Extreme values of solar proton penetration boundaries in the Earths magnetosphere

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***Abstract*—Solar proton penetration into the polar caps during the main phase of magnetic storm is one of the important sources of radiation danger in the near-Earth space. The size of the energetic particle penetration area depends on proton energy and on geomagnetic conditions. Low-altitude polar satellite experiments demonstrate that both the intensity of energetic solar particles and data concerning the boundaries of solar particle penetration in the Earth's magnetosphere are important for the estimation of possible SEP damage.**

Main goal of presented work was to find the possibility to estimate the extreme (the most low latitude) solar particle penetration boundary location during the strong magnetic storms using geomagnetic indices using CORONAS-F and "Universitetskiy-Tatiana" satellites measurements.

1. Introduction

THE studies of the of solar activity influence on the radiation conditions in the near-Earth's space remains one of the important problems of space physics till now.

It is known that if there is a magnetic storm during the solar cosmic ray (SCR) arrival to the Earth, then during its main phase and in the beginning of recovery one SCR get deeply enough into the Earth's magnetosphere.

Many researchers investigated the dynamics of penetration boundary (PB) during the magnetically quiet time. For example, the penetration boundary of protons with energies from 1.2 to 39 MeV was examined at Kp < 1 [1] and Kp<2 [2]. The relationship between the PB for protons with energies above 1 MeV and geomagnetic disturbances at different MLT was examined by authors of [3].

Solar particles can be used as test particles in the study of the magnetosphere [4]. From the other hand, the data about energetic proton PB dynamics and SCR spectra, measured by low-altitude polar satellites, allow to estimate a radiation dose which will be measured in high-altitude areas of an orbit by space stations, for example, for the International space station (ISS) [5]. The good agreement of experimental (measured on board ISS) radiation doses and calculated ones using the data about SCR spectra and their PB dynamics obtained in the experiment on board "Universitetskiy-Tatiana" satellite [6] in high-altitude areas has been shown in [7].

It is clear that, SCR PB locations were not measured for all SEP accompanied by a magnetic storm. Despite numerous attempts to describe SCR PB by means of geomagnetic indices at different level of geomagnetic activity (for example, [1-4]), the general formula allowing to describe them adequately using existing geomagnetic indices, is not created yet. Therefore working out of the technique, allowing to estimate the extreme (minimal) latitude on which solar protons can penetrate during a magnetic storm with known geomagnetic activity level (Dst and Kp indices), is a main objective of the presented paper.

The minimal latitudes of SEP penetration boundaries were detected in evening and night magnetic local time in different experiments [8-10] due to weaker intensity of the geomagnetic field on the night side, so only the data received in evening and night sector were used for the estimations of extreme SCR penetration boundaries.

2. Solar flares and magnetic storms - conditions of experiments

More then 50 solar particle events affecting the near-Earth's environment were observed from August, 2001 till March, 2007 in the experiments on board CORONAS-F and "Universitetskiy-Tatiana" satellites.

The most intensive SEP were measured during Solar Extreme Events periods of 2003 and 2005 years and during September and November 2001, April and August 2002, May and July 2003, November 2004, May and September 2005, December 2006.

Some of these SEP events were accompanied by the powerful geomagnetic storms (e.g. November 6, 2001 (Dst=-257 nT), November 24, 2001 (Dst=-221 nT), October 29-30, 2003 (Dst=-400 nT), November 7-8, 2004 (Dst =-374 nT)). During the main phases of these storms energetic solar particles have penetrate extremely deep into the Earth's magnetosphere – lower than 50 degrees of invariant latitude. The example of PB variations is presented in Fig. 1. They were measured during morning (open blue diamonds) and evening (closed violet diamonds) magnetic local time (MLT) sectors. Dst-variations are shown by black solid line. One can see that PB and Dst -variations strongly correlate.

We should note that even moderate magnetic storms with Dst about 150-250 nT observed during September 2001, April

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2002, July 2004 and May 2005 led to the SEP penetration rather deep in the Earth's magnetosphere – up to invariant latitudes about 55-57 degrees.

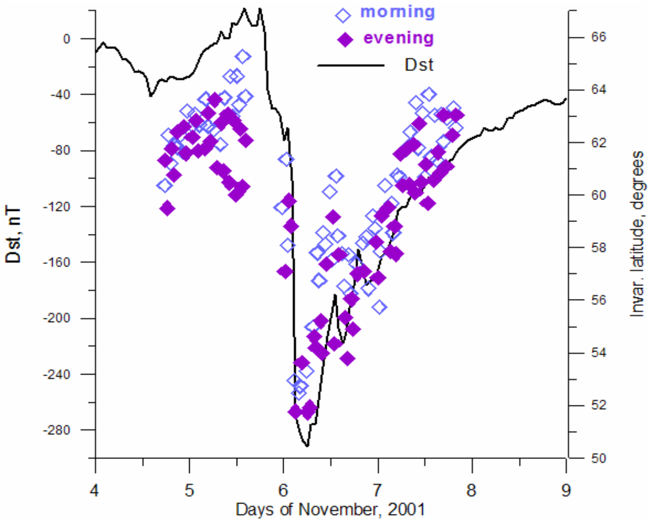

Figure 1. Boundaries of SCR penetration for 50-90 MeV protons (4-8 November, 2001) for morning and evening MLT sectors and Dst-variations.

2. EXPERIMENTS

A. CORONAS-F satellite

One of the 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 SEP events influence on the near-Earth's environment. CORONAS-F was launched to the orbit with initial altitude about 500 km and final one 350 km, the inclination 82.5^o. It operated from July 31, 2001 until December 12, 2005. The orbital period is 94.8 min. Protons with the energies 1-90 MeV were measured by semiconductor and plastic scintillator detectors in this experiment [11].

B. Universitetskiy-Tatiana satellite

«Universitetskiy-Tatiana» satellite was launched to the orbit with the initial altitude about 1000 km, inclination 83^o on January 20, 2005, and was operated until March, 08, 2007. The main scientific task of this satellite experiment was the monitoring of radiation conditions near the Earth. In this work we used data on protons with energies 2-100 MeV obtained by semiconductor detector (1000 mkm Si) and scintillation detector (CsJ(Tl) 15×20 mm) [6].

3. STATISTICAL STUDIES

At first only the extreme and strong magnetic storms were taken into account – ones with the maximum Dst-index amplitude exceeded 100 нT. During CORONAS-F operating time (since August 2001 till June 2005) 48 such storms occurred. Solar protons with the energies 1-5 MeV were observed in polar caps in experiment on board CORONAS-F during 22 storms and protons with the energies 50-90 MeV - during 14 ones.

Many different criteria exist for the analysis of the penetration boundary position. In this work the traditional criterion similar, for example, to [8-12] – "half of the maximum SEP flux" was used. The SCR PB was determined for each polar cap region crossing when the intensity of the SEP flux exceeded half of the maximal flux of SEP in this polar cap.

For these extreme data the correlation coefficient *Rcorr* of invariant latitude Λ with Dst was equal to 0.9 (1-5 MeV) and 0.84 (50-90 MeV) in evening and night sectors of magnetic local time MLT. The obtained Rcorr for Λ and Kp was lower, ~ 0.58-0.64.

Application of the multiple regression for estimation Λ dependence on values of both indices simultaneously (Dst and Kp) has shown that at the moment of a maximum of Dst-variation its value allows to estimate roughly Λ of SCR PB only with the help of this maximal Dst –variation value.

This fact can be explained due to presence of enough rigid connection between Kp and Dst at the moment of a maximum of a magnetic storm. Beside that Kp is measured each three hours whereas changes of SCR PB invariant latitude occur much faster.

However, the number of the investigated cases was rather small (22 and 14). To increase statistics a) «Universitetskiy-Tatiana» satellite data were included into consideration and b) we have used all SCR PB data, measured during the moments when the Dst-variation value was low than –150 nT. Thus, we have used the values of SCR PB measured during the main phase of the magnetic storms and in the beginning of the recovery phase.

The correlation plots of invariant latitude Λ of SCR PB with Dst-variation and Kp-index measured for evening and night sectors MLT are presented in figures 2 and 3.

In Fig. 2 and 3 PB locations for solar protons with the energy 1-5 MeV measured on board *CORONAS-F* are shown by open blue squares, ones with the energy 2-14 MeV («Universitetskiy-Tatiana») – lilac crosses, ones with the energy 50-90 MeV (*CORONAS-F)* – by closed black triangles and ones 40-100 MeV – by open green diamonds.

The results of more detailed correlation and regression analysis are presented in the next paragraph.

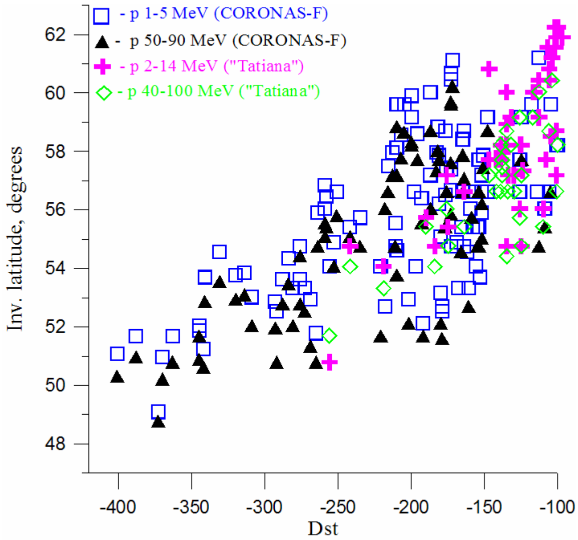

Figure 2. The correlation plot of invariant latitude Λ of SCR PB with Dst-variation.

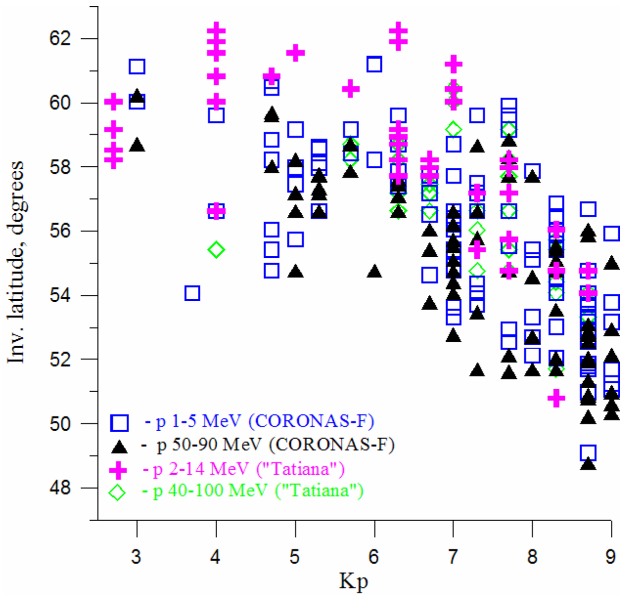

Figure 3. The correlation plot of invariant latitude Λ of SCR PB with Kp-index.

4. Correlation and Analysis

The results of linear correlation analysis SCR PB with Dst and Kp are presented in the tables 1 and 2. Since the data file of PB locations measured on board «Universitetskiy-Tatiana» is rather small (less than 50 SCR PB values for 1-5 MeV protons and 31 ones – 40-100 MeV protons), the regression coefficients were calculated for CORONAS-F data (105 and 78 SCR PB values) and total data file containing CORONAS-F and «Universitetskiy-Tatiana» data.

Invariant latitude Λ was calculated as $\Lambda = A + B*Dst$ and $\Lambda = A + B*Kp$, obtained values of *A*, *B*, and linear *Rcorr* are shown the tables 1 and 2.

One can see that the *Rcorr* values Λ with *Dst* are higher than

TABLE I
Regression coefficients of $\Lambda = A + B*D_{ST}$.

	N	R_{CORR}	A	B
p 1-5 MeV	105	0.65	60.8±0.6	0.024±0.003
Σ p 1-5 MeV & p 2-14 MeV	153	0.72	61.8±0.5	0.028±0.002
p 50-90 MeV	78	0.7	60.9±0.7	0.027±0.003
Σ p 50-90 MeV & p 40-100 MeV	109	0.73	60.7±0.5	0.026±0.002

TABLE II
Regression coefficients of $\Lambda = A + B*K_P$.

	N	RCORR	A	B
p 1-5 MeV	105	-0.66	63.6±0.9	-1.11±0.13
Σ p 1-5 MeV & p 2-14 MeV	153	-0.65	63.5±0.7	-1.03±0.10
p 50-90 MeV	78	-0.74	64.7±1.0	-1.40±0.14
Σ p 50-90 MeV & p 40-100 MeV	109	-0.66	64.8±1.0	-1.30±0.14

ones with *Kp*.

All values of *Rcorr* presented in tables 1 and 2 are distinct from zero with the good statistical significance (probabilities of their equality to zero are less than 0.1 percent). We should notice that correlation coefficients and the parameters of linear regression obtained earlier for extreme values (for minimum of Dst-variation) are in a good agreement within the specified errors coincide with ones presented in the tables 1 and 2. It demonstrates the possibility of a preliminary estimation of the extreme (minimal) latitudes of SCR PB at low latitudes with the help of value of Dst-variation in its minimum.

Nevertheless, after including into regression analysis the SCR PB data obtained before the magnetic storm maximum and during the recovery phase, it is useful to take into account not only Dst, but also Kp, responsible for geomagnetic activity at higher latitudes.

Results of multiple regression of invariant latitude Λ of SCR PB both from *Dst* and *Kp* are shown in table 3. Multiple regression of invariant latitude Λ was presented as $\Lambda = A + B*Dst + C*Kp$.

The comparison of tables 1, 2 and 3 shows that using of

TABLE III
Multiple regression coefficients of $\Lambda = A + B*Dst + C*Kp$.

	N	R_{CORR}	A	B	C
p 1-5 MeV	105	0.74	64.1±0.8	0.015±0.003	-0.72±0.14
Σ p 1-5 & 2-14 MeV	153	0.78	64.0±0.6	0.021±0.002	-0.58±0.1
p 50-90 MeV	78	0.81	65.3±0.9	0.016±0.003	-0.94±0.15
Σ p 50-90 & 40-100 MeV	109	0.82	65.2±0.8	0.019±0.002	-0.82±0.12

multiple linear regression (as it is should to expect) permits to increase correlation coefficients in comparison with ones of bivariate linear regression. The constant A represents in this case invariant latitude Λ on which solar protons penetrate in absence of significant geomagnetic activity.

In our earlier studies [12] the dynamics of the penetration boundary (PB) of solar energetic particles (electrons and protons) to the Earth's magnetosphere during the solar extreme events - solar flares and related geomagnetic disturbances in November 2001 and October-November 2003 was analyzed using also *CORONAS-F* data. The relationship between PB location and the geomagnetic activity indices was investigated for six different magnetic local time (MLT) intervals. It was obtained, that correlation coefficients between the invariant latitude Λ of SCR PB with Kp and *D*st indices for protons with energies from 1 to 5 MeV were higher in the night-side sector as compared to the dayside sector. Only the Λ-Kp correlation was observed in early evening hours. For protons with energies from 50 to 90 MeV, the correlation is high at all MLT.

The regression coefficients presented in this work are in good agreement with the results of [12] for night and evening MLT sectors, in spite of about one thousand cases of SCR PB were studied in [12], since all moments of solar proton penetration in the Earth's magnetosphere were used independently on Dst-variations value.

5. Conclusion

The *CORONAS-F* and *«Universitetskiy-Tatyana»* experiments due to their low polar orbits have demonstrated that for the estimation of possible SEP damage both the intensity of energetic solar particles and data concerning the boundaries of solar particle penetration in the Earth's magnetosphere are very important. High energy solar particle penetration in the polar caps during the main phase of magnetic storms is an important source of radiation danger in the near-Earth space, especially for low-altitude satellites.

The experiments on board *CORONAS-F* and *«Universitetskiy-Tatyana»* satellites permit us to measure SCR penetration boundary variations during magnetic storms and to use obtained experimental data for the creation of empirical model.

It was obtained that extreme locations of solar protons penetration boundaries, measured near the geomagnetic storm maximum in evening and night sectors MLT, can be described with the help of geomagnetic indices Dst and Kp with sufficient reliability.

The maximal amplitude of Dst-variation is sufficient for preliminary estimation of extreme location of SCR penetration boundaries observed in night-evening MLT sector during the strong magnetic storms.

Acknowledgments

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