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Magnetospheric response to magnetic clouds: multi-satellite observations during 1995-1998

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Abstract. On the basis of ISTP spacecraft and ground observations during first 40 months of INTERBALL operation in 1995-1998 we study magnetosphere response to magnetic cloud passages including geomagnetic storms and polar activations. During this time 35 magnetic clouds were measured in the solar wind which resulted in 14 from 19 strong (peak D_{st} $<$ -100 nT) magnetic storms observed at the ground stations. The low and moderately high changes in magnetic cloud IMF and solar wind parameter variations result in the usual magnetosphere response to the similar changes without magnetic cloud passages. Extremely high jumps of parameters in the magnetic clouds generate unusual response: (1) strong and complicated magnetospheric compression and deformation relative to average locations; (2) large-amplitude oscillations of geomagnetic tail structures past satellites, and (3) acceleration of ions and electrons in the plasma sheet and their injections in the polar regions. During magnetic clouds the value of peak $|D_{st}|$ correlates with number of polar activations, and the same dependence is observed for strong magnetic storms.

Key words. Magnetic cloud, magnetosphere, magnetic storms and substorms

1 Introduction

One of the main problems of solar-terrestrial physics concerns which magnetospheric responses are caused by different variations in the solar/interplanetary medium. This problem plays a key role in our understanding of geophysics. Also, this knowledge has a practical application in many areas of mankind's activity.

Many papers describe the processes of solar wind energy input into the magnetosphere and the development of magnetospheric disturbances in response (see, e.g. (Gonzales *et al.* (1994, 1999); Kamide *et al.* (1998); Petrukovich and Klimov (2000); Wilson (2000) and references therein). It was shown that the existence of southward component of the interplanetary magnetic field (IMF) results in the input of solar wind energy to the magnetosphere and its accumulation in the magnetic tail. When this energy reaches a sufficient level it can be released by the reconfiguration of current systems and as plasma acceleration or heating, which results in the magnetospheric disturbances, such as magnetic storms and substorms.

Another group of investigators has studied selected events in the solar atmosphere, in the interplanetary space and in the magnetosphere and correlations between these events (see, e.g. Gosling *et al.* (1991); Webb (1995); Tsurutani *et al.* (1995); Crooker (2000) and references therein). They found that geoeffective events (in the sense that they can cause geomagnetic storms) in the interplanetary space include magnetic clouds (MC), which are interplanetary manifestation of the coronal mass ejections, and corotating interaction regions (CIR) derived from the interaction of fast and slow streams in the solar wind. MCs and CIRs are often geoeffective because they are faster than the ambient plasma and compress any southward IMF in the vicinity of their edges or inside the event. However, the measurements both during maximum (Gosling *et al.*, 1991) and minimum (Yermolaev *et al.*, 2000a,b) of the solar cycle showed that not all MCs are geoeffective. Thus, influence of MCs on the magnetosphere calls for further investigations.

Correlation of MC passages with polar magnetospheric disturbances is not sufficiently studied yet because these disturbances have characteristic time of several tens minutes and they should be compared not with the magnetic cloud as a whole, but with its separate structures and disturbances. These include the interplanetary shock (IS) before MC, the leading and trailing edges (LE and TE) of MC, the IS before TE, the jump of plasma pressure, the changes in IMF magnitude and orientation. It is also important to study the displacement of magnetospheric boundaries (including the bow shock and magnetopause) under these unusual interplanetary conditions. Such an analysis of several strong magnetic clouds has already been done on the basis of multi-satellite INTERBALL project (Yermolaev *et al.*, 1997a, 1998, 2000a,b), and here we summarize the results of our analysis on the basis of full statistics of magnetic clouds during the first 40 months of INTERBALL observations (August, 1995 - De-

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cember, 1998). We limited our study to the time interval of relatively low solar activity before the maximum of the solar cycle.

2 General view of interval

It is known that substantial variations occur over the 11-year solar cycle in disturbances of solar wind and Earth's magnetosphere. We study the time interval in the vicinity of minimum (1996) and the growth phase of the cycle. To evaluate magnetospheric disturbances the geomagnetic indices measured at the ground stations are usually used. The D_{st} index, which connects with the geomagnetic field near the equator and the disturbance of the ring current, adequately describes the development of the global large-scale disturbances - magnetic storms.

Figures 1 - 3 show hour-averaged values of D_{st} index (http:// spidr.ngdc.noaa.gov) during 47 solar rotations (40 months from August, 1995 to December, 1998). Large magnetic storms (peak D_{st} $\leq$-100 nT) are indicated by red triangles. There were 19 large storms, and their number slightly increased in the end of interval, closer to the maximum of solar cycle. This tendency is confirmed by D_{st} index data for 1999-2000 period when there were 17 strong magnetic storms during 24 months (Yermolaev , 2001).

To analyze interplanetary conditions for magnetic storms we use the key parameters of plasma and magnetic field measured by WIND (Ogilvie *et al.*, 1995; Lepping *et al.*, 1995) and, in some cases, by the other spacecraft (SOHO and IMP-8) (http://cdaweb.gsfc.nasa.gov). Green and brown horizontal lines in top of panels present time intervals of MC and CIR observations, respectively, and red vertical lines IS preceding them. Characteristic behavior of plasma and magnetic field in MC and CIR has been previously discussed in the literature and may be found in papers by Gosling and Pizzo (1999) and Crooker (2000). MCs are characterized, among other features, by high and rotating magnetic field, and low density and temperature. We will not present the total SW and IMF data sets and show only results of our analysis. Figures 1 - 3 show that the 19 large storms were connected with 14 magnetic clouds and 5 corotating interaction regions. At the same time the analysis of data indicated at least 35 MCs during August, 1995 - December, 1998. A part of them was studied earlier (Yermolaev *et al.*, 1998, 2000a,b), another part was added from the list of coronal mass ejections (Gopalswamy *et al.*, 2000), and a part was selected recently. Thus we compare MCs connected with magnetic storms in wide range of D_{st}.

The list of events considered is presented in Table 1, which includes the date and duration of MC observations (the interval between MC IS and LE is indicated additionally in brackets). Also indicated here are the regions of space in which the INTERBALL/Tail Probe (INTERBALL-1 hereafter) satellite was situated: SW is the solar wind, MSH - the magnetosheath, MS - magnetosphere (the tail lobes, plasma and neutral sheets, mantle, LLBL and PSBL). As seen from Table 1, INTERBALL-1 was in different regions of the magnetosphere and measured the parameters of plasma, magnetic field and energetic particles there. The INTERBALL/Auroral Probe (INTERBALL-2) satellite with a low-apogee 6-hour orbit measured various parameters in the polar magnetosphere. Owing to a variety of satellite locations at the time MC passages, we have a possibility of investigating the different magnetospheric regions under different solar wind conditions.

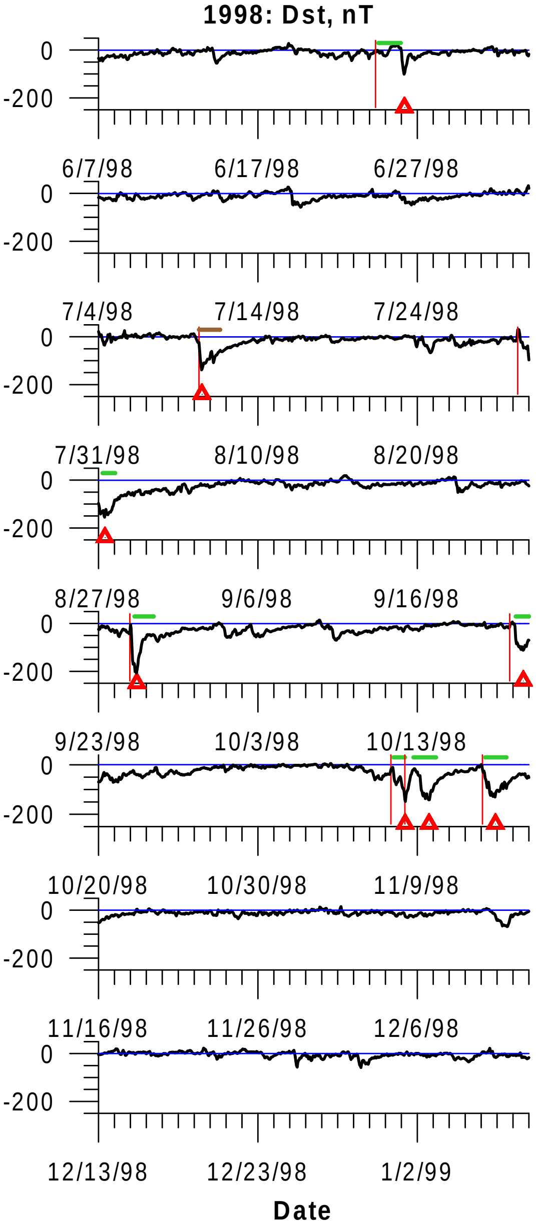


Fig. 3. One-hour averaged D_{st} variations for June - December, 1998

3 Geoeffectiveness of magnetic clouds

As indicated in Figures 1 - 3, the magnetic storm durations are close to those of the magnetic cloud. For instance for January 10-11, 1997 magnetic cloud (Burlaga *et al.*, 1998), duration of magnetic storm and magnetic cloud were ∼18 h and

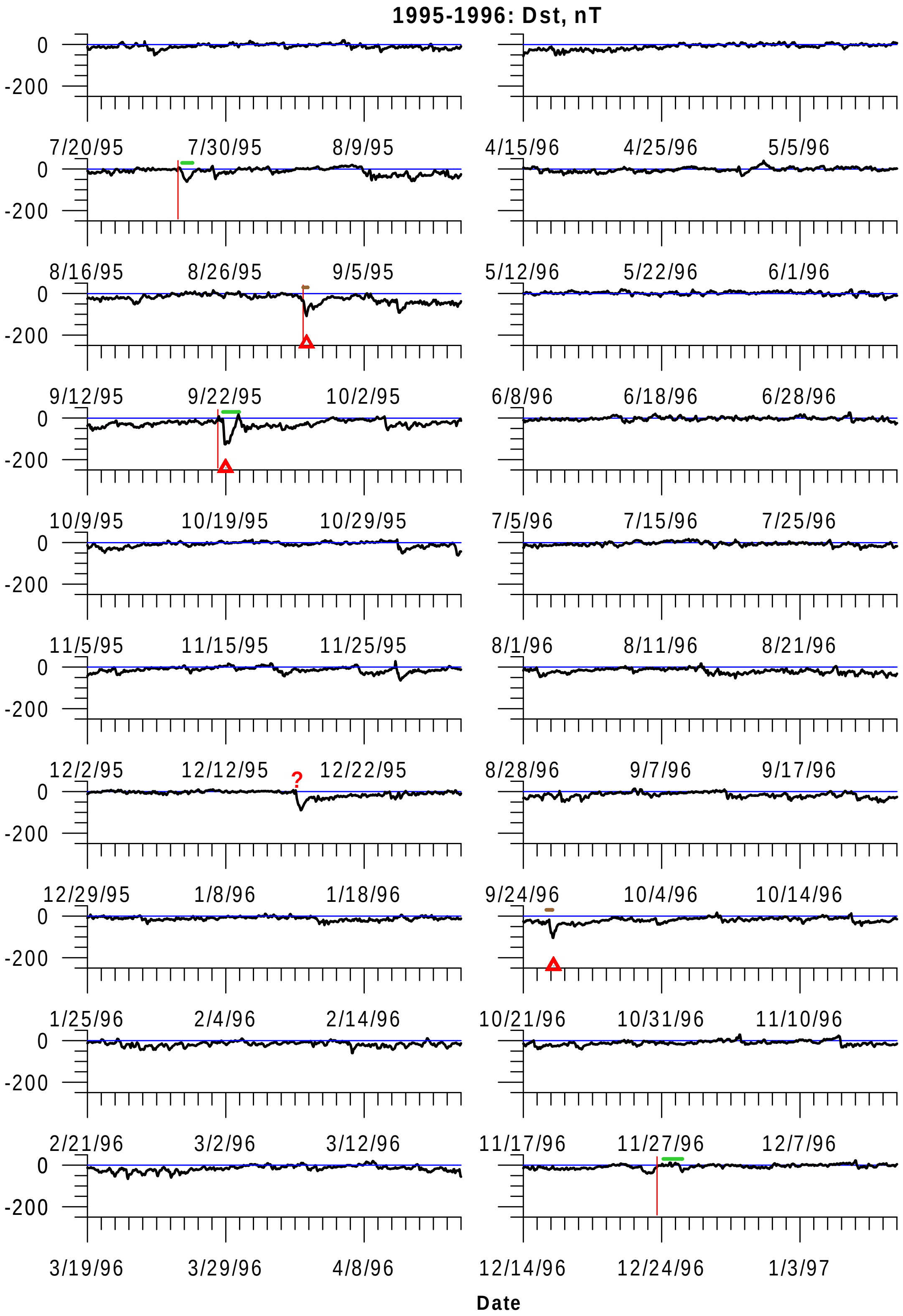


Fig. 1. One-hour averaged D_{st} variations for August, 1995 - December, 1996

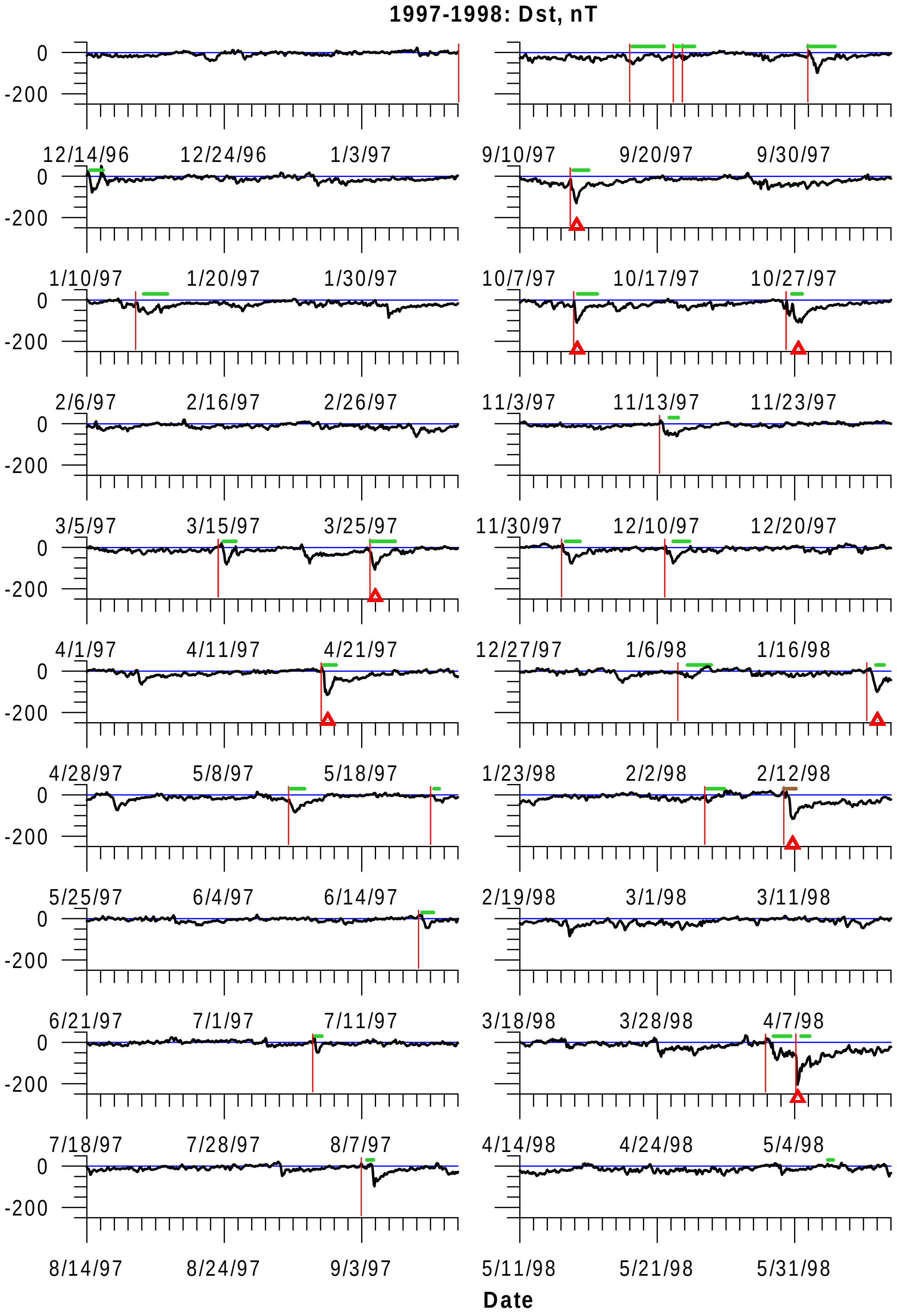


Fig. 2. One-hour averaged D_{st} variations for January, 1997 - May, 1998

Table 1. Magnetic clouds observed on INTERBALL-1 as well as on WIND (*) and SOHO+IMP-8 (**).

N	Date	Durations, h		Space regions by	Conditions in SW
		MC	(+ Shock)	INTERBALL-1	
	1995				
1	Aug.22-23 *	19	(+7)	MS/MSH/SW	B_z and P jumps
2	Oct.18-19 *	28	(+8)	MS/MSH/MS	B_z variations
	1996				
3	Dec.24-25 *	33	(+10)	MS/MSH/MS	P jumps
	1997				
4	Jan.10-11 *	23	(+4)	MS/MSH/MS	SW with N ~150 cm^{-3}
5	Feb. 9-11 *	41	(+14)	SW/MSH/MS/MSH/SW	$B_z < 0$
6	Apr.10-11 *	22	(+9)	SW	Sharp B_z changes
7	Apr. 21-23 *	43	(+1)	SW	P jumps
8	May 15-16 *	46	(+4)	SW	B_z changes
9	June 8-9 *	24	(+3)	MS/MSH/SW	Multiple P jumps
10	June 19 *	10	(+6)	SW	Quiet SW
11	July 15-16 *	45	(+6)	SW	$B_z < 0$
12	Aug. 3-4 *	13	(+4)	SW/MSH/SW	Quiet SW
13	Sept. 3 *	12	(+10)	SW/MSH/MS	B_z jumps
14	Sept.18-20 *	56	(+4)	MS/MSH/MS	B_z jumps
15	Sept. 21 *	5	(+5)	MSH	P jumps
16	Sept.21-22 *	19	(+3)	MSH/SW	P jumps
17	Oct. 1-2 **	42	(+4)	MS/MSH/MS	-
18	Oct. 10-12 *	45	(+5)	MSH	P jumps
19	Nov. 7-8 *	24	(+7)	MS	P and B_z variations
20	Nov. 22-23 *	18	(+10)	MS	$B_z < 0$
21	Dec. 10-11 *	15	(+16)	MS	B_z jumps
22	Dec. 30-31 *	25	(+7)	MS	P and B_z jumps
	1998				
23	Jan. 7-8 *	29	(+14)	MS	B_z jumps
24	Feb. 4-5 *	41	(+17)	MSH/MS	P jumps
25	Feb. 17-18 *	14	(+16)	MS/MSH	P and B_z jumps
26	Mar 4-5 *	30	(+4)	MS/MSH/SW	B_z jumps
27	May 2-3 *,**	?	(+14)	SW	$B_z < 0$
28	May 4-5 *	15	(+9)	SW/MSH	B_z jumps
29	June 2 *,**	8	?	SW	Quiet SW
30	June 24-25 *	35	(+4)	SW	P jumps
31	Sept. 25-26 *	29	(+7)	MSH/MS	P jumps
32	Oct. 18-20 *	22	(+9)	MC/MSH	B_z jumps
33	Nov. 7-8 *,**	?	(+4)	MS	P and B_z variations
34	Nov. 8-10 *	34	(+13)	MS	P jumps
35	Nov. 13-14 *	32	(+4)	MS	B_z and P jumps
	Average	27	(+8)		

23 h, respectively. Therefore, we can compare the instant of magnetic storm beginning with MC structure. Our analysis of SW and IMF data for all events shows that, on the whole, the large drop of D_{st} index is observed after southward IMF turning with 0-2 h delay (We used 1-hour averaged D_{st} index data). Usually these IMF turnings occurred in the compressed region between IS and MC LE or inside of MC body due to slow IMF rotation, and our observations agree with previous results (Burlaga *et al.*, 1998; Crooker , 2000).

To describe the polar disturbances we used either the magnetic field data of several polar ground stations, near which the events took place, or the integral polar indices. In particular, we analyzed *Contracted Oval, Standard Oval,* and *Expanded Oval* calculated for 3 systems of stations located on 3 concentrical circles near the northern magnetic pole (For more details see the Auroral Oval Indices on the Cluster/Ground-Based Data Center web site http://www.wdc.rl.ac.uk/gbdc/ovals/plots). The analysis of additional data indicates that these indices are sensitive to substorms and allow us to select them. However, in a small number of cases they demonstrate polar activations which are not substorms. In our analysis the activations were determined as follows. If even one of three indices on the interval of 15 minutes decreased more than 200 nT from the previous level, and duration of this reduction was more than 10 minutes we call all these phenomena "activations". It is necessary to have in mind that about 2/3 of the cases relate to substorms. Figures 4 - 5 show these indices for magnetic cloud of January 10-12,1997. The comparison of Fig.3 in paper by Burlaga *et al.* (1998) and Figs. 4,5 shows that the drop in indices are observed soon after the passage of MC LE. However, the changes in the IMF orientation and jumps in the field magnitude and SW pressure for this event can be found not for all activations. The SW and IMF data and Auroral Oval Indices were analyzed in detail and the similar comparison of polar indices variations with MC structures was made for all MCs shown in Figs. 1 - 3 and Table 1.

Table 2 presents the minimum of hour-averaged values of D_{st} index and number of activations of polar indices related to the set of MC structures. For event of January 10-11, 1997, MC LE (at ~04:30 UT) corresponds to activation (this is designated as 1 activation per 1 structure, i.e. 1/1), while no activation corresponds to IS before MC LE (at ~01:00 UT) and MC TE (at ~01:00 UT on January 11) (this is designated as 0/1). The decreases of the D_{st} index were observed usually for all MCs. However, in some cases (for example, on September 21, 1997 and on June 24-25, 1998) the index pointed to very weak magnetic storms or even their absence (on June 2, 1998). In last cases the IMF B_z component was less than -5 nT only during short time intervals (less 1.5 h).

The comparison of activations with the MC structure has shown that only 185 of 237 activations (78% of their total number) can be associated with IS before MC LE (IS1), LE, TE, IS before TE (IS2), the sign of IMF B_z ($B_z < 0$), and the jumps of field ($\varDelta B_z$) and dynamical pressure of SW plasma ($\varDelta P$). In this case, the highest relative frequency of activations (the ratio of the number of activations to the number of events of selected type) is observed after IS1 and LE. However, some strong jumps of P and IMF (as, for example, a very high pressure at MC TE on January 11, 1997 when SW could push the magnetosphere at geosynchronous orbit) have not resulted in activations. It should be noted that this large jump was observed after 8 h of positive IMF B_z.

The data about D_{st} and number of activations presented in Table 2 were shown by black diamonds in Figure 6 and approximated by solid line. The activations can be connected not only with MCs, but also with magnetospheric disturbances caused by other reasons. The dependence of the number of activations NA on D_{st} index for large magnetic storms ($D_{st} < -90$ nT), which is presented by open circles and dashed line, is very closed to dependence for all magnetic clouds, but the number of activations for strong storms is slightly less than for magnetic clouds. These data allow us to suggest that there is a relation between number of activations NA and D_{st} index. Despite a high scatter of the data, we note that the passage of MC causing strong decrease of D_{st} index is accompanied by a higher number of polar activations (the linear approximation gives the dependence for number of activations $NA = -0.06 D_{st} + 1.5$). The problem of establishing a relation between slowly varying global geomagnetic indices and rapidly varying polar indices has been already discussed in the literature (see, e.g. Kamide *et al.* (1998) and Wilson (2000)). However, the observed difference between $NA.vs.D_{st}$ dependences for strong storms and magnetic clouds can be explained by fact that duration of magnetic storm, as a rule, is shorter than duration of MC. The details of such a relation during MC passage periods requires further investigations.

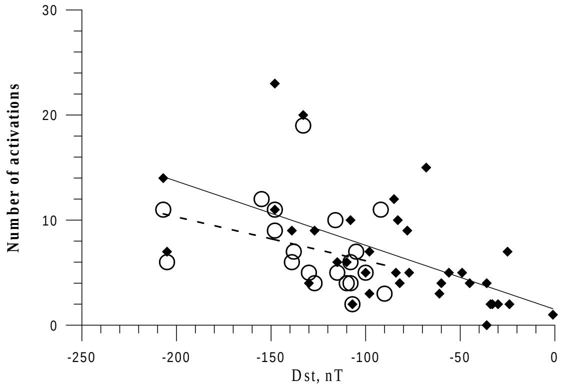


Fig. 6. Observed values of the number of activations NA and minimum of D_{st} index for magnetic clouds (black diamonds) and strong magnetic storms (white circles) periods.

4 Magnetospheric boundaries

Since the location of the magnetopause (MP) is determined by the balance of plasma and magnetic field pressures in the solar wind, decelerated and heated at the bow shock (BS), and inside the magnetosphere, any change of conditions in the interplanetary medium results in a displacement of the MP and hence in the displacement of the BS, for which MP is an obstacle when the solar wind flows around it. The INTERBALL-1 satellite locations at BS and MP crossings allow the BS and MP locations to be compared with the solar wind conditions determined by other spacecraft and with model predictions.

We considered 44 MP crossings by the INTERBALL-1 satellite at MC passage time. Figure 7 presents the locations of these crossings in the meridional plane (XR_{YZ}, where $R_{YZ} = \sqrt{Y^2 + Z^2}$) and at the cross-section of the tail (YZ), as well as the average locations of MP (at SW pressure of P ~2 nPa (Sibeck *et al.*, 1991)) and BS (Fairfield , 1971). It is seen from the figure the deviation of a real MP location from average one varies from 1-2 R_E on the MS dayside up to 5-7 R_E in the tail. In this case the real MP more often occurs to be closer to the Earth than average location predicted by the model.

SW parameters (the plasma pressure P and the IMF B_Z component) were determined for each MP crossing taking into account the time delay of plasma propagation between two spacecraft. The range of variation of these parameters for MCs under consideration was found to be rather wide: $0.3 < P < 42$ nPa and $-21 < B_Z < 21$ nT. The existing

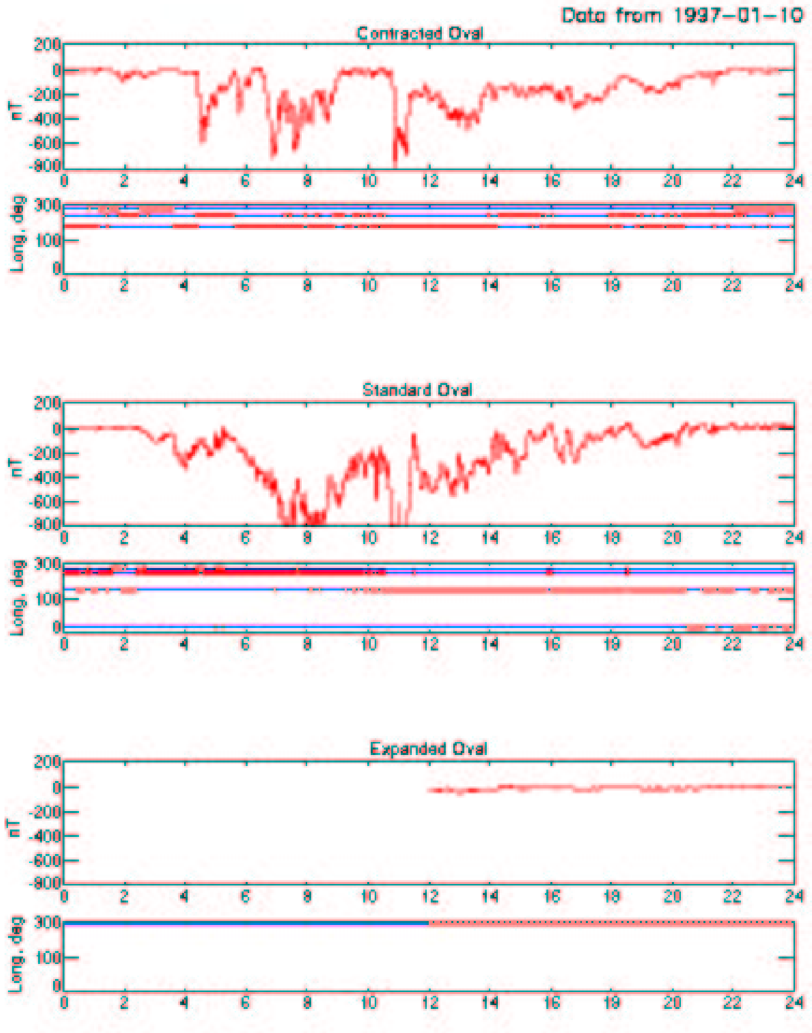


Fig. 4. Time dependences of the auroral indices *Contracted Oval*, *Standard Oval*, and *Expanded Oval* on January 10, 1997.

MP models (Sibeck *et al.*, 1991; Roelof and Sibeck, 1993; Petrinec and Russell, 1996; Kuznetsov and Suvorova, 1997; Shue *et al.*, 1997) have narrower range of variation. The last version of the MP model (Shue *et al.*, 1998) was obtained using higher SW parameters. We compared the real MP crossings with two models, and figure 8 presents the distance between the measured location and those predicted in the models by Shue *et al.* (1997) (circles) and Shue *et al.* (1998) (diamonds). In this case, positive distances correspond to the event when the measured boundary lies inside model predictions (i.e., closer to the Earth). The distance was measured along the normal to the model boundary.

Figure 8 clearly demonstrates that both models well predict the MP position in the subsolar region (at $X \geq 0$) and worse in the tail ($X < 0$): on the dayside the MP is located by 1-2 R_E closer to the Earth and in the tail the scatter is from -5 to +2 R_E. Our statistics do not allow us to compare quantitatively both models with sufficient reliability. However, the larger scatter of MP crossing with respect to model predictions testifies that the MP motion during MC passage is more complicated than it is predicted by empirical models which were mainly constructed for the conditions of weakly disturbed SW.

Table 3 presents the results of comparison of the MP location with predictions of the model by Shue *et al.* (1998) as well as the comparison of BS location with its average position. Similar statistical models for BS, which take into account the conditions in the interplanetary space, are absent now; by this reason, the real BS crossing was compared with average BS location. However, since the MP is obstacle for SW in forming BS, we plan to take into account the MP motion depending on conditions in the SW and to investigate the correlation between changes of BS and MP location. Now we can only notice that the deviation of BS from average location is approximately the same as that for MP.

The MP shape and motion for MC of January 10-11, 1997 were studied, in particular, by Nikolaeva *et al.* (1998) and Safrankova *et al.* (1998). The results indicated that the change of magnetosphere size was accompanied by more complicated deformations than a simple compression when different parts of the magnetosphere simultaneously undergo proportional displacement, by surface waves on the boundaries and

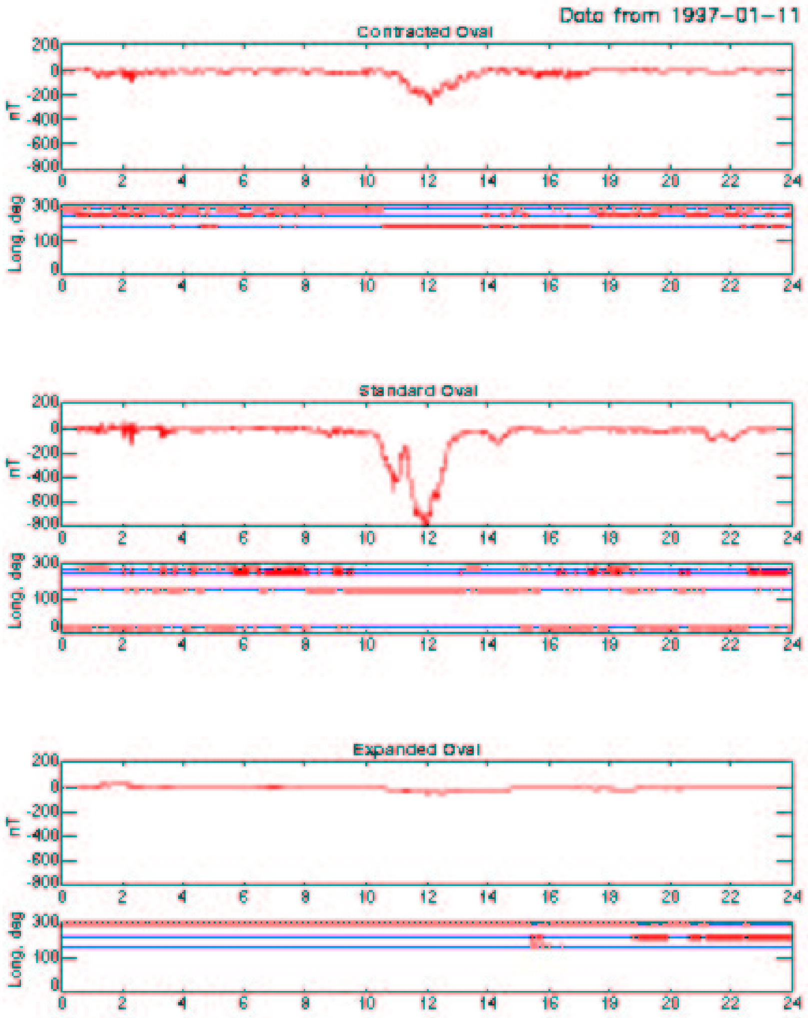


Fig. 5. Time dependences of the auroral indices *Contracted Oval*, *Standard Oval*, and *Expanded Oval* on January 11, 1997.

by oscillation of the tail (Yermolaev *et al.*, 1997a; Nikolaeva *et al.*, 1998). More complicated character of MS compression follows also from observations on October 18-19, 1995, since these data were interpreted as a result of reconnection of magnetic field not in the subsolar region or near the cusp but rather on the MP in the far tail at distances $|X|$ larger than 20 R_E (Savin *et al.*, 1997).

5 Magnetosphere state.

As was shown in previous Section, the MC passage to the Earth is accompanied by the displacement of MS boundaries. This implies partially that the place where one physical region of space is usually observed (which is characterized by typical values of plasma and magnetic field parameters) occurs to be occupied by another region which is observed far from this place under normal conditions. Though small displacement of various regions is a rather frequent phenomenon in such a dynamical system as MS, displacements to distance comparable with the size of regions or even greater are quite rare phenomena. This fact should be taken into account when comparing the parameters of the usual magnetosheath, for instance, with those magnetosheath-like plasmas which we observed in the region of usual plasma sheet observations. Such an analysis is very important since it provides additional information on the dynamics and mechanisms of different MS region formation. We have considered only several examples from the large set of various cases of anomalous location of MS regions, and the results presented below can be considered only as a first step in this direction.

Figure 9 shows the dynamic energy spectrograms of ions (the abscissa is time, the ordinate is energy, the color from blue to red indicates increasing value of ion flux) for three successive orbits of INTERBALL-1 during the period of January 6-15, 1997. In this case the data, placed on the same vertical straight line, were obtained approximately at the same satellite coordinates. (Due to annual satellite orbit evolution with respect to the Sun-Earth axis the planes of successive orbits in GSE frame are displaced relative to each other by an angle of $\sim 4^o$.) These data were obtained by the CORALL instrument (Yermolaev *et al.*, 1997b) with the help of a sen-

Table 2. Geoeffectiveness of magnetic clouds' structures.

Date	Dst, nT	Number of substorms and activations							
		Total	IS1	LE	$B_z$jump	B_z<0	Pjump	IS2	TE
1995									
Aug. 22-23	-61	3	0/1	0/1	3/5	0	0/2	0/0	0/1
Oct. 18-19	-127	9	1/1	1/1	1/1	2	1/3	1/1	0/1
1996									
Dec. 23-25	-33	2	0/1	0/1	0/5	1	1/1	0/0	0/1
1997									
Jan. 10-11	-78	9	0/1	1/1	2/3	2	1/3	0/1	0/1
Feb. 8-11	-68	15	1/1	1/1	2/4	3	3/5	0/0	1/1
Apr. 10-11	-82	4	0/1	1/1	1/2	0	0/0	0/0	1/1
Apr. 21-23	-107	2	1/1	0/1	0/5	0	1/1	0/0	0/0
May 15-16	-115	6	0/1	1/1	2/6	3	0/1	0/0	1/1
June 8-9	-84	5	1/1	0/1	0/5	0	1/6	0/0	0/0
June 19	-36	0	0/1	0/1	0/0	0	0/0	0/0	0/0
July 15-16	-45	4	0/1	1/1	0/0	3	0/0	0/0	0/0
Aug. 3-4	-49	5	0/0	1/1	1/1	0	1/1	0/0	0/1
Sept. 2-3	-98	3	0/1	1/1	0/0	0	1/2	0/0	1/1
Sept. 18-20	-56	5	1/1	0/1	1/3	0	1/3	0/0	1/1
Sept. 21	-24	2	0/1	1/1	0/1	0	0/3	0/0	1/1
Sept. 21-22	-30	2	1/1	1/1	0/0	0	0/1	0/0	0/1
Oct. 1-2	-98	7	1/1	1/1	1/1	0	1/2	0/0	0/1
Oct. 10-12	-130	4	1/1	1/1	1/2	1	0/2	0/0	0/1
Nov. 7-8	-110	6	1/1	1/1	1/3	2	0/1	0/0	0/1
Nov. 22-23	-108	10	1/1	1/1	1/1	6	0/1	0/0	1/1
Dec. 10-11	-60	4	0/1	1/1	1/3	1	0/0	0/0	1/1
Dec. 30-31	-77	5	0/1	1/1	1/1	3	0/0	0/1	0/1
1998									
Jan. 7-8	-83	10	0/1	1/1	4/6	0	0/1	0/0	0/1
Feb. 4-5	-34	2	1/1	0/1	0/0	0	0/6	0/0	0/1
Feb. 17-18	-100	5	0/1	1/1	1/1	1	0/0	1/1	0/1
Mar. 4-5	-36	4	1/1	0/1	2/6	1	0/0	0/0	0/1
May 2-3	-85	12	1/1	1/1	0/3	8	0/1	1/1	0/0
May 4-5	-205	7	1/1	0/1	1/3	1	0/0	0/0	0/1
June 2	-1	1	0/0	1/1	0/1	0	0/0	0/0	0/1
June 24-25	-25	7	0/1	1/1	0/4	5	2/6	0/1	0/1
Sept. 25-26	-207	14	1/1	1/1	1/2	6	0/1	0/0	1/1
Oct. 18-20	-139	9	0/1	1/1	6/10	2	1/2	0/0	0/1
Nov. 7-8	-148	11	0/1	1/1	7/17	2	1/4	0/0	0/0
Nov. 8-10	-148	23	1/1	0/0	10/12	11	1/4	0/0	1/1
Nov. 13-14	-133	20	1/1	1/1	?	?	?	0/0	1/1
Total	-	237	17/33	25/34	51/117	64	17/65	3/6	8/28
Avarage	-86	7							

sor oriented perpendicular to the satellite spin axis, i.e., in the plane normal to the Sun-Earth direction.

The upper panel, whose data were obtained before the MC passage, shows at first a hot and low density plasma of the plasma sheet. During interval from 22 UT on January 6 to 02 UT on January 7, when satellite was close to geomagnetic equator ($X \sim$ -17 and $Y_{GSM} \sim 16 R_E$) the plasma of a low-latitude boundary layer (LLBL) was observed. After this the satellite began to approach the Earth while crossing the plasma mantle several times and the tail lobes and the satellite reached the radiation belt at $\sim$ 23 UT.

Before the MC passage on January 10 the plasma sheet ions (more precisely PSBL ions) were observed. However, at about 01:20 UT the satellite crossed the MP and entered the very hot magnetosheath. Then, from ∼06 to ∼20 UT, the instrument recorded both long (for 1-2 h) intervals and short (a few minutes) bursts of plasma sheet with lower density and higher energy than on the previous orbit. The plasma sheet

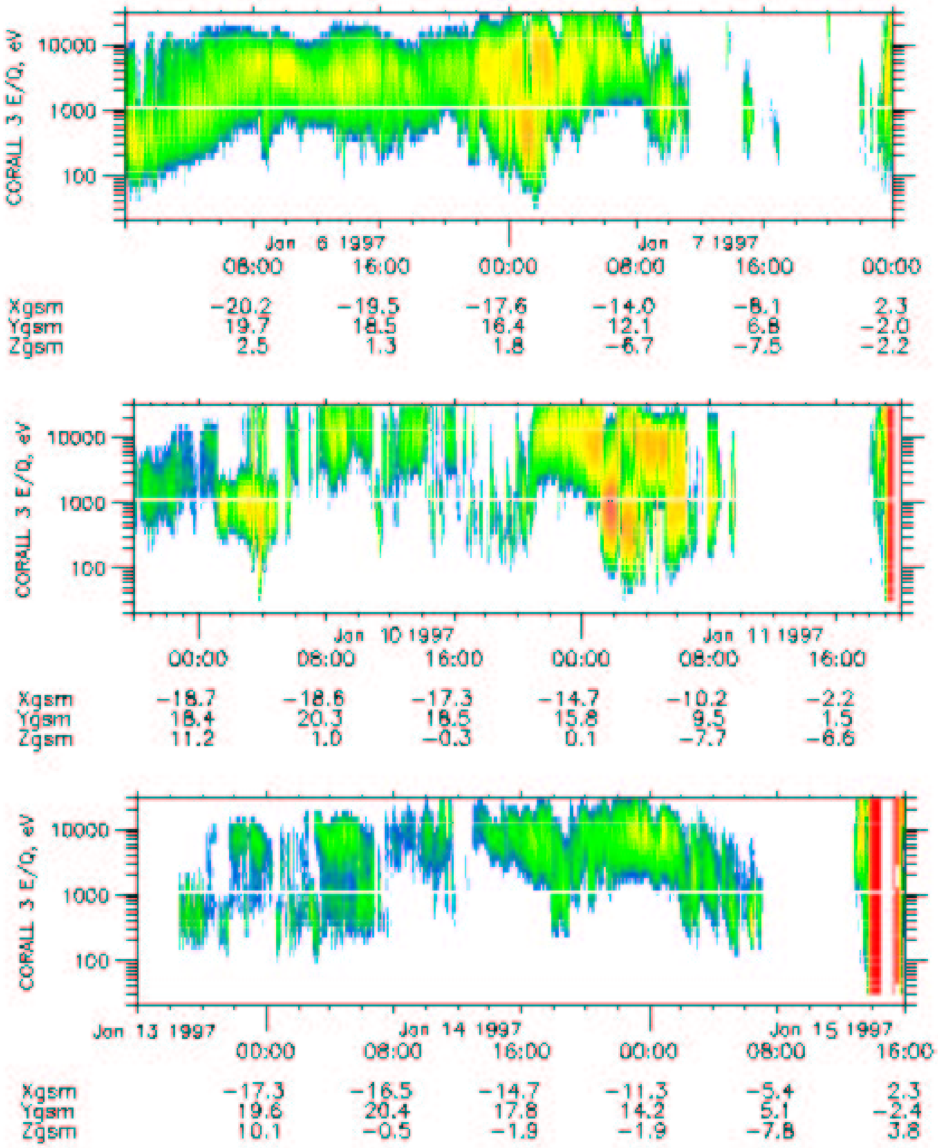


Fig. 9. The ion energy spectrograms during 3 successive orbits of INTERBALL-1 on January 6-15, 1997.

observations were interrupted by satellite entering the lobes which connected with fast tail motion with respect to a rather slowly moving satellite. After MC trailing edge passage at about 01:20 UT on January 11, the satellite from the plasma sheet quickly entered a very dense and hot magnetosheath, then at ∼02 UT it was in the LLBL (at a rather large distance from geomagnetic equator with $Z_{GSM} \sim 8 - 9R_E$) and then in the plasma sheet.

On the third panel of figure the ion measurements are shown after MC passage on January, 13-15, 1997. Till 18:30 the CORALL instrument was switched off. First the satellite consistently crossed MSH, PSBL and LLBL, and at 07:30 UT has come PS. As a whole the boundaries of magnetospheric regions are located near to their average positions, and fluxes of plasma in all regions are appreciably lower, than on two previous panels, especially low density of ions in PS. Also it

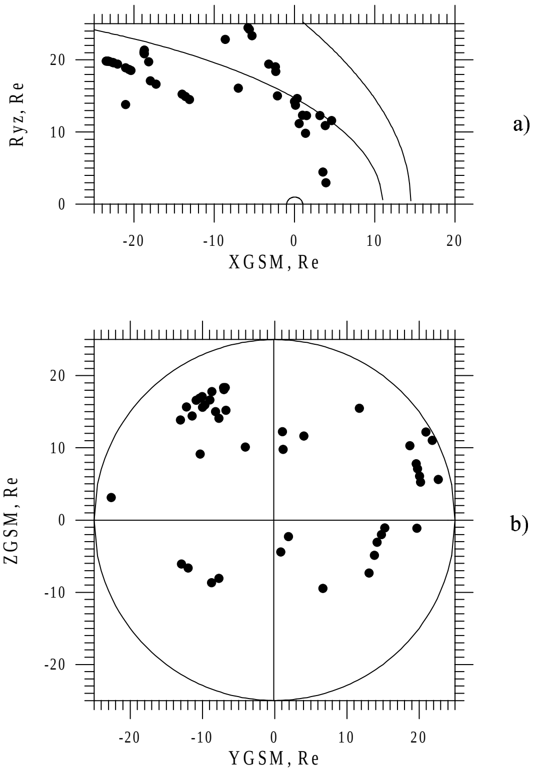


Fig. 7. INTERBALL-1 magnetopause crossings during magnetic cloud passages in the (a) XR_{YZ} and (b) YZ planes.

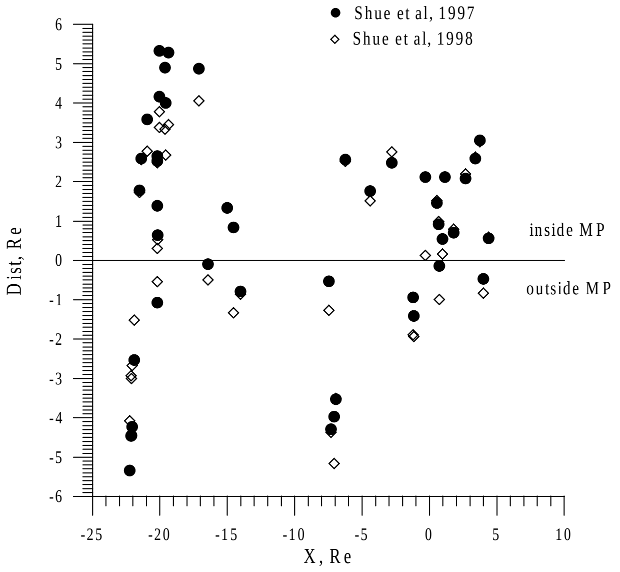


Fig. 8. Comparison of magnetopause crossings with model (Shue *et al.*, 1997) (circles) and (Shue *et al.*, 1998) (diamonds) predictions.

Table 3. Magnetospheric boundary locations.

Date	Distance*(R_E) between boundary crossing and	
	Bow Shock	Magnetopause
1995		
Oct. 18	-	-2.4 ... 1.4
Oct. 19	-	-4.4 ... 0.6
1996		
Dec.25	~ 5	
1997		
Jan. 10	-	-0.9 ... 1.4
Jan. 11	-	0.0 ... 1.5
Feb. 8	3	-
Feb. 9	2 ... 3	-
Feb. 10	4	-3.2
Feb. 11	3 ... 6	-
June 9	-5 ... -6	-0.5
July 3	-2 ... -4	-
July 4	2	-
Sept. 03	2	1.0 ... 2.8
Sept. 18	7	-3.5
Sept. 20	7	-
Sept. 21	7	-
1998		
Feb. 3	-	-0.9
Feb. 4	-	-4.7 ... -2.0
Feb. 18	-	1.7
Mar. 4	-3 ... 3	3.5
Mar. 5	3 ... 4	1.0
May 4	0	1.7

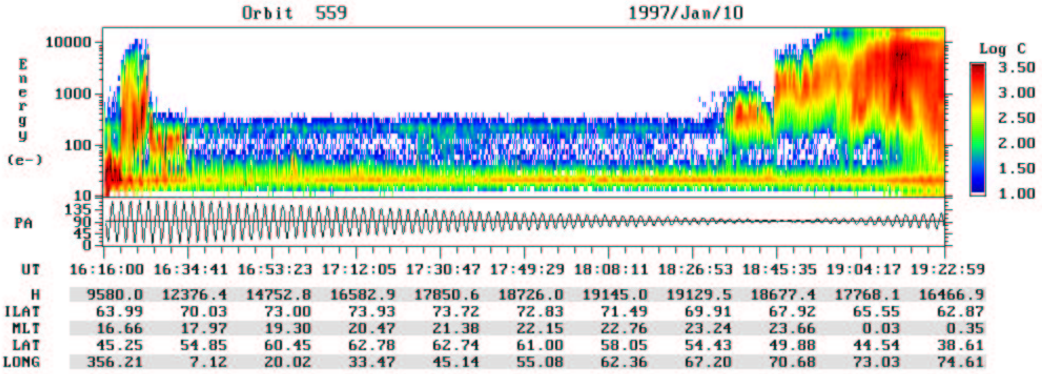
* Distance is possitive if the boundary is located closer to the Earth than the model boundary

is possible to note, that variability in PS is significantly lower, than on the previous orbit, and it basically is connected not with memory of magnetosphere about passage of the magnetic cloud, and with current variations of SW and IMF parameters.

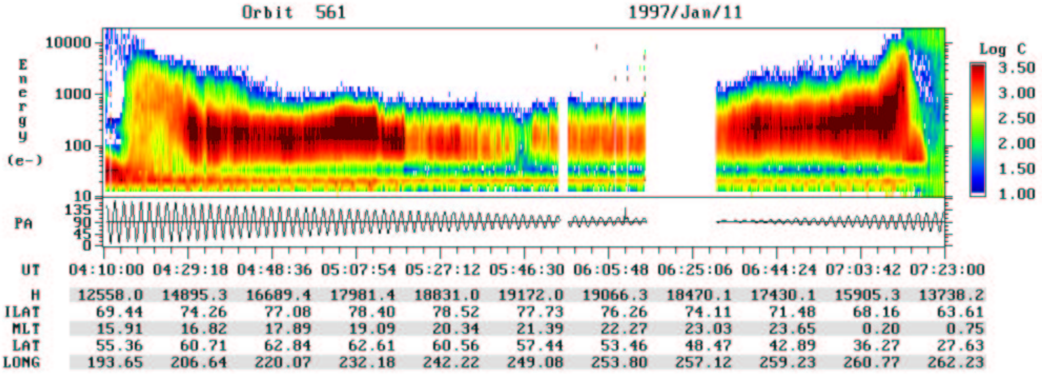
The dynamic energy spectrograms of electrons, measured by ION instrument (Sauvaud *et al.*, 1997) on subsequent orbits of the INTERBALL-2 satellite, are presented in Figure 10. Before the MC passage in the polar cap (invariant latitude $\lambda > 65^o$) the fluxes of electrons had low energy of several tens of electronovolts and too low intensity to be observed. However after the MC TE passage on January 11, 1997, high fluxes of electron with energy 100-300 eV were detected in the polar cap. This interval coincides with the INTERBALL-1 exit from the plasma sheet into the magnetosheath and LLBL, i.e., the disturbance of distant tail of MS coincided with electron precipitation in the polar cap.

Thus, several features of the magnetosphere and magnetosheath plasma observed during the MC passage can be summarized as follows.

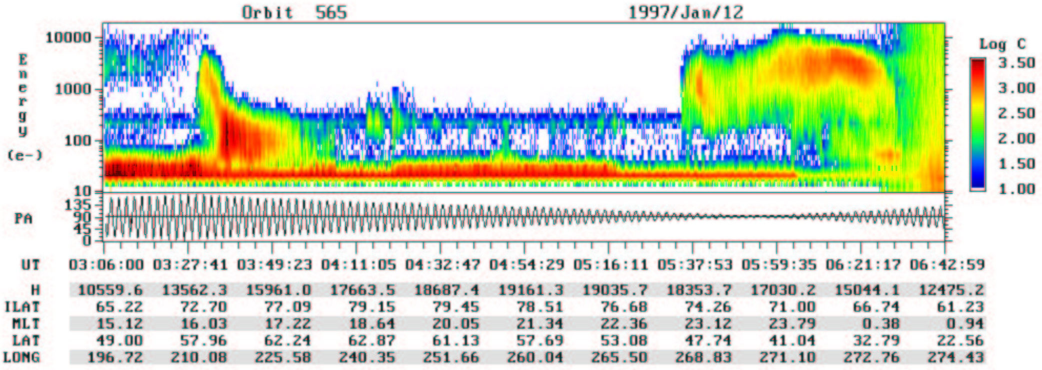
The magnetosheath ion temperature (or ion energy) is usually higher than in the average MSH. This effect is stronger during passage of pressure jumps on the IS, LE and TE. Density in MSH correlates with SW density. Simulta-



UT	16:16:00	16:34:41	16:53:23	17:12:05	17:30:47	17:49:29	18:08:11	18:26:53	18:45:35	19:04:17	19:22:59
H	9580.0	12376.4	14752.8	16582.9	17850.6	18726.0	19145.0	19129.5	18677.4	17768.1	16466.9
ILAT	63.99	70.03	73.00	73.93	73.72	72.83	71.49	69.91	67.92	65.55	62.87
MLT	16.66	17.97	19.30	20.47	21.38	22.15	22.76	23.24	23.66	0.03	0.35
LAT	45.25	54.85	60.45	62.78	62.74	61.00	58.05	54.43	49.88	44.54	38.61
LONG	356.21	7.12	20.02	33.47	45.14	55.08	62.36	67.20	70.68	73.03	74.61



UT	04:10:00	04:29:18	04:48:36	05:07:54	05:27:12	05:46:30	06:05:48	06:25:06	06:44:24	07:03:42	07:23:00
H	12558.0	14895.3	16689.4	17981.4	18831.0	19172.0	19066.3	18470.1	17430.1	15905.3	13738.2
ILAT	69.44	74.26	77.08	78.40	78.52	77.73	76.26	74.11	71.48	68.16	63.61
MLT	15.91	16.82	17.89	19.09	20.34	21.39	22.27	23.03	23.65	0.20	0.75
LAT	55.36	60.71	62.84	62.61	60.56	57.44	53.46	48.47	42.89	36.27	27.63
LONG	193.65	206.64	220.07	232.18	242.22	249.08	253.80	257.12	259.23	260.77	262.23



UT	03:06:00	03:27:41	03:49:23	04:11:05	04:32:47	04:54:29	05:16:11	05:37:53	05:59:35	06:21:17	06:42:59
H	10559.6	13562.3	15961.0	17663.5	18687.4	19161.3	19035.7	18353.7	17030.2	15044.1	12475.2
ILAT	65.22	72.70	77.09	79.15	79.45	78.51	76.68	74.26	71.00	66.74	61.23
MLT	15.12	16.03	17.22	18.64	20.05	21.34	22.36	23.12	23.79	0.38	0.94
LAT	49.00	57.96	62.24	62.87	61.13	57.69	53.08	47.74	41.04	32.79	22.56
LONG	196.72	210.08	225.58	240.35	251.66	260.04	265.50	268.83	271.10	272.76	274.43

Fig. 10. The electron energy spectrograms during 3 orbits of INTERBALL-2 on January 10-12, 1997.

neous observations on GEOTAIL and INTERBALL-1 satellites showed that during large increasing in MSH density (for example, on 11 January, 1997 when the density in MSH increased up to $N \sim 150$ cm^{-3}) the change in PS density was small (Yermolaev *et al.*, 1997a).

The MC passages result in observations of different magnetospheric regions far from their average locations and multiple crossings of boundaries between them. These observations allow us to suggest a large-scale geomagnetic tail oscillations relative to the satellite, so that the displacements of some magnetospheric regions are comparable to characteristic size of the regions. These motions can result in the development of disturbances and acceleration of ions and electrons in the plasma sheet, their subsequent injection and precipitation in polar regions of the magnetosphere (Yermolaev *et al.*, 1997a, 2000a,b).

6 Conclusions.

The results on the analysis of magnetic clouds observed on interplanetary spacecraft and INTERBALL-1,2 satellites during August, 1995 - December, 1998 (near minimum of solar cycle), allow us to make several conclusions about the magnetospheric response to these events.

The geoefectiveness of magnetic clouds depends on the value of parameter variations in the magnetic cloud. For low, medium, or moderately high variations of plasma and magnetic field in the cloud, the magnetospheric response is the same as for similar variations in the interplanetary space in the absence of magnetic clouds, and strongly depends on the interplanetary magnetic field prehistory:

-after prolonged energy transfer to the magnetosphere (at the southward IMF) practically all changes in the solar wind pressure or in the IMF magnitude and orientation can result in auroral activations, substorms and magnetic storms;

-with prolonged northward IMF all changes in magnetic cloud parameters are not geoeffective and do not have significant influence on the state of the magnetosphere and on the geomagnetic field.

Extremely high jumps of parameters in magnetic clouds (mainly near their boundaries: in shocks, at leading and trailing edges) can result in the unusual behavior of the magnetosphere:

-strong and rather complicated compression and deformation (with large and disproportional displacement of boundaries) of the magnetosphere relative to its usual position;

-large-scale oscillations of geomagnetic tail structures relative to satellite;

-the development of disturbances in the plasma sheet, which result in acceleration of ions and electrons and their injections in the polar cap.

The magnetic clouds resulting in a greater number of polar disturbances like substorms are accompanied, as a rule, by stronger global disturbance like magnetic storms.

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