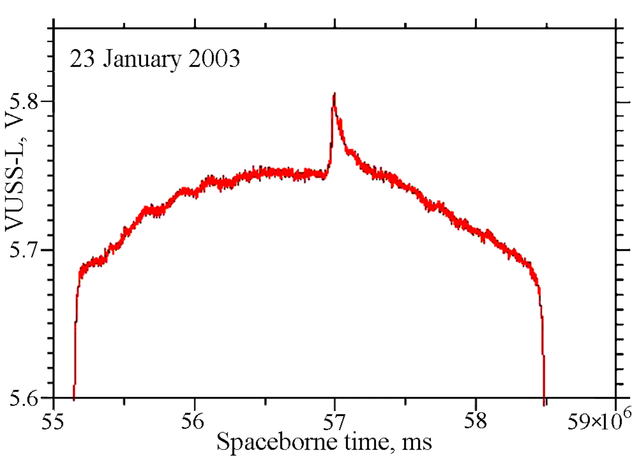

Figure 10. Registration of the ultraviolet emission flux from the 21 January 2003 flare in the $L\alpha$ line (in the wavelength region shorter than 130 nm). The ultraviolet solar spectrophotometer VUSS-L.

[26] Strong variations of the SCR penetration boundary were observed also during strong magnetic storms in November 2001. The variations of the penetration boundary of protons of SCR with an energy of 1–5 MeV and 50–90 MeV and electrons of SCR with an energy of 0.3–0.6 MeV as a function of the geomagnetic activity indices Kp and Dst for the dusk and dawn sectors of the magnetic local time (MLT) were observed. The stronger magnetic disturbances (larger values of Kp and larger negative values of Dst) the lower the Λ value, and so solar energetic particles penetrate to lower latitudes and lower heights.

[27] The experimental dependence of the penetration boundary of solar cosmic rays on the Dst and Kp indices of geomagnetic activity was approximated by the analytical formula in the form: $\Lambda = a + b \cdot Dst + c \cdot Kp$. The results of this approximation showed that for the electrons penetration boundary there exists a correlation between Λ and Kp at the daytime side of the Earth, whereas at the nighttime side the correlation between Λ, Kp, and Dst is of a small significance. For the penetration boundary of protons with an energy of 1–5 MeV, there exists a correlation between Λ, Kp, and Dst in the early morning and late evening hours, whereas in the early evening hours there exists a correlation between Λ and Kp. For the penetration boundary of protons with an energy of 50–90 MeV, there exists a correlation between Λ, Kp, and Dst almost in all hours when the measurements were conducted, except the early evening hours when it is enough to take into account the known relation between Λ and Kp.

[28] International Space Station having the inclination of the orbit plane to the equatorial plane of 51° is able (taking into account the inclination of the magnetic dipole axis to the

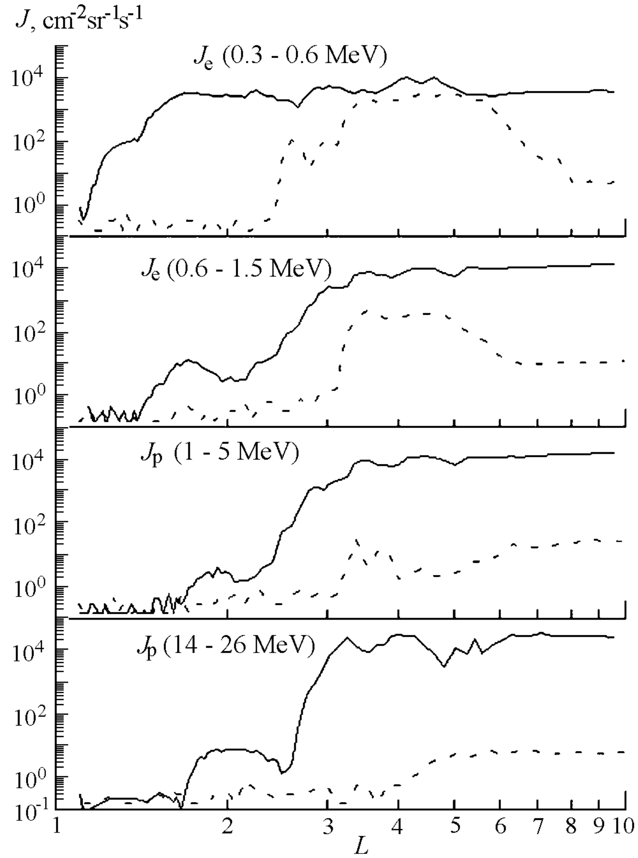

Figure 11. Changes in the distributions of electron (J_e) and proton (J_p) fluxes over L-shells illustrating the deformation of the magnetosphere and radiation belts and penetration of energetic particles into the magnetosphere and radiation belts in the period of strong magnetic storms on 28 October 2003 (dashed curve) and 29 October 2003 (solid curve). The SCR experiment.

axis of the Earth's rotation $\sim 11°$) to cross during its motion along the orbit the L-shells with $L > 4$ at one–two orbits over the North America and Australia and only there to enter the region of penetration of protons with Ep>50 MeV. However, according to the results obtained by the SONG device, if a powerful flare occurs during a strong magnetic storm (as it was the case, for example, on 29 October 2003), then ISS enters the region of SCR penetration at more than a half of the orbits. In such situation, a SCR burst presents a serious radiation danger for cosmonauts.

[29] On the basis of the measurements by the CRM (Cosmic Ray Monitor) device of the SCR scientific equipment, the dynamics of the outer radiation belt of the Earth during strong magnetic storms caused by active events on the Sun is studied and the relation of its dynamics to the structural rebuilding of the magnetosphere is determined. The interaction of coronal mass ejections with the magne-

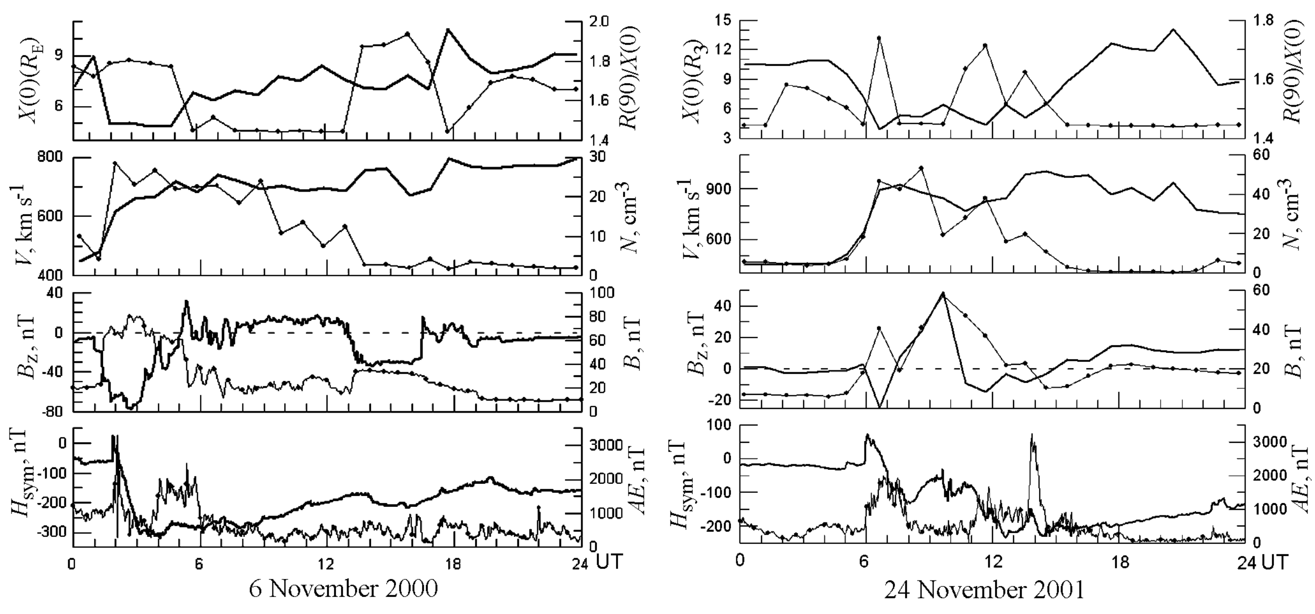

Figure 12. Disturbances in the magnetosphere and interplanetary environment during the magnetic storms on 6 and 24 November 2001. The bottom panel shows the data on $H_{\rm sym}$ (total field) and AE indices. The next panel shows the data on the B_z component of the interplanetary magnetic field and its total value B. The second panel from the top shows the data on the solar wind velocity V and its density N. The top panel shows the calculated values of the distances to the subsolar point of the magnetopause $X(0)$ and the ratio of the distances to the magnetopause at the angle of 90° and at the sunward direction $R(90)/X(0)$. $R_{\rm E}$ – Earth's radius.

tosphere of the Earth led to a magnetic storm which was accompanied by a structural rebuilding of the magnetosphere: shrinking of the region of closed drift shells (region of the radiation belts), redistribution of the field lines into the magnetospheric tail, and increase in the polar cap dimensions.

[30] The dynamics of the radiation belts of the Earth and structural rebuilding of the magnetosphere were studied in detail by the CRM device in the periods of magnetic storms on 6 and 24 November 2001, 29 and 30 October 2003, and 15 May 2005. The integral effect of the magnetic storm impact on the outer radiation belt was also studied for the magnetic storm on 20 November 2004. The obtained data on the disturbances in the Earth's magnetosphere are shown in Figure 12 at the example of the magnetic storms on 6 and 24 November 2001 caused by mass ejections from the Sun. The storms had sudden commencements at 0153 LT on 6 November 2001 and 0556 LT on 24 November 2001, respectively.

[31] One can see in Figure 12 that in the 6 November 2001 event just after the sudden commencement of the magnetic storm, a main phase of the magnetic storm began. It was caused by the redistribution of magnetic field lines from the middle of the magnetosphere into its tail, intensification of the current in the plasma layer of the magnetospheric tail and its approaching the Earth. In the event on 24 November 2001 after the sudden commencement of the magnetic storm during 50 min the first phase of the magnetic storm was observed: compression of the magnetosphere with a weak increase of the field in the plasma layer of the magnetospheric tail with an increase of the field in the middle and with an adiabatic acceleration of the captured particles (the latter fact is seen in the increase of particle fluxes in Figure 13).

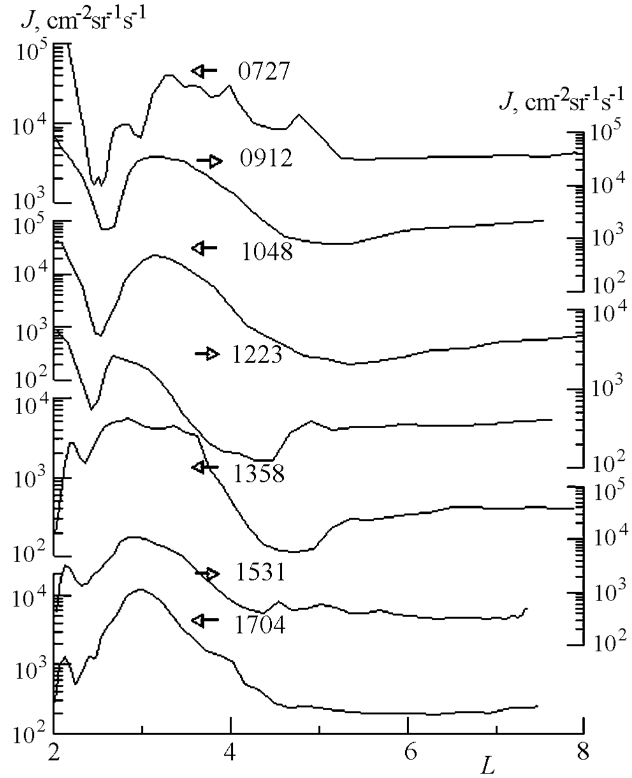

Figure 14. Changes in the structure of the radiation belt of electrons with E_e=0.3–0.6 MeV at the development of the main phase of the 24 November 2001 magnetic storm (according to the CRM device data). The electron flux intensity is shown at the ordinate.

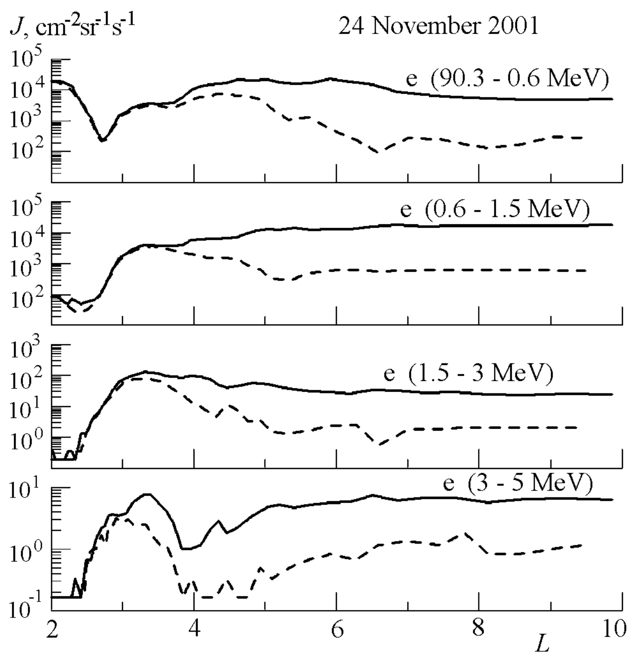

Figure 13. Increase in the electron fluxes during the first phase of the magnetic storm on 24 November 2001. The data obtained at the previous passage of the satellite (before the commencement of the magnetic storm) are shown by dashed curves. L is the magnetic coordinate (the number of the L-shell). According to the data of the CRM device.

[32] Comparing Figures 13 and 14, one can see that at the main phase of the magnetic storm the region of the captured radiation existence shrank and the radiation belt maximum shifted to the $L \sim 3$ shell reached by the boundary of SCR penetration. At the $L < 3$ shells, the intensity of electrons almost did not change. One can see in Figure 14 that the recovery of the radiation belt of electrons in the 24 November 2001 event began only after 1700 UT.

[33] The minimal intensity of electrons in the maximum of the radiation belt and the minimal value of L in the belt maximum position were observed at 1223 UT in the maximum of the magnetic storm main phase. The dynamics of the radiation belt of electrons of various energies (0.3–0.6, 0.6–1.5, 1.5–3 and 3–6 MeV) during the magnetic storms of November 2001 and in the intervals between magnetic storms is shown in Figure 15. Till 6 November 2001, the maximum of the outer radiation belt for electrons with energies of 0.3–0.6 MeV and 0.6–1.5 Mev was located at the $L \sim 4$ shell. After 6 November 2001, the maximum of the radiation belt of these electrons was formed at the $L \sim 3$

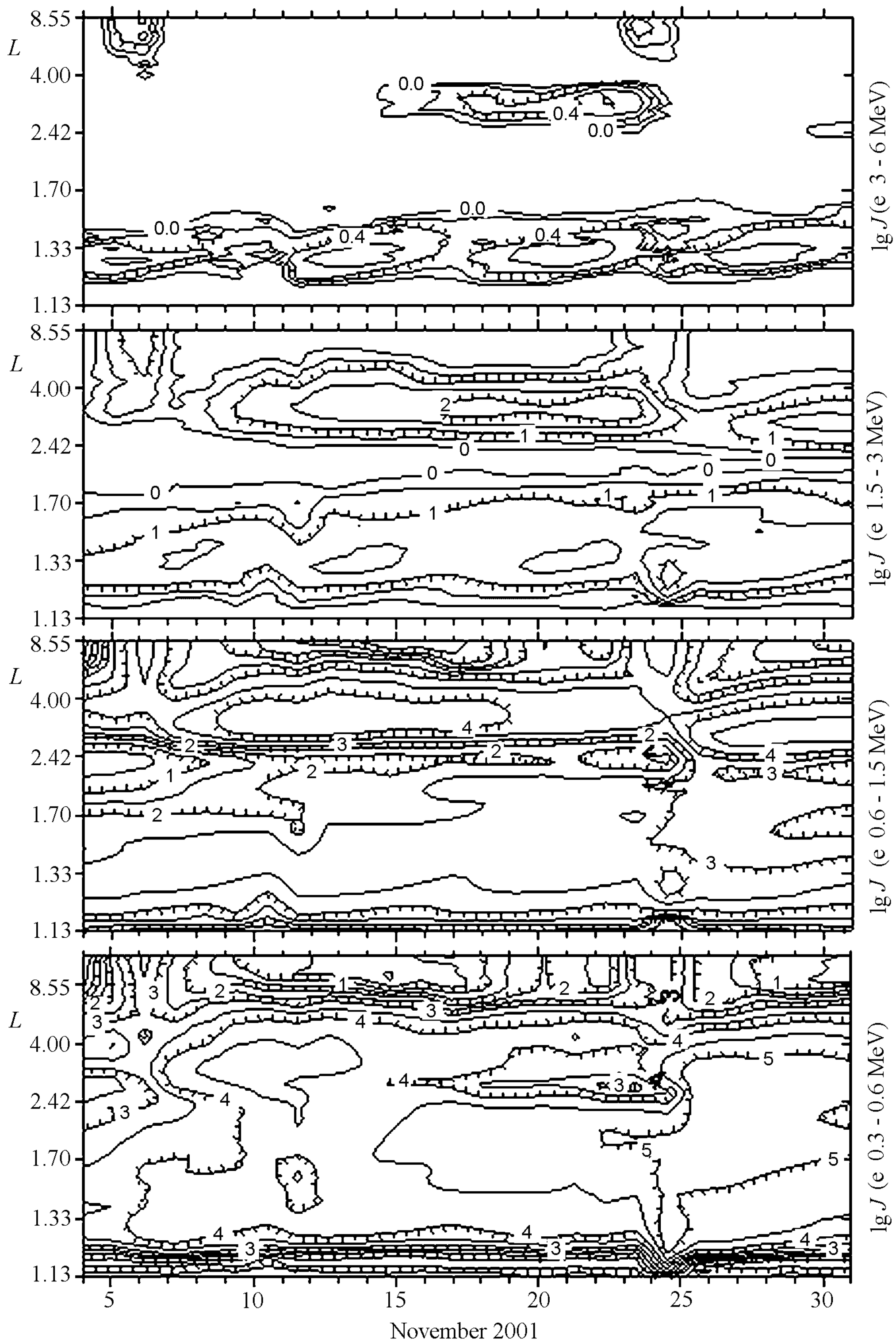

Figure 15. Changes in the structure of the electron radiation belt during the period 4–30 November 2001. Some isolines are marked by short perpendicular dashes. The dashes are directed to the intensity decrease. According to the data of the CRM device.

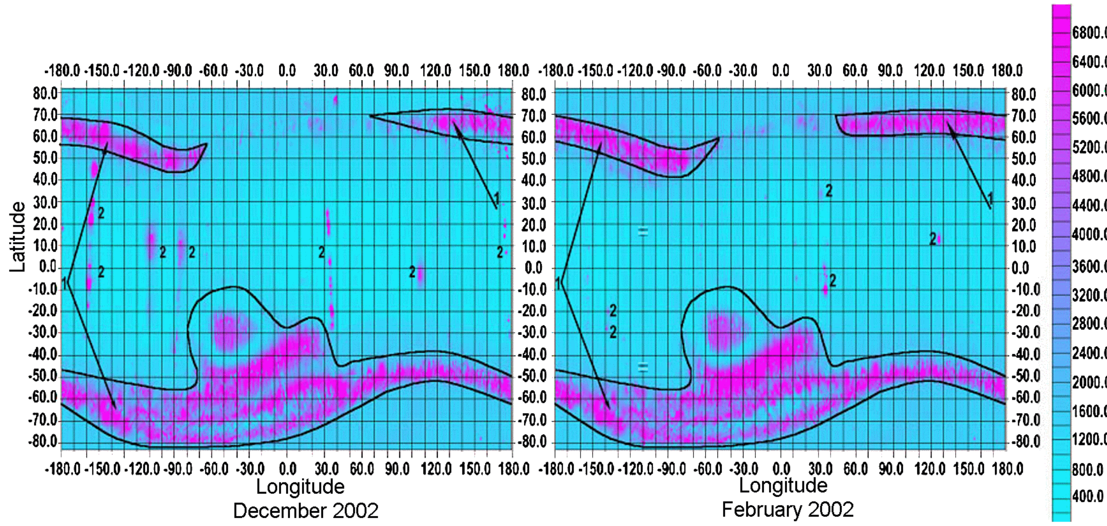

Figure 16. Maps of the quasi-stationary precipitations of energetic particles from the magnetosphere: (1) radiation belts, (2) quasi-stationary precipitations. The Amplitude–time spectrometer AVS-F.

shell with increased values of the intensity. At the $L \sim 3$ shell to 15 November 2001, the electron belt with energies of 1.5–3 MeV and 3–6 MeV was gradually formed. For electrons with energies of 0.3–0.6 MeV to 15 November 2001, a gap began to be formed at the $L \sim 3$ shell and two maxima at the $L \sim 2.5$ and $L \sim 4$ appeared. On 24 November 2001, the next magnetic storm changed the structure of the outer radiation belt again. The maximum of the radiation belt with increased intensity for electrons with energies of 0.3–0.6 MeV and 0.6–1.5 MeV was formed again at the $L \sim 3$ shell.

[34] Thus the structural rebuilding of the magnetosphere during a magnetic storm leads to a shrinking of the region of the outer radiation belt. After the end of a magnetic storm (the recovery phase), the outer radiation belt recovers. First the electron fluxes increase at the boundary of the penetration of SCR electrons at the moment of the magnetic storm, then the fluxes of electrons with an energy of a few MeV increase, and so the radiation belt structure could have two maxima.

[35] Thus it is proved on the basis of the conducted measurements that the effect of the disappearance of the outer radiation belt of electrons at the main phase of magnetic storms at the energies above 1.5 MeV is due to the shrinking of the region in which the captured radiation could exist. After the end of a magnetic storm, the region of existence of the captured radiation recovers up to the pre-storm state.

3.2. Upper Atmosphere of the Earth

[36] At the observations of the upper atmosphere of the Earth, besides the known precipitations of energetic particles from the magnetosphere to the ionosphere in the near-polar regions and in the zone of the Brazilian anomaly, the AVS-F device detected localized (about 30° and 10° along geographic latitude and longitude, respectively) quasi-stationary low-latitude and equatorial precipitations as shown on Figure 16 provided by I. V. Arkhangel'skaya et al., (in press, 2008). These precipitations are characterized by a considerable increase in the radiation background (by 20–30%). Their lifetime can reach 8 days.

[37] According to the experiment with the RPS (X-ray spectrometer) device in the X-ray range 3–31.5 keV, charts of the emission of the nighttime upper atmosphere of the Earth caused by the impact on the atmosphere of fluxes of solar radiation, galactic cosmic rays, and charged particles precipitating from the magnetosphere were drawn (Figure 17). On the basis of these data, important regularities in the behavior of this emission are revealed: The existence of the long-period seasonal and depending on solar activity level variations in the nighttime emission of particular regions of the globe, such as the Brazilian anomaly region, regions of the outer radiation belt of electrons in the Southern and Northern Hemispheres, and also the smaller regions, such as global magnetic anomalies, is detected. For the first time the information also obtained on the fluxes of low-energy electrons of the radiation belts of the Earth precipitating into the Earth's atmosphere and responsible for its soft X-ray emission.

[38] Using the solar X-ray telescope of the CORONAS-F satellite, the upper atmosphere of the Earth was studied on the basis of the absorption of the hard X-ray radiation of the Sun at the entrances of the satellite to the shadow and exits out of it [*Slemzin et al.,* 2003] (see Figure 18). On the basis of such observations, the height dependences of the absorption coefficients of the X-ray radiation were obtained with a high vertical resolution. The dependence of the density and composition of the Earth's atmosphere at altitudes up to 500 km on solar activity was studied. The content of molecular nitrogen and atomic oxygen was determined. For similar observations, fluxes of the solar radiation in the ul-

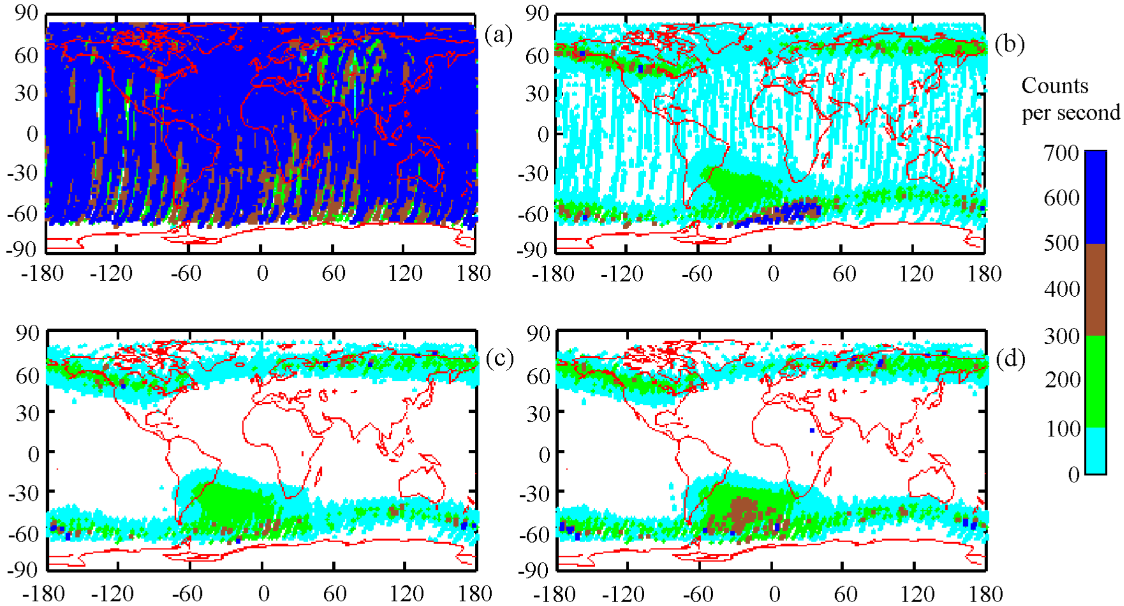

Figure 17. Maps of the emission of the nighttime atmosphere of the Earth drawn for four energetic intervals: a – 3–5 keV, b – 5–8keV, c – 8–16keV and d – 16–31 keV according to the data of the RPS-1 device obtained during a year of observations from 23 September 2002 to 23 March 2003 (winter).

traviolet range were measured by the SUFR radiometer and VUSS spectrophotometer.

[39] The observations of the upper atmosphere of the Earth carried out in the scope of the CORONAS-F project made it possible to obtain experimental data for creation of a modern model of the Earth's atmosphere. This is important in the light of the recent publication on the possible systematic trends in the parameters of the upper atmosphere and in relation to the global warming problem.

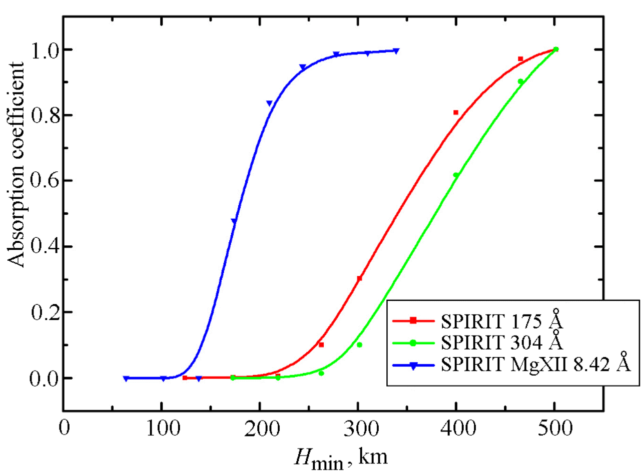

Figure 18. The dependence of the coefficient of the X-ray radiation absorption by the Earth's atmosphere on the $H_{\min}$ height (the shortest distance between the Earth's surface and the line connecting the Sun and CORONAS-F spacecraft). The SPIRIT experiment.

4. Conclusions

[40] During the half-century period from the International Geophysical Year (1957) to the International Heliophysical Year (2007), from the first artificial satellite (1957) to the solar space observatory CORONAS-F (2001–2005), thanks to the entire series of solar and heliospheric space projects (SOHO, TRACE, ULYSSES, Solar A, RHESSI, and CORONAS-F) in the studies of solar activity and its impact on the Earth a considerable success was achieved in understanding of the main processes occurring in the Sun–Earth system. This understanding allows us to estimate correctly the influence of the space weather on the human activity on the Earth and in Space. It makes also possible to provide the necessary level of space weather prediction needed to provide the safety of cosmonauts, space vehicles, communication and navigation systems, and extended ground-based communication and transport systems.

[41] The acting (SOHO, STEREO, Hinode, TRACE, RHESSI), prepared to be launched (SDO, Solar probe, CORONAS-PHOTON, and others), and being developed (Interhelioprobe, Solar Orbiter, and others) heliospheric and solar space missions of various space agencies continue fundamental and vitally important solar–terrestrial studies. A start to these studies was given in 1957 by the launching of the first artificial satellite and by the wide program of the International Geophysical Year.

[42] This paper presents only some of the most important results of the CORONAS-F project. One can find their more detailed description in the reviews [*Kuznetsov,* 2004, 2005, 2006a, 2006b, 2007; *Kuznetsov et al.,* 2004, 2005; *Oraevsky and Sobelman,* 2002; *Oraevsky et al.,* 2002, 2003] and in the references therein.

[43] **Acknowledgments.** The author thanks the leaders of the experiments on board the CORONAS-F satellite I. A. Zhitnik, S. N. Kuznetsov , Yu. D. Kotov, V. M. Pankov, A. A. Nusinov, E. P. Mazets, and Ya. Sylwester for the presented information used at writing of this paper.

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