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Abstract: We review recent data on geoeffectiveness (possibility to generate magnetic storms on the Earth) of solar and interplanetary disturbances. We selected papers using (1) the analysis on direct and back tracing of events, and (2) solar (coronal flares and CMEs), interplanetary (CIR, magnetic clouds and ejecta) and geomagnetic disturbances (storms on Dst and Kp indices). The classifications of magnetic storms by the Kp and Dst indices, the solar flare classifiations by optical and X-ray observations, and the classifitions of different geoeffective interplanetary events are compared and discussed. Taking into account this selection, all published results on the geoeffectiveness agree to each other in each subset: "CME to Storms" - 40-50%, "CME to MC;Ejecta" - 60-80%, "MC;Ejecta to Storm" - 50-80%, "Storm to MC;Ejecta" - 30-70%, "MC;Ejecta to CME" - 50-80%, "Storm to CME" - 80-100%, "Flare to Storms" - 30-40%, "Storms to Flare" - 50-80% and "CIR to Storms" - 33 %. Higher values of correlations were obtained by back racing, that is, by method, in which they were defined as the probability of finding candidates for a source of geomagnetic storms among CMEs and flares, and, strictly speaking, these values are not true estimates of the geoeffectiveness. The latter results are also in contrast with the results of the two-stage tracing of the events: first a storm to an interplanetary disturbance, and then an interplanetary disturbance to a CME/flare. We present also a brief review on comparison of conditions in the interplanetary space during geomagnetic storms which are usually generated by 2 large-scale interplanetary phenomena - interplanetary coronal mass ejection (ICME) and corotating interaction region (CIR). ICMEs (or magnetic clouds) are sources of stronger magnetic storms. We take into account that 2 parts of ICME may be geoeffective - compressed region between shock and leading edge of ICME (Sheath) and the body of ICME (MC). We use superposed epoch method with storm onset time as zero time for analysis of 628 magnetic storms during 1976-2000. Higher southward IMF component is observed in MC but stronger storms are usually generated by the sheathes (not body of MC). In MC the magnitudes and variations of proton temperature, total ion density, minor ion abundance, beta-parameter and others differ from ones in CIR and Sheath. These facts may be used for modeling interplanetary disturbance dynamics as well as for forecasting the Space Weather conditions near the Earth.

Magnetic Storm Dependence on Solar and Interplanetary Events

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Abstract

We review recent data on geoeffectiveness (possibility to generate magnetic storms on the Earth) of solar and interplanetary disturbances. In the literature on the solar-terrestrial relations there are different estimations of storm effectiveness of solar and interplanetary events - from 30 up to 100%. Different results arise due to differences in the methods used to analyze the data: (1) the direction in which the events are compared, (2) the pair of compared events, and (3) the methods of the event classifications. We selected papers using (1) the analysis on direct and back tracing of events, and (2) solar (coronal flares and CMEs), interplanetary (CIR, magnetic clouds and ejecta) and geomagnetic disturbances (storms on Dst and Kp indices). The classifications of magnetic storms by the Kp and Dst indices, the solar flare classifications by optical and X-ray observations, and the classifications of different geoeffective interplanetary events are compared and discussed. Taking into account this selection, all published results on the geoeffectiveness agree to each other in each subset: "$CME \to Storms$" - 40-50%, "$CME \to MC, Ejecta$" - 60-80%, "$MC, Ejecta \to Storm$" - 50-80%, "$Storm \to MC, Ejecta$" - 30-70%, "$MC, Ejecta \to CME$" - 50-80%, "$Storm \to CME$" - 80-100%, "$Flare \to Storms$" - 30-40%, "$Storms \to Flare$" - 50-80% and "$CIR \to Storms$" - 33 %. Higher values of correlations were obtained by back tracing, that is, by method, in which they were defined as the probability of finding candidates for a source of geomagnetic storms among CMEs and flares, and, strictly speaking, these values are not true estimates of the geoeffectiveness. The latter results are also in contrast with the results of the two-stage tracing of the events: first a storm → an interplanetary disturbance, and then an interplanetary disturbance → a CME/flare. We present also a brief review on comparison of conditions in the interplanetary space during geomagnetic storms which are usually generated by 2 large-scale interplanetary phenomena - interplanetary coronal mass ejection (ICME) and corotating interaction region (CIR). ICMEs (or magnetic clouds) are sources of stronger magnetic storms. We take into account that 2 parts of ICME may be geoeffective - compressed region between shock and leading edge of ICME (Sheath) and the body of ICME (MC). We use superposed epoch method with storm onset time as zero time for analysis of 628 magnetic storms during 1976-2000. Higher southward IMF component is observed in MC but stronger storms are usually gen-

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Key words: Magnetic storm, Coronal Mass Ejection, Magnetic Cloud, Corotating Interaction Region
PACS: 94.30.Lr, 96.60.Rd, 96.60.Wh

1 Introduction

Solar and interplanetary causes of magnetosphere disturbances are one of the most actual and important problem of the solar-terrestrial physics. General concept did not change during many years: the main cause of magnetospheric disturbances is negative (southward) component Bz of interplanetary magnetic field (IMF) because magnetosphere becomes open and energy can be transferred from solar wind to magnetosphere and result in magnetic storms. IMF usually lies in ecliptic plane and does not contain any Bz component, and only disturbed types of solar wind can contain IMF Bz component (including southward one). In accordance with modern point of view there are 2 chains of energy transport from Sun to geomagnetosphere: (1) Solar disturbances (solar flares and Coronal Mass Ejections, CMEs) → interplanetary CME (ICMEs, ejecta and Magnetic Clouds, MCs) including southward IMF Bz → magnetic storms, and (2) coronal holes generating fast solar wind streams → interaction of fast streams with preceded slow ones and formation of compression regions (Corotating Interaction Regions, CIRs) with southward IMF Bz → magnetic storms. Although this problem has been investigated for a long time and there is now a large body of experimental and theoretical results (see, for example, the recent collection of papers (Lilensten, 2007) and reviews (Schwenn, 2006; Pulkkinen, 2007) and references therein), the problem is far from being solved.

On the one side, the investigation must include a long link of space regions with different physical processes, the problem has a pronounced multidisciplinary character, and the joint efforts of scientists of different specialties are required to solve it. On the other side, there are interface regions between known regions where we have no direct experimental data and can only suggest a hypothesis about relations between these areas. For example, there are

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data about solar and near-Sun space obtained by remote methods; there are direct measurements in near-Earth space, but we have no information about region between near-Sun and near-Earth areas because of absence measurements there (as well as about thin fronts of bow shock and magnetopause because of too fast motion of boundaries relative to spacecraft). So, in this paper we shall not discuss problems of regions where there are experimental data and which are discussed in special literature in details but we shall concentrate our attention on the "interface" between them.

In our previous papers (Yermolaev and Yermolaev, 2003b, 2006; Yermolaev et al., 2005a) it has been shown, that quantitative relations between the various phenomena strongly depend on some methodical problems. Therefore in following sections of paper we shall discuss the questions how quantitative definitions of the phenomena and ways of their comparison effect on obtained estimations of correlation between them. After that we shall present some estimations of these correlations on the basis of numerous observations. Finally we shall show that in most cases the generation of magnetic storms besides southward IMF component is characterized by the certain behaviour of other parameters of solar wind. It allows us to assume that magnetic storms generated by Sheath, MC, and CIR can be raised by different physical mechanisms.

2 Phenomena on the Sun

In contrast with the data on magnetospheric and interplanetary events which are obtained by in-situ measurements, the data on solar events are obtained by the remote sensing (ground-based or near-Earth space-based) of the solar atmosphere in different frequency ranges of electromagnetic waves. The frequency of emission is defined by conditions in the emitting plasma volume, and, generally speaking, the measurements made in different frequency ranges yield characteristics of different regions of the Sun. The problem of specifying the dynamics of the solar event (including its spatial motion, especially along the line of sight), is rather complicated and ambiguous, since in this case different parts of the phenomena whose characteristics and position are varying in time, must be observed by different instruments, and it is assumed that these measurements performed by several instruments can be used to study the same event.

Solar flares were first detected in the optical range of wavelengths with ground-based instruments, and their classification was based on optical measurements (see for example paper by Krajcovic and Krivsky (1982)). However, with the beginning of the space era, an orbital X-ray observations of the Sun were carried out on the spacecraft, and the X-ray flare classification based on the measurements on the GOES satellites was developed (for more details see the site http://www.ngdc.noaa.gov/stp/GOES/goes.html). The optical and X-ray emissions are formed at different stages and in different regions of the solar flare. Thus, the importances (classes) of flares determined by the two methods have different physical grounds. The relationship between optical and X-ray importances of solar flares for the interval of 1976-2000 is presented in Fig. 1, where the large flares with X-ray importance M5 and higher are shown (Yermolaev and Yermolaev, 2003b, 2006). This figure clearly shows that the correlation exists only in the statistical sense, because some events can have high optical importance and low X-ray importance and visa versa.

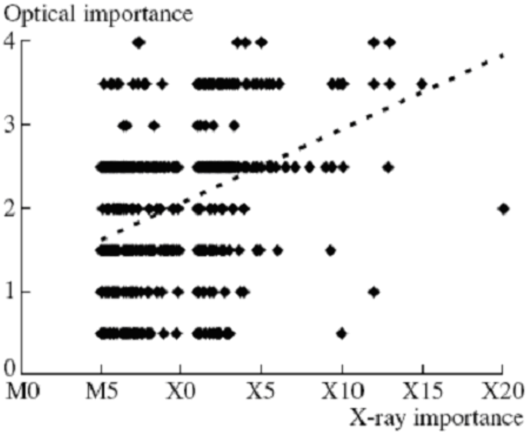

Fig. 1. Dependence of optical importance on X-ray importance for 643 solar flares with X-ray importance $\geq M5$ during 1976-2000 (Yermolaev and Yermolaev, 2003b, 2006)

For a long time all disturbances in the solar wind and the Earth's magnetosphere were connected extremely with the solar flares. Later, in the beginning of 1970s, other powerful solar processes such as coronal mass ejections (CMEs) were discovered with instruments on spacecraft. Nevertheless for a long time the CMEs were studied by independent researchers and as a whole they were not used almost in consideration of a chain of solar-terrestrial connections. However, after the landmark paper by Gosling (1993) the situation has significantly changed, and now CME is considered almost as the unique cause of all interplanetary and geomagnetic disturbances, though both these phenomena are closely interconnected (see discussion by Harrison (1996); Cliver and Hudson (2002); Yashiro (2005)).

A very large body of CME data has been obtained with LASCO coronagraph on SOHO spacecraft (`http://cdaw.gsfc.nasa.gov/CME_list/`). In contrast to the flare, very important problem of CME geoeffectiveness is determination of location of CME on the solar disk and first of all on what side of the Sun: visible or back. To solve this problem the white light observations of CME out of solar disk are compared with observations on the disk in other ranges of wavelength and with other solar phenomena: flare, EUV or X-ray dimming, EUV brightening, and posteruption arcade (in X rays or EUV). This procedure of comparing of white light and EUV observations is illustrated by an example in Fig. 2 (Gopalswamy, 2002). It is necessary to keep in mind that CME location obtained by method above is only hypothesis (not experimental fact) because researchers must use measurements made: (1) by different instruments; (2) in different frequency ranges; (3) in different spatial places and (4) at different time. So we should only statistically consider CME location on the solar surface obtained on the basis of images in other ranges of wavelength.

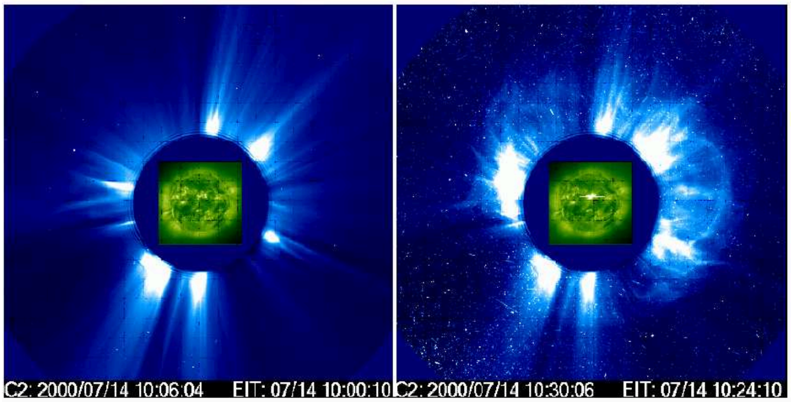

Fig. 2. Superposition of SOHO/LASCO (blue-white) and SOHO/EIT (green-yellow) images for an Earth-directed CME occurred on 14 July, 2000 ("Bastille day event"). The "snow storm" background in the right panel is due to energetic particles hitting the SOHO detectors. (Gopalswamy, 2002)

There are experimental data that some halo-CMEs result in interplanetary CME and magnetospheric disturbances but have no any visible signatures on the solar disc (Zhang et al., 2003). If this effect is not taken into account CMEs of this type can be included in backside CME list on the basis of only solar observations and lead to incorrect conclusions about halo-CME geoeffectiveness.

In contrast to the flare and CME, the coronal holes are quiet stable solar structures and they can live during several solar 27-day rotations. Coronal holes have open magnetic field which allows corona to generate the fast solar wind streams (Fig. 3). These fast streams interact with slow streams, create CIRs and can result in magnetic storms. In the modern literature the coronal holes are sufficiently seldom studied as sources magnetospheric disturbances. However recently new important results on CIRs have been published and some of them may be found in review by Tsurutani et al. (2006) and other papers in special issue of Journal of Geophysical Research, 2006.

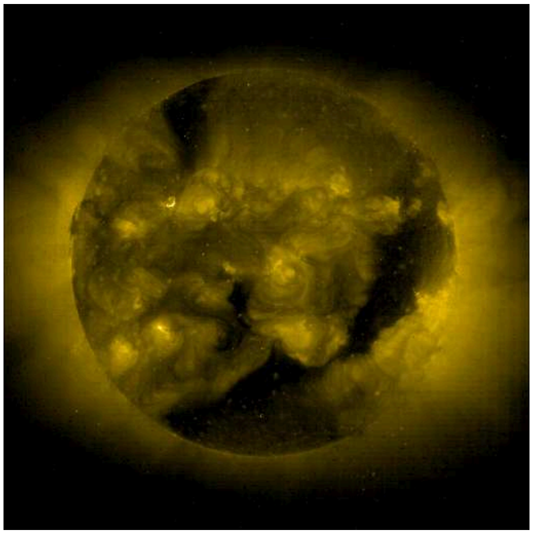

Fig. 3. The image of the lower corona made by EIT on board the SOHO spacecraft (http://www.lmsal.com/YPOP/ProjectionRoom/latest/eit/full/eit284-128.gif). Bright regions on the main body of the Sun are the active regions while the large dark regions are the coronal holes

3 Interplanetary events

The classification of events in the interplanetary space started with the beginning of the space era. Though methods of classification are rapidly developing now, general representations about types of a solar wind did not change significantly. According to numerous observations there are six main large-scale types of interplanetary phenomena (see Fig. 4): (1) - heliospheric current sheet; (2) - slow solar wind from coronal streamers; (3) - fast solar wind from coronal holes; (4) - compressed streams of solar wind (corotating interaction region, CIR, and Sheath, streams ahead magnetic clouds, MC), (5) - magnetic clouds (ejecta), and (6) - decompressed streams of solar wind but only 4th and 5th types are geoeffective because they may include long southward Bz component of IMF ((Gosling and Pizzo, 1999; Gonzalez at al., 1999; Crooker, 2000; Bothmer, 2004)).

There is no unique method of identification of interplanetary phenomena: different researchers use different sets of parameters as well as different numerical criteria of their analysis. For example, to identify magnetic cloud the methods include from 2 to 10 parameters (see, for example, Yermolaev and Yermolaev (2003b) and references therein). In the literature there are several lists of ICME (MC and ejecta) (see, for example, paper by Cane and Richardson (2003)) and one list of CIRs (see paper by Alves et al. (2006)) but there are not any lists including another types of solar wind streams or including simultaneously different types. We prepared a list of all types solar wind for interval of 1976-2000 based on OMNI dataset (see paper by Yermolaev et al.

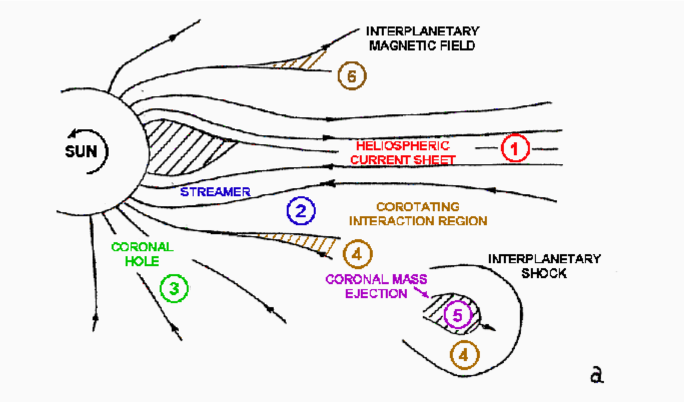

Fig. 4. Schematic view of 6 types of interplanetary event (Yermolaev, 1990, 1991; Yermolaev and Stupin, 1997).

(2008) and site ftp://ftp.iki.rssi.ru/pub/omni/catalog/).

In the large number of papers the various types of solar wind are considered as isolated events and interaction between them is neglected. However, the interaction between two CMEs close to the Sun (Gopalswamy et al., 2001, 2002) and between magnetic clouds near the Earth (see, for instance, Burlaga et al. (2001); Berdichevsky et al. (2003); Gonzalez-Esparza et al. (2004); Farrugia et al. (2006a) and reference therein) has been reported. A number of papers showed that several strong magnetic storms (see, for instance, events on 31 March, 2001, Dst peak value of -387 nT, 11-13 April, 2001, Dst = -271 nT, (Wang et al., 2003); 28-30 October, 2003, Dst = - 363 nT, (Veselovsky et al., 2004; Skoug et al., 2004); 20 November, 2003, Dst = -472 nT, (Ermolaev et al., 2005; Gopalswamy et al., 2005); 8-10 November, 2004, Dst = - 373 nT, (Yermolaev et al., 2005b) have been generating by multiple interacting magnetic clouds. Recently Farrugia et al. (2006b) studied interplanetary conditions for magnetic storms during 1995-2003 and found "that a significant number of our large events (6 out of 16) consisted of ICMEs/magnetic clouds interacting with each other forming complex ejecta." Xie et al. (2006) studied 37 long-lived geomagnetic storms (LLGMS events) with Dst < -100 nT and the associated CMEs which occurred during 1998-2002 and found that 24 of 37 events were caused by successive CMEs and number of interacting magnetic clouds was observed from 2 up to 4. This result may be explained by compression of interacting magnetic clouds and formation of complex structure (complex ejecta) which has properties relatives both to magnetic cloud and to Sheath (below it will be shown that the Sheath has a greater geoeffectiveness than the body of magnetic cloud).

Table 1
Classification of magnetic storms on the basis of the Dst index using the 1957-1993 measurements (Loewe and Prolss, 1997)

Class	Number	%	Dst, nT	$< Dst >$	$< ap >$	$< Kp >$	$< AE >$,nT
Weak	482	44	-30...-50	-36	27	4_o	542
Moderate	346	32	-50...-100	-68	48	5_o	728
Strong	206	19	-100...-200	-131	111	7_-	849
Severe	45	4	-200...-350	-254	236	8_+	1017
Great	6	1	<-350	-427	300	9_-	1335

4 Magnetospheric events

Geomagnetic disturbances arise due to sharp variations in the existing current system in the Earth's magnetosphere and ionosphere or due to generation of new currents. The state of magnetosphere is described by different indices calculated on the basis of ground-based magnetic field measurements (Mayaud, 1980). As different sets of stations were used to construct the indices, the responses to different magnetospheric/ionospheric current systems were included in them.

In this case, we cannot expect the identical behavior of different indecis during the same event (see, for example, 15-23 UT on 24 October, 2003 (Veselovsky et al., 2004) when at high Kp index Dst index shows quiet conditions). However, we can assume that at the sufficient statistics, the correlation between different indices can be found for the magnetic storm maximum. Such an analysis was performed, for example, for 1085 magnetic storms in 1957-1993 (Loewe and Prolss, 1997) and results are shown in Table 1. Dependence of Kp index on Dst index for 611 magnetic storms with $-300 < \mathrm{Dst} < -60$ nT during 1976-2000 (Yermolaev and Yermolaev, 2003b) is presented in Fig.5. Kp and Dst indices are measured at different geomagnetic latitudes and sensitive to different currents systems (magnetospheric phenomena): auroral electrojet (magnetic substorms) and ring current (magnetic storms). Thus, it is necessary to use Dst index to exclude auroral phenomena from analysis and to study the magnetic storm effectiveness.

5 Correlations between events

There is usual situation in the solar-terrestrial physics when we have no strict evidences on cause and effect relationships between the studied phenomena. The unique experimental fact is that one phenomenon is observed after another during a "window", in advance chosen time interval. As a rule any additional information on the phenomena is indirect for studying relation between these phenomena. As an example we shall consider dependence between flares and

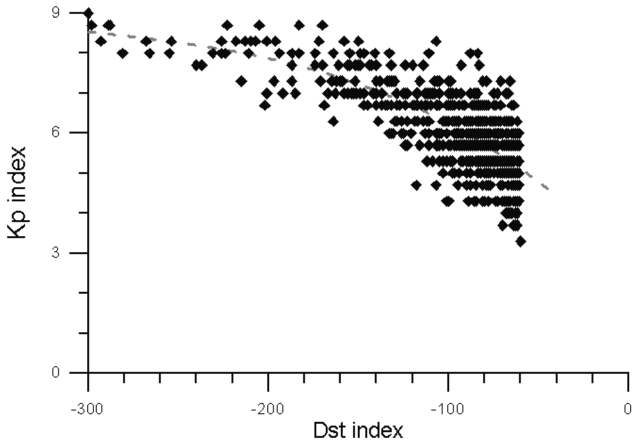

Fig. 5. Dependence of Kp index on Dst index for 611 magnetic storms with Dst < - 60 nT during 1976-2000 (Yermolaev and Yermolaev, 2003b)

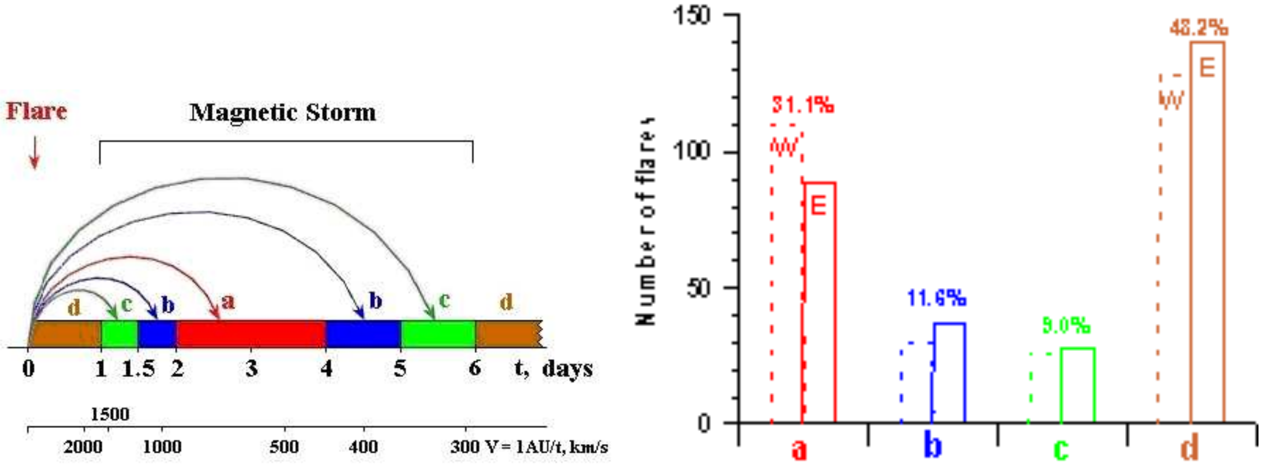

Fig. 6. Top: schematic view of correspondance between flares and storms for different time windows a, b, c, and d. Bottom: The number of western and eastern strong solar flares (dashed and solid lines) resulting in storms with (a) high, (b) intermediate, and (c) low probabilities and (d) not resulting in storms (Yermolaev and Yermolaev, 2003a).

magnetic storms (Fig. 6). In this case values of windows are determined by average speed of disturbances motion (it is shown under time axis) from the Sun up to the Earth, and windows a, b, c, and d correspond to intervals for which "flare-storm" relations are suggested to have high, intermediate, and low probabilities and to be absent, respectively. Bottom panel shows probability of storm generation after flare on the west and east hemispheres of the Sun. Only two levels of correspondance between events (probable and non-probable) are used in many studies.

We briefly described various methods of identification of solar (CMEs and solar flares), interplanetary (CIRs, Sheaths, MCs, ejecta and others) and geomagnetospheric (magnetic storms) events. In addition to the ambiguity of comparison of the results connected with different approaches to event classification, there is also an ambiguity connected with a technique of comparison of phenomena in two space areas. If two phenomena with samples X1 and X2 were chosen for the analysis and conformity was established for number of phenomena X12, then the "effectiveness" of the process X1 $\rightarrow$ X2 is usually defined as a ratio of values X12/X1; which differs from the "effectiveness" of the process X2$\rightarrow$ X1 equal X21/X2 = X12/X2; because samples X1 and X2 are selected by various criteria and can be of different value. Thus, the "effectiveness" determined in different investigations depends on the direction of analysis of the process. If one takes into account that sometimes sample X2 is not fixed prior to the beginning of the analysis, i.e. the rule (or criteria) of selection of events for sample X2 originally is not fixed, the ambiguity of calculation of process "effectiveness" can be additionally increased.

As in solar-terrestrial physics we investigated two-step process: the Sun-solar wind and the solar wind-magnetosphere, the data on the intermediate region (if available) can increase the reliability of estimations for the entire chain. Let us assume that there are data sets on the Sun (X1 and Y1), in the interplanetary medium (Y2 and Z1) and in the magnetosphere (X2 and Z2), for which some estimations of "effectiveness" of the processes X1 $\rightarrow$ X2 (equal to X12/X1), Y1 $\rightarrow$ Y2 (Y12/Y1) and Z1 $\rightarrow$ Z2 (Z12/Z1) were obtained. In this case it is natural to assume that the "effectiveness" of the entire process should be close to a product of "effectivenesses" of each of its parts, i.e. X12/X1 = (Y12/Y1)(Z12/Z1). In particular, it means that the "effectiveness" of the entire process cannot be higher than the "effectiveness" of each of parts: X12/X1 $\leq$ Y12/Y1 and X12/X1 $\leq$ Z12/Z1. The published works contain the data sufficient for such an analysis as we demonstrate below.

It is important to note that many authors frequently treat as "geoeffectiveness" of a phenomenon completely different values obtained with different procedures. In strict sense of this word, geoeffectiveness of the solar or interplanetary phenomenon is defined as percentage of corresponding set of the solar or interplanetary phenomena that resulted in occurrence of magnetic storms, and storms of a certain class. In other words, first of all it is necessary to select the solar or interplanetary phenomena by a certain rule, then one should examine each phenomenon from this list using a certain algorithm of occurrence of a storm. As have been mentioned above the time of delay between the phenomena is used as an algorithm of comparison of the various phenomena: either characteristic times of phenomenon propagation between two points, or time delay determined on some initial data.

Some authors apply an inverse method and use the back tracing analysis: initially they take the list of storms and extrapolate them back to the interplanetary space or on the Sun to search there for suitable phenomenon. This method is important and allows one to find candidates for the causes of given magnetic storms in the interplanetary space or on the Sun rather than to determine geoeffectiveness. The phenomena of different classes (if they are suited on time) are frequently used as such candidates and this is one of the reasons of divergence of results in many papers.

6 Results and discussion

We selected published results on CME, flare and interplanetary effectiveness using: (1) direct and back tracings and (2) different pairs of event types: "CME → Storm", "CME → MC, Ejecta", "MC, Ejecta →Storm", "Storm → MC, Ejecta", "MC, Ejecta → CME", "Storm →CME", "Flare → Storm" and "Storm → Flare". Results of the selection are presented in Table 2 and schematically shown in Fig. 7 (Yermolaev and Yermolaev, 2003b; Yermolaev et al., 2005a; Yermolaev and Yermolaev, 2006). In contrast to previos our paper we added recent papers and new process "CIR → Storm" (Alves et al., 2006). Record "CME → Storm" means that for the initial data set the CME list was taken, the number of analyzed cases of CMEs is presented in a column "Number of cases". The CMEs are compared with magnetic storms, the value of storm is defined by an index which is submitted in a column "Remark". Thus, we summarized the published data by 6 types of phenomena comparison (3 space areas and 2 directions of tracing): I: CME → Storm; II: CME → Magnetic clouds; Ejecta; III : Magnetic clouds; Ejecta → Storm; IV: Storm → CME; V: Storm → Magnetic clouds; Ejecta and VI: Magnetic clouds; Ejecta →CME: In II, III, IV and V we included both magnetic clouds and ejecta (including Sheath and body in both cases) which are similar in the physical characteristics, but in a column "Number of cases" we noted identification of authors by symbols MC (Magnetic clouds) and E (Ejecta). The table also presents data on VII: Flare → Storm; VIII: Flare → SSC, IX: Storm → Flare and X: CIR → Storm correlations.

Analysis of "CME → Storm" allows us to make a conclusion, that geoeffectiveness of Earth-directed halo-CME for magnetic storms with Kp >5 (Dst < - 50 nT) is 40-50% at sufficiently high statistics of 38 up to 305 CMEs, and the values obtained in papers by Webb (2002); Zhao and Webb (2003); Gopalswamy et al. (2007) are overestimated (see below). Results of back tracing analysis IV: Storm → CME are in good agreement (83-100%), but it is not high geoeffectiveness of CME that is shown by them: they indicate that it is possible to find possible candidates among CMEs on the Sun for sources of strong magnetic storms with a high degree of probability.

The analysis of a sequence of two-step direct tracing II: (CME → Magnetic clouds, Ejecta) and III : (Magnetic clouds, Ejecta → Storm) allows us to estimate a probability of the entire process CME → Storm as the product

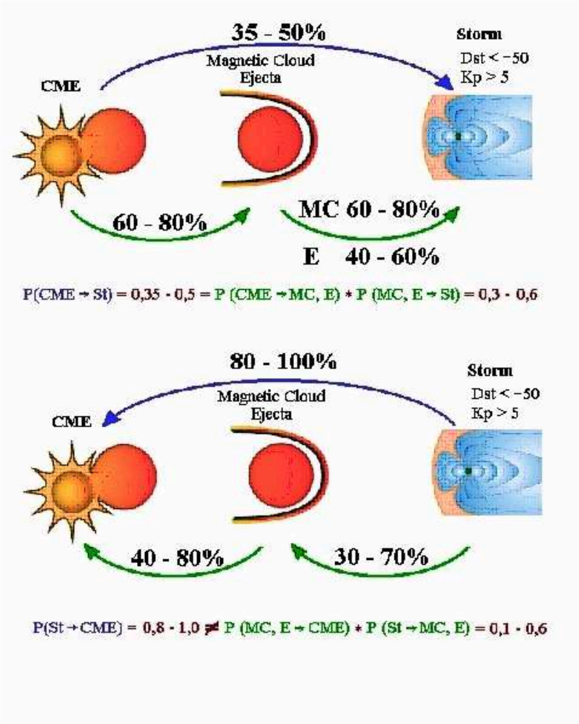

Fig. 7. Schematic view of correlations between CME, MC/ejecta and magnetic storms for direct (top panel) and back (bottom panel) tracings. Relations of probabilities for 1– and 2–step tracings are shown below each panel (Yermolaev et al., 2005a; Yermolaev and Yermolaev, 2006)

of probabilities, and for magnetic clouds we obtain a value (0.60 ... 0.70) * (0.57 ... 0.82) = 0.34 ... 0.57, which is close to above-mentioned results (40-50%) for the direct analysis of process I: (CME → Storm) and is lower than the estimation obtained by Zhao and Webb (2003); Gopalswamy et al. (2007). For ejecta this approach resulted in lesser value. The analysis of a sequence of two-step back tracing V: (Storm → Magnetic clouds; Ejecta) and VI: (Magnetic clouds; Ejecta → CME) does not allow us to obtain the high correlation Storm → CME in comparison with 83-100% in the entire process IV : (0.25 ... 0.73) * (0.42 ... 0.82) = 0.11 ... 0.60. Thus, the results of comparison of two-step and one-step processes for direct tracing CME → Storm are in good agreement while results of two-step process for back tracing differ several-fold from the results of one-step process. It means that the values for processes (Storm → Magnetic clouds; Ejecta), (Magnetic clouds; Ejecta → CME) and (Storm → CME) are not effectivenesses (probabilities) of causes → effects processes.

Though storm effectiveness obtained in papers by Webb et al. (2000); Webb (2002); Zhao and Webb (2003); Gopalswamy et al. (2007) relates to direct process I: (CME → Storm) and is lower, than in back process IV: (Storm → CME); the values obtained in these papers are (1) regularly higher than in other papers in process I: (CME → Storm), (2) higher than in process III : (Magnetic clouds, Ejecta → Storm) (excluding papers by Wu and Lepping

(2002a,b); Echer and Gonzalez (2004); Echer et al. (2005)), (3) close to values of papers related to process II: (CME → Magnetic clouds, Ejecta), and (4) higher than for two-step process II: (CME → Magnetic clouds, Ejecta) * III : (Magnetic clouds, Ejecta → Storm) = (0.6 ... 0.8) * (0.2 ... 0.8) = 0.1 ... 0.6. Thus, effectiveness in papers by Webb et al. (2000); Webb (2002); Zhao and Webb (2003); Gopalswamy et al. (2007) is likely to be overestimated. As has been noted in paragraph 2, there is the danger, that some Earthward CMEs may be related to backside CMEs (Zhang et al., 2003), and apparently, this mistake has been made in the specified works.

In our previous study (Yermolaev and Yermolaev, 2002, 2003a) we carried out direct tracing events Flare → Storm and estimated geoeffectiveness of 653 solar flares of importance (on X-ray emission) $\geq$M5 and slighter 126 flares of importance $\geq$M0 and following by solar energetic particle events near the Earth which in 40% cases resulted in magnetic storms with Dst $<$ -60 nT. If we carry out back tracing Storm → Flare and take the list of strong magnetic storms with Dst $<$ -100 nT, among the given set of flares only 20% can be sources of storm. The similar analysis had been made earlier. For example, in paper (Krajcovic and Krivsky, 1982) in which back tracing Storm → Flare was analyzed on large set of solar flares (on optical emission), it was shown that for the period 1954-1976 for 116 storms with `Kp > 7_`; among flares were revealed 59% possible sources. In paper by (Cliver and Crooker, 1993) back tracing Storm → Flare also is analyzed and it was shown that for 25 strongest magnetic storms with Dst$<$-250 nT observed in 1957-1990, at least in 22 (88%) cases it is possible to offer solar flare as the candidate of source. High values of "effectiveness" in papers by (Krajcovic and Krivsky, 1982; Cliver and Crooker, 1993) in addition to the back direction of comparison of the phenomena, apparently, is connected with fact that even weak solar flares can be considered as possible sources of storms while in our work we analyzed only strong flares.

Comparison of events Flare → SSC (i.e. not with geomagnetic storms, and with the phenomena which frequently precede storms) was carried out in recent work by Park et al. (2002) for 4836 flares of importance $>$M1 for the period 1 September 1975-31 December 1999. In result the estimation of geoeffectiveness for time of delay of 2-3 days for all flares was 35-45 % and for long duration flares a little bit more 50-55%. This result is close to effectiveness of Flare → Storm events mentioned above.

As have been noted above the storms are mainly generated by different types of solar wind: ICME including Sheath and body of ICME (MC) and CIR (see, for instance, Vieira et al. (2004); Huttunen and Koskinen (2004); Yermolaev et al., (2005); Yermolaev and Yermolaev (2006)). Yermolaev and Yermolaev (2002) showed that time variations in percentages of CIR-induced and ICME-induced storms have 2 maximuma (minimuma) per solar cycle and change with opposite phases. On the other side, there are experimental evidence that there

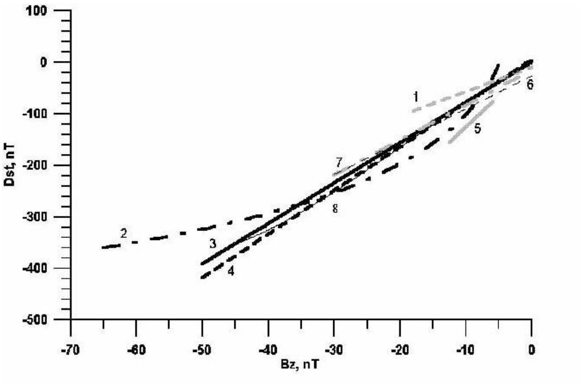

Fig. 8. Dst-Bz correlation for different types of solar wind. CIR: 1 - Alves et al. (2006); 5 - Richardson and Cane (2005); 7 - Yermolaev et al. (2007b) and (Sheath + MC): 2 - Naitamor (2005); 3 - Wu and Lepping (2002b, 2005); 4 - Richardson and Cane (2005); 6 - Yermolaev et al. (2007b); 8 - Yurchyshyn et al. (2004)

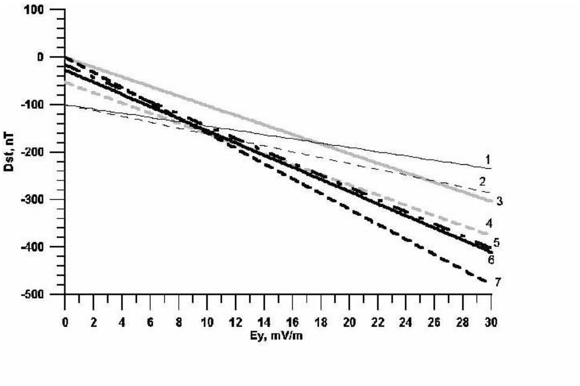

Fig. 9. Dst-Ey correlation for different types of solar wind. CIR: 3 - Alves et al. (2006); 4 - Yermolaev et al. (2007b) and (Sheath + MC): 1 - Srivastava and Venkatakrishnan (2004); 2 - Kane (2005); 5 - Wu and Lepping (2005); 6 - Yermolaev et al. (2007b); 7 - Wu and Lepping (2002b)

are differences between storms generated by Sheath, MC and CIR (Borovsky and Denton, 2006; Denton et al., 2006; Pulkkinen et al, 2007b). Peak-to-peak Bz - Dst and Ey - Dst (Ey - electric field in the solar wind during southward IMF) correlations are studied in some papers separately for MC- and CIR-induced storms. These results are summarized in Figs. 8 and 9, which show that there is no significant difference in these dependences for MC- and CIR-induced storms. These results were obtained without selection between Sheath and MC but conditions in Sheath and CIR are close to each other and this similarity of conditions can mask possible differences. We checked this possibility and calculated Bz - Dst and Ey - Dst dependences separately for CIR, Sheath and MC but did not find any significant differences at large spread of data (Yermolaev et al., 2007b). So, differences of CIR-, Sheath- and MC-induced storms may be connected not with values of Bz and Ey peaks, but with another parameters of IMF and plasma of solar wind and their dynamics.

The analysis of solar wind conditions resulting in 623 magnetic storms with Dst < -60 nT during the 1976-2000 period was carried out (Yermolaev et al., 2007a,b). The analysis was performed by the superposed epoch technique (with zero time equal to the storm beginning time) for the OMNI database parameters, supplemented by some parameters calculated on the basis of this database, separately for CIR, Sheath, and MC. Differences in time profiles of solar wind and IMF parameters for CIR (121 storms), Sheath (22) and MC (113) are shown in Fig. 10. We designated as "Unknown" also 367 storms for which there are not full set of measurements in OMNI data set or the type could not be defined unambiguously. Fig. 10 shows parameters: (Left column) N - density, V - velocity, Pdyn - dynamic pressure, T - proton temperature, T/Texp - ratio of measured proton temperature to calculated temperature using velocity, Dst index, (Right) β - ratio of thermal to magnetic pressure, B, Bx, By and Bz - magnitude and GSM components of IMF and Kp index. Curves for different types of solar wind are presented by different color. The variability of data for all parameters and for all types of solar wind is sufficiently large. In several cases the distinctions between curves are less than corresponding dispersions, and in this case it is necessary to consider these distinctions as a tendency rather than a proved fact.

The our investigations (Yermolaev et al., 2007a,b) have shown the following.

1. The behavior of solar wind parameters during magnetic storms essentially differs for various types of the solar wind; however, for all types of the wind the Bz- component of the IMF turns southward 1-2 h before the storm onset (reaching a minimum in 2-3 h after the storm onset) together with increasing solar wind density and dynamic pressure.
2. Though the lowest values of the Bz-component of the IMF are observed in the MC, the lowest values of the Dst-index are achieved in the Sheath. Thus, the strongest magnetic storms are induced during the Sheath rather than during the MC body passage, probably, owing to higher value and variance of pressure in the Sheath.
3. Higher values of nkT, T/Texp, and β-parameters are observed in the CIR and Sheath and lower ones in the MC, which corresponds to the physical essence of these solar wind types and indirectly confirms the correctness of thus performed selection of the wind types.

Detailed discussion of data in Fig. 10 and results may be found in papers by Yermolaev et al. (2007a,b).

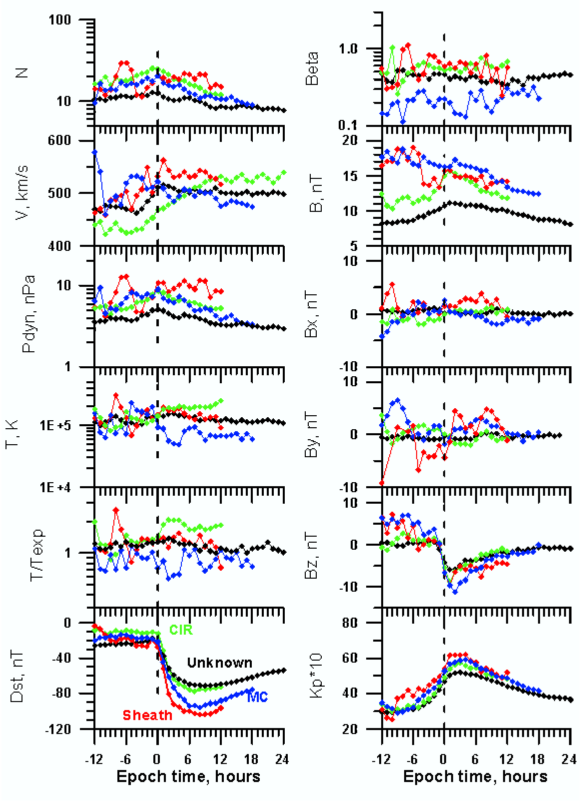

Fig. 10. Behavior of plasma and IMF for magnetic storms generated by CIR, Sheath, MC and "Unknown" types of solar wind during 1976-2000 obtained using OMNI dataset by superposed epoch method with zero time chosen as first 1-hour point of abrupt drop of Dst (http://arxiv.org/abs/physics/0603251).

7 Conclusions

Our results and published data on the geoeffectiveness of solar and interplanetary events show that:

- Geoeffectiveness depends on methods of event identification and classification.
- Geoeffectiveness depends on methods and direction of event correlation.
- CME and Flare geoeffectivenesses are 40-60%.
- Forecast of geomagnetic storms on the solar observations can contain high level of false alarm.
- ICME (Sheath + MC body) geoeffectiveness is 60-80%
- CIR (Corotating interaction region) geoeffectiveness is 33%
- No difference in peak-to-peak Dst-Bz and Dst-Ey dependences for MC, Sheath and CIR has been found.
- Minimum values of Bz IMF component are observed in MC, the minimum values of Dst index are reached in Sheath. Thus, the greatest magnetic storms are on the average raised during Sheath rather than during passage

of body of MC, probably, due to more high values of magnitude and variation of pressure and density in Sheath.

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Table 2

Correlation between solar, interplanetary and magnetospheric phenomena.

N	%	Number of events	Remarks	Reference
I. CME → Storm				
1	50	38	Kp	Webb et al. (1996)
2	71	7	$Dst < -50$	Webb et al. (2000); Crooker (2000); Li et al (2001)
3	35	40	$Kp > 6$	Plunkett et al. (2001)
4	45	20	$Kp > 5$	Berdichevsky et al. (2002)
5	35-92	?	$Dst < -50$	Webb (2002)
6	45	132^a	$Kp > 5$	Wang et al. (2002)
	20	132^a	$Kp > 7$	
7	35	125^a	$Dst < -60$	Yermolaev and Yermolaev (2003a)
	40	125^a	$Dst < -50$	Yermolaev and Yermolaev (2003b)
8	64	70^b	$Dst < -50$	Zhao and Webb (2003)
	71	49^c	$Dst < -50$	
9	58	12^c	$Dst < -50$	Moon et al (2005)
10	42	218^a	$Dst < -50$	Yermolaev and Yermolaev (2006)
11	40	305^b	$Dst < -50$	Kim et al (2005)
12	71	229^b	$Dst < -50$	Gopalswamy et al. (2007)
^{a} - Earth-directed halo-CME, ^{b} - frontside halo CME, ^{c} - centered frontside halo CME.				
II. CME → Magnetic cloud, Ejecta				
1	63	8	Earth-directed halo-CME	Cane et al (1998)
2	60-70	89	Frotside halo-CME	Webb et al. (2001)
3	80	20	halo-CME	Berdichevsky et al. (2002)
4	50-84	181	All CME	Schwenn et al. (2005)
	53-90	154	Earth-directed CME	
	59-93	91	Full halo Earth-directed CME	
III. Magnetic cloud, Ejecta → Storm				
1	44	327 E	$Kp > 5$	Gosling et al. (1991)
2		28 MC		Gopalswamy et al. (2000)
	67		$Dst < -60$	Yermolaev and Yermolaev (2002)
3	63	30 MC	$Dst < -60$	Yermolaev et al. (2000)
4		48 MC		Gopalswamy et al. (2001)
	57		$Dst < -60$	Yermolaev and Yermolaev (2003b)
5	82	34 MC	$Dst < -50$	Wu and Lepping (2002a)
6	73	135 MC	$Dst < -50$	Wu and Lepping (2002b)
7	50	214 E	$Dst < -50$	Cane and Richardson (2003)
	43	214 E	$Dst < -60$	
8	77	149 MC	$Dst < -50$	Echer and Gonzalez (2004); Echer et al. (2005)
9	76	104 MC+E	$Dst^* < -30$	Zhang et al. (2004)
	56	104 MC+E	$Dst^* < -50$	
	34	104 MC+E	$Dst^* < -100$	
IV. Storm → CME				
1	100	8	$Kp > 6$	Brueckner et al. (1998)
2	83	18	$Kp > 6$	St.Cyr et al. (2000); Li et al (2001)
3	94	?	?	Srivastava (2002)
4	96	27	$Dst < -100$	Zhang et al. (2003)
5	83	23	$Dst \leq -100$	Watari et al. (2004)
6	100	10	$-100 < Dst < -200$	Srivastava and Venkatakrishnan (2004)
	83	54	$Dst < -100$	

Table 3
Continuation.

N	%	Number of events	Remarks	Reference
			V. Storm → Magnetic cloud, Ejecta	
1	73	37	$Kp > 7_-$	Gosling et al. (1991)
2	67	12	$Dst < -50$	Webb et al. (2000)
3	25	?	$Dst(corr)$	Vennerstroem (2001)
4	19	1273 E	$Kp > 5_-$, Solar minimum	Richardson et al. (2001)
	63	1188 E	$Kp > 5_-$, Solar maximum	
5	33	618	$Dst < -60$	Yermolaev and Yermolaev (2002)
	25	414	$-100 < Dst < -60$	
	52	204	$Dst < -100$	
6	32	90	$-100 < Dst < -50$	Huttunen et al. (2002)
	21	100	$7_- > Kp > 5$	
	76	21	$-200 < Dst < -100$	
	38	21	$8 > Kp > 7_-$	
7	70	30	$Dst < -100$	Watari et al. (2004)
8	24	150	$Dst < -50$, 1978-1982	Li and Luhmann (2004)
	32	187	$Dst < -50$, 1995-2002	
9	29	271	$Dst^* < -30$	Zhang et al. (2004)
			VI. Magnetic cloud, Ejecta → CME	
1	67	49 E	CME	Lindsay et al. (1999)
2	65	86 E	CME	Cane et al (2000)
	42	86 E	Earth-directed halo-CME	
3	82	28 MC	CME	Gopalswamy et al. (2000)
4	50-75	4 MC	halo-CME	Burlaga et al. (2001)
	40-60	5 E	halo-CME	
5	56	193 E	CME	Cane and Richardson (2003)
6	48	21 MC	halo-CME	Vilmer et al. (2003)
			VII. Flare → Storm	
1	44	126^a	$\geq M0$	Yermolaev and Yermolaev (2002)
2	40	653	$\geq M5$	Yermolaev and Yermolaev (2003a)
3	33	571	$\geq 3(optic)$	Ivanov and Miletsky (2003)
4	44	746	$\geq M5$	Yermolaev and Yermolaev (2006)

^{a} - with solar energetic particle events

N	%	Number of events	Remarks	Reference
			VIII. Flare → SSC	
1	35-45	4836	$\geq M0$	Park et al. (2002)
			IX. Storm → Flare	
1	59	116	$Kp > 7_-$	Krajcovic and Krivsky (1982)
2	88	25	$Dst < -250$	Cliver and Crooker (1993)
3	20	204	$Dst < -100$	Yermolaev and Yermolaev (2003a)
			X. CIR → Storm	
1	33	727	$Dst < -100$	Alves et al. (2006)