ISSN 0010-9525, Cosmic Research, 2007, Vol. 45, No. 6, pp. 461–470. © Pleiades Publishing, Ltd., 2007.
Original Russian Text © Yu.I. Yermolaev, M.Yu. Yermolaev, I.G. Lodkina, N.S. Nikolaeva, 2007, published in Kosmicheskie Issledovaniya, 2007, Vol. 45, No. 6, pp. 489–498.

Statistical Investigation of Heliospheric Conditions Resulting in Magnetic Storms: 2

Yu. I. Yermolaev, M. Yu. Yermolaev, I. G. Lodkina, and N. S. Nikolaeva
Space Research Institute, Russian Academy of Sciences, Profsoyuznaya st. 84/32, Moscow 117997, Russia
Received August 15, 2006

Abstract—This work is a continuation of investigation [1] of the behavior of the solar wind's and interplanetary magnetic field's parameters near the onset of geomagnetic storms for various types of solar wind streams. The data of the OMNI base for the 1976–2000 period are used in the analysis. The types of solar wind streams were determined, and the times of beginning (onsets) of magnetic storms were distributed in solar wind types as follows: CIR (121 storms), Sheath (22 storms), MC (113 storms), and "uncertain type" (367 storms). The growth of variations (hourly standard deviations) of the density and IMF magnitude was observed 5–10 hours before the onset only in the Sheath. For the CIR-, Sheath- and MC-induced storms the dependence between the minimum of the IMF B_z-component and the minimum of the D_{st}-index, as well as the dependence between the electric field E_y of solar wind and the minimum of the D_{st}-index are steeper than those for the "uncertain" solar wind type. The steepest D_{st} vs. B_z dependence is observed in the Sheath, and the steepest D_{st} vs. E_y dependence is observed in the MC.

PACS: 96.50.Uv; 96.50.Qx; 94.30.Lr

DOI: 10.1134/S0010952507060020

INTRODUCTION

This paper represents the second part of the work devoted to studying the interplanetary medium parameters before the magnetic storm onset. In the first part of the work [1] we have studied, by the superposed epochs technique, the behavior of solar wind (SW) and interplanetary magnetic field (IMF) parameters before 625 magnetic storms with $D_{st} < -60$ nT in the 1976–2000 period using the OMNI database. For the intervals including the period before storms and after their onset the types of solar wind streams were determined, and the times of beginning (onsets) of magnetic storms were distributed in solar wind types as follows: CIR (Corotating Interaction Regions or the regions of compression in the interface fast rapid and slow streams) corresponds to 121 storms, the Sheath (the region of compression between the undisturbed solar wind and magnetic cloud's body) is responsible for 22 storms, MC (magnetic cloud) produced 113 storms, and the "uncertain type" is associated with 367 storms. The intervals, attributed to the "uncertain type", mainly included the intervals, for which the absence of any parameters did not allow one to reliably identify the type of stream, or the phenomenon had so complicated character that it was impossible to separate unambiguously long intervals for any of above mentioned types of streams. The basic result obtained in paper [1] consisted in the fact that the lowest values of the B_z-component of IMF were observed in the MC, while the lowest values of the D_{st}-index were reached in the Sheath. Thus, the strongest magnetic storms are excited, on the average, during the Sheath rather than during the MC body. The obtained data have shown that one of possible reasons of this situation could be higher values of pressure in the Sheath before the storm as compared to the other solar wind types.

The relationship between the minimum of the B_z-component of the IMF and the D_{st} index was studied in many works, the major part of them being aimed at studying the processes occurring inside the magnetosphere at negative B_z-component of the IMF, disregarding the question about the types of interplanetary disturbances that have generated these magnetic storms (see, e.g., [2, 3] and references therein). And only a small number of works the relationship between these parameters (the minima of the B_z-component and the D_{st}-index) are analyzed in specific types of solar wind streams, such as magnetic clouds MC [4–8], CIR [9, 10], or in the streams behind the interplanetary shock (IS) [11]. However, in none of them these relationships have been compared for various types of solar wind.

It was shown in numerous research studies that the key parameter, resulting in magnetic storms, is the component of induced electric field $E_y = V_x B_z$ (V_x is the radial velocity component) of the solar wind for the negative B_z-component of the interplanetary magnetic field (see papers [3, 12–14] and references therein). Since variations of E_y are mainly associated with variations of the B_z-component, the behavior of E_y near the magnetic storm onset occurred to be similar to the

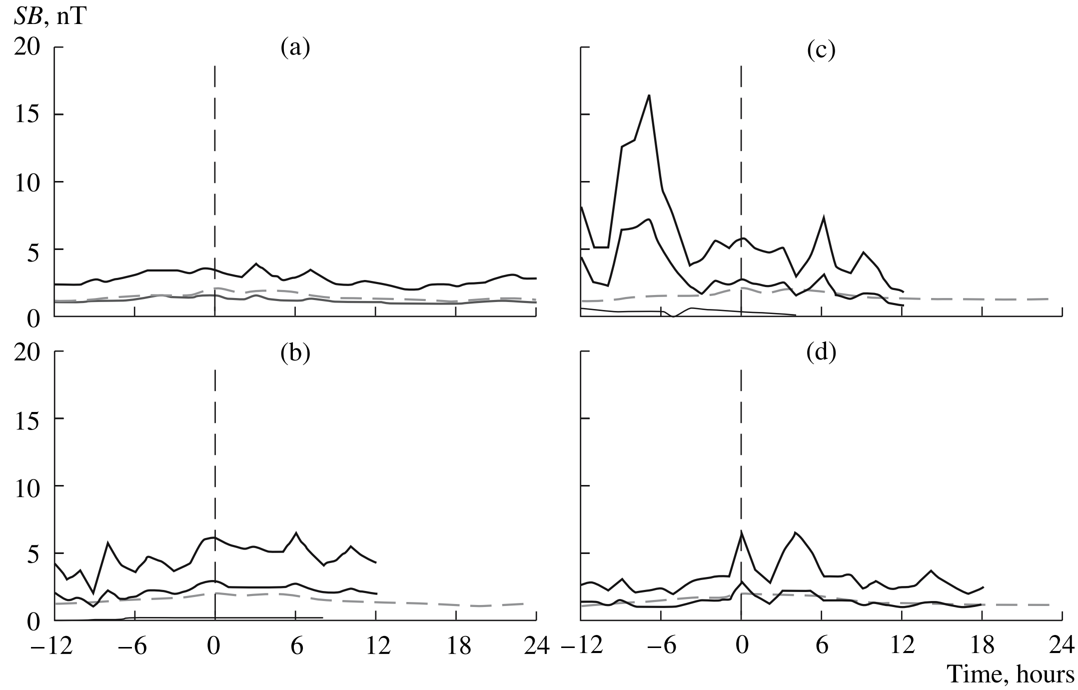

Fig. 1. Time behavior of the hourly standard deviations of the magnetic field magnitude obtained for all events (the gray dashed line in all panels), for the "uncertain type" (*a*), CIR (*b*), Sheath (*c*), and MC (*d*). The central line in the *a*–*d* panels shows the behavior of the average, while the upper and lower lines are offset from the middle one by the dispersion value.

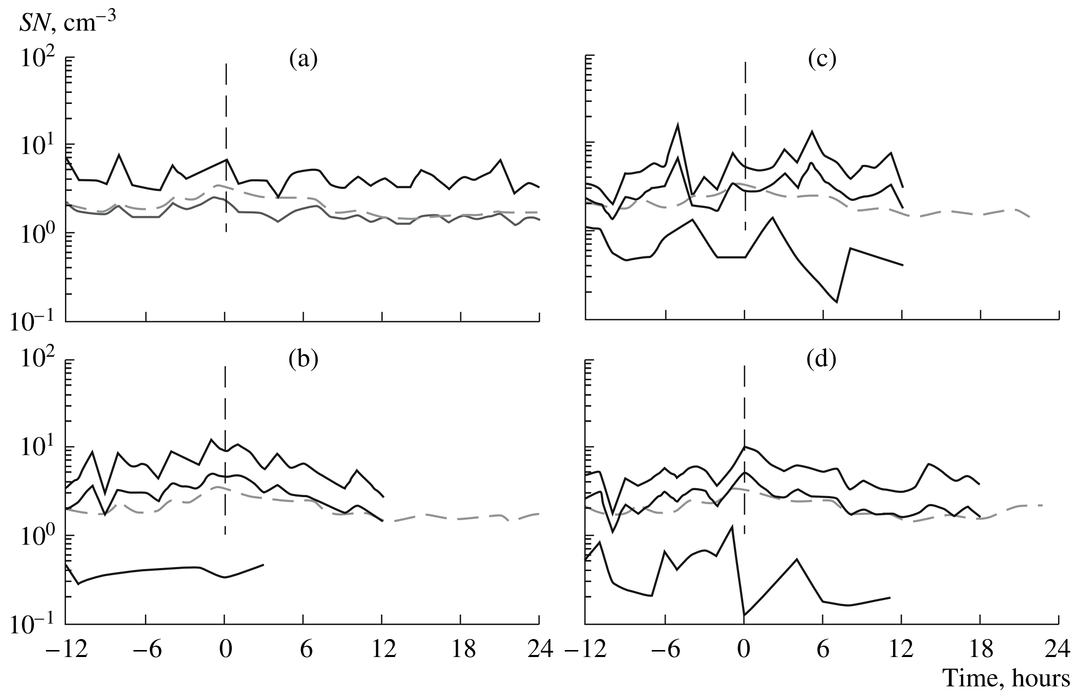

Fig. 2. The same as in Fig. 1 for the hourly standard deviations of the solar wind density.

behavior of the B_z-component (see Fig. 10 in paper [1]), we have not presented these results because of a place limit. The dependences of the D_{st}-index minimum on the electric field were studied in a number of works [4, 5, 9, 15, 16], and we compare our results with them below.

The hypothesis is often stated in the literature, that one of the parameters promoting excitation of magnetic

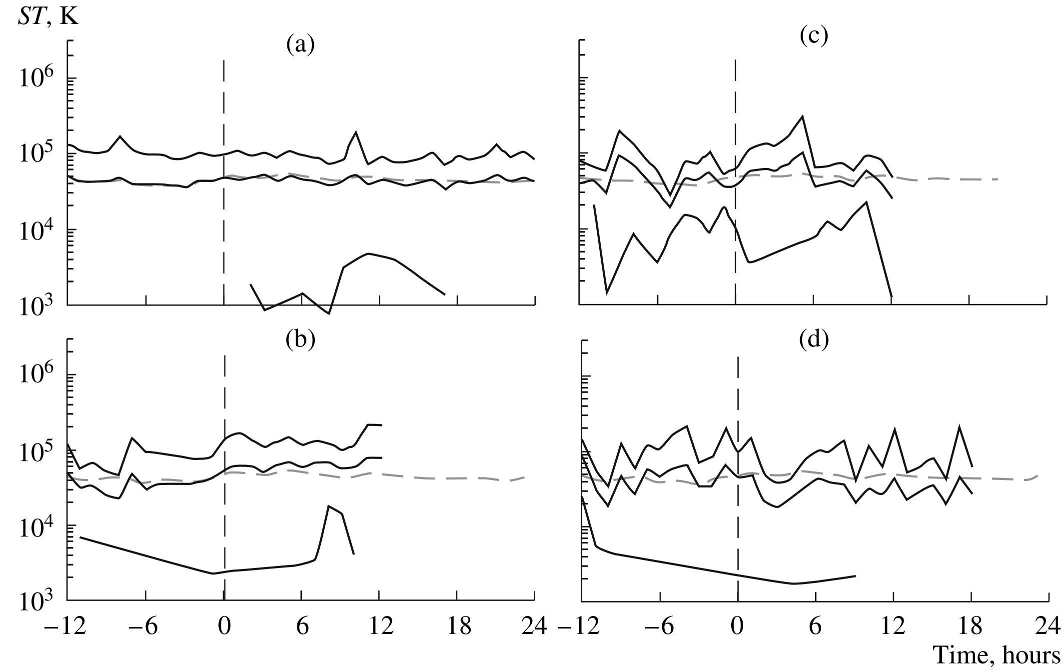

Fig. 3. The same as in Fig. 1 for the hourly standard deviation of proton temperature of the solar wind.

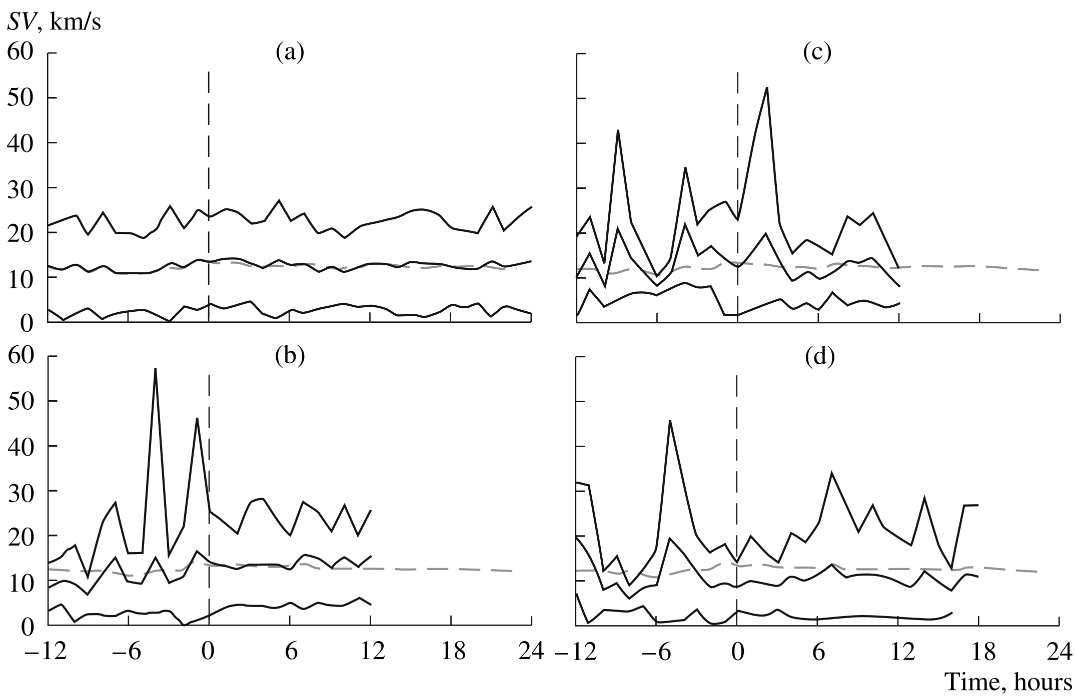

Fig. 4. The same as in Fig. 1 for the hourly standard deviation of the solar wind velocity.

storms can be the presence of oscillations of some parameters of the solar wind (density, velocity, temperature) and of the interplanetary magnetic field [17–21]. However, this issue has not also been discussed in our previous work. So, in the present work we discuss in detail the influence on the excitation of magnetic

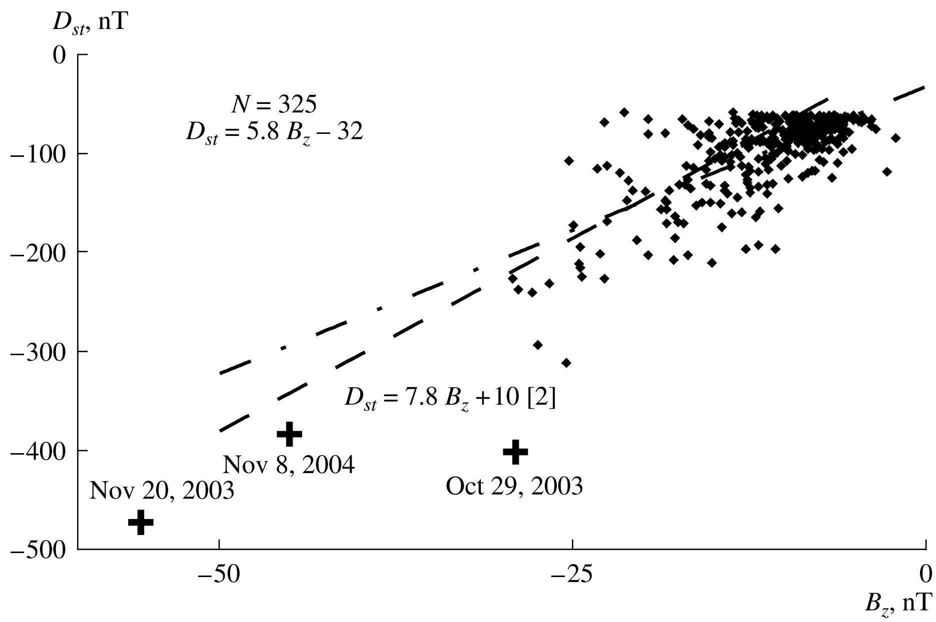

Fig. 5. Dependence of the minimum of the D_{st}-index on the minimum of the B_z-component of the interplanetary magnetic field according to the OMNI database for 1976–2000 (black diamonds), its approximation (dash-dotted line), and the extreme events of 2003–2004 (big crosses). The dashed line is the approximation of the data made in paper [2].

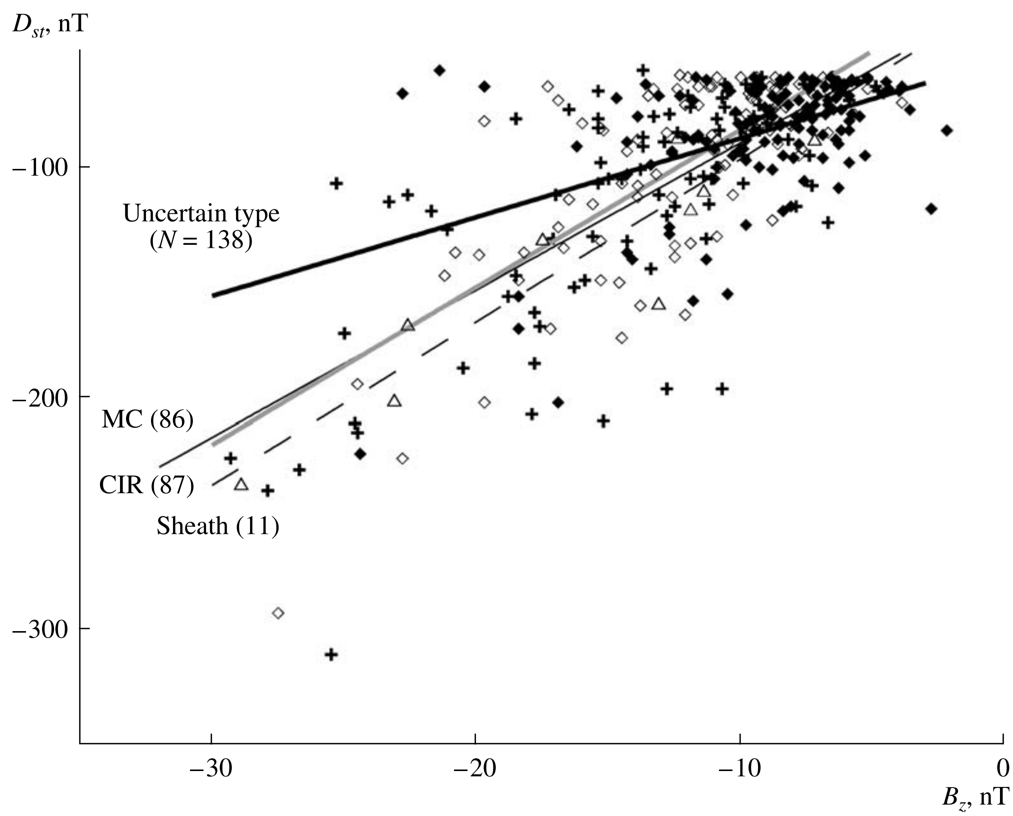

Fig. 6. Dependence of the minimum of the D_{st}-index on the minimum of the B_z-component of the interplanetary magnetic field according to the OMNI database for the 1976–2000 interval for various solar wind types: "Uncertain type" (black diamonds and thick solid black line); CIR (light diamonds and gray line); Sheath (light triangles and black dashed line); and MC (crosses and thin black line).

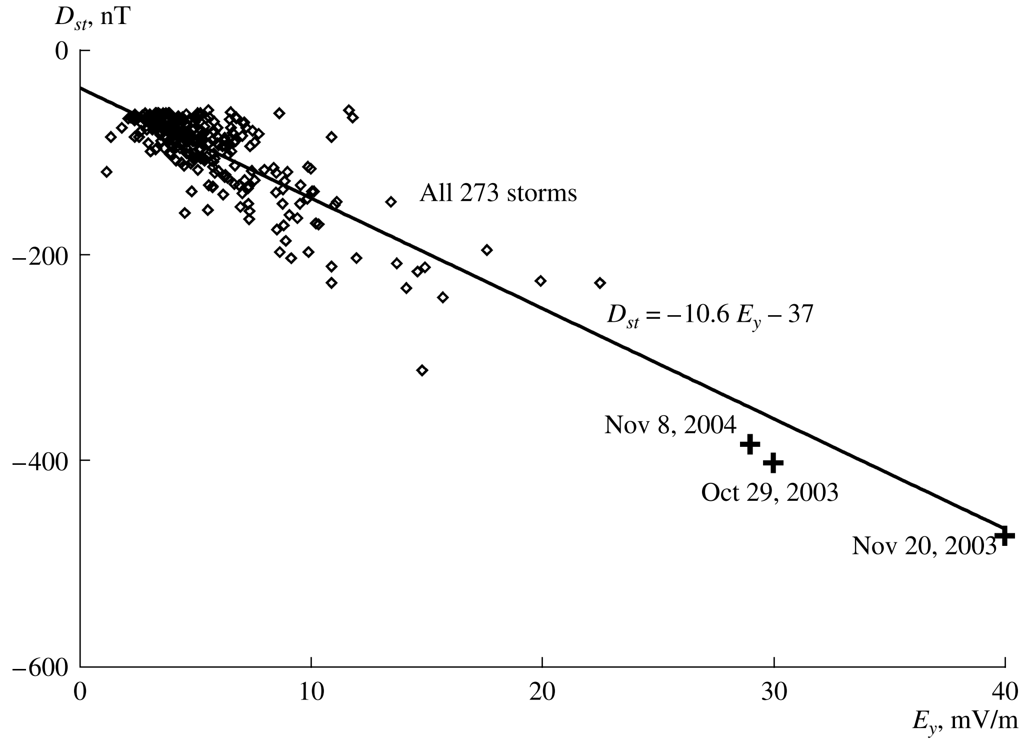

Fig. 7. Dependence of the minimum of the D_{st}-index on the E_y-component of the electric field according to the OMNI database for the 1976–2000 interval for various solar wind types (diamonds), its approximation (solid line), and extreme events of 2003–2004 (big crosses).

storms of: (1) oscillations of solar wind's and IMF's parameters, (2) the B_z-component value, and (3) the electric field E_y in various solar wind types.

METHODS AND RESULTS

The data and technique of selecting the intervals of various solar wind types and statistical data processing have been described in detail in previous papers [22, 1]. The OMNI database contains, along with hourly average values of SW and IMF parameters, also (for some parameters) the root-mean-square (standard) deviations per hour, which were calculated in the process of calculating the mean values of these parameters. We have processed the values of root-mean-square deviations of the solar wind velocity, temperature, and density, as well as the values of the IMF magnitude, by the same technique as in the previous paper. Then we use these values as a measure of variability of the parameters near the magnetic storm onset in various solar wind types (see Figs. 1–4).

Figure 1 shows the time dependence of a standard deviation of the magnetic field magnitude *SB* in a similar manner, as it was done in the previous paper [1], i.e., by the superposed epoch technique, for 4 SW categories: (a) "uncertain" type, (b) CIR, (c) Sheath, and (d) MC. Zero on the abscissa axis corresponds to the onset of the magnetic storm, obtained from the beginning of decreasing the D_{st}-index. Here, the dashed line in each panel shows the time dependence of this parameter for all magnetic storms (i.e., without selection in the SW type), the middle line shows the parameter behavior for the corresponding SW type, and the upper and lower lines (some part of the latter line can be absent, if it is below the chosen scale in the figure) show the statistical average scatter of this parameter. In a similar manner, Figs. 2–4 present the results for variations of the solar wind density *SN*, temperature *ST*, and velocity *SV*. It is seen in Fig. 1 that considerable (about 5–7 nT) variations of the IMF magnitude, 6–10 h before the onset, are observed only in the Sheath, while in the other solar wind types they are insignificant both before the onset and during it.

Figure 2 shows a considerable peak in variation of density *SN* (5–7 cm^{-3}) 5–8 h before the magnetic storm onset in the Sheath. In this case, just at the onset instant in CIR, Sheath, and MC the density variations increase, though not so significantly (by 2–4 cm^{-3}), as it took place 5–8 h before the magnetic storm onset in the Sheath.

As seen in Figs. 3 and 4, the insignificant increases of variations of velocity *SV* (by about 20 km/s) and temperature *ST* (by about ~$5 \cdot 10^4$ K) are observed in the periods of 2–4 and 8–10 h before the onset in the Sheath and 3–6 h before the inset in the MC.

The dependence between the minimum of the B_z-component of the IMF and the minimum of the D_{st}-

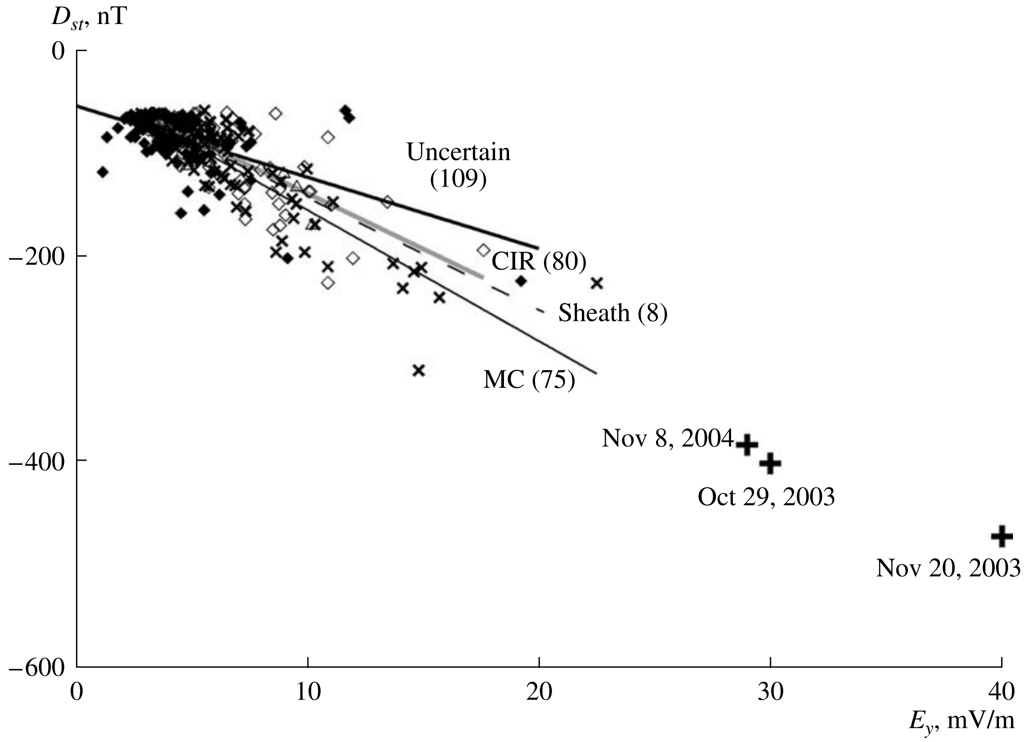

Fig. 8. Dependence of the minimum of the D_{st}-index on the E_y-component of the electric field according to the OMNI database for the 1976–2000 interval for various solar wind types: "Uncertain type" (black diamonds and thick solid black line); CIR (light diamonds and gray line); Sheath (light triangles and black dashed line); MC (skew crosses and thin black line); and extreme events of 2003–2004 (big crosses).

index is shown in Fig. 5. The dashed line shows the approximation of similar data in paper [2]. Our approximation of the data (the dash-dotted line) occurred to be less steep, apparently, because of the fact that, due to the lack of data in the OMNI base, the strong magnetic storms with $D_{st} < -300$ nT did not virtually fall within our data set. For this reason, we have added in Fig. 5 the data of the last extreme events of October–November, 2003 [23, 24] and of November, 2004 [25] with $D_{st} < -400$ nT. The same dependence, but for various

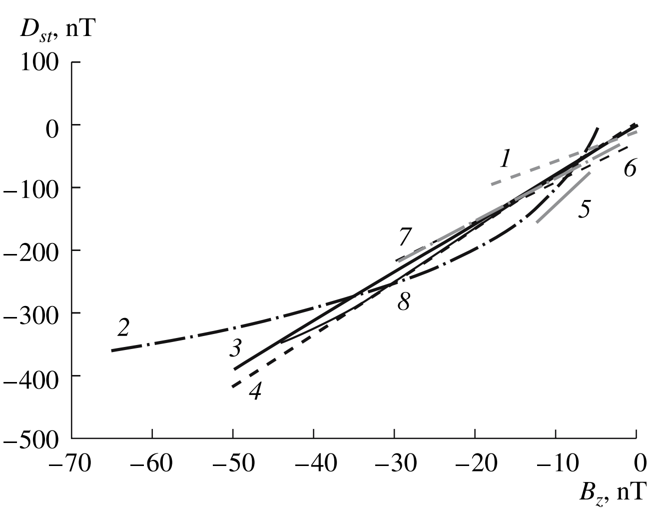

Fig. 9. Approximations of the dependence of the minimum of the D_{st}-index on the minimum of the B_z-component of the IMF. For CIR: *1* [9]; *5* [10]; *7* our results; for MC: *2* [8]; *3* [4, 5]; *4* [7]; *6* our results, *8* [6], thin line.

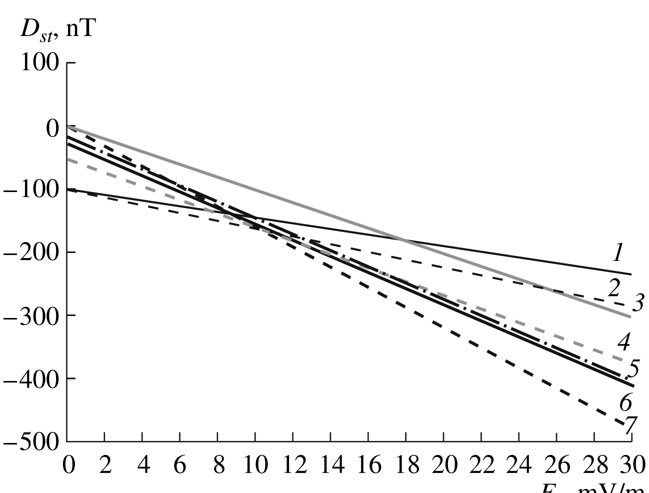

Fig. 10. Approximations of the dependence of the minimum of the D_{st}-index on the E_y-component of the electric field. For CIR: *3* [9]; *4* our results; for MC: *1* [15]; *2* [16]; *5* [5]; *6* our results; *7* [4].

solar wind types separately, is shown in Fig. 6. This figure demonstrates that the dependencies between the B_z-component of the IMF and the D_{st}-index are steeper in the CIR, MC, and Sheath than in the "uncertain" type, and, though the distinctions (with regard to high scatter of data for the CIR, MC, and Sheath straight lines) are insignificant, the steepest dependence is observed for the Sheath (see Table 1, which presents the results of linear approximation for various types of the solar wind streams).

Figure 5 shows that either the dependence between the minimum of the B_z-component of the IMF and the minimum of the D_{st}-index is non-linear (it becomes steeper with increasing B_z-component) or it is necessary to take into account the additional factors influencing the magnetic storm intensity. As is shown by Figs. 7 and 8, the dependence of the D_{st}-index minimum on the electric field strength E_y (i.e., the product of the B_z-component of IMF by the radial velocity component) has lower scatter relative to the middle line, and the data approximation for the 1976–2000 interval (without extreme events) well describes the data for extreme events of years 2003–2004 (see Fig. 7). As well as in Fig. 6, the dependencies between the E_y-component of the electric field and the D_{st}-index are steeper in the CIR, MC, and Sheath than in the "uncertain" type; however, the steepest dependence is observed for MC rather than for Sheath events (see Table 1).

DISCUSSION AND CONCLUSION

Before discussing the results, we would like to discuss some methodological issues. The data included in the OMNI base were obtained as a result of processing the measurements carried out by different instruments on various spacecraft. The database authors have undertaken strong efforts to perform inter-calibration of the data from various instruments by comparing the measurements at those time intervals, when these instruments operated simultaneously. This procedure can eliminate only displacements of the mean values, if the zero point of an instrument is drifted away, or its sensitivity has dropped during operation in space. However, this procedure cannot take into account the fact that distinctions in the design and resolution (for example, in angle or time) of various instruments can lead to the situation, when "the instrumental contribution" to the distribution of measured parameters can occur to be essential and distinctive, and the measurement results have different statistical characteristics, including such as the root-mean-square deviations. No sufficient information is available for us to investigate this problem in detail throughout the studied interval; however, we hope that sufficiently great statistics of events decreases the effect of "instrumental" and other "methodological" factors, and the root-mean-square variations of parameters presented in Figs. 1–4 characterize the real "variability" of these parameters. The validity of such an assumption is confirmed by the fact that the curves in Figs. 1–4 have sufficiently smooth shape. And this is true both for the curves with a great number of events, and for the curves with a small number of events (such as Sheath). Nevertheless, the results presented in these figures should be considered as some hypotheses that require careful checking rather than as strictly established facts. We plan to perform such checking at a later time.

Figures 1–4 indicate that only variations of the IMF magnitude and density can be geoeffective, and even this only in the Sheath, while solar wind temperature and velocity variations, most likely, cannot be considered to be geoeffective parameters. These conclusions can be drawn only for variations in the range of about one-minute periods, that is, in the range, where the parameters of solar wind plasma and field were measured. These results qualitatively coincide with the results on geoefficiency of the magnetic field [17–19, 21] and density [20] variations. However, a new result consists in the indication that correlation between variations of these parameters and magnetic storms is most probable only in the Sheath. The plasma fluxes and the magnetic field in the Sheath are highly disturbed by virtue of the fact that these streams are generated in the region of interaction of undisturbed stream with a piston, which is represented in the particular case by the magnetic cloud. Therefore, strictly speaking, the question, whether the magnetic storm generation is associated namely with the growth of variations of these parameters in the Sheath or with the other characteristics in the Sheath, requires further investigation.

Table 1. Linear approximations of the dependence of the D_{st}-index minimum on the B_z-component of the magnetic field and on the E_y-component of the electric field in various solar wind types according to the OMNI database for the 1976–2000 period

SW type	Dependence on B_z	Number of points	Dependence on E_y	Number of points
Uncertain type	$D_{st} = 3.4B_z - 53$	138	$D_{st} = -7.0E_y - 53$	109
CIR	$D_{st} = 6.8B_z - 15$	87	$D_{st} = -10.8E_y - 53$	80
Sheath	$D_{st} = 7.1B_z - 26$	11	$D_{st} = -10.9E_y - 33$	8
MC	$D_{st} = 6.4B_z - 26$	86	$D_{st} = -12.8E_y - 27$	75

Table 2. Published approximations of the dependence of the D_{st}-index minimum on the B_z-component of the magnetic field and on the E_y-component of the electric field in various solar wind types

No.	Approximation	SW type	Reference
1	$D_{st} = 7.8B_z + 10$	Any SW	[2]
2	$D_{st} = 7.85B_z + 0.83$	MC	[4.5]
3	$D_{st} = -2.846 + 6.54B_z - 0.118B_z^2 - 0.002B_z^3$	Ejecta	[6]
4	$D_{st} = 8.49B_s + 5.6$	MC	[7]
5	$D_{st} = 8.6 - 318.92\ \ln(-B_z/4.52)$	MC + Sheath	[8]
6	$D_{st} = 4.7B_s - 10$	CIR	[9]
7	$D_{st} = 12.0B_s - 6$*	CIR	[10]
8	$D_{st} = 4.8B_z - 27$	without IS	[11]
	$D_{st} = 6.9B_z - 20$	with IS	[11]
1	$D_{st} = -16E_y$*	MC	[4]
2	$D_{st} = -4.5E_y - 100$*	MC	[15]
3	$D_{st} = -12.89E_y - 16.48$	MC	[5]
4	$D_{st} = -6.2E_y - 100$*	MC	[16]
5	$D_{st} = -10.1E_y - 1.01$	CIR	[9]

Note: Symbol "*" marks approximations we derived from the plots in mentioned papers.

As it was noted in the Introduction, only a small number of works has analyzed the relationship between the minimum of the B_z-component of the IMF and the minimum of D_{st}-index in the specific types of solar wind streams, such as magnetic clouds MC [4–8], CIR [9, 10], or in the streams after the interplanetary shock waves [11]. In order to compare the results of these works with our results, we have compiled them into a Table 2. Here, for all the results, for which only graphical information was presented in the original works, we have found, by ourselves, numerical coefficients for approximating straight lines, and these approximations are marked in Table 2 by asterisks. These dependencies are shown in Fig. 9 with regard to those limits of determination of existing functions, as they are presented in the original works.

First of all, it should be noted that Fig. 9 demonstrates a large scatter of approximating functions in the inclination. In this case, if the quantitative distinction between the values of these functions in the region of weak, moderate, and not very strong storms ($D_{st} > -150$ nT and $B_z > -20$ nT) is rather small, this distinction becomes significant for strong storms. In addition, in papers [6, 8] the approximation curves are deflected from straight lines upwards, i.e., they become less steep than the linear dependence. Our data in Fig. 5 show that the strong storms lie below the linear approximation. And this fact was interpreted as an evidence that, in a great number of cases, the interplanetary medium disturbances during the strongest storms cannot be considered as isolated, since they propagate through the disturbed medium, and the D_{st} vs B_z dependence occurs to be steeper [2, 23–25]. Thus, one of the factors resulting in distinctions between approximation curves, can be the selection of events (especially extreme events) for the data set under study. However, this cause is, most likely, not unique, since the dependencies, obtained, for example, in papers [9, 10] for CIR and rather weak storms, differ considerably from each other.

By virtue of the above result, the distinctions between the D_{st} vs B_z dependence for the CIR, Sheath, and MC obtained by us, being statistically reliable within the framework of the performed selection of data, are less than those differences which can be found in the literature for similar dependences for the other data sets. Therefore, the validity of our statements must be verified by further investigations.

The analysis of the dependence of D_{st} on the electric field E_y, published in various papers [4, 5, 9, 15, 16], also demonstrates a large scatter of data approximations (see Table 2 and Fig. 10). As for the D_{st} vs B_z curves, the coefficient of proportionality between D_{st} and E_y can differ as much as 2–3 times. This is especially unexpected in view of the fact that in our analysis the extreme events of 2003 and 2004 lie closer to the approximating straight line for the D_{st} vs E_y plots (see Fig. 7) than for the D_{st} vs B_z plots (see Fig. 5). Nevertheless, the existing scatter of results in the literature compels us to make the same stipulations concerning our results on various D_{st} vs E_y dependencies in various solar wind types, as those we have made above concerning the D_{st} vs B_z dependence.

Thus, with regard to all remarks made above, the conclusion can be formulated that the analysis of the behavior of solar wind and interplanetary magnetic field's parameters for 625 magnetic storms with $D_{st} < -60$ nT for the 1976–2000 period has shown the following.

(1) For the CIR-, Sheath- and MC-related storms a small increase of variations (hourly standard deviation) of the solar wind density is observed near the onset; and in the Sheath, in addition, a higher increase of density oscillations is observed 5–8 h before the onset.

(2) The increase of the IMF magnitude variation before the onset is observed 6–10 h before the onset only in the Sheath.

(3) For the CIR-, Sheath- and MC-related storms the dependence between the minimum of the B_z-component of the IMF and the minimum of the D_{st}-index is steeper than that for the "uncertain" type of the solar wind, and the steepest D_{st} vs B_z dependence is observed in the Sheath.

(4) For the CIR-, Sheath- and MC-related storms the dependence between the electric field E_y of the solar wind and the minimum of the D_{st}-index is also steeper than that for the "uncertain" type of solar wind, and the steepest D_{st} vs E_y dependence is observed in the MC rather than in the Sheath, as it takes place for D_{st} vs B_z dependence.

(5) The found distinctions in the D_{st} vs B_z and D_{st} vs E_y dependencies in various solar wind types occur to be less than the distinctions in the same dependencies published in the literature. This, most likely, indicates to the fact that the form of these dependences strongly depends on selection of events.

ACKNOWLEDGMENTS

The authors are grateful to the OMNI database developers for the possibility to use it in the investigations. The work was partially supported by the Russian Foundation for Basic Research, project nos. 04-02-13161 and 07-02-00042.

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