The geometry of relativistic electron fluxes maxima during strong magnetic storms time according CORONAS-F data.

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***Abstract* - We investigated relativistic (0.6-1.5 MeV) electron fluxes dynamic in outer radiation belt using MKL device measurements on CORONAS-F satellite within intervals of 31 strong magnetic storms during years 2001-2005. We obtained some characteristic parameters of Dst index, the most earthward position of electron fluxes maximum L_{max} and maximal fluxes of these electrons during individual magnetic storms, which characterize the dynamic and the geometry of relativistic electrons. The average earthward velocity of radial shift during the main storm phase is higher by factor 2 in comparison with the velocity of the outer radiation belt maximum return. As result we got superposed relativistic electrons geometry, typical for geomagnetic storm period.**

1. INTRODUCTION

The outer electron radiation belt is populated by relativistic electrons, strongly enhanced following some geomagnetic storms. These ~1 MeV electrons are called killer electrons, because they represent a serious potential hazard to orbiting satellites, space stations and humans in space. In this paper we investigated relativistic electrons with energies 0.6 - 1.5 MeV, during 31 strong magnetic storms (Dst < -100 nT) [1], measured by MKL device (complex SKL) on CORONAS-F satellite during years 2001-2005. A short description of SKL complex measuring the energetic particles can be found in [2].

2. ANALYSIS OF EXPERIMENTAL RESULTS

For all magnetic storms we analyzed the L profiles of relativistic (0.6 - 1.5 MeV) electrons in the time of CORONAS-F (low altitude ~500 km polar orbiting Russian satellite), crossing the outer radiation belt. Trapped radiation is described by particle fluxes as function of energy and of the geomagnetic co-ordinates L and B. The L is radial distance of the field line from the axis at the geomagnetic equator and B is the magnetic field strength. For correct comparison we selected the orbits when satellite crossed the same line in L-B space. This comparison is possible only with one day step.

Figure 1 displays L profiles of relativistic electrons around the geomagnetic storm on November 5, 2001: before storm onset (a), at the beginning of recovery phase (b), at the end of recovery phase (c) and after the end of this storm (d). This figure illustrates the typical outer radiation belt relativistic electron dynamics. The pre-storm position of electron fluxes maximum was around L ~ 4 Re (Earth's radii). During geomagnetic storm it is shifted to L ~ 3 Re and after storm it returned to the pre-storm position with lower intensity. Time behavior of *Dst* index, the maximum 0.6 - 1.5 MeV electron fluxes position and maximal electrons fluxes around that geomagnetic storm are plotted in the Fig. 2. This storm had $|Dst_{max}|$ = 292 nT and it rank among severe storms with *Dst* between -200 nT and -350 nT. Some parameters, which we studied in all researched geomagnetic storms, are also marked in this figure. They characterize the dynamics and the geometry of relativistic electron population regions in outer radiation belt during individual geomagnetic storms. Mainly there are the beginning time of main phase of magnetic storm t_b, the time of the *Dst* maximum value t_{Dst}, the time of L_{max} position, t_{max}, the time of the storm recovery phase end t_r, the minimum flux of 0.6 - 1.5 MeV electrons in the time of main phase I_{min}, the maximum flux of these electrons during the recovery phase I_{max}, the time shift of I_{max} position according to the beginning of storm main phase Δt_f, the positions of electron flux maximum L_b, L_{Dst} and L_r in the times t_b, t_{Dst} and t_r resp., the most Earth-ward position of electron fluxes maximum L_{max}, the time shift between $|Dst_{max}|$ and L_{max} positions Δt_{max} and the time shift between L_{max} position and the end of recovery phase of geomagnetic storm Δt_2. All parameters for studied geomagnetic storms are listed in Tables 1 and 2. The Table 1 contains the day and the hour (in UT) of storm main phase beginning t_b, the maximum value of *Dst* index during this storm Dst_{max}, the minimal value of relativistic electrons with energies 0.6-1.5 MeV maximum position L_{max} and its calculated value according to the Tverskaya formula [3], class of single storms using Loeve and Prölss, classification (ST-strong, SE-severe G-great and MO-moderate storms) [1], t_{Dst}, Δt_{max}, Δt_2, I_{min}, I_{max} and Δt_1 values and also the maximum fluxes of >0.5 MeV and >2 MeV electrons measured in the geostationary orbit by GOES-10 satellite in the time of main storm phase. These data are completed by parameters of interplanetary magnetic field (IMF) and solar wind plasma during the time of main storm phase. There are the magnetic field module $|B|$, its B_z component magnitude together with the plasma speed w_p and density n_p measured on ACE satellite and by solar wind speed in the time of main storm phase w_{sw} measured on SOHO satellite.

On the Figure 3 L of peak-flux of the storm relativistic electrons with energies 0.6-1.5 MeV L_{max} measured by CORONAS-F during 31 studied magnetic storms are given against amplitude of a magnetic storm $|Dst_{max}|$. The result of this dependence according empirical formula proposed by Tverskaya is indicated by full lines.

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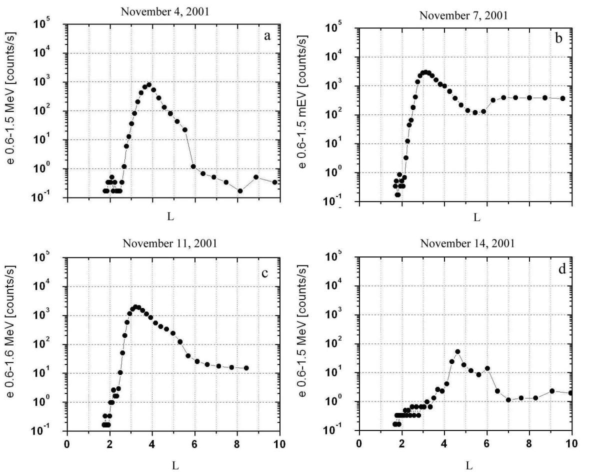

Fig. 1. The radial profiles of relativistic 0.6 - 1.5 MeV electrons fluxes (e fluxes) during the period including the geomagnetic storm on November 5, 2001.

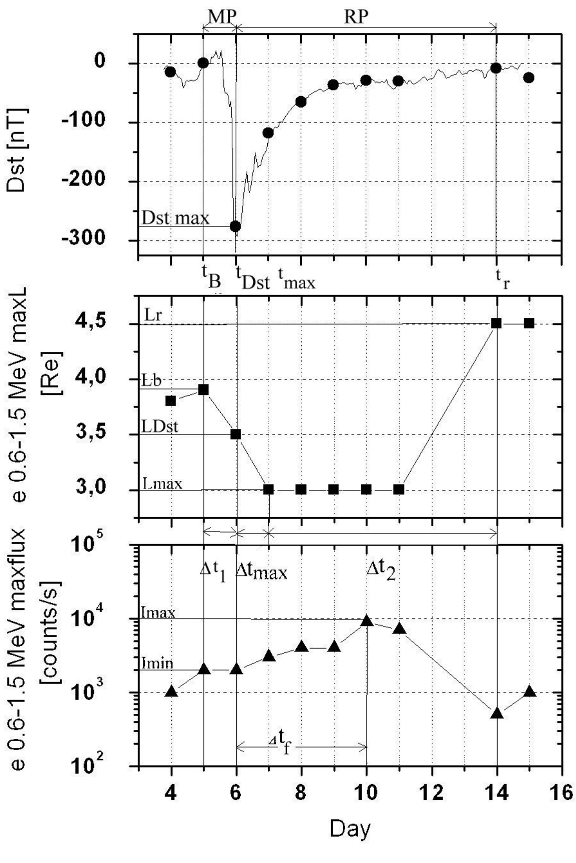

Fig. 2. The example of the typical time behavior of *Dst* index, the position of maximum of 0.6 -1.5 MeV electron fluxes and maximal fluxes of these electrons around the November 5, 2001 geomagnetic storm (MP - main phase of the storm; RP - recovery phase of the storm).

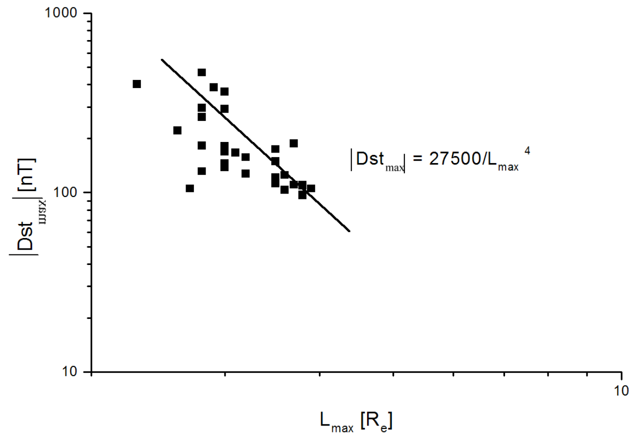

Fig.3 The dependence between Dst index and relativistic electron flux maximum position L_{max} . The solid line shows values according to the empirical formula $|Dst_{max}| = 27500/L_{max}^4$, proposed by Tverskaya [3].

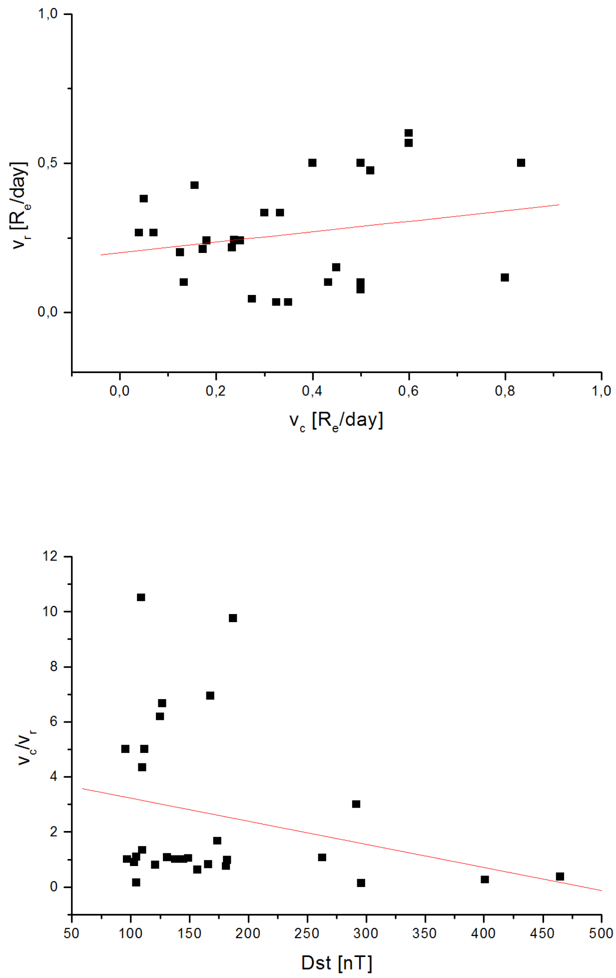

Fig.4. The dependences of the average Earth-ward velocity of the electron maximum shift v_c and its return velocity v_r (a) and the dependence between v_c / v_r proportion and Dst (b) for all 31 investigated magnetic storms. The solid lines represent the best linear fits.

Data and time of main phase beginning t_B	Dst_{max} [nT]	Lmax exp/cal [R_E]	CLASS	t_{Dst} [day/hour]	Δt_{max} [in days]	Δt_2 [in days]	CORONAS F 0.6-1.5 MeV electron fluxes			GOES-10 electron fluxes		ACE IMF and plasma parameters				SOHO solar wind
							Imax [counts/s]	Imin [counts/s]	Δt_f [in days]	E_e>0.5 MeV [/cm^2.s.sr]	E_e>2 MeV [/cm^2.s.sr]	B [nT]	B_z [nT]	w_p [km/s]	n_p [1/cm^3]	w_{sw} [km/s]
25.09.2001/02	-166	3.1/3.6	ST	03.10./15	3	9	3.10^4	4.10^3	4	4.10^5	10^4	45	-30	550	10	750
21.10.2001/19	-187	3.7/3.5	ST	22.10./22	2	9	3.10^3	2.10^2	7	10^4	10^1	30	-20	600	10	700
28.10.2001/05	-157	3.2/3.6	ST	28.10./12	2	4	10^4	10^3	7	5.10^4	10^1	20	-20	450	10	500
05.11.2001/21	-292	3.0/3.1	SE	06.11./07	1	10	10^4	2.10^3	5	10^4	10^3	80	-80	-	-	>750
24.11.2001/18	-221	2.6/3.3	SE	24.11./17	5	1	5.10^4	10^4	3	4.10^4	10^2	60	-40	850	2	>750
11.05.2002/13	-110	3.7/4.0	ST	11.05./20	2	5	10^4	2.10^3	2	10^3	2.10^2	20	-20	400	7	500
23.05.2002/13	-109	3.8/4.0	ST	23.05./18	1	2	10^4	10^3	2	3.10^3	10^3	60	-40	800	1	750
04.09.2002/01	-109	3.8/4.0	ST	04.09./06	1	3	2.10^4	10^3	1	10^3	10^1	20	-20	500	10	-
07.09.2002/16	-181	3.0/3.5	ST	08.09./01	3	5	2.10^4	10^4	2	10^5	3.10^2	25	-25	450	20	580
01.10.2002/05	-176	3.5/3.6	ST	01.10./17	1	2	10^4	10^2	6	5.10^3	3.10^2	25	-15	400	20	500
29.05.2003//20	-131	2.8/3.8	ST	30.05./03	2	6	3.10^4	2.10^4	2	5.10^4	5.10^3	35	-20	700	20	>750
18.06.2003/03	-145	3.0/3.7	ST	18.06./10	2	2	4.10^4	10^4	1	10^5	10^3	20	-15	600	15	580
18.08.2003/16	-168	3.0/3.6	ST	18.08./02	0.5	13	3.10^4	10^2	0	2.10^5	10^3	25	-20	460	5	460
28.10.2003/17	-363	3.0/3.0	G	30.10./01	1	-	5.10^3	2.10^3	1	2.10^4	10^3	60	-60	>1500	-	>750
30.10.2003/19	-401	2.5/2.9	G	30.10./23	1	9	2.10^4	5.10^3	-	5.10^5	10^2	40	-20	>1500	-	>750
20.11.2003/04	-465	2.8/2.8	G	20.11./20	1	4	10^4	2.10^3	4	10^5	10^2	50	-50	600	20	750
22.01.2004/06	-149	3.5/3.7	ST	22.01./14	2	5	3.10^4	8.10^3	3	10^5	10^3	30	-20	650	10	700
03.04.2004/16	-112	3.5/4.0	ST	04.04./01	1	5	10^4	10^3	3	10^4	10^2	10	-5	500	30	500
22.07.2004/20	-182	2.8/3.5	ST	27.07./14	2	7	2.10^4	10^2	2	10^5	10^1	20	-5	600	5	400
30.08.2004/02	-125	3.6/3.9	ST	30.08./22	3	9	10^4	10^3	2	10^4	10^2	12	-15	420	-	400
07.11.2004/22	-384	2.9/2.9	G	08.11./04	2	-	4.10^4	10^3	1	10^4	10^3	40	-40	700	10	>750
09.11.2004/12	-296	2.8/3.1	SE	10.11./11	3	4	10^4	10^3	6	3.10^5	2.10^3	40	-20	750	5	>750
07.01.2005/13	- 96	3.8/4.1	MO	08.01./03	1	3	4.10^3	10^3	2	9.10^5	9.10^3	20	-20	543	21	654
18.01.2005/00	-121	3.5/3.9	ST	18.01/09	0.5	1	3.10^4	10^4	1	10^5	2.10^3	20	-20	-	-	845
21.01.2005/20	-105	2.7/4.0	ST	22.01/07	0.5	4	2.10^4	5.10^3	1	7.10^3	6.10^1	40	-30	935	23	1004
07.05.2005/21	-127	3.2/3.8	ST	08.05/19	2	5	2.10^4	$2. 10^2$	3	5.10^4	10^3	20	-15	831	32	782
15.05.2005/06	-263	2.8/3.2	SE	15.05/09	1.5	3	3.10^4	10^3	1	10^4	-	80	-50	944	11	814
20.05.2005/05	-103	3.6/4.0	ST	20.05/09	2	3	3.10^3	2.10^2	2	2.10^4	10^1	15	-10	478	19	496
29.05.2005/23	-138	3.0/3.8	ST	30.05/14	1.5	4	10^4	3.10^3	1	$5. 10^4$	5.10^2	20	-20	503	13	477
12.06.2005/19	-105	3.9/4.0	ST	12.06/23	0.5	3	10^4	10^3	1	10^6	10^3	20	-18	490	5	465
22.06.2005/20	- 97	3.8/4.1	MO	23.06./11	0.5	1	5.10^3	10^2	1	2.10^5	9.10^2	20	-10	417	92	467

Table 1. Parameters of 31 studied geomagnetic storms

Geomag.storm	Dst_{max} [nT]	L_b [R_e]	L_{Dst} [R_e]	L_{max} [R_e]	L_r [R_e]	Δt_1 [days]	Δt_{max} [days]	Δt_2 [days]	v_1 [R_e/day]	v_2 [R_e/day]	v_c [R_e/day]	v_r [R_e/day]
25.09.2001	-166	5	4	3.1	5	8	3	9	0.125	0.300	0.173	0.211
21.10.2001	-187	5	3.8	3.7	4	2	2	9	0.6	0.050	0.325	0.033
28.10.2001	-157	3.7	4.5	3.2	4	2	2	4	-	0.65	0.125	0.2
05.11.2001	-292	3.9	3.5	3	4.5	1	1	10	0.4	0.5	0.45	0.15
24.11.2001	-221	5.5	3.4	2.6	2.6	3	5	1	0.7	0.16	0.363	-
11.05.2002	-110	5	4	3.7	4.2	1	2	5	1	0.15	0.433	0.1
23.05.2002	-110	4.2	4.5	3.8	4	2	1	2	-	0.7	0.133	0.1
04.09.2002	-109	4.5	3.9	3.8	3.9	1	1	3	0.6	0.1	0.35	0.033
07.09.2002	-181	3.9	3.3	3	4.2	2	3	5	0.3	0.1	0.18	0.24
01.10.2002	-174	6	4.8	3.5	4.5	2	1	2	0.6	1.3	0.833	0.5
29.05.2003	-131	3.5	2.9	2.8	4.1	2	1	6	0.3	0.1	0.233	0.217
16.06.2003	-145	5	3.2	3	4	2	2	2	0.9	0.1	0.5	0.5
18.08.2003	-168	5	3.1	3	4.5	2	0.5	13	0.95	0.2	0.8	0.115
28.10.2003	-363	5	3.5	3	3	16	1	-	0.094	0.5	0.118	-
30.10.2003	-401	3	2.5	2.3	4.7	9	1	9	0.056	0.2	0.07	0.267
20.11.2003	-465	4.2	2.9	2.8	4.5	8	1	4	0.163	0.1	0.156	0.425
22.01.2004	-149	4.5	3.6	3.5	4.7	2	2	5	0.45	0.05	0.25	0.24
03.04.2004	-112	4.5	3.9	3.5	4	1	1	5	0.6	0.4	0.5	0.1
22.07.2004	-182	4.7	3.2	2.8	4.5	6	2	7	0.25	0.2	0.238	0.243
30.08.2004	-125	4.7	3.7	3.6	4	3	1	9	0.333	0.1	0.275	0.044
07.11.2004	-384	5.2	3	2.9	-	1	2	-	2.2	0.05	0.767	-
09.11.2004	-296	3	2.9	2.8	4.7	1	3	5	0.1	0.333	0.05	0.38
07.01.2005	-96	4.8	4	3.8	4.1	1	1	3	0.8	0.2	0.5	0.1
18.01.2005	-121	4.5	3.7	3.5	4	2	0.5	1	0.4	0.4	0.4	0.5
21.01.2005	-105	4	3.5	2.7	4.6	2	0.5	4	0.25	1.6	0.52	0.475
07.05.2005	-127	4.7	3.7	3.2	3.5	1	2	4	1	0.25	0.5	0.075
15.05.2005	-263	4.3	3.9	2.8	4.5	1	1.5	3	0.4	0733	0.6	0.567
20.05.2005	-103	4.5	4.8	3.6	4.6	1	2	3	-	0.6	0.3	0.333
29.05.2005	-138	4.5	4.1	3	4	3	1.5	3	0.133	0733	0.333	0.333
12.06.2005	-105	4	3.95	3.9	4.7	2	0.5	3	0.025	0.1	0.04	0.267
22.06.2005	-97	5	4.4	3.8	5	1	1	2	0.6	0.6	0.6	0.6

Table 2. Some parameters of relativistic electron fluxes maximum geometry for single storms during the geomagnetic storm period.

We calculated the average velocity of outer radiation belt electron maximum shift during the main storm phase (time interval Δt_1) to the Earth direction v_1, the average velocity of the electron maximum shift to the Earth direction during whole Δt_{max} time interval v_2, the total velocity of the electron maximum shift to the Earth direction v_c and average velocity of the electron maximum return to the prestorm position during the time interval Δt_2 v_r. Table 2 contains some parameters of relativistic electron maximum geometry. There are in addition to date and strength of single magnetic storms the positions of their maxima L_b, L_{Dst}, L_{max}, and L_r in the times t_b, t_{Dst}, t_{max} and t_r resp., time intervals Δt_1, Δt_{max}, Δt_2 and average velocities of outer radiation belt electron maximum shift during single storm phases v_1, v_2, v_c and v_r.

Figure 4 shows the dependences of the average earthward velocity of the electron maximum shift v_c and its return velocity v_r (a) and the dependence between v_c / v_r proportion and Dst (b) for all 31 strong magnetic storms.

3. RESULTS AND CONCLUSION

We analyzed 31 strong magnetic storms (Dst < -100 nT) [2] measured by MKL device on CORONAS-F satellite during years 2001-2005. We investigated the dynamic of relativistic electrons with energies 0.6-1.5 MeV during single phases of these storms.

The location of relativistic electron maxima L_{max} in the time of main storm phase depends on the geomagnetic storm strength, represented by minimal values of Dst index Dst_{max} according to the empirical formula $|Dst_{max}| = 27500/L_{max}^4$ proposed by Tverskaya [3]. This dependence describes good the maximum of relativistic electrons location during single geomagnetic storm times. The most differences between experimental and theoretical values of L_{max} were find for storms at May, 29 2003, October 30, 2003 and January 21, 2005. There are the typical multi-step storms, in which already during main storm phase was position of their electron maximum relatively close to the Earth (3-3.5 Re) owing to previous magnetic storms influence.

The outer radiation belt maximum shifts during the main storm phase to the Earth direction with the average velocity v_1 = 0.51 Re/day. After time t_{Dst} the shift to the Earth is slower with the average velocity v_2 = 0.36 Re/day during whole Δt_{max} time interval. After the achievement of it's nearest to the Earth position L_{max} in the time t_{max}, the outer radiation belt maximum returns to the pre-storm position with average velocity v_r = 0.26 Re/day during the second part of recovery storm phase.

The total average velocity of the outer radiation belt maximum in Earth direction v_c and their return average velocity v_r are depend each other and also are depend on magnetic storm strength which we can demonstrate by high correlation between v_c /v_r proportion and Dst and L_{max}.

The average values of parameters which characterize the geometry of outer radiation belt electron maxima presented for single magnetic storms in Table 1 and Table 2 are: v_1 = 0.51 Re/day, v_2 = 0.36 Re/day, v_c = 0.38 Re/day, v_r = 0.26 Re/day, t_1=2.93 day, t_{max}=1.58 day, t_2=4.86 day, t_f=2.4 day, Dst $_{min}$ = -186 nT, L_b= 4.49 Re, L_{Dst}= 3.68 Re, L_{max}= 3.22 Re, L_r= 4.28 Re, I_{min} = 3355 counts/s and I_{max} = 18065 counts/s. Their use enable to us to sketch superposed relativistic electron fluxes geometry in the time of strong geomagnetic storm (see Fig.5).

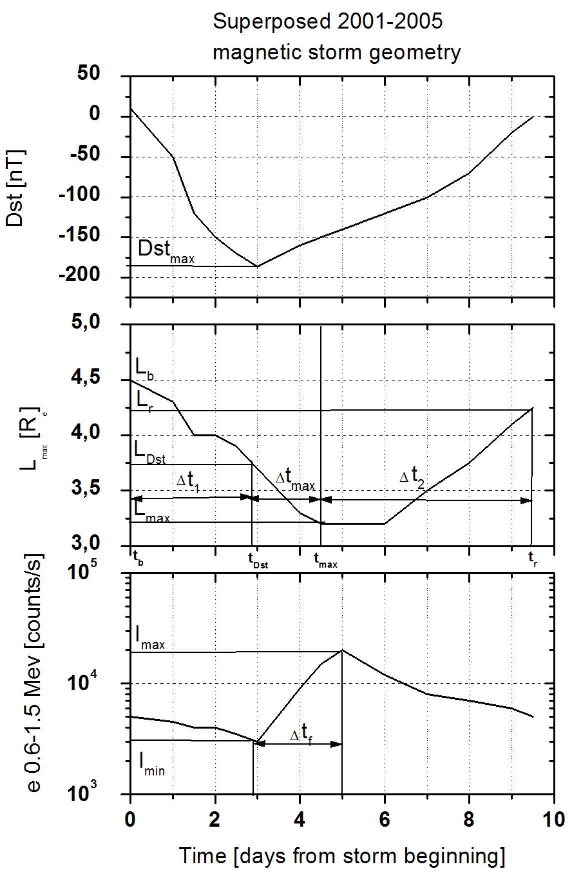

Fig.5 The sketch of the superposed relativistic electron fluxes geometry in the time of strong geomagnetic storm.

We can see from the Table 2 , that the typical value of relativistic electron maxima position during the main phase of magnetic storm is L_b= 4-5 Re. Lower values of L_b (for October 30, 2003 or November 9, 2004 storms) were caused probably by previous magnetic storms, after that the electron fluxes maxima didn't catch to return in the location typical for quiet time geomagnetic period. Thus behavior is characteristic for "two-step" or "multi-step" magnetic storms.

In the time t_{Dst} (the time, when Dst index get the minimum value Dst $_{min}$) is the maximum position L_{Dst} > L_{max} e.g. the maximum position of L (L_{max}), which created on the beginning of the recovery storm phase. The value of L_{max} depends on magnetic storm strength and also on its character (single or multi-step).

The return of relativistic electron maxima realized during all the recovery storm phase and in some events (e.g. October 28, 2003) don't catch the values $L_r \geq 4$ Re typical for quiet geomagnetic period, mainly owing to next geomagnetic storm, which main phase merged in the time with the recovery phase of previous magnetic storm.

The fluxes of 0.6-1.5 MeV electrons increase during recovery storm phase about 1-2 orders in comparison with their minimum value.

The solar wind velocity in the time of single geomagnetic storms was from 400 to 1000 km/s and B_z component of IMF has the southward orientation and it ranges from -5 nT to -80 nT.

The strong magnetic storms accompanied by high shift of relativistic electron fluxes on the radial distance L_{max} < 3 Re are characteristic by high velocity of solar wind $v_{sw} \geq 600$ km/s, and also by southward orientation of IMF with B_z component between -15 nT and -80 nT. During these magnetic storms the high fluxes of relativistic electrons were registered on the geostational satellite GOES-10 (see Table 1). The detailed analysis of these selected storms shows the better correlation between v_c and v_r velocities and also between v_c /v_r proportion and Dst in comparison with others magnetic storms.

ACKNOWLEDGEMENT

The author thanks all the providers of ACE, GOES, SOHO and geomagnetic data. This work was supported also by the VEGA Grant agency; project 4064 .

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