Solar Flares, Solar Energetic Particle Events and Their Influence on Near-Earth Environment in May 2005 as Observed by CORONAS-F and Universitetskiy-Tatiana Spacecrafts

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In spite of the fact that the year 2005 is far enough from the maximum of the current solar cycle, some rather powerful flares and solar energetic particle (SEP) events were observed during the first half of May 2005. These solar events were detected by instruments onboard two Russian polar low-altitude satellites: CORONAS-F and Universitetskiy-Tatiana. It was obtained that the location of SEP penetration boundary in the Earth's magnetosphere was similar at 350 km and 1000 km. The real disappearance of the outer Earth Radiation Belt (ERB) during the main phase of a geomagnetic storm and a significant increase of relativistic electron flux at L=4-5.5 during several days after the recovery phase were observed in both experiments.

Introduction

Space weather is the conditions and processes occurring in the space which have the potential to affect the near-Earth environment. The effects of space weather can range from damage to satellites to disruption of power grids on Earth. The most important part of this damage is caused by solar energetic particles (SEP) – protons and electrons. The basic patterns of solar energetic particle interplanetary transport by interplanetary shocks were published during 1960-80s (e.g. [1-4]). The results of recent experiments and theoretical studies (e.g. [5-6]) show that interplanetary shocks driven by Coronal Mass Ejections (CMEs) play a major role in accelerating the SEPs.

The variations of the Earth's Radiation Belts (ERB) and SEP cut-off during magnetic storms can affect the near-Earth environment also. Direct measurements of these variations at low altitudes are very important for space weather conditions estimation. The new experiments, especially simultaneous measurements of neutral and charged solar flare emission are useful. Soft X-rays (SXR), hard X-rays (HXR) and γ-rays produced at the Sun, their time history and spectrum in a wide energy interval provide us with the most direct information about particle injection and acceleration processes in solar flares.

Experiments

CORONAS-F satellite

One of the main goals of the Russian solar observatory CORONAS-F (**C**omplex **OR**bital **O**bservations in the **N**ear-Earth space of the **A**ctivity of the **S**un) was the study of CME and SEP events influence on the Earth's magnetosphere. CORONAS-F was launched to the orbit with the inclination 82.5^0, initial altitude about 500 km and final one 350 km, on July 31, 2001, and was operated until December 12, 2005. The orbital period was 94.8 min [7]. The experiment SONG is an instrument of the SKL suite (Solar Cosmic Rays) developed in Skobeltsyn Institute of Nuclear Physics, Moscow State University. The SONG instruments (CsI(Tl) large crystal) detected X-ray and gamma-emission in a wide energy range 0.03-200 MeV [8]. Charged particles in different energy ranges (protons with energy 1-90 MeV, electrons 0.3-12 MeV) were measured by semiconductor and plastic scintillator detectors [7].

Universitetskiy-Tatiana satellite

Space Scientific and Education project of Lomonosov Moscow State University "MSU-250" is timed to its 250-th anniversary (Internet site http://cosmos.msu.ru/eng/). Its main task is the development of scientific potential of young scientists in Russia and other countries. Universitetskiy-Tatiana satellite was launched to the orbit with the inclination 83^0, initial altitude about 1000 km on January 20, 2005 (during the most powerful SEP event of 2005) and is operated until now. The scientific task of this satellite is monitoring of radiation conditions near the Earth. In this work we used data on protons with energies 2-100 MeV and electrons with energies 0.07-3.5 MeV, obtained by semiconductor detector (1000 mkm Si) and scintillation detector (CsJ(Tl) 15×20 mm).

Data Analysis

Soft and Hard X-ray emission

During May 5 – 14, 2005, twelve soft X-ray solar flares (reported by GOES) were detected by SONG instrument and only one of them, on May 13, 2005, was rather intense. This flare had SXR-class M8.0, optical class 2B, maximum of soft X-ray (0.5-4 Å) was detected by GOES at 16:57:00 UT.

Unfortunately, during this flare CORONAS-F was in the shadow of the Earth and could not detect its HXR and gamma-emission. But the HXR emission was detected during some of C-class flares, e.g. C9.3 flare on May 06, 2005. The maximum of soft X-ray (0.5-4 Å) intensity was detected by GOES at 03:14:00 UT. The HXR emission (80-220 keV) peaked at 03:08:45 UT. The time history of HXR emission obtained by SONG for this flare is presented in Figure 1. We can see that the peak in HXR-emission was

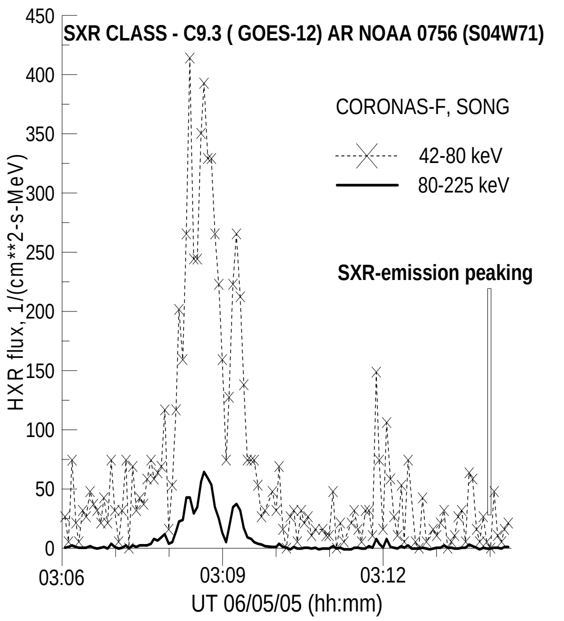

Fig.1. HXR-emission measured by SONG (CORONAS-F satellite) during May, 06, 2005 solar flare.

observed by SONG before the peak in SXR-emission, in agreement with Neupert effect [9].

We should note that significant flux of HXR-emission is rather unusual for C-class flares. During more than four years of CORONAS-F operation the significant flux of HXR-emission was detected only in two C-class flares. The HXR-emission detection provides us with the evidence of a very hard spectrum of neutral emission produced in these flares. It is well known that the high energy neutral emission of solar flares is the result of charged particles interaction with the solar atmosphere (e.g. [10-11]). So the very hard spectrum of neutral emission shows that the charged energetic particles were accelerated in this flare up to rather high energies. We assume that the C9.3 flare observed on May 06, 2005 was the source of the proton flux enhancement which began in the evening on May 06, 2005 and had the maximum near the noon on May 07, 2005 (see next section for more details).

Solar protons

Solar energetic particles are very important source of radiation damage in the near-Earth space. So SEP detection, studies of their dynamics and spectral characteristics are very important for space weather questions. Some CORONAS-F results of such studies for November 2001, October-November 2003 and November 2004 solar extreme events were published in [12-14].

Fig. 2 presents the time profiles of solar proton flux measured on board four different satellites during the time period 4-20 May - Universitetskiy-Tatiana, CORONAS-F, ACE and GOES-10. We compare particle fluxes in similar energy ranges and GOES-10 integral flux data.

Solar particles were detected on board Universitetskiy-Tatiana and CORONAS-F satellites in the polar caps (the duration of measurements in polar caps is ~10-15 min. Nevertheless, it is clearly seen from Fig. 2 that data obtained by all four satellites are in a good agreement.

From Fig. 2 we can see that during the studied period (May 4 – 20, 2005) several SEP events were detected. The most powerful of them was the event that started at 05:25 UT on May 14 and peaked at 02:40 UT on May 15. This SEP event was associated with the M8.0/2B flare mentioned earlier.

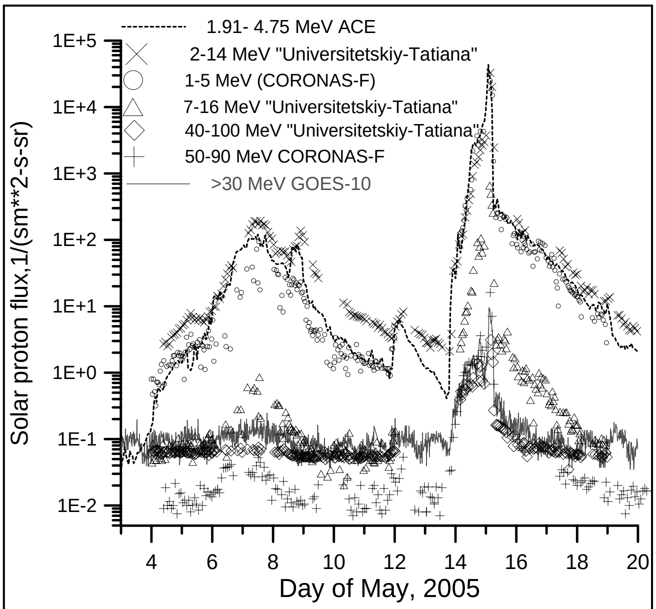

Fig.2. Time history of solar protons measured by different experiments in May 2005.

As for other earlier and weaker SEP events, we can assume that the small enhancement of the proton flux (in the energy range of 50-90 MeV) detected onboard CORONAS-F in the morning of May 6 was related to the eruption accompanying the C9.3 solar flare (peaking at 03:08:30 UT for 80-220 keV energy range) on May 6 that had rather hard spectra of neutral emission. A small SEP event with energy about 1 MeV (with peak intensity four orders of magnitude lower than May 14 event) was also detected by Universitetskiy-Tatiana, CORONAS-F and ACE satellites. This fact demonstrates good sensitivity of CORONAS-F and Universitetskiy-Tatiana experiments.

SEP cut-off rigidity variations

The boundaries of solar protons penetration into the Earth's magnetosphere according to Universitetskiy-Tatiana and CORONAS-F satellite data are presented in Fig. 3.

High energy solar protons penetrating in polar caps during main phase of magnetic storms are one of important sources of radiation danger in the near-Earth space, especially for low-altitude satellites. The size of the proton penetration area depends on proton energy and on geomagnetic conditions. Some earlier CORONAS-F results of similar studies were published in [13-15].

In this work we present and discuss the variations of the SEP penetration boundary (or SEP cut-off rigidity variations) measured by Universitetskiy-Tatiana (protons with energies 2-14 MeV and 40-100 MeV), CORONAS-F (protons with energies 1-5 MeV and 50-90 MeV) during magnetic storms on May 8 (Fig.3a) and May 15 (Fig.3.b), 2005. The proton flux on the penetration boundary does not fall down abruptly.

Therefore it is possible to apply different criteria to the analysis of the penetration boundary position. As well as in [10-12], in this work we use the traditional for Skobeltsyn Institute of Nuclear Physics Lomonosov Moscow State University criterion - twice below the maximum of the SEP flux. Penetration boundary of high energy protons can be measured only for the second magnetic storm (May 15), because during May 8 – 9 the flux of high energy protons was low. The values of penetration boundary obtained during the morning MLT are marked as open symbols, during evening MLT – as closed ones.

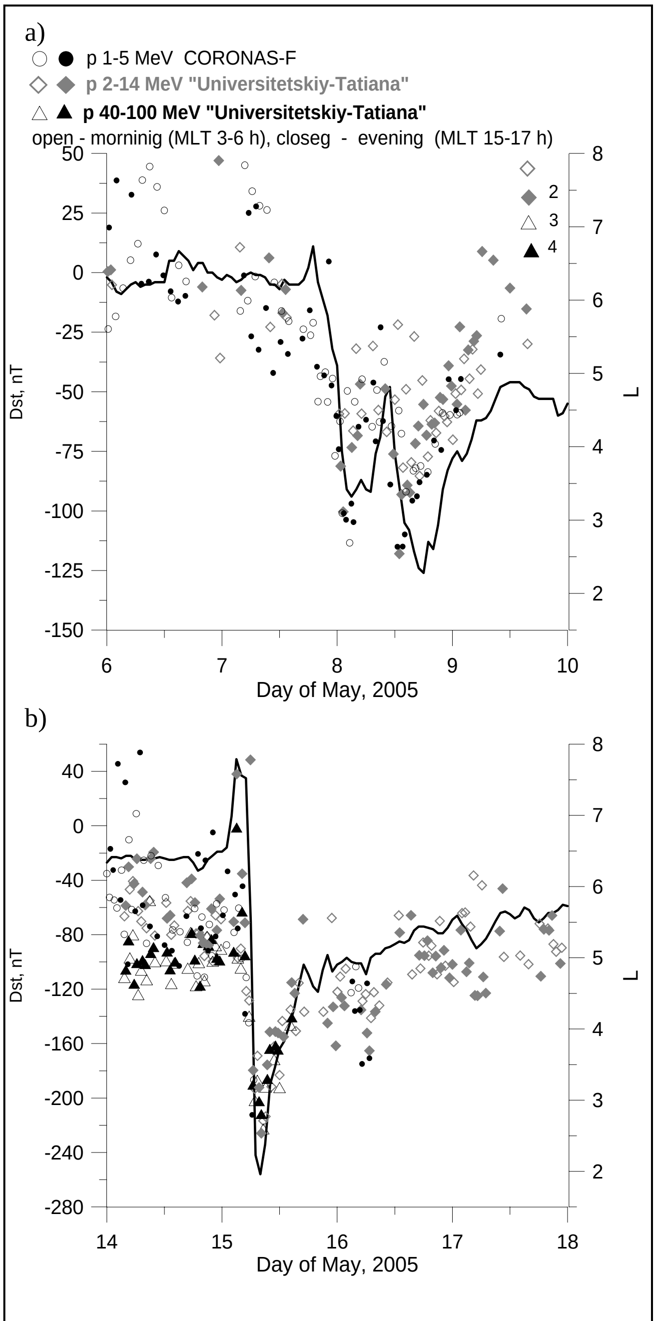

Fig.3. SEP penetration boundary variations during geomagnetic storms in May 2005. Dst-variation is shown by solid line.

The time variation of the Dst index is also shown in Fig. 3 for comparison.

The two main results from Fig.3(a, b) are:

- Universitetskiy-Tatiana and CORONAS-F data are in a good agreement both for morning and evening sectors of MLT;
- the penetration boundary is shifted closer to the Earth (to L~2.5) not only during the strong magnetic storm on May 15 (Dst=-260 nT) but also during the significantly weaker storm on May 8 (Dst=-125 nT).

For both storms we can see a good correlation between the penetration boundary position and the Dst index.

Outer radiation belt variations

The dynamics of the Earth's radiation belts (ERB) is one of the most important physical processes during magnetic storms. The measurements of the ERB variation, especially those of relativistic electrons flux at low altitudes, are important for space weather studies.

Fig.4 shows the relativistic electron dynamics in the outer radiation belt during May 2005 according to CORONAS-F (1.5 – 3 MeV) and Universitetskiy-Tatiana (>3.5 MeV) measurements. X and Y axes show days of May 2005 and the L-shell value respectively. The electron flux is shown by grey-scale color. White color indicates the absence of data mostly connected with telemetry problems. Such electrons are sometimes named "killer electrons" as they are very dangerous to electronic devices, in particular the microcircuits working in space. Relativistic electrons of the outer ERB produce volumetric ionization in microcircuits of spacecrafts and break their normal operation. Therefore, the research on relativistic electrons dynamics has both practical and scientific interest (e.g. [13, 16] and references therein). The relativistic electrons (with energies more than 1.5 MeV for CORONAS-F and more than 3.5 MeV for Universitetskiy-Tatiana) were detected in polar caps only during the second SEP event on May 14 – 15, 2005, but Fig.4 demonstrates that relativistic electrons exist in the outer radiation belt not only during SEP events. The main variations are observed after the maximum of this SEP event, during the recovery phase of the geomagnetic storm and several days later.

The data presented in Fig.4 indicate that the dynamics of relativistic electrons in the radiation belts during the May 2005 geomagnetic storms is rather similar to the dynamics observed during the strong storms of April 2002 [16], October-November 2003 [13] and November 2004 [14]. The relativistic electrons flux measured by CORONAS-F and Universitetskiy-Tatiana significantly decreased during the main phase of geomagnetic storms (during the storms on May 8 and May 15 these decreases are clearly seen in Fig.4).

During the recovery phase of geomagnetic storms (and even several days after that) the relativistic electron flux of the outer ERB is pronouncedly increased, the electron's belt is widened and the belt maximum is shifted to smaller L. It is clearly seen in Fig.3 after the first weaker storm on May 8 in the data from both satellites. During the recovery phase the Earth's magnetosphere is slowly expanding again, and the outer radiation belt is forming much closer to the Earth. During the next days the belt comes back to its position before the storm.

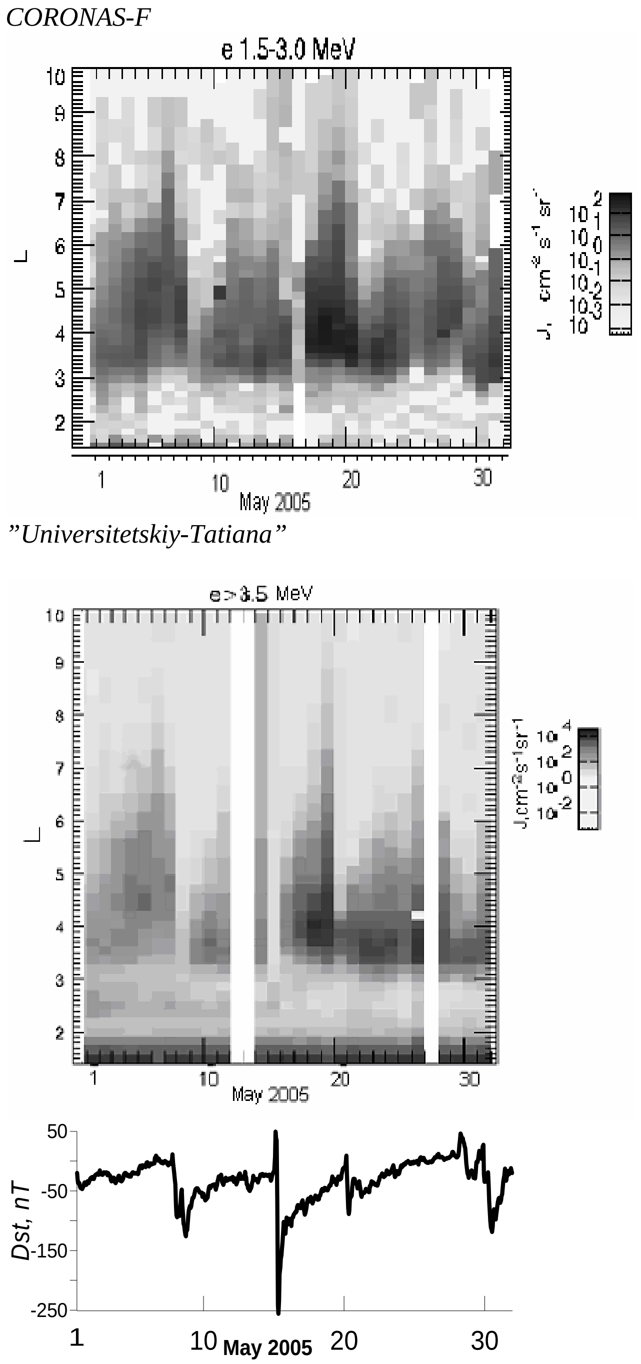

Fig.4. Relativistic electron flux variation in the outer ERB in May 2005 according to CORONAS-F (top panel) and "Universitetskiy-Tatiana" (middle panel) data. Bottom panel shows the Dst index.

Simultaneously, a significant increase of relativistic electron flux at L=4-5.5 was observed both at 350 km (CORONAS-F) and 1000 km (Universitetskiy-Tatiana). We observed this electron flux increase not only after the strong geomagnetic storm on May 15, but also after a significantly weaker storm on May 8 (see Fig.4). Therefore, significant changes in the outer ERB occur both during both strong and moderate magnetospheric disturbances.

We suppose that a strong reduction of the electron flux observed during the main phase of a geomagnetic storm is possibly connected to a strong reduction of the size of the Earth's magnetosphere, as discussed in [16].

Summary

Universitetskiy-Tatyana and CORONAS-F experiments permit us to measure the SEP penetration boundary variations during magnetic storms and to estimate the radiation damage for different space missions.

We found that the location of the SEP penetration boundary in the Earth's magnetosphere correlates well with the geomagnetic activity (e.g. Dst index) at altitudes both 350 and 1000 km.

We have observed the real disappearance of the outer ERB (electrons with the energy from 1.5 up to more than 3.5 MeV) during the main phase of a geomagnetic storm and a significant increase of relativistic electron flux at L=4-5.5 during several days after the recovery phase both at 350 km (CORONAS-F) and 1000 km (Universitetskiy-Tatiana). The comparison of CORONAS-F and Universitetskiy-Tatiana data provides us with the evidence that the observed variations of relativistic electrons flux in the outer ERB at low altitudes (from 350 to 1000 km) during and after geomagnetic storms are real and are not connected with the setup of experiments.

In conclusion, the experiments onboard CORONAS-F and Universitetskiy-Tatiana spacecraft are important for the space weather and space climate research.

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