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Magnetic storm of November, 2004: Solar, interplanetary, and magnetospheric disturbances

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Abstract

We briefly review data on observations of the Sun, interplanetary medium, and magnetosphere, obtained by participants of the "Solar Extreme Events in 2004 (SEE'04)" collaboration before and during one of the strongest (4th in the 23rd solar cycle) magnetic storm of November 08, 2004 with Dst = -373 nT.

Keywords: Solar flares; Coronal mass ejections; Interplanetary disturbances; Geomagnetic storms

1. Introduction

Investigation of the effects of solar and interplanetary (heliospheric) events on the near-Earth space is one of the most important components of the solar–terrestrial physics. In spite of the large body of experimental and theoretical data have been accumulated, the prediction of effects of the space weather faces serious difficulties

Table 1
Flare events in AR 10696 in November 2004

N	Data, UT	Coordinates	Class	CME
1	Nov.3, 15:35	N11 E40	M5.0/SN	No
2	Nov.4, 08:45	N08 E28	C6.3/SN	P.Halo
3	Nov.4, 21:42	N11 E19	M2.5/1N	P.Halo
	Nov.4, 22:34		M5.4/1N	P.Halo
4	Nov.5, 11:23	N08 E15	M4.0/1F	–
	Nov.5, 19:10	N09 E07	M1.2/SF	–
5	Nov.6, 00:11	N10 E08	M9.3/2N	Halo
	Nov.6, 00:44		M5.9	Halo
	Nov.6, 01:40		M3.6	Halo
6	Nov.7, 15:42	N09 W17	X2.0/2B	Halo
7	Nov.9, 16:59	N07 W51	M8.9/2N	Halo
8	Nov.10, 01:59	N09 W49	X2.5/3B	Halo

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(Yermolaev and Yermolaev, 2006). The greatest difficulties regarding the prediction of space weather effects exist for the strongest, extreme disturbances as the number of such events is sufficiently low and data sets of measurements on these events are insufficiently complete. An excellent example of interdisciplinary approach is the collaboration of the researchers (SEE'03) from more than 10 Russian scientific institutions, which was organized in order to study the extreme events that occurred on the Sun, in the heliosphere, and on the Earth in October–November 2003 (see papers by Veselovsky et al., 2004; Panasyuk et al., 2004; Ermolaev et al., 2005 and special issues of Cosmic Research (N4, 2004), Geomagnetism and Aeronomy (N1, 2005), Geophysical Research Letters (N3 and 12, 2005), and Journal of Geophysical Research (N A9, 2005)).

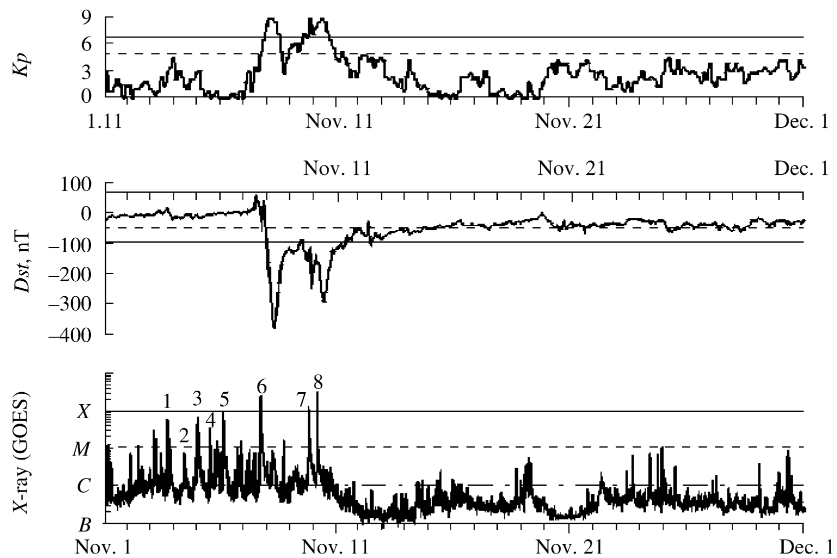

Fig. 1. The series of solar and ground-based measurements in November 2004. Nos. 1–8 correspond to the flares presented in Table 1.

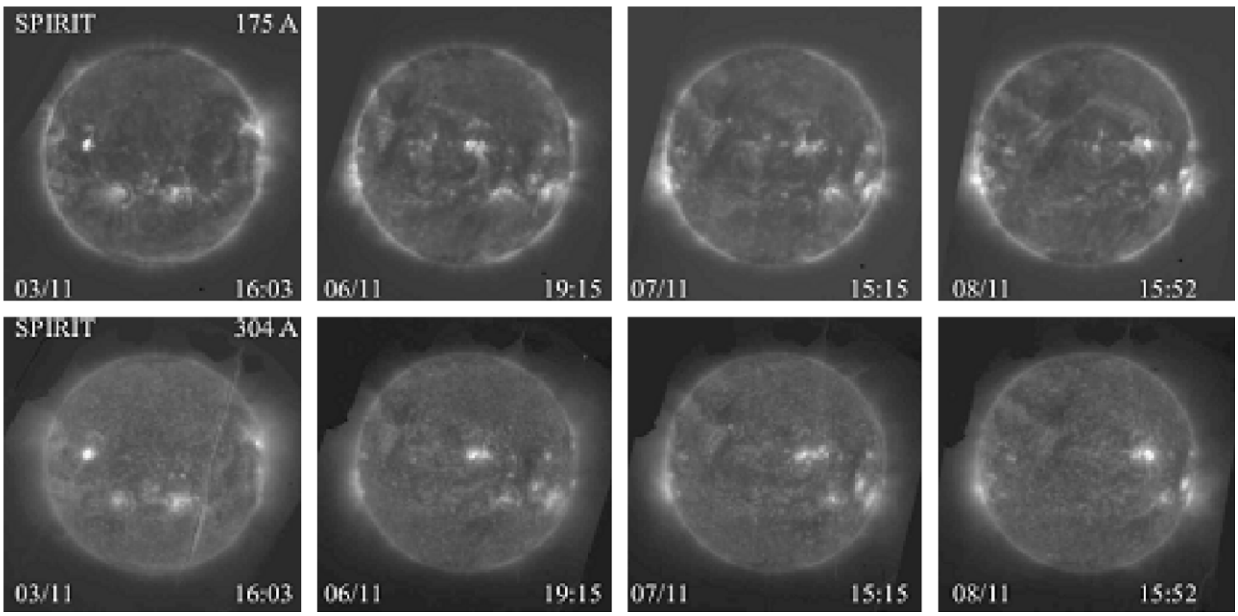

Fig. 2. SPIRIT/CORONAS-F images of the Sun in the 175 and 304 Å channels obtained on November 3–7, 2004.

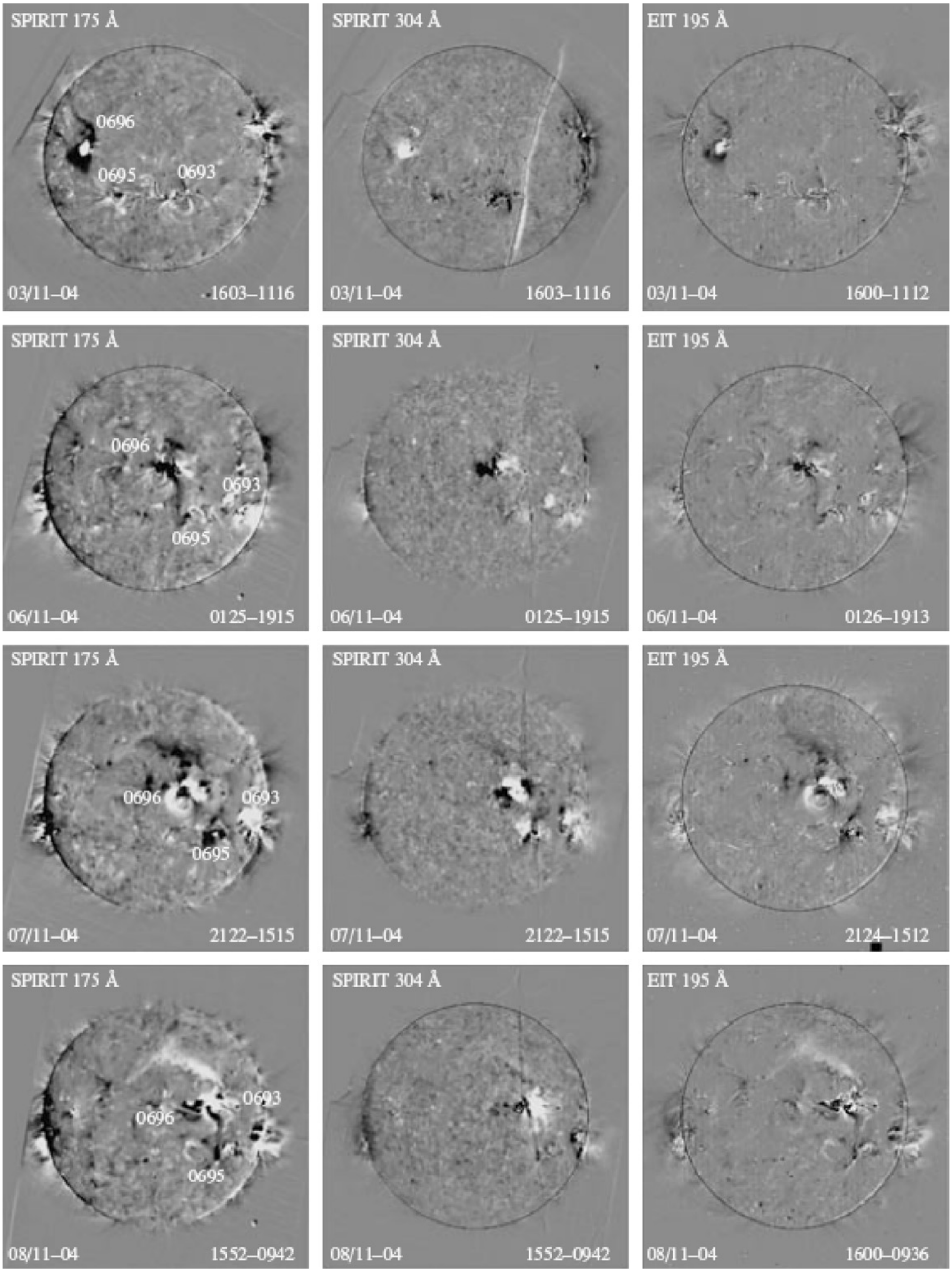

Fig. 3. Fixed-base difference images in the 175 and 304 Å channels of the SPIRIT telescope and similar images in the 195 Å channel of the SOHO/EIT telescope obtained on November 3, 6, 7, and 8, 2004.

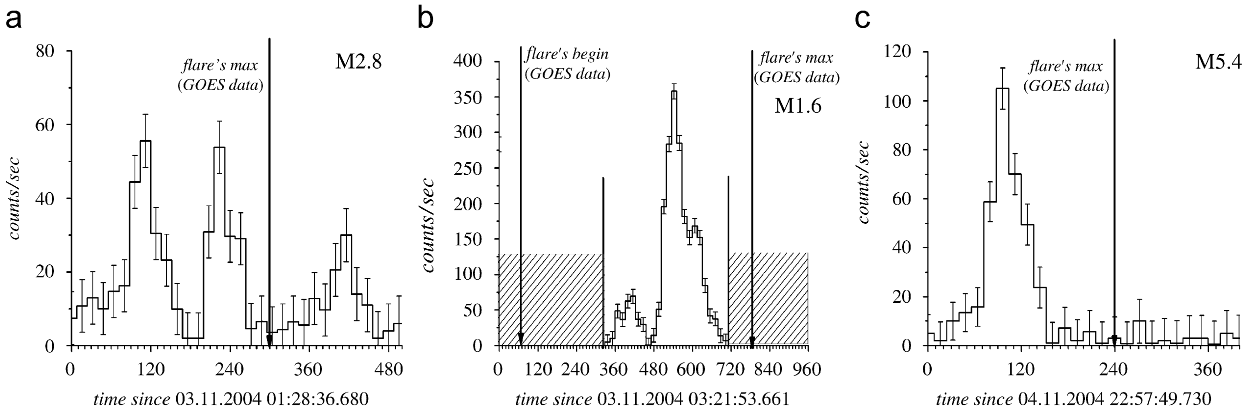

Fig. 4. Temporal profiles of solar flares observed by AVS-F instrument in November 3–4 2004 in energy band 0.1–1 MeV. Dashed areas correspond to satellite passing through Earth radiation belt.

Exactly a year later, at the end of October to beginning of November 2004, the Sun was again very active and generated a number of strong interplanetary and magnetospheric disturbances (see Fig. 1, Table 1 and papers by Yermolaev et al., 2005; Chertok, 2006; Kozyreva et al., 2006; Lundstedt, 2005 and Geomagnetism and Aeronomy, issue No. 5, 2006). The values of some parameters measured during this period of 2004 were slightly smaller than the extreme values observed in 2003. Nevertheless solar activity in 2004 can be considered among the strongest events not only in the 23rd solar activity cycle but also during the history of space observations. The aim of this paper, prepared mainly by the group of researchers of the previous active period, is to generally describe the state of different spatial regions during this period and to present the main Russian experimental data.

2. Solar observations

The burst of solar-flare and eruptive activity at the declining phase of 23rd solar cycle was observed during period from the end of October to beginning of November 2004. This burst was related to the passage of two sunspot groups—active regions (ARs) 10691 and 10696—over the visible solar disk.

The SPIRIT telescope on the CORONAS-F satellite was used to take solar observations on November 1–8, 2004. Total disk images in the channels 175 and 304 Å were registered four times per day at intervals of 4–8 h and complete spectrograms were registered two times a day. Several obtained telescopic images are shown in Fig. 2.

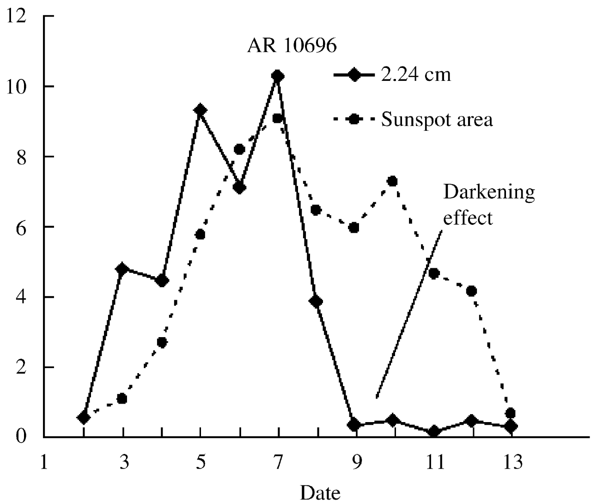

Fig. 5. Darkening effect in AR 10696 before the M2.5 flare of November 10, 2004. Dots show a change in the Sunspot area in the group at the level of the photosphere. Solid line corresponds to the total emission flux from AR 10696 at a wavelength of 2.24 cm.

Fixed-base difference images obtained using the SPIRIT telescope as compared with SOHO/EIT images are presented in Fig. 3. A classical pair of compact dimmings, corresponding to footpoints of an eruptive magnetic loop, was generated as a result of the flare and eruptive event occurred on November 3 near AR 10696. These dimmings are very contrasting in the channels 175 and 195 Å, but are much less distinct in the channel 304 Å, which can be caused by the delay in the dimming development in the transition layer.

APV-F and SONG instruments on CORONAS-F spacecraft were used to measure the soft gamma-ray and hard gamma-ray and neutrons from solar flares, respectively, and they allowed us to obtain important information about solar activity during October–November 2003 events (Veselovsky et al., 2004; Kuznetsov et al., 2006; Arkhangelskaja et al., 2006). Because of telemetry limits there are no measurements of these instruments for solar flares during 5–6 November, 2004. Nevertheless, three solar flares were detected by AVS-F instrument on 3–4 November and time profiles of gamma-ray are shown in Fig. 4.

The RATAN-600 radiotelescope was used in the daily observations in the wave band 1.83–15 cm performed from 07:00 to 11:00 UT on November 2–11, 2004. These measurements demonstrated the evolution of emission in AR 10696. Sharp decrease in the emission flux on November 8 and 9 is apparently related to the origination of a darkening effect (Tokhchukova et al., 2003). Fig. 5. demonstrates a change in the total radio flux at a wavelength of 2.24 cm during the entire period of observations (November 1–13, 2004), which is comparable with the sunspot area in this active region. It is evident that the radio flux started decreasing much more abruptly than the total sunspot area after November 7. The above data on the darkening effect and our model calculations indicate that hot plasma interlayers are probably generated on the emission propagation path. Prominences and filaments that form CMEs can be such interlayers.

The presented solar data allow us to confirm the conclusions that for all extreme magnetic storms there are similar solar features which can result in strong storms (Veselovsky et al., 2004; Ermolaev et al., 2005; Chertok, 2006):

1. existence of two or more active regions, the intercoupling and interacting of multiple flux loop systems, and, probably, transequatorial magnetic loops on the Sun,
2. fast sequence of strong flares and CMEs which can interact with each other in the solar atmosphere and in the interplanetary space.

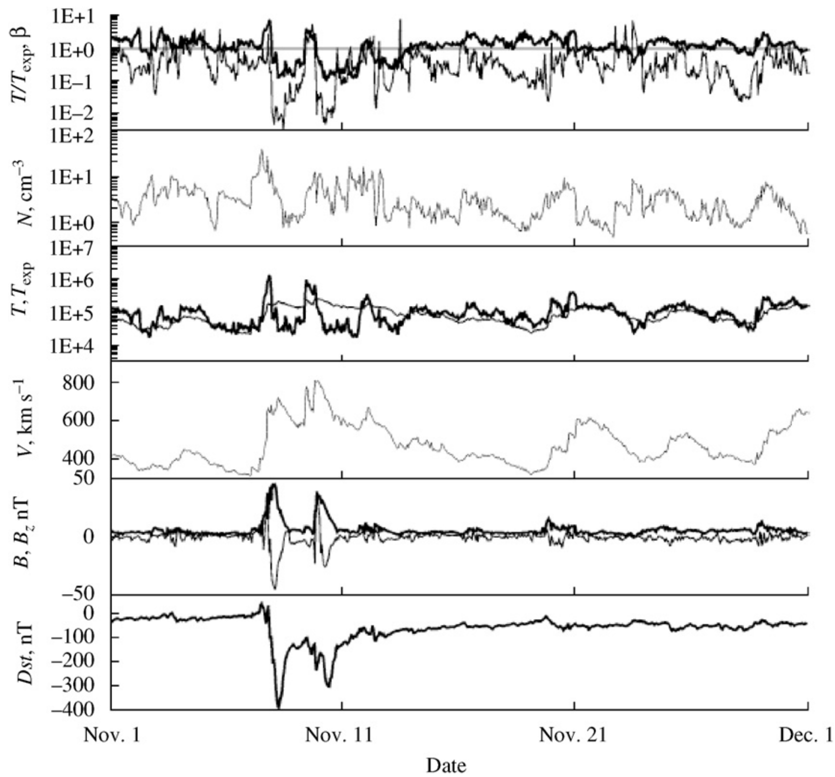

Fig. 6. Interplanetary space parameters in November 2004. Panels: 1—β-parameter (the ratio of the thermal and magnetic pressures, thin line) and the ratio of the proton temperature to such a temperature calculated from the average dependence of temperature on velocity, $T/T_{\exp}$ (thick line), 2—density, N, 3—proton temperatures T (thick line) and Texp (thin line), 4—solar wind velocity, V, 5—IMF magnitude B (thick line) and B_z component (thin line), 6—Dst index.

3. Interplanetary measurements

In contrast to the situation in 2003, when large fluxes of energetic particles caused serious failures in the operation of instruments that measured parameters of the interplanetary medium on spacecraft, the complete sets of data on the solar wind and IMF were obtained. An analysis of ACE data in Fig. 6 makes it possible to preliminarily conclude that the studied time interval was characterized by strongly disturbed conditions in the solar wind. Thus, six interplanetary shocks and several magnetic clouds (interplanetary coronal mass ejections, ICMEs) were observed on November 7–11. The values of all plasma parameters (velocity V, temperature T, and density N) were not extreme. At the same time, the values of B and IMF B_z component reached extremely large values (>45 and -45 nT, respectively) on November 8 due to interaction of ICMEs. It resulted in the generation of the strongest magnetic storm (Veselovsky et al., 2004; Kozyreva, 2006).

Fig. 7 indicates that a considerable increase in the flux of protons with energies of 1–5 MeV was registered by CORONAS-F on November 5–6 and, consequently, was caused by a flare that occurred before November 7. Fig. 7a demonstrates that the fluxes of protons with energies of 14–26 MeV and higher started increasing only on November 7 after X2 flare. We assume that this increase in SCRs of low energies could be caused by an M9.3 flare that occurred near midnight on November 4–5 in the AR 10696 (N09E05). Fig. 7b indicates that fluxes of electrons with energies higher than 3 MeV appeared together with protons with energies higher than 14 MeV, and an insignificant (by a factor of 3–4) increase in the fluxes of electrons in the channels 300–600 and 600–1500 keV, probably related to the earlier flare mentioned above, was observed on the previous two days.

4. Magnetospheric and ground observations

The dynamics of the Earth's radiation belts is one of the main physical processes during magnetic storms. Fig. 8 shows the radiation belt dynamics during the strong magnetic storms at the beginning of November 2004 based on the CORONAS-F satellite. Due to the parameters of the orbit, the CORONAS-F instruments could register trapped radiation only in the region of the South Atlantic magnetic anomaly.

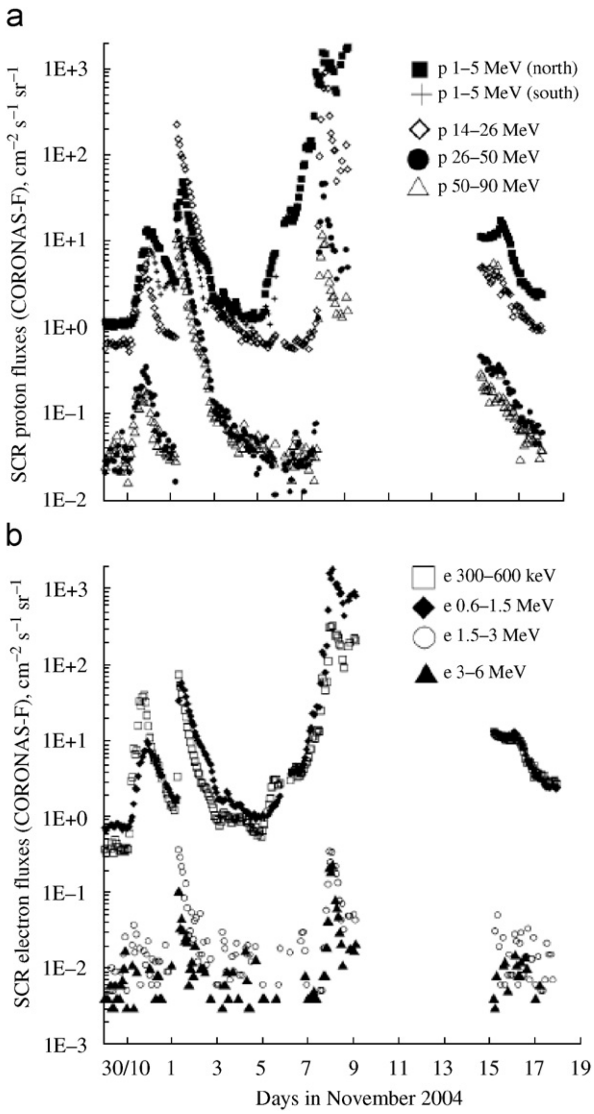

Fig. 7. Fluxes of (a) protons in both polar caps and (b) electrons in the northern polar cap from October 29 to November 18, 2004, according to the CORONAS-F satellite data.

The presented data indicate that the radiation belt dynamics during the November 2004 storms was rather similar to such a dynamics during the strong storms of October–November 2003 (Veselovsky et al., 2004; Panasyuk et al., 2004; Ermolaev et al., 2005), namely:

1. the intensity of the flux of 1.5–3 MeV electrons decreased during the magnetic storm main phase;

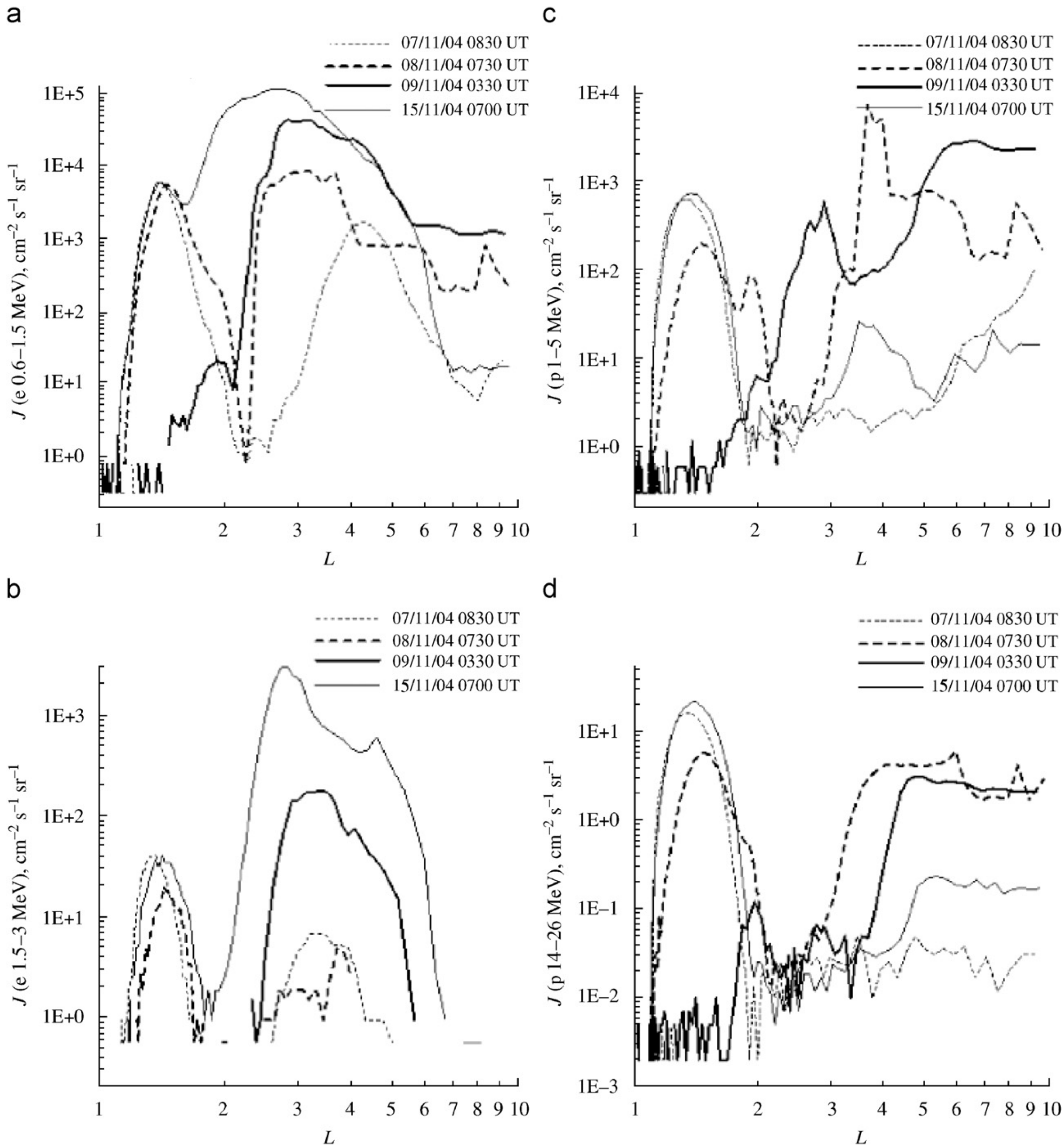

Fig. 8. Comparison of the profiles of the radiation belt particle fluxes: electrons with energies of (a) 600 keV–1.5 MeV and (b)1.5–3 MeV and protons with energies of (c) 1–5 MeV and (d) 14–26 MeV.

2. during the recovery phase the intensity of the electron fluxes from the Earth's outer radiation belt pronouncedly increased, the electron belt widened, and the belt maximum shifted to smaller L;
3. the additional maximum of protons with energies of 1–5 MeV appeared near $L = 3$.

Fig. 9 shows that the cosmic ray density behavior was slightly unusual on November 8 due to the Forbush effect. At that time the density increased (by about 2%) for approximately 12 h. The peak of this increase coincides with the solar wind disturbance and with the Dst minimum −373 nT.

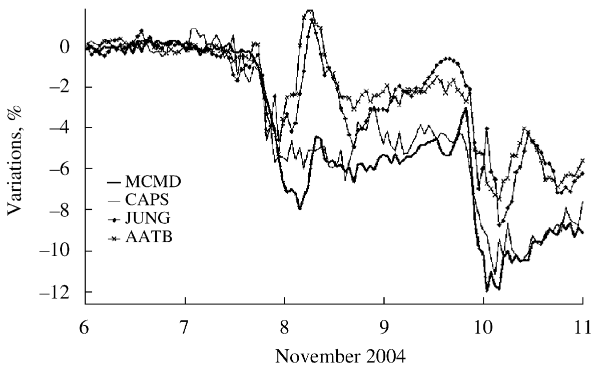

Fig. 9. Variations in the neutron monitor count rate relative to the base on November 6 at the stations: McMurdo (MCMD), Rc = 0.01 GV; Cape Schmidt (CAPS), Rc = 0.52; Jungfrauioh (JUNG), Rc = 4.48; Alma Ata 3300 m (AATB), Rc = 6.69 GV in November 2004.

5. Conclusions

As follows from the observations performed for the last several years, the main surprises took place during the declining phase of the 23rd solar cycle. Solar activity was high in 2001–2003, although the solar maximum (at least with respect to the number of sunspots) was observed in 2000. For example, the events of October–November 2003 are extreme with respect to a number of parameters (Veselovsky et al., 2004; Panasyuk et al., 2004; Ermolaev et al., 2005). In our previous (Yermolaev et al., 2005) and this papers, we presented the experimental observations of the Sun, heliosphere, and magnetosphere and performed a preliminary analysis for the next period of high disturbance, which was accompanied by the strongest geomagnetic storm of November 8–10, 2004, with Dst = −373 nT. This work not only presents comprehensive and various experimental data of observations in different regions but also demonstrates possible cause–effect relations between different phenomena in the complex chain of solar–terrestrial physics.

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