Geomagnetic storm dependences on solar and interplanetary events: Statistic study for two solar cycles (1976-2000)

Yu. I. Yermolaev [a], M. Yu. Yermolaev [a], G. N. Zastenker [a], J.-A. Sauvaud [b]

[a] *Space Research Institute, Russian Academy of Sciences, Profsoyuznaya 84/32, 117997 Moscow, Russia*

[b] *CESR, B.P. 4346, 9, avenue du Colonel Roche, 31028 Toulouse, France*

Abstract

Within the framework of the "Space weather" program, 25-year sets of solar x-ray observations, measurements of plasma and magnetic field parameters in the solar wind and D_{st} index variations are analyzed with the purpose of revealing the factors rendering the greatest influence on development of magnetospheric storms. Value of correlation between solar flares and magnetic storms (∼30%) practically does not exceed a level of correlation of random processes. Furthermore it was not possible to find out any dependence between importance of solar flares and value of magnetic storms. *SOHO* data on Earth-directed halo-CME for time interval 1996-2000 show that geoeffectiveness of CME is about 35-40%. The most geoeffective interplanetary phenomena are magnetic clouds (MC) which, as many believe, are interplanetary manifestations of CMEs and compressions in the region of interaction of slow and fast streams in the solar wind (so-called Corotating Interaction Region, CIR): About 2/3 of all observed magnetic storms. For storms with -100 $< D_{st} <$ -60 nT the numbers of storms from MC and CIR are approximately equal, and for strong storms with $D_{st} <$ -100 nT the part of storms from MC is considerably higher. Year numbers of storms from MC and CIR have 2 maxima per solar cycle and change in antiphase. In summary the problems of reliability of a prediction of geomagnetic disturbances on the basis of observations of the Sun and conditions in the interplanetary space are discussed.

Key words: Geomagnetic storms, solar flares, coronal mass ejections, interplanetary events

---

Email address: `yermol@afed.iki.rssi.ru` (Yu. I. Yermolaev).

1 Introduction

One of key problems of solar-terrestrial physics in general, and of "Space weather" programs in particular, is a problem of revealing of the solar and interplanetary factors causing magnetospheric disturbances, and construction of models, allowing to make a prediction of a condition in near-Earth space and magnetosphere on the basis of observations of the Sun and the interplanetary medium. Though research of this question has a long history, and to present time there are a large set of experimental and theoretical results (see, for example, the collections of papers "Solar Drivers of Interplanetary and Terrestrial Disturbances", edited by K.S. Balasubramaniam, S.L. Keil, and R.N. Smartt (1996), "Space Weather" edited by P. Song, H. J. Singer, and G. L. Siscoe (2001) and "The Second Solar Cycle and Space Weather Euroconference" edited by H.Sawaya-Lacoste (2002) and reviews and recent papers by Webb (1995); Gonzalez (1999); Crooker (2000); Richardson et al. (2000); Vennerstroem (2001); Richardson et al. (2001) and references therein), the problem is far from the final decision.

As a whole it is possible to present the concept describing connection of the geomagnetic phenomena with processes on the Sun, as follows. An energy source of the geomagnetic phenomena is the Sun which transfers energy to the Earth's magnetosphere by means of streams of the solar wind (SW). The magnetosphere is usually closed for SW, and energy from SW put in magnetosphere only in a case when interplanetary magnetic field (IMF) has a significant component parallel to the terrestrial magnetic dipole, i.e. approximately negative (southward) IMF B_z component (see, for example, papers by Russell and McPherron (1973); Akasofu (1981); Gonzalez (1999); Petrukovich et al. (2001) and references therein). In a case when rate of energy input is higher than rate of its quasi-stationary dissipation, energy collects in the magnetosphere. When its amount reaches and exceeds some certain level, any small disturbance outside or inside magnetosphere can result in release of this energy (so-called "trigger" mechanism) as reconnection of magnetic field, global reorganization of current systems of magnetosphere and heating/acceleration of plasma, i.e. generate magnetospheric disturbance.

Quasi-stationary SW usually does not contain long intervals of southward components of IMF since the field basically lays in the ecliptic plane. However sometimes in SW the large-scale disturbances propagate, such as interplanetary shocks (IS), magnetic clouds (MC), regions of compression on boundary of slow and fast streams (corotating interaction region - CIR) and some other ones which or contain inside itself, or modify an environment in such a manner that appreciable southward IMF B_z component can be presented in SW within several hours. Such behavior of IMF can result in energy input into magnetosphere and in generation of magnetospheric disturbances (Gosling et al., 1991; Gosling and Pizzo, 1999; Gonzalez, 1999; Crooker, 2000). It is necessary to note that the term "corotating interaction region", having a long history in the literature, it is very unsuccessful in our opinion, as not all CIR are corotating, i.e. repeating with the period of Sun's rotation, and it would be better to call them "stream interaction region - SIR", but we shall adhere to traditions and to use the settled term.

It has been historically developed in such a manner that originally from all active processes on the Sun the solar flares were discovered (see paper by Gosling (1993)), and during long time all disturbances in SW and the Earth's magnetosphere tried to connect extremely with solar flares (see, for example, paper on solar-terrestrial connections in encyclopedia by Miroshnichenko (1986) and the book by Hargreaves (1992)). After opening in the beginning of 70th years of other powerful solar process - coronal mass ejection (CME) long time CMEs were studied by only separate researchers and as a whole in consideration of a chain of solar-terrestrial connections were not used almost. However after known paper by Gosling (1993) the situation has sharply changed, and now CME is considered almost as the unique cause of all interplanetary and geomagnetic disturbances (Webb, 1995; Crooker, 2000; Webb et al., 2000).

Nevertheless in the literature there are various estimations of CME geoeffectiveness from 35-45% (Wang et al., 2002; Yermolaev and Yermolaev, 2003a) up to 83-100% (Brueckner et al., 1998; St.Cyr et al., 2000; Zhang et al., 2003) (see also papers by Webb et al. (1996, 2000); Crooker (2000); Plunkett et al. (2001); Li et al (2001); Yermolaev and Yermolaev (2003b)) and interplanetary CME (ICME), ejecta and magnetic cloud (MC) geoeffectiveness from 25% (Vennerstroem, 2001) up to 82% (Wu and Lepping, 2002) (see also papers by Gosling et al. (1991); Gopalswamy et al. (2000, 2001); Yermolaev et al. (2000); Richardson et al. (2001); Yermolaev and Yermolaev (2002, 2003a,b) which do not agree with each other. Recently new papers with the statistical analysis of connection between geomagnetic storms and solar flares were published and they gave estimations 30-45% (Park et al., 2002; Yermolaev and Yermolaev, 2002, 2003a), in former works there are the data on geoeffectiveness of flares from 59% (Krajcovic and Krivsky, 1982) up to 88% (Cliver and Crooker, 1993). We believe that both CMEs and flares are different (with different spatial and temporal scales) manifestations of one global process on the Sun (see for example discussions (Harrison, 1996; Forbes, 2000; Low, 2001; Cliver and Hudson, 2002) and references therein). A question, what from these processes is better to use as the indicator of the solar events resulting in interplanetary disturbances and then to a geomagnetic storm, remains open. Therefore in this paper we analysed also last data on connection between solar flares and geomagnetic storms. It is necessary to note, that different authors under the term "geoeffectiveness" mean the different values obtained by different techniques, and this fact is necessary for taking into account by comparison of results of various papers and it will be discussed in section "Discussion".

In the present paper we research geoeffectiveness of the solar and interplanetary phenomena on an example of long-term observations of the Sun, the interplanetary space and geomagnetic D_{st} index, i.e. their ability to generate magnetic storms on the Earth. We also discuss some aspects of forecasting of geomagnetic disturbances on the basis of solar and interplanetary observations.

2 Data and methods of their analysis

We analyzed magnetic storms as a measure of strong global disturbances of geomagnetic field. Originally (since 1932) global magnetospheric disturbance was described by 3-hour Kp index determined with indications of several middle-latitude ground magnetic stations. Then it was shown, that the magnetic storm is connected basically with the Earth ring current laying near to equator and Kp index determined on middle-latitude stations is inexact for the description of magnetic storms. Consequently in 1957 the interest to Dst index suggested by Chapmen in 1919 was reborn (more in detail see discussion in paper by Grafe (1999)) which was determined with measurements on equatorial magnetic stations. In some cases it is used so-called corrected Dst index which turns out subtraction from an initial index of that part which is defined by currents on a surface of magnetopause and can be calculated on measured dynamic pressure $Pdyn$ of the solar wind: $Dst(corr) = Dst + A\,Pdyn + B = Dst - (0.02\,v\,n^{1/2} - 20nT)$, where v[km/s] - speed and n[cm^{-3}] - density (Burton et al., 1975; Gonzalez et al., 1989). Except for mentioned above for the description of magnetosphere condition other indexes with measurements on stations of different geographical position and with different way of data presentation are used also: AE, aa, Ap and others (Mayaud, 1980).

Because various works used both different types of indexes and different values of indexes for classification of magnetic storms it is necessary to find quantitative connection between the storms determined with various indexes for comparison of results of these works. As different sets of stations were used for construction of indexes the indexes included responses of different currents of a magnetosphere/ionosphere systems, and, strictly speaking, they analyzed the different physical systems attributed to one global phenomenon - magnetic storm. In this case it is impossible to expect full coincide of behaviour of various indexes during the same event (see, for example, paper by Vennerstroem (2001)), however it is possible to assume, that at sufficient statistics one can find correlation between various indexes during a maximum of a magnetic storm. Such analysis, for example, was made for 1085 magnetic storms for the period of 1957-1993 (Loewe and Prolss, 1997). As we analyzed the data for the distinguished period, we have repeated comparison Dst and Kp indexes for the period of 1976-2000 and have received rather close result (Yermolaev and Yermolaev, 2003b). A large number of papers used Kp index for classification of storm and moderate and strong storms are defined as storms with $Kp > 5$ and $Kp > 7$ (or $Dst <$ -50 and $Dst <$ -100 nT). We used uncorrected Dst index and stronger criterion for moderate storm $Dst <$ -60 nT (like in paper (Yermolaev and Yermolaev, 2002)) because in the range of $-50 < Dst <$ -60 nT there are a large number of overlapping storms which do not allow to correctly estimate the time of solar event propagation.

Geomagnetic storms have been also classified as recurrent (or corotating) and transient (or sporadic). Recurrence usually refers to solar/interplanetary disturbances that repeat with the 27-day synodic rotation period of the Sun. Recurrent source is usually attributed to fast solar wind stream emanating from coronal hole which reacts with slow stream from coronal streamer and leads to compressed region on leading edge of fast stream named corotating interaction region (CIR)(see reviews by Crooker and Cliver (1994); Tsurutani et al. (1995); Gosling and Pizzo (1999) and references therein).

Initially occurrence of the transient storms was connected with "driver gas" or "pistons" which propagate in the solar corona and/or interplanetary medium and can generate interplanetary shocks when their velocity is higher than velocity of enviroment plasma. Now this term is usually replaced with terms "magnetic clouds (MC)", "ejecta" and "interplanetary CME (ICME)". Magnetic clouds are frequently considered as special cases of two others which, apparently, can be considered as synonyms. For identification of these phenomena performance of several conditions (in various combinations) is usually supposed: (1) Plasma (ion and electron) components are colder than an environment, (2) Stable (with a low level of fluctuations) and slowly rotating magnetic field, (3) The low ratio of thermal pressure to magnetic (parameter β <1), (4) The high abundance of α-particles and others minor ion components of the solar wind, (5) Presence of bidirectional thermal electrons, (6) Presence of bidirectional energetic ($>$ 20 Kev) protons, (7) Decrease of energetic ($>$ 1 Mev) ions, (8) Presence unusual ionization states of thermal ions of the solar wind (Burlaga et al., 1981, 1990; Yermolaev, 1991; Gosling et al., 1991; Gosling, 1993; Shodhan et al., 2000; Richardson et al., 2001; Vennerstroem, 2001). Distinctive feature of magnetic clouds is suggested to be presence of a high magnetic field in comparison with environmental plasma of solar wind. Rather frequently all these criteria are not carried out simultaneously (correlation coefficients for various pairs of parameters are found in range of 49-93% (Richardson et al., 1993)). It is necessary to note that several of these characteristics are rare in occurrence, for example, single-ionized atoms of helium He^+ were observed several tens times for all space age (Zwickl et al., 1982; Yermolaev et al., 1989; Skoug et al., 1999). Therefore sometimes different authors can define even the same phenomenon on different types depending on the criteria chosen them, and in this case identification of the interplanetary phenomena can have ambiguous character.

Here it is required to make one serious comment concerning the data used in other studies. Many researchers use measurements of solar wind and IMF instead of direct CME observations in the solar corona. As it has been shown by earlier carried out analysis, parameters of SW and IMF measured in 2-4 days after CME observations in the corona have features which are close to the characteristics of the magnetic clouds or ejecta (ICME). Though such CME-MC/ICME correlation is high enough (see section Discussion), questions whether always CME results in MC/ICME, and whether MC/ICME can be caused by other solar sources, remain unclear. Nevertheless frequently it is possible to see in the literature as MC/ICME refer to CME, and are drawn conclusions on connections for CME though actually connections are found out for MC/ICME. As an example of such approach it is possible to use already mentioned paper by Gosling (1993). As it was revealed earlier (Gosling, 1993) the bi-directional streams of electrons (or counterstreaming halo electrons - CSHE) rather are frequently found out in MC/ICME observed after registration of CME in the corona. Existence of CSHE usually speaks that both CME and MC/ICME have a magnetic field in the shape of a loop or the closed spiral. In the paper by Gosling (1993) this result was used and all CSHE intervals for the 50-month's period of study are considered as intervals of CMEs. The dependences received in this case concern only to CSHE, and it is not known how much from them is really connected with CME. We agree that use of the additional information on SW stream (such as CSHE, the helium enhancement, unusual ionization conditions of heavy ions etc.) allows one to identify types of SW streams more strictly and to establish more strict relation between MC streams and CMEs. However now, in our opinion, to speak about such relation it is premature (Shodhan et al., 2000). As it will be shown below, we used usual data analysis method and selected some types of SW (including MC, CIR and IS) on the basis of measurements in interplanetary space however their connection with the solar phenomena (such as CME or solar flare) and magnetic storms is considered as a task of the paper.

If the data about magnetospheric indexes and the phenomena in the interplanetary medium are measured *in situ* the data on the solar phenomena in the atmospheres of the Sun are obtained by remote sounding (ground or space basing) in different frequency ranges of electromagnetic waves, thus the received signal is the integrated characteristic on all length of a beam of sight. Frequency of radiation is connected to conditions in radiating volume of plasma, and generally speaking, the measurements executed in different frequency ranges, give the characteristic of various areas of the Sun. Definition of dynamics of the solar phenomenon including spatial movement (especially along a beam of sight) is difficult enough and ambiguous problem as it is supposed that one parts of the phenomenon varying the characteristics and position are observed by one channel/device, other parts - others, and these measurements by several channel/devices can be used for research of the same phenomenon.

Originally solar flares were measured in an optical range of wave lengths and classification of flares was constructed on the basis of optical measurements (see foe example paper by Krajcovic and Krivsky (1982)), however with the beginning of space age the continuous orbital control of the Sun in a X-ray range was created, and classification is made on the basis of these measurements (see for example GOES site http://www.ngdc.noaa.gov/stp/GOES/goes.html). Optical and X-ray emissions are formed at different stages in different areas of solar flare as a result of different processes. Therefore the importance (class) of the flares determined by two ways has the various physical reasons in the basis. Connection between optical and X-ray indexes of solar flares for an interval of 1976-2000 years is sufficiently low and exists only in statistical sense as several strong events on an optical index can be weak enough on X-ray index and on the contrary (Yermolaev and Yermolaev, 2003b).

More complex procedure is used for studying halo-CME motion on measurements of *SOHO* interplanetary observatory: position of dimming which is considered as beginning of CME is determined on a disk with measurements by EIT instrument in ultra-violet range, and CME motion behind a disk - in white light coronagraph LASCO at which diaphragma closes (cuts out in sight) area equal to the size of a solar disk and C2 and C3 channels allow to study of corona at distances of 2-6 and 3-32 solar radii (see paper by Brueckner et al. (1995) and site http://lasco-www.nrl.navy.mil). Thus the specified two instruments measure emission not only in different ranges of frequencies, but also in different spatial areas and in different time. This comparison is very important for the decision of a question of principle: whether halo-CME goes to the Earth or from it, but a question on how much these two phenomena, measured by two instruments, are connected to each other in our opinion requires the further studying.

Thus, for the analysis we used the solar, interplanetary and magnetospheric data obtained via the Internet:

I. Two lists of strong solar flares (1) flares of importance (in X-ray range) $\geq M0$, but only such which were accompanied by increase of streams of solar cosmic rays (SCR) on *GOES* satellites (http://sec.noaa.gov/ftpdir/ indices/SPE.txt) and (2) all flares of importance $\geq M5$ (ftp:// ftp.ngdc.noaa.gov /STP/SOLAR_DATA/SOLAR _FLARES/XRAY_FLARES); list of CME observations on *SOHO* spacecraft (http://cdaw.gsfc.nasa.gov/CMElist/);

II. Parameters of plasma of the solar wind (velocity, temperature and density of ions) and the magnitude and three components of IMF (http:// nssdc.gsfc.nasa.gov/);

III. Hourly average values (not corrected) D_{st} index (http:// nssdc.gsfc.nasa.gov/ and http:// swdcdb.kugi.kyoto-u.ac.jp/dstdir/) in the time interval of 1976-2000.

Inclusion in the analysis of two sets of solar flares is caused by fact that solar flares, CMEs and interplanetary shocks accelerate particles and can produce SCR near the Earth (see for example (Richardson et al., 1991; Cliver and Crooker, 1993; Richardson et al., 1996; Anastasiadis, 2002; Malandraki et al., 2002) and references therein). In 1-st case we analyzed weaker (beginning with importance M0 in comparison with M5 in 2-nd set) flares, but such flares which have proved in SCR on the Earth orbit, and in 2-nd case we have taken a full set of strong flares without any preliminary selection of the data. The preliminary analysis of the 1-st set data is described by (Yermolaev and Yermolaev, 2002). The statistics in both cases was enough large: 126 and 653 flares, respectively. As for data on CME, regular CME catalogues are available for *SOHO* observations only since 1996 (http://cdaw.gsfc.nasa.gov/CMElist/) and consequently we were compelled to be limited to only 5-years (1996-2000) interval of observations, and also discussion of earlier published results on CME observations. It is necessary to note that if measurements of X-ray emission of solar corona and terrestrial D_{st} index cover practically 100% part of the interval, the data sets on the interplanetary medium before launch of spacecraft *Wind* (1994) and *ACE* (1997) have significant gaps in the data, and the time resolution of the early data was not better 1 hour.

3 Results

3.1 General characteristic of the period

The general condition of the considered 25-years period can be characterized by figure 1 in which the dashed line (curve 1) shows year-average number of sunspot, the thick lines (2 and 3) - the number of strong (importance not lower M0) solar flares with SCR increases and of all strong (importance not lower M5) flares, respectively, and the thin line (4) - number of strong magnetic storms (see definition below). The period began with a minimum of solar cycle in 1976, then there were two full cycles of solar activity, and in 1996 the 23-rd cycle started which in 2000 has reached the maximum. Numbers of strong flares and strong storms have maxima simultaneously within maxima of sunspot. The attention the fact draws, that the curves 3 and 4 have very similar shapes (coefficient of correlation is 0.92) and this correlation specifies that

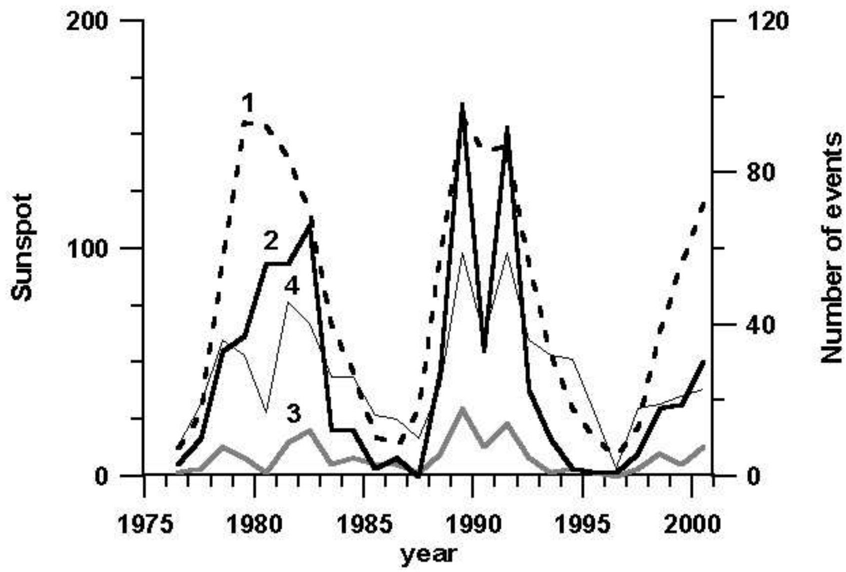

Fig. 1. Time variations of year-averaged values of sunspot (curve 1, scale at the left), numbers strong (importance $\geq M5$) solar flares (curve 2, scale on the right), numbers of strong (importance $\geq M0$) flares with SCR increase (curve 3, scale on the right) and numbers of magnetic storms with values of D_{st} index in a minimum less than -60 nT (curve 4, scale on the right).

variations of these two parameters can have one common reason. However, as we shall show below, magnetic storms appear to be practically not connected with solar flares.

3.2 Magnetospheric state

As the indicator of geomagnetic activity we use measurements of D_{st} index (see the continuous line in Figs. 2-6) which basically is connected with a geomagnetic field near equator and a condition of ring current and well describes development of global large-scale geomagnetic disturbances - magnetic storms. We present the initial data on D_{st} index without taking into account the contribution of currents on the surface magnetopause to value of D_{st} index. In quiet time D_{st} index varies near zero, slightly changing in the range from -30 up to + 30 nT. The magnetic storm is usually accompanied by sharp (during 1-10 hours) drop of D_{st} index down to some minimal value (value of magnetic storm) and by slow (1-3 day) recovery of value of D_{st} index up to the initial condition near zero.

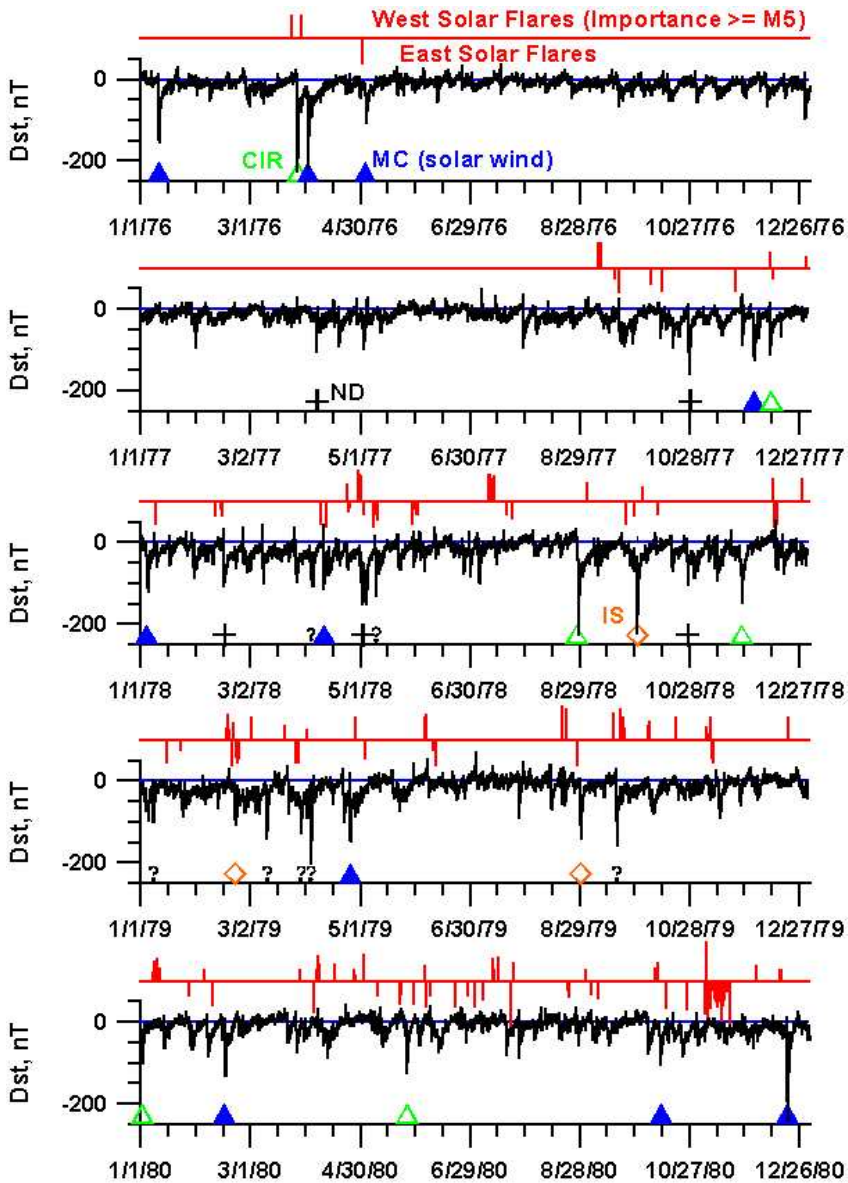

Fig. 2. Each panel shows time variations of solar, interplanetary and geomagnetic parameters during one year. The top parts of panels: vertical upward and downward segments concerning a horizontal line - strong solar west (upward) and east (downward) flares. Middle parts of panels: time variation of D_{st} index. The bottom parts of panels: phenomena in the interplanetary space (dark triangle - MC, light triangle - CIR, rhombus - IS, question mark - uncertain type of event, dagger - no data).

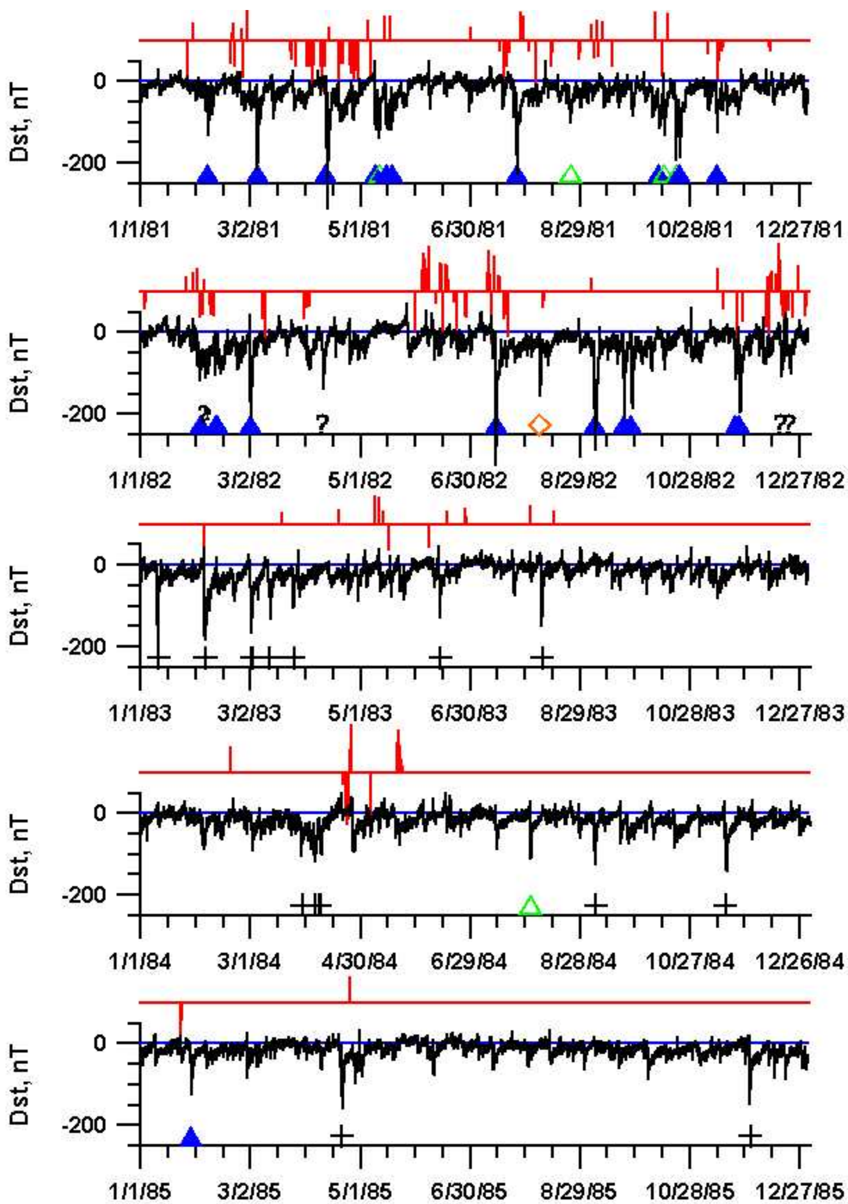

Fig. 3. Continuation of figure 2.

In figure 7 distributions of hourly average values of D_{st} index for total period of 1976-2000 (thick line, scale on the right), and also for disturbed year 1989 (thin continuous line) and quiet year 1976 (shaped line) are shown. Scales are picked up in such a manner that all 3 distributions have approximately identical areas. All distributions have a bell-like part in a range of values from -30 up to + 20 nT which contains a huge part of values. However on

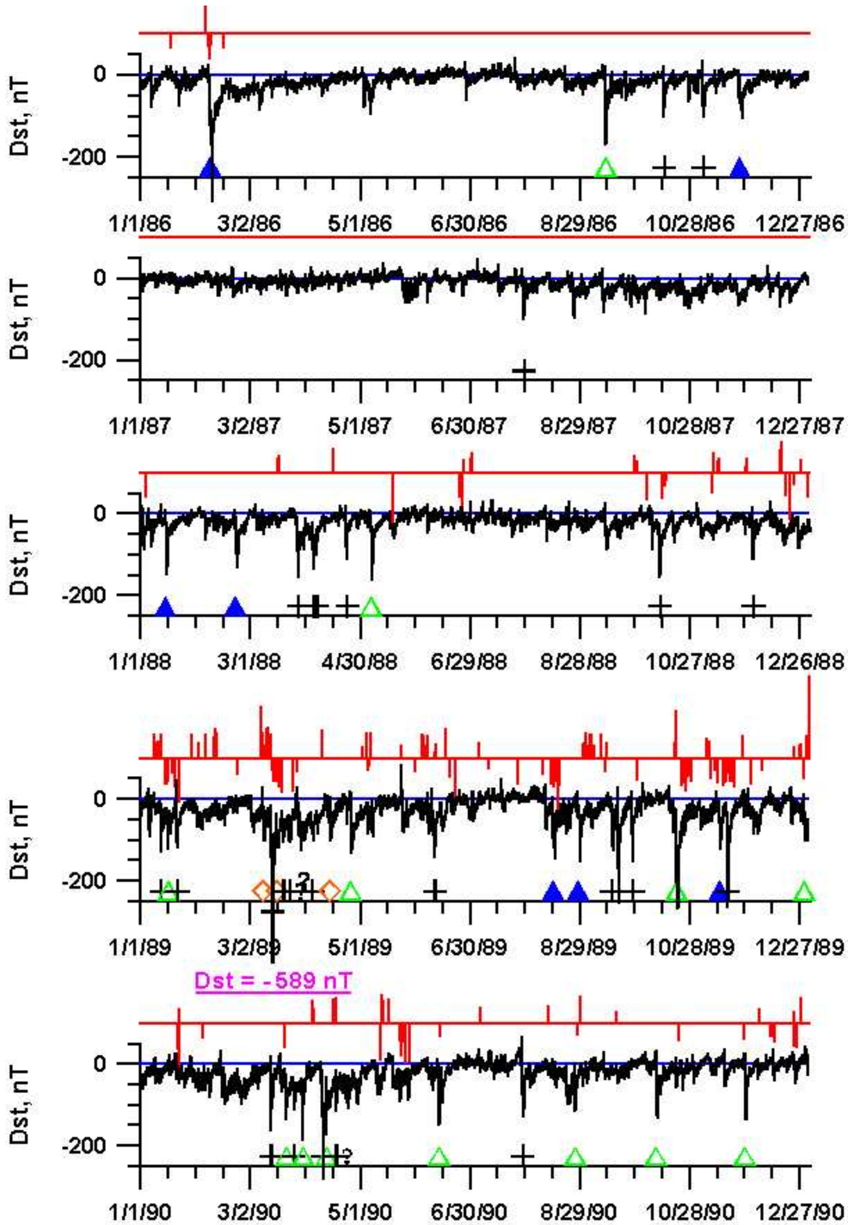

Fig. 4. Continuation of figure 2.

all distributions (and especially for the disturbed year) there are "tails" in the region of negative values of D_{st} index. Decreases less -30 nT usually is named magnetic storms. We shall adhere enough frequently used gradation and consider storms with D_{st} index from -30 up to -60 nT as "weak", from -60 up to -100 nT as "moderate" and less than -100 nT as "strong". There are too much weak storms that they could be considered as isolated from each

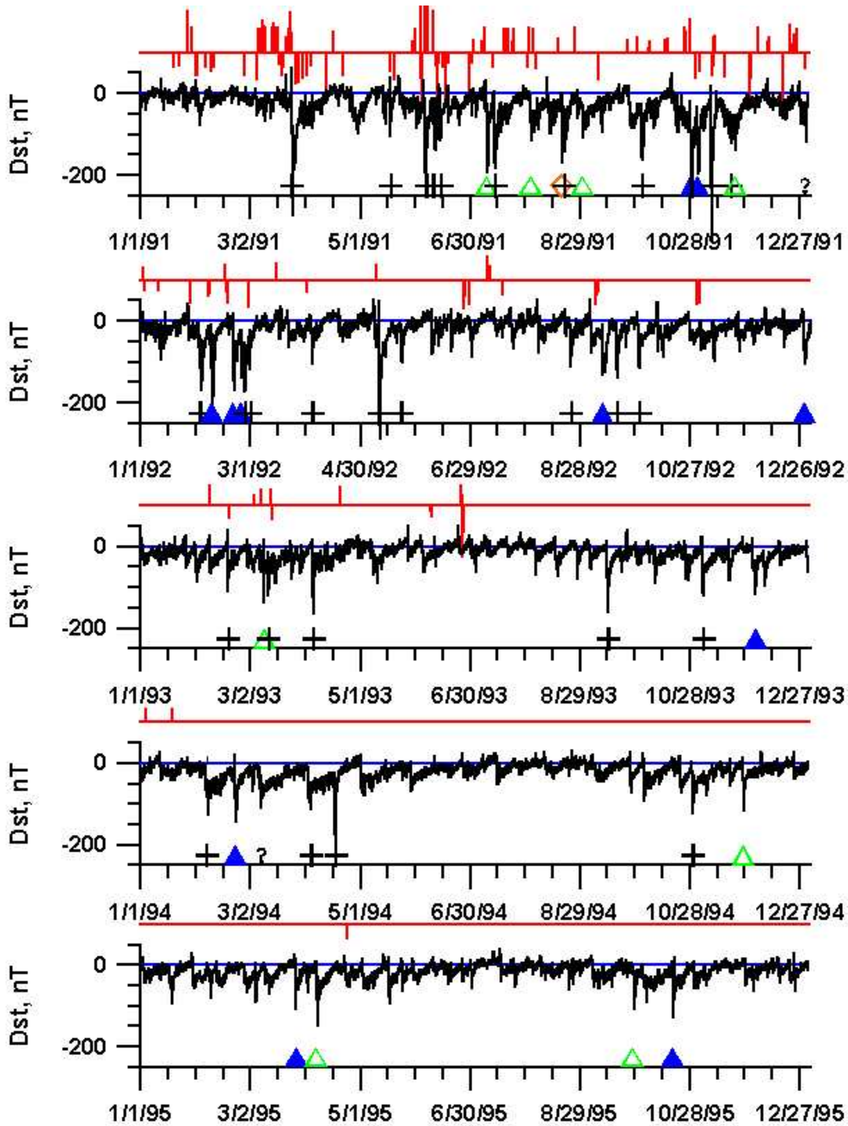

Fig. 5. Continuation of figure 2.

other: they not only can be observed in time closely to each other but also to overlap. It strongly complicates (and in some cases makes impossible) the analysis on their comparison to the phenomena on the Sun because the time of SW motion from the Sun up to the Earth is from 2 up to 4 days. Therefore we excluded weak storms from the analysis and were limited by only moderate and strong storms which total number was 618: moderate 414 and strong 204. Thus, on the average for all 25-year period the strong or moderate magnetic storm is observed 1 time per ∼15 days. In quiet years this period can grow up

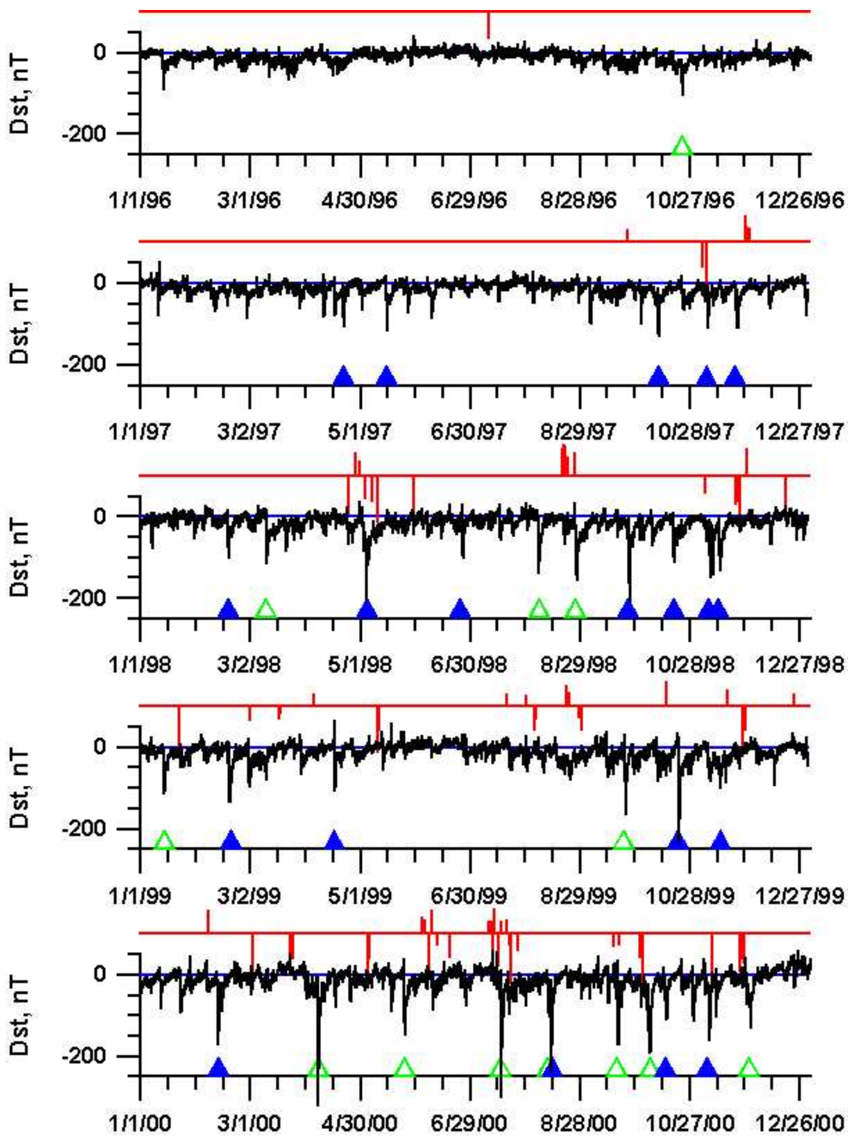

Fig. 6. Continuation of figure 2.

to ∼45 days, and in disturbed year decrease down to ∼6.8 days. The strongest magnetic storm for the 25-years period was observed on March 14, 1989, and peak of D_{st} index has value -589 nT (for this storm in Fig. 4 we have cut off values at a level ∼ -300 nT).

Besides variations in a cycle of solar activity (see Fig. 1) the number of storms varies and within one year. Dependences of number of strong solar flares (line 1) and number of strong solar flares with SCR increases (line 2) and magnetic

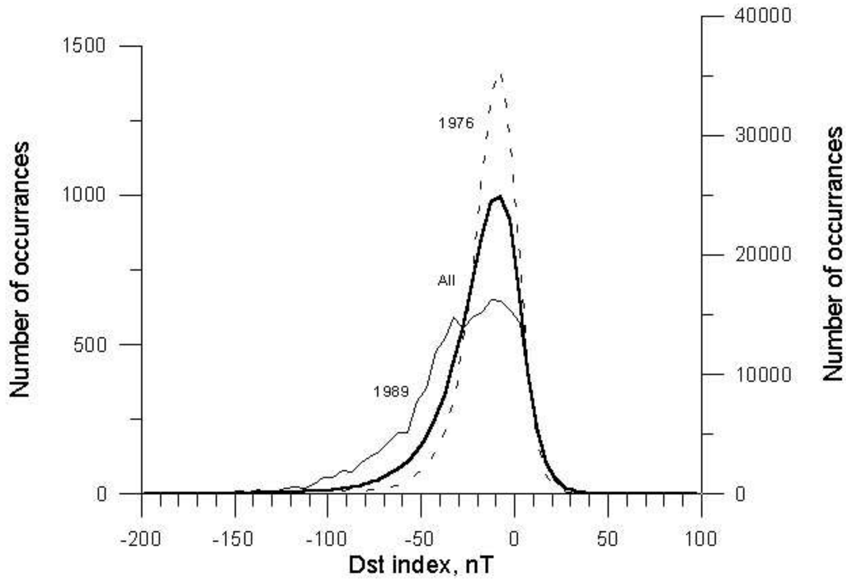

Fig. 7. Distributions of hour average values of D_{st} index for 1976-2000 (thick line, scale on the right), for quiet year 1976 and disturbed year 1989 (shaped and thin continuous lines, scale at the left).

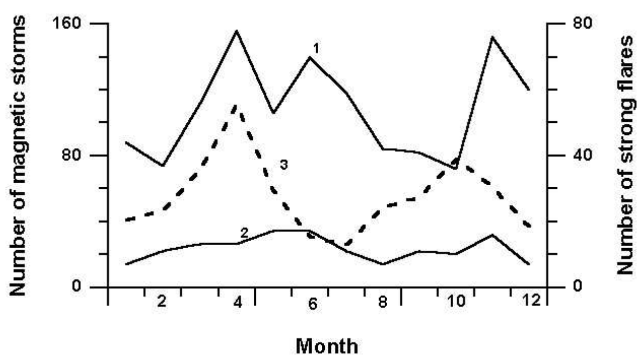

Fig. 8. Distributions of number of strong solar flares (continuous line 1) and flares with SCR increases (continuous line 2) and numbers of strong magnetic storms (dashed line 3) on the months, obtained by the superposition epoch method for the period of 1976-2000.

storms (dashed line 3) on month determined by the method of epoch superposition are shown in Fig. 8. Without dependence on level of magnetic storms the number of storms has two maxima: in the spring and the autumn. This result confirms the Russell-McPherron effect (Russell and McPherron, 1973) which can be connected with annual evolution of the geomagnetic dipole orientation relative to the Sun - Earth line. In particular such explanation of this effect is correct at the assumption that SW energy input in magnetosphere not only when IMF component parallel to the dipole simply exists, but also this component is perpendicular to incident SW stream. In this case at a deviation of the Earth rotation axis in perpendicular direction to the Sun - Earth line in spring and autumn months (near to days of an equinox) the IMF B_y component can bring an additional contribution in IMF component parallel to the Earth' magnetic dipole. If from the solar-ecliptic (GSE) systems of coordinates to pass in the solar-magnetic (GSM) system, in which the magnetic dipole of the Earth always lays in the XZ plane, the change of dipole direction will be taken into account automatically. In the further statement we shall use the GSM system of coordinates. This result can be also related to the equinoctial effect that makes B_z coupling less effective (by $\sim 25\%$ on everage) at the solstices (Cliver et al., 2000).

3.3 Relations of storms with solar sources

We begin to study the relations between magnetic storm occurrence and solar sources with the analysis of solar flares. The catalogue of strong flares with SCR increases is given in the tables 1-4 in which date and time of flare, its importance on X-ray and optical observations, its coordinates and area number on the Sun are given. Besides we have added some additional information in this catalogue on SW types which description and a method of its selection will be described below. If it was possible to identify the type of interplanetary disturbance (the main types were basically MC, CIR and IS) this type of disturbance and date and time of its beginning, and also a minimum of observed D_{st} index are indicated. If the type of interplanetary disturbance was unable to be determined, or for the appropriate interval there are no data the date and time of D_{st} index minimum are given in the table. For flares for which it was not possible to find a magnetic storm in the given time interval (see below), the data about D_{st} index and SW type are absent. We have excluded the those flares from the analysis which importance was lower M0 or for which there was no information on time of its beginning, and also flares at which time of previous flares differed less than 2 days. Thus, we have obtained the list of 126 strong solar flares with SCR increases. The similar analysis was carried out also for all flares of importance $\geq M5$, and such flares appeared 653, that it is too much to present this list here completely. It will be shown below that the majority of statistical characteristics for both sets of solar flares is

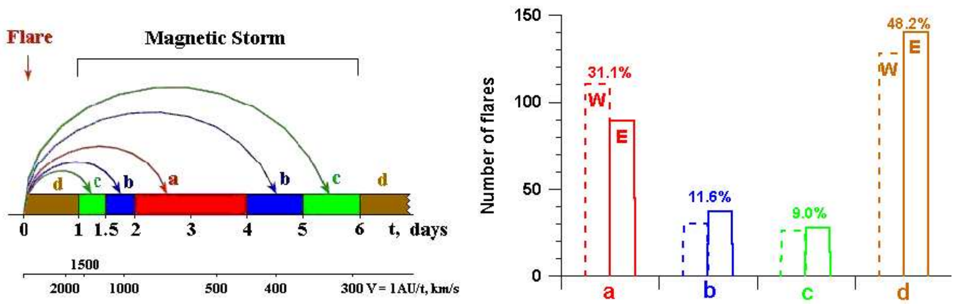

Fig. 9. Top: Schematic view of classification of solar sources of magnetic storms. Bottom: The number of west and east strong (importance $\geq M5$) solar flares (shaped and continuous lines) after which it is most probably (a), probable (b), less probable (c) and impossible (d) to observe the magnetic storms.

similar.

Though dataset on solar flares with SCR shown in Fig.8 have rather small statistics, it is possible to assume that dependences of number of storms and number of strong flares on months have extrema in different months of year. If two-peak distribution of numbers of storms is well explained by the Russell-McPherron effect (Russell and McPherron, 1973) (see the previous section), two-peak (for flares with SCR) or three-peak (for all strong flares) distributions of number of flares and in general their correlation with the period of motion of the Earth around the Sun are represented unexpected. Nevertheless the figure shows absence of correlation of flares and magnetic storms on scales less than year.

In Figs. 2-6 besides the hourly average values of D_{st} index presented by a continuous line, vertical segments in the top part of the panel specify the instants and values of strong solar flares, and upward segments correspond to flares on the west part of the Sun's disk, and downward - on east part. The figures show that any flares do not correspond to a large number of storms (including strong ones), and many flares are observed far on time from storms, before or after them. We have correlated all flares with storms on the following algorithm: if disturbance in SW (or minimum of D_{st} index if the SW type could not be determined) was observed in 2-4 days after flare such storm was considered as the potential ("most probable") candidate for a solar source of this storm; flare was considered as "probable" if it got already in the expanded interval of times of 1.5-2 and 4-5 days, as "less probable" if in the interval of 1-1.5 and 5-6 days, and as "improbable" if at all it did not get in interval of 1-6 days. It is necessary to note that time delay of 2-4 days

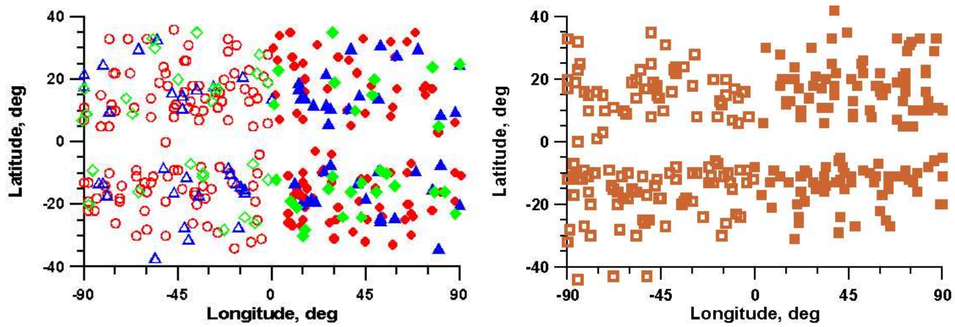

Fig. 10. Coordinates of geoeffective (Top) and nongeoeffective (Bottom) of solar flares.

corresponds to average velocity of disturbances 430 - 870 km/s on a line the Sun - Earth and it is usual velocity of SW in the orbit of the Earth. Results of such analysis are shown as histograms in the top part of Fig.9 by shaped and continuous lines - for west and east flares respectively, and histograms "a", "b", "c" and "d" concern, respectively, to most probable sources (31.1 % for all strong flares and 25.4 % for flares with SCR) of storms, to probable (11.6 and 18.3 %) and less probable (9.0 and 19.0 %) sources and the flares which have not resulted in the storms (48.2 and 37.3 %). Distinctions between two sets are insignificant and consist of higher values in "a" and "d" groups and of lower values in "c" and "b" for the large set of flares. The total number of the west flares as a whole appeared more than east but after normalization on number of those and other types of flares the difference between distributions of west and east flares in all histograms practically disappears. Fig.10 shows that geoeffective ("a","b" and "c" groups) and non-geoeffective ("d" group) strong solar flares have similar distributions on the solar disk.

For flares from first three groups we investigated a dependence of minimum of D_{st} index during a storm on the importance (i.e. the flux of X-ray radiation or energy) of flares. The top and bottom panels of Figs.11 show these dependences for flares with SCR increases and all strong flares, respectively, and triangles, squares and circles correspond to most probable, probable, and less probable sources, and light and dark symbols - to west and east flares, respectively. The figure does not demonstrate any dependence of storm value on flare energy neither for all flares as a whole, nor for any one of the subclasses of flares while the flux of X-ray radiation of the flares varies in figure on 2.5 orders of magnitude. It is interesting that for the strongest flare of importance X20 there was storm with D_{st} index $\sim$-100 nT while for flares of smaller importance (X0-X5) the strongest storm with D_{st} index $\sim$-600 nT was observed.

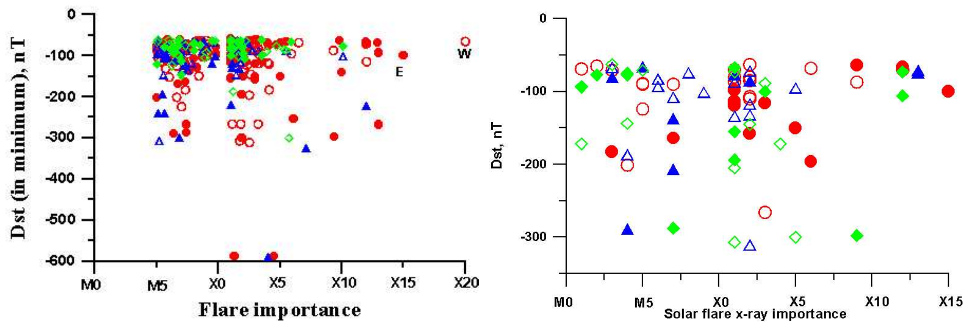

Fig. 11. Dependence of minimum of D_{st} index during magnetic storms on the importance (flux of energy) of solar flares. Top: flares with SCR increases. Bottom: all strong flares. Designations: light and dark symbols - west and east flares; triangles, diamonds and circles - events such as a, b and c on Fig.9.

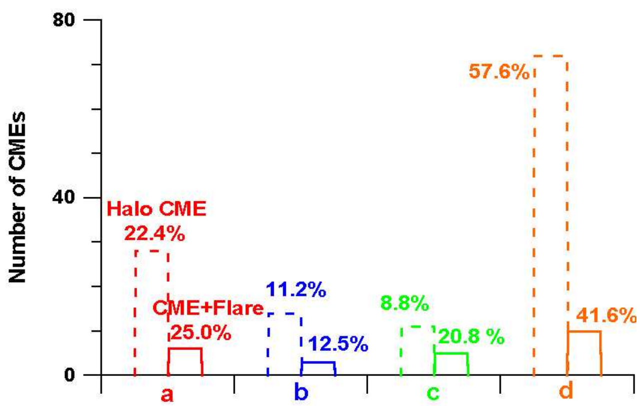

Fig. 12. The number of CME accompanying and not by solar flares (continuous and shaped lines) after which it is most probably (a), probably (b), less probably (c) and impossibly (d) to observe the magnetic storms.

The set of CMEs registered on *SOHO* spacecraft during 1996-2000 contains 125 so-called Earth-directed halo-CMEs (i.e. CME occupying all space around the Sun on the corona images and as it is supposed moving in the direction of the observer, to the Earth), and 24 from them were accompanied by strong flares from already described set of strong flares. Applied to the CME the described above technique of definition of possible geoeffectiveness on the time delay between CME and magnetic storm gives low geoeffectiveness of CMEs (see.

Fig.12): for type *a* 22.4 % and 25.0 %, for type *b* 11.2 % and 12.5 %, for type *c* 8.8 % and 20.8 % and for type *d* 57.6 % for all CMEs and 41.6 % for CMEs accompanied by solar flares. Received geoeffectiveness of CMEs appears below not only geoeffectiveness of several published sets of CMEs (see Introduction), but even geoeffectiveness of solar flares. Distinctions between our estimations of CME geoeffectiveness and the published data will be discussed below.

3.4 Relations of storms with interplanetary sources

At the analysis of interplanetary sources we did not analyze all data file on SW and, using the time of observation of magnetic storms, we searched for interplanetary disturbances which could precede and result in moderate and strong magnetospheric disturbances. Therefore geoeffectiveness of interplanetary disturbances discussed below has some other sense than mentioned for solar flares and CMEs in the previous section. The methods of SW types identification used by us are in detail described in papers by Gosling et al. (1991); Yermolaev (1991); Gosling and Pizzo (1999); Lepping et al. (1997); Richardson et al. (2000). Result our analysis is given in Fig.2-6 where various symbols show the identified types of SW streams which could be interplanetary sources of strong storms (we do not present results for moderate storms because they could make the figure unreadable). Measurements of interplanetary parameters are available only for ∼2/3 (404 events) of 618 moderate and strong magnetic storms and it allows us to estimate distribution between different geoeffective SW types with enough good statistics: interplanetary sources of (in brackets for moderate and strong, respectively) magnetic storms in 33.2 % (24.9 % and 51.5 %) cases are MCs, in 30.2 % (29.9 % and 32.8 %) cases - CIRs, in 5.7 % (6.9 % and 3.7 %) - ISs and in 30.9 % (38.3 % and 11.9 %) - other SW types. Thus, in comparison with moderate storms the part of strong storms from MCs grows from ∼1/4 up to ∼1/2, from CIRs remains at a level ∼1/3, and from ISs and other SW types appreciably falls.

The analysis of behavior of solar wind and IMF parameters (here they are not shown) for geoeffective events in the interplanetary space confirms the known fact that the sources of magnetospheric disturbances are events in which large negative (southward) IMF component is observed sufficiently long time. Just the similar situation is most frequently registered in MC, CIR and after IS passage. It is possible to explain this fact if the southward IMF component was in originally undisturbed solar wind as a result of dynamic processes during motion of MC, CIR and IS there is a compression and increase of all IMF components in the region of compression including IMF components parallel to the terrestrial magnetic dipole.

In our previous paper (Yermolaev, 2001) it was shown that on the growth

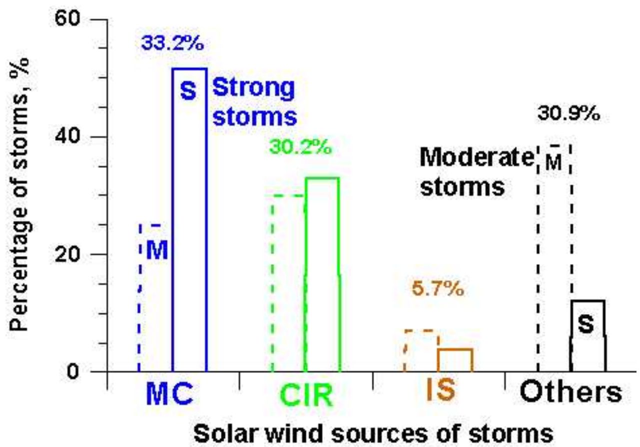

Fig. 13. Geoeffectiveness of different types of solar wind for moderate (dashed line) and strong (solid line) magnetic storms.

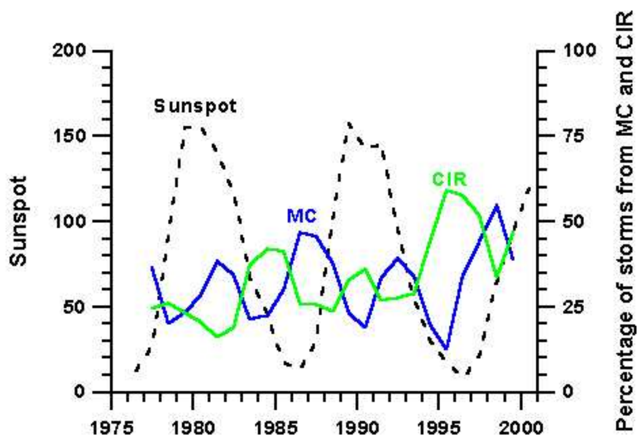

Fig. 14. Time variation of part of the magnetic storms excited by MC (black line) and by CIR (grey line). Dashed line - the sunspot (scale on the left).

phase of 23-rd solar cycle initially the number of the storms generated by MCs increases then the number of such storms decreases, but the number of storms from CIR grows. Here we have possibility to investigate the change of a distribution of storms from MC and CIR in cycle during more than 2 solar cycles. For this purpose for each year we found the ratio of total number of moderate and strong storms respectively from MC and CIR to the number of storms for which it was possible to determine SW type. These results are presented in Fig. 14. As the statistics of number of year average storms is not so large, especially in the minimum of cycle, to remove the high-frequency fluctuations connected with small statistics, we carried out smoothing these ratios by sliding average over three points. The Fig.14 confirms the conclusion made earlier (Yermolaev, 2001) for the beginning growth phases, however shows that curves for MC and CIR have 2 maxima for a solar cycle.

4 Discussion

To study the relation of our results with results of other papers it is necessary to make some remarks which will allow us to compare the results obtained by different methods of selection of solar, interplanetary and magnetospheric phenomena and by different direction (direct or back) of tracing phenomena between different space areas.

4.1 Comparison of analysis methods

Methods described in section 2 allow us to estimate more critically those relations between solar, interplanetary and magnetospheric phenomena which were obtained by us and other researchers. Except for the ambiguity of comparison of the results connected with different approaches of event classification there is also an ambiguity connected with a technique of comparison of phenomena in two space areas. If for the analysis two phenomena with samples $X1$ and $X2$ were chosen and conformity was established for number of phenomena X12 then "effectiveness" of process $X1 \rightarrow X2$ is usually defined as ratio of values $X12/X1$ which differs from "effectiveness" of process $X2 \rightarrow X1$ equal $X21/X2 = X12/X2$, because samples $X1$ and $X2$ are selected by various criteria and can be different value. Thus the "effectiveness" determined in different works depends on a direction of the analysis of process. If to take into account that sometimes sample $X2$ is not fixed prior to the beginning of the analysis, i.e. the rule (or criteria) selection of events for sample $X2$ originally is not fixed the ambiguity of calculation of process "effectiveness" can grow in addition.

As in solar-terrestrial physics we investigated process of 2 parts: the Sun - solar wind and the solar wind - magnetosphere, the presence of the data on an intermediate link can increase the reliability of estimations for all chain. We shall assume that there are data for sets on Sun $X1$ and $Y1$, in interplanetary medium $Y2$ and $Z1$ and in magnetosphere $X2$ and $Z2$ for which estimations of "effectiveness" of processes $X1 \rightarrow X2$ equal $X12/X1$ were obtained, $Y1 \rightarrow Y2$ equal $Y12/Y1$ and $Z1 \rightarrow Z2$ equal $Z12/Z1$. In this case it is natural to assume that "effectiveness" of full process should be close to product "effectivenesses" of each of parts, i.e. $X12/X1 = (Y12/Y1)(Z12/Z1)$. In particular it means the "effectiveness" of full process can not be higher "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 analysis, however it has not been made yet and we shall carry out it below.

It is important to note that authors frequently understand "geoeffectiveness" of this or that phenomenon as completely different values obtained with the help of different procedures. In strict sense of this word, geoeffectiveness of the solar or interplanetary phenomenon is defined as percentage corresponding set of the solar and interplanetary phenomena resulted in occurrence of magnetic storms, and storms of the certain class. In other words, first of all it is necessary to select the solar or interplanetary phenomena by the certain rule, then to investigate each phenomenon from this list with occurrence of a storm using certain algorithm. The time of delay between the phenomena which should be stacked in some beforehand given "window" is used as algorithm of comparison of the various phenomena: or characteristic times of phenomenon propagation between two points, or time delay determined on some initial data.

Very much frequently the authors act on the contrary: as the initial list they take the list of storms and extrapolate them back in the interplanetary space or on the Sun and search there for suitable phenomenon. This way defines not geoeffectiveness and allows to find candidates in the interplanetary space or on the Sun on the reason of the given magnetic storms. If to take into account that the phenomena of different classes are frequently used as such candidates if they only suited on time this is clear reason of divergence of results of many works.

4.2 Comparison of results

The analysis of 25-year sets of observations of the Sun, the solar wind and magnetospheric disturbances confirmed several earlier found effects, such as correlation of number of sunspot with number of solar flares and number of magnetic storms on the Earth, and also Russell-McPherron effect (Russell and McPherron, 1973) and equinoctial effect (Cliver et al., 2000), i.e. primary excitation of magnetic storms in spring and autumn months of year. However the data presented on connection of solar, interplanetary and magnetospheric disturbances contain as well new results.

We shall consider more in detail connection between strong solar flares and

CMEs, on the one hand, both moderate and strong magnetic storms, on the other hand. First for simplicity we assume that among probable and less probable flares (see section 3) the number of events resulted and not resulted in magnetic storms is distributed as 3:1 and 1:3, respectively. Then the numbers of geoeffective and nongeoeffective strong solar flares are 44 % and 56 %, respectively. Our estimation of correlation of Earth-directed halo-CMEs and storms during 1996-2000 showed that geoeffectiveness of CME is ∼35%, i.e. close to geoeffectiveness of strong solar flare. We shall consider how much these conclusions are statistically significant. As it has been already noted above, the period of occurrence of moderate and strong magnetic storms varies during solar cycle from ∼6.8 days in the disturbed years up to ∼45 days in quiet years with average value of ∼15 days. As we are interested in years when the Sun was sufficiently active it is possible to take value of 8-10 days for the further analysis. As the interval of delay from solar event up to the geomagnetic storm usually undertakes duration ∼3.5 days ("window" from 1.5 to 5 days) it is possible to estimate probability to observe a storm if both a solar event and a storm occur in the random manner as the ratio of duration of "window" to the average period between storms. This estimation gives that "correlation" between the solar and ground phenomena will be observed in 35-44 % of cases even at random distribution of these phenomena. Therefore the obtained geoeffectiveness of strong solar flares and CMEs can be in part or completely referred to random processes. This is supported by the absence of correlation between importance of solar flare and value of magnetic storm (see Fig. 11).

We should note that the obtained here estimations of geoeffectiveness of flares and CMEs are also too low for use in predictions of "space weather" as the number of false predictions is very great and this conclusion agree with another results (St.Cyr et al., 2000; Plunkett et al., 2001). The unique way to increase the efficiency of a prediction technique is to select the solar events on the basis of additional parameters resulting in rejection of events which have not sufficient geoeffectiveness. In this direction the method of definition of magnetic field orientation in the extending plasma on its initial configuration in the solar atmosphere (Crooker, 2000) is very perspective. Also it is important to predict a trajectory and dynamics of the geoeffective solar phenomenon in the interplanetary space: on the one hand, to estimate probability of its coming to the Earth magnetosphere, and on the other hand, to predict sufficiently exact times of arrival from the Sun up to the Earth.

In contrast to the analysis of solar sources of magnetic storms where lists of events on the Sun undertook as a basis, at the analysis of interplanetary sources of storms the intervals of solar wind corresponding to the moderate and strong magnetic storms were analyzed only. Therefore the sense of concept of "geoeffective event" differs (see section 4.1.). The main interplanetary sources of moderate and strong magnetic storms are MC and CIR, each of which contains ∼1/3 from all geoeffective SW types; and in comparison with moderate storms the part of strong storms from MC grows and reaches half of all geoeffective SW types, number of storms from CIR practically does not change, and from other SW types significantly falls. Our result on correlation of magnetic storms and MCs is in good agreement with the similar data of paper by Gosling et al. (1991) though in contrast with our paper there MCs were determined on the basis of counterstreaming electrons, and storms on K_p index. Our dependence of the part of the magnetic storms excited by MCs (as well as by CIRs) on the phase of solar cycle has two maxima for a cycle. Thus curves for storms from MCs and from CIRs change in an antiphase that was necessary to expect as the sum of parts of storms from MCs and from CIRs should be a constant close to 2/3, and 1/3 makes other SW types.

Observations of distribution of magnetic storms from SW streams such as MCs and CIRs carried out in period of 1979-1988 at distance 0.7 AU on *PVO* spacecraft (Lindsay et al., 1995) showed that MC is more geoeffective in a maximum and CIR in a minimum of a solar cycle. Our results could be considered as totally coincided with observations on *PVO* spacecraft if our results would be ignored in the minimum of cycle in 1986-1988 (see Fig. 14). As a whole the dependence obtained by us has more complicated character at the extent longer period than in paper by Lindsay et al. (1995).

Irrespective of SW type which has resulted in magnetospheric storm, the southward IMF component (in GSM system of coordinates) with value from -5 up to -15 nT and duration from 1-3 h and more is always observed in the interplanetary space. Intervals of southward IMF components are observed more often (1) after shock wave, both isolated and connected with MC or CIR, (2) in the region of compression directly ahead of MC body and in CIR and (3) in MC body. Though models of a prediction of geomagnetic disturbances on the basis of SW and IMF measurements in real time in the libration L1 point (for example, on *WIND* (1994) and *ACE* (1997) spacecraft) have short-term character (about 0.5-1.0 hour), their reliability satisfies to practical criteria (Petrukovich and Klimov, 2000). Reliable long-term (more than 1 day) techniques of prediction of magnetospheric disturbance for today do not exist. For such predictions it is required to begin the forecast with the analysis of the phenomena on the Sun and as we have already noted above, the reliability of available techniques for estimation of the geoeffective solar phenomena is insufficiently high.

The results of comparison of CMEs, solar flares and the various interplanetary phenomena with magnetic storms for several last years are shown in table 5. First of all it is necessary to note, that we selected results on the comparing phenomena and the direction of tracing. For example, record "$CME \rightarrow Storm$" 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): $I.CME \rightarrow Storm$, $II.\ CME \rightarrow Magnetic\ clouds, Ejecta$, $III.\ Magnetic\ clouds, Ejecta \rightarrow Storm$, $IV.\ Storm \rightarrow CME$, $V.\ Storm \rightarrow Magnetic\ clouds, Ejecta$ and $VI.\ Magnetic\ clouds, Ejecta \rightarrow CME$. In II, III, IV and V we included both magnetic clouds and ejecta(ICME) which are close under 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 presented data on $VII.\ Flare \rightarrow SSC, Storm$ and $VIII.\ Storm \rightarrow Flare$ correlations.

Geoeffectiveness of CME is shown as direct tracing $I.\ CME \rightarrow Storm$ which includes 5 data sets and changes from 35 up to 71% (Webb et al., 1996, 2000; Plunkett et al., 2001; Wang et al., 2002; Yermolaev and Yermolaev, 2003a,b). Result 71% (Webb et al., 2000) (later reproduced in papers by Crooker (2000); Li et al (2001)) was obtained with rather small statistics of 7 cases. Other results obtained with statistics from 38 up to 132 CMEs are in a range of 35-50% and are in good agreement with each other. In our preliminary paper Yermolaev and Yermolaev (2003a) the result 35% was obtained for magnetic storms with $Dst < -60$ nT and if we include weaker storms with $Dst < -50$ nT in analysis (it corresponds to storms with $Kp > 5$ like in work by Wang et al. (2002)) we obtain geoeffectiveness CME $\sim 40\%$ (Yermolaev and Yermolaev, 2003b). Thus, it is possible to make a conclusion, that geoeffectiveness of halo-CME for magnetic storms with $Kp > 5 (Dst < -50$nT) is 40-50% at sufficiently high statistics from 38 up to 132 CMEs.

Results of back tracing analysis $IV.\ Storm \rightarrow CME$ contain 3 data sets with values from 83 up to 100% and at lower statistics from 8 up to 27 of strong magnetic storms with $Kp > 6$ and $Dst < -100$ nT (Brueckner et al., 1998; St.Cyr et al., 2000; Li et al, 2001; Zhang et al., 2003). These results are in good agreement but they show not high geoeffectiveness of CME: they indicate that it is possible to find possible candidates on the Sun among CMEs for sources of strong magnetic storms with a high degree of probability.

The comparison of direct and back tracings $II.$ ($CME \rightarrow Magnetic\ clouds$, $Ejecta$) and $VI.$ ($Magnetic\ clouds,\ Ejecta \rightarrow CME$) for Earth-directed halo-CMEs shows that in the first case 63% is observed at small statistics of 8 events (Cane et al, 1998) and in the second - 42% at statistics of 86 events (Cane et al, 2000). Other results are obtained for any CMEs (Lindsay et al., 1999; Gopalswamy et al., 2000) and are not so reliable as for first results. From comparison $III.$ ($Magnetic\ clouds,\ Ejecta \rightarrow Storm$) follows that correlation for magnetic clouds is a little bit higher 57-82% (Gopalswamy et al., 2000; Yermolaev et al., 2000; Yermolaev and Yermolaev, 2002; Wu and Lepping, 2002) than for ejecta - ~ 42 %(44% in paper by Gosling et al. (1991)

and 41% - average of 19 and 63% (Richardson et al., 2001)). Back tracimg $V.$ $(Storm \rightarrow Magnetic\,clouds,\, Ejecta)$ yields inconsistent results: 73% (Gosling et al., 1991) and 25% (Vennerstroem, 2001) and it is necessary to emphasize that in both cases the definitions of storms and ejecta are different and in the first case the statistics is less (50 months and 32 years, i.e. more than in 7 times). For magnetic clouds in the period 1976-2000 our estimations 33% for moderate and strong storms (25% for moderate storms and 52% for strong storms) (Yermolaev and Yermolaev, 2002) are in good agreement with results of work by Vennerstroem (2001).

The analysis of a sequence of 2-step direct tracing $II.$ $(CME \rightarrow Magnetic\, clouds,\, Ejecta)$ and $III.$ $(Magnetic\, clouds,\, Ejecta \rightarrow Storm)$ allows us to estimate a probability of total process $CME \rightarrow Storm$ how product of probabilities and for magnetic clouds we obtain a value 0.63 * (0.57 - 0.82) = 0.36 - 0.52 which is close to above mentioned results 40-50% for the direct analysis of process $I.$ $(CME \rightarrow Storm)$. For ejecta this approach resulted in less value. The analysis of a sequence of 2-step back tracing $V.$ $(Storm \rightarrow Magnetic\, clouds,\, Ejecta)$ and $VI.$ $(Magnetic\, clouds,\, Ejecta \rightarrow CME)$ does not allow us to obtain the high correlation $Storm \rightarrow CME$ in comparison with 83 - 100% in total process IV : (0.25 - 0.73) * 0.42 = 0.11 - 0.31. Thus, comparison of two-step and one-step processes for direct tracing $CME \rightarrow Storm$ are in good agreement while for two-step process for back tracing differs in several times from one-step process. It means that techniques of the analysis of processes $(Storm \rightarrow Magnetic\, clouds,\, Ejecta)$, $(Magneticclouds, Ejecta \rightarrow CME)$ and $(Storm \rightarrow CME)$ require significant improvement.

As it has been shown above and in our previous study (Yermolaev and Yermolaev, 2003a) we carried out direct tracing events $Flare \rightarrow Storm$ and estimated geoeffectiveness of 653 solar flares of importance (on X-ray emission) $\geq M5$ which in 32% cases resulted in magnetic storms with $Dst < -60$ nT. If we carry out back tracing $Storm \rightarrow Flare$ 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. In paper (Krajcovic and Krivsky, 1982) in which back tracing $Storm \rightarrow Flare$ 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 $Storm \rightarrow Flare$ 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) besides 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 $Flare \rightarrow SSC$ (i.e. not with geomagnetic storms, and with the phenomena which frequently precede storms) was carried out in recent work (Park et al., 2002) for 4836 flares of importance $\geq M1$ for the period September, 1, 1975 - December, 31, 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%.

5 Conclusions

The presented comparison of methods and results of the analysis of the phenomena on the Sun, in the interplanetary space and the Earth's magnetosphere shows on an example of our original data and the numerous published results that besides the methods used in each of areas the large importance for research of all chain of solar-terrestrial physics has also a way of comparison of the phenomena in various areas or direction of data tracing. For research of geoeffectiveness of the solar and interplanetary phenomena (i.e. their abilities to generate the magnetic storms on the Earth) originally it is necessary to select the phenomena, respectively, on the Sun or in the solar wind and then to compare the phenomenon with event at the following step of a chain. Thus the obtained estimations of CME influence on the storm both directly (by one step $CME \rightarrow Storm$) and by multiplication of probabilities of two steps ($CME \rightarrow Magnetic\,cloud, Ejecta$ and $Magnetric\,cloud, Ejecta \rightarrow Storm$) are close to each other and equal 40-50% (Webb et al., 1996; Cane et al, 1998; Yermolaev et al., 2000; Gopalswamy et al., 2000; Plunkett et al., 2001; Wang et al., 2002; Wu and Lepping, 2002; Yermolaev and Yermolaev, 2002, 2003a,b). This value strongly differs from results 83-100% obtained in papers by Brueckner et al. (1998); St.Cyr et al. (2000); Zhang et al. (2003) by search of back tracing correlation which characterizes not geoeffectiveness of CME and a probability to find the appropriate candidates among CME for magnetic storms. The obtained value 83-100% are not confirmed by the two-step analysis of sources of storms as at steps $Storm \rightarrow Magnetric\,cloud, Ejecta$ and $Magnetric\,cloud, Ejecta \rightarrow CME$ values are (25-73)% (Gosling et al., 1991; Vennerstroem, 2001; Yermolaev and Yermolaev, 2002) and $\sim 40\%$ (Cane et al, 2000) each of which is less than the factor obtained by the one-step analysis $Storm \rightarrow CME$. Thus, to remove this contradiction the suggested in papers by Brueckner et al. (1998); St.Cyr et al. (2000); Zhang et al. (2003) techniques of the analysis of the data require the further development.

The obtained estimations of CME geoeffectiveness 40-50% are close to estimations of geoeffectiveness of solar flares 30-40% (Park et al., 2002; Yermolaev and Yermolaev, 2003a) and exceed them only a little. As we have shown above and in paper by Yermolaev and Yermolaev (2002), for random distribution of solar processes and the magnetic storms the formally counted coefficient of correlation can be 30-40%. It means that the obtained estimations of CME and solar flare geoeffectiveness can be result of random processes and therefore the forecast of geomagnetic conditions on basis of observations of the solar phenomena can contain high level of false alarm. Thus, there is a paradoxical situation at which the modern science in the retrospective approach successfully can explain an origin almost all strong geomagnetic disturbances, but can not predict their occurrence with a sufficient degree of reliability on the basis of observation of the Sun. To increase reliability of the forecast, the further analysis of the solar data and revealing of characteristics which would allow to select the phenomena among CMEs and/or flares with higher geoeffectiveness are required.

The authors gratitude the international scientific data centers SEC NOAA, NSSDC/GSFC NASA and WDC-C2 for the information, and also A. A. Petrukovich, L.M.Zelenyi, R.A.Kovrazhkin and J.L.Rauch for attention, the help and useful discussion of materials of the paper. The work was in part supported by grants INTAS 99-0078, RFBR 01-02-16182, 02-02-17160, Program N16 of Department of Physics Sciences RAS and by French - Russian scientific cooperation program (PICS grant APIC0090 and RFBR grant 00-02-22001).

References

Akasofu, S.-I., 1981. Energy coupling between the solar wind and the magnetosphere. Space Science Reviews 28, no. 2, 121-190.

Anastasiadis, A., 2002. Acceleration of solar energetic particles: the case of solar flares. Journal of Atmospheric and Solar-Terrestrial Physics 64, 5-6, 481-488

Brueckner, G. E., Howard, R. A., Koomen, M. J. et al., 1995. The Large Angle Spectroscopic Coronagraph (LASCO). Solar Physics 162, 357.

Brueckner, G. E., Delaboudiniere, J.-P., Howard, R. A., Paswaters, S. E., St. Cyr O. C., Schwenn, R., Lamy, P., Simnett, G. M., Thompson, B., Wang, D., 1998. Geomagnetic storms caused by coronal mass ejections (CMEs): March 1996 through June 1997. Geophysical Research Letters 25, 15, 3019.

Burlaga, L., Sittler, E., Mariani, F., Schwenn, R., 1981. Magnetic loop behind an interplanetary shock - Voyager, Helios, and IMP 8 observations. Journal of Geophysical Research 86, 6673-6684.

Burlaga L. F., Lepping R. P., Jones, J. A., 1990. Global configuration of a magnetic cloud. In: Physics of Magnetic Flux Ropes, eds. C. T. Russell, E. R. Priest, L. C. Lee, Geophysical Monograph Series, 58, 373.

Burlaga L.F.E. 1991. Magnetic clouds. In: Physics of the inner magnetosphere, V.2, ed. R.Schwenn and E.Marsch, Springer-Verlag, New York.

Lepping, R. P., Burlaga, L. F., Szabo, A., Ogilvie, K. W., Mish, W. H., Vassiliadis, D., Lazarus, A. J., Steinberg, J. T., Farrugia, C. J., Janoo, L., Mariani, F., 1997. The Wind magnetic cloud and events of October 18-20, 1995: Interplanetary properties and as triggers for geomagnetic activity. Journal of Geophysical Research 102, A7, 14049-14064.

Burlaga, L., Fitzenreiter, R., Lepping, R., Ogilvie, K., Szabo, A., Lazarus, A., Steinberg, J., Gloeckler, G., Howard, R., Michels, D., 1998. A magnetic cloud containing prominence material: January 1997. Journal of Geophysical Research 103, 277.

Burton R. K., McPherron R.L., Russell C.T. 1975. An empirical relationship between interplanetary conditions and Dst. Journal of Geophysical Research 80, 4204.

Cane, H. V., Richardson, I. G., St. Cyr, O. C., 1998. The interplanetary events of January-May, 1997, as inferred from energetic particle data, and their relationship with solar events. Geophysical Research Letters 25, 14, 2517.

Cane H. V., Richardson I. G., St. Cyr O. C., 2000. Coronal mass ejections, interplanetary ejecta and geomagnetic storms. Geophysical Research Letters 27, 21, 359.

Cliver E. W., Crooker N. U., 1993. A seasonal dependence for the geoeffectiveness of eruptive solar events. Solar Physics 145, 2, 347.

. Cliver, E. W., Kamide, Y., Ling, A. G., 2000. Mountains versus valleys: Semiannual variation of geomagnetic activity. Journal of Geophysical Research 105, A2, 2413-2424.

Cliver, E. W., Hudson, H. S., 2002. CMEs: How do the puzzle pieces fit together? Journal of Atmospheric and Solar-Terrestrial Physics 64, 2, 231-252.

Crooker, N. U., 2000. Solar and heliospheric geoeffective disturbances, Journal of Atmospheric and Solar-Terrestrial Physics 62, 1071.

Crooker, N. U., Cliver, E. W., 1994. Postmodern view of M-regions, Journal of Geophysical Research 99, A12, 23,383-23,290.

Forbes, T. G., 2000. A review on the genesis of coronal mass ejections, Journal of Geophysical Research 105, A10, 23153-23166.

Gonzalez W.D., Tsurutani B.T., Gonzalez A.L.C. et al., 1989. Solar-wind magnetosphere coupling during intense magnetic storms (1978-1979). Journal of Geophysical Research 94, 8835.

Gonzalez, W. D., Tsurutani B. T., Clua de Gonzalez A. L., 1999. Interplanetary origion of geomagnetic storms. Space Science Review 88, 529.

Gopalswamy N., Lara A., R. P. Lepping R.P. et al., 2000. Interplanetary acceleration of coronall mass ejections, Geophysical Research Letters 27, 145.

Gopalswamy N., Lara A., Yashiro S., Kaiser M. L., Howard R. A., 2001. Predicting the 1-AU arrival times of coronal mass ejections. Journal of Geophysical Research 106, A12, 29207.

Gosling J.T., 1993. The solar flare myth. Journal of Geophysical Research 98, 18937.

Gosling J. T., McComas D. J., Phillips J. L., and Bame S. J., 1991. Geomagnetic activity associated with Earth passage of interplanetary shock disturbances and coronal mass ejections. Journal of Geophysical Research 96, 7831.

Gosling, J. T., Pizzo V. J., 1999. Formation and evolution of corotating interaction regions and their three-dimensional structure. Space Science Review 89, 21.

Grafe A., 1999. Are our ideas about Dst correct? Annales Geophysicae 17, 1.

Harrison, R. A., 1996. Coronal Magnetic Storms: a New Perspective on Flares and the 'Solar Flare Myth' Debate. Solar Physics 166, 441-444.

Hargreaves, J. K., 1992. The Solar-Terrestrial Environment, Cambridge University Press, New York.

Krajcovic, S., Krivsky, L., 1982. Severe geomagnetic storms and their sources on the sun. Astronomical Institutes of Czechoslovakia, Bulletin, 33, N 1, 47.

Li Y., Luhmann J.G., Mulligan T., Hoeksema J. T., Arge C. N., Plunkett S. P., St. Cyr O. C., 2001. Earthward directed CMEs seen in large-scale coronal magnetic field changes, SOHO LASCO coronagraph and solar wind. Journal of Geophysical Research 106, A11, 25103.

Lindsay G.M., Russell C.T., Luhmann J.G., 1995. Coronal mass ejection and stream interaction region characteristics and their potential geomagnetic effectiveness. Journal of Geophysical Research 100, 16999.

Lindsay G.M., Luhmann J.G., Russell C.T., Gosling J.T., 1999. Relationship between coronal mass ejection speeds from coronagraph images and interplanetary characteristics of associated interplanetary coronal mass ejections. Journal of Geophysical Research 104, 12515.

Loewe C. A., Prolss G. W., 1997. Classification and mean behavior of magnetic storms. Journal of Geophysical Research 102, 14209.

Low, B. C., 2001. Coronal mass ejections, magnetic flux ropes, and solar magnetism. Journal of Geophysical Research 106, A11, 25141-25164.

Malandraki, O.E., Sarris, E.T., Lanzerotti, L.J., Trochoutsos, P., Tsiropoula, G., Pick, M. Solar energetic particles inside a coronal mass ejection event observed with the ACE spacecraft. Journal of Atmospheric and Solar-Terrestrial Physics 64, 517-525.

Mayaud P.N., 1980. Derivation, meaning and use of geomagnetic indices, AGU Geophysical Monograph 22.

Miroshnichenko L.I., 1986. Solar-terrestrial relations. In: Physics of space: the small encyclopedia, Ed. R.A.Sunyaev, M.: Sov. Encyclopedia, 629. (in Russian)

Park, Y. D., Moon, Y.-J., Kim, Iraida S., Yun, H. S., 2002. Delay times between geoeffective solar disturbances and geomagnetic indices, Astrophysics and Space Science 279, 4, 343-354.

Petrukovich A.A., Klimov S.I., 2000. The Use of Solar Wind Measurements for the Analysis and Prediction of Geomagnetic Activity. Kosmicheskye Issledovaniva 38, 5, 463. (In Russian, translated Cosmic Research 38, 5, 433.)

Petrukovich, A. A., Klimov, S. I., Lazarus, A., Lepping, R. P., 2001. Comparison of the solar wind energy input to the magnetosphere measured by Wind and Interball-1. Journal of Atmospheric and Solar-Terrestrial Physics 63, 15, 1643-1647.

Plunkett S.P., Thompson B.J., St.Cyr O.C., Howard R.A., 2001. Solar source regions of coronal mass ejections and their geomagnetic effects. Journal of Atmospheric and Solar-Terrestrial Physics 63, 389-402.

Proceedings of "The Second Solar Cycle and Space Weather Euroconference", 2002. ESA SP-477.

Richardson, I. G., Cane, H. V., von Rosenvinge, T. T., 1991. Prompt arrival of solar energetic particles from far eastern events - The role of large-scale interplanetary magnetic field structure. Journal of Geophysical Research 96, 1, 7853-7860.

Richardson I. G., Cane H.V., 1993. Signatures of shock drivers in the solar wind and their dependence on the solar source location. Journal of Geophysical Research 98, 15295.

Richardson, I. G., Cane, H. V., 1996. Particle flows observed in ejecta during solar event onsets and their implication for the magnetic field topology, Journal of Geophysical Research 101, A12, 27521-27532.

Richardson, I. G., Cliver, E. W., Cane, H. V., 2000. Sources of geomagnetic activity over the solar cycle: Relative importance of coronal mass ejections, high-speed streams, and slow solar wind, Journal of Geophysical Research 105, A6, 12579-12592.

Richardson I. G., Cliver E. W., Cane H. V., 2001. Sources of geomagnetic storms for solar minimum and maximum conditions during 1972-2000. Geophysical Research Letters 28, 2569.

Russell C.T., McPherron R.L., 1973. Semiannual variation of geomagnetic activity. Journal of Geophysical Research 78, 241.

Shodhan S., Crooker N.U., Kahler S.W. et al., 2000. Countersreaming electrons in magnetic clouds. Journal of Geophysical Research 105, 27261.

Skoug R.M., Bame S.J., Feldman W.C., Gosling J.T., McComas D.J., Steinberg J.T., Tokar R.L., Riley P., Burlaga L.F., Ness N.F., Smith C.W., 1999. A prolonged He+ enhancement within a coronal mass ejection in the solar wind, Geophysical Research Letters 26, 161-164.

Solar Drivers of Interplanetary and Terrestrial Disturbances, 1996. eds. K.S. Balasubramaniam, S.L. Keil, and R.N. Smartt, ASP Conference Series.

Space Weather, 2001. Ed. by Paul Song, Howard J. Singer, and George L. Siscoe, Geophysical Monograph Series 125.

St. Cyr O. C., Howard R. A., Sheeley N. R. Jr., Plunkett S. P. et al., 2000. Properties of coronal mass ejections: SOHO LASCO observations from January 1996 to June 1998. Journal of Geophysical Research 105, A8, 18169.

Tsurutani, B. T., Gonzalez, W. D., Gonzalez, A. L. C., Tang, F., Arballo, J. K., Okada, M., 1995. Interplanetary origin of geomagnetic activity in the declining phase of the solar cycle, Journal of Geophysical Research 100, A11, 21717-21734.

Vennerstroem, S., 2001. Interplanetary sources of magnetic storms: Statistic study. Journal of Geophysical Research 106, 29175-2914.

Wang, Y. M., Ye, P. Z., Wang, S., Zhou, G. P., Wang, J. X., 2002. A statistical study on the geoeffectiveness of Earth-directed coronal mass ejections from March 1997 to December 2000. Journal of Geophysical Research 107, A11,

10.1029/2002JA009244
Webb D.F., 1995. Coronal mass ejections: The key to major interplanetary and geomagnetic disturbances. Reviews of Geophysics 33, S1, 577-583.
Webb D.F., Jackson, B. V., Hick, P. 1996. Geomagnetic Storms and Heliospheric CMEs as Viewed from HELIOS. In Solar Drivers of Interplanetary and Terrestrial Disturbances, ASP Conference Series 95, 167.
Webb D.F., Cliver E.W., Crooker N.U. et al., 2000. Relationship of halo coronal mass ejections, magnetic clouds, and magnetic storms. Journal of Geophysical Research 105, 7491.
Wu C.-C., Lepping R.P., 2002. Effects of magnetic clouds on the occurrence of geomagnetic storms: The first 4 years of Wind. Journal of Geophysical Research 107, A10, SMP 19-1 to SMP 19-8 10.1029/2001JA000161.
Yermolaev, Yu. I., Zhuravlev, V. I., Zastenker, G. N., Kogan, V. T., Koshevenko, B. V., 1989. Observation of singly ionized helium in the solar wind, Kosmicheskie Issledovaniia 27, 717-725. (In Russian)
Yermolaev Yu.I., 1991. Large-scale structure of solar wind and its relationship with solar corona: Prognoz 7 observations. Planetary and Space Science 39, 10, 1351.
Yermolaev Yu. I., Zastenker, G. N., Nikolaeva, N. S., 2000. The Earth's Magnetosphere Response to Solar Wind Events according to the INTERBALL Project Data. Kosmicheskie Issledovaniia 38, 6, 563. (in Russian, translated Cosmic Research 38, 6, 527.)
Yermolaev Yu. I., 2001. Strong Geomagnetic Disturbances and Their Correlation with Interplanetary Phenomena during the Operation of the INTERBALL Project Satellites. Kosmicheskie Issledovaniia 39, 3, 324. (in Russian, translated Cosmic Research 39, 3, 303.)
Yermolaev Yu. I., Yermolaev M. Yu., 2002. Statistical relationships between solar, interplanetary, and geomagnetic disturbances, 1976-2000. Kosmicheskie Issledovaniia 40, 1, 3. (in Russian, translated Cosmic Research 40, 1, 1.)
Yermolaev Yu. I., Yermolaev M. Yu., 2003a. Statistical relationships between solar, interplanetary, and geomagnetic disturbances, 1976-2000,2. Kosmicheskie Issledovaniia 41, 2, 115. (in Russian, translated Cosmic Research 41, 2, 105)
Yermolaev Yu. I., Yermolaev M. Yu., 2003b. Statistical relationships between solar, interplanetary, and geomagnetic disturbances, 1976-2000,3. Kosmicheskie Issledovaniia 41, in press.
Zhang J., Dere K.P., Howard R. A., Bothmer V., 2003. Identification of Solar Sources of Major Geomagnetic Storms between 1996 and 2000. Astrophysical Journal 582, 520.
Zwickl R. D., Asbridge J. R., Bame S. J., Feldman W. C., Gosling J. T., 1982. He^+ and other unusual ions in the solar wind - A systematic search covering 1972-1980. Journal of Geophysical Research 87, 7379.

Table 1
Strong solar flares with SCR increases and corresonding interplanetary phenomena
and minimum of D_{st} index

Solar flares						Corre-	Interplanetary events				D_{st}
NN	Date	Time UT	Import. x/opt.	Coord.	NN region	lation	SW type	Bound.	Date	Time UT	nT
1	30.04.1976	21.14	X2/2B	S09W47	700	a	MC ?	IS	02.05.1976	06	-107
2	19.09.1977	10.54	X2/3B	N08W58	889	b	no data		21.09.1977	10	-72
3	22.11.1977	10.06	X1/2N	N24W38	939	a	MC	IS	25.11.1977	12	-87
4	13.02.1978	02.55	M7/0B	N22W13	1001	b	no data		15.02.1978	11	-108
5	11.04.1978	13.53	X2/2B	N19W54	1057	a	MC ?	IS	13.04.1978	18	-80
6	28.04.1978	13.06	X5/4B	N22E41	1092	a	no data		01.05.1978	23	-150
7	07.05.1978	03.30	X2/2B	N22W64	1095	b	no data	Bz¡-5	09.05.1978	08	-132
8	31.05.1978	10.09	M5/2B	N23W50	1129	c	?	IS	04.06.1978	13	-71
9	22.06.1978	17.09	M2/3B	N19E18	1164	c	no data	Bz¡-5	26.06.1978	10	-77
10	23.09.1978	10.23	X1/3B	N35W50	1294	d			. .		
11	10.11.1978	00.42	M1/2N	N17E02	1385	c		IS	12.11.1978	01	-93
12	16.02.1979	02.00	X2/2B	N15E48	1574	d			. .		
13	05.06.1979	05.29	X2/1N	N20E16	1781	d			. .		
14	18.08.1979	14.16	X6/1B	N10E90	1943	d			. .		
15	14.09.1979	08.02	X2/	N10E90	1994	a	?	Bz¡-10	18.09.1979	00	-158
16	15.11.1979	16.39	M1/0B	N34W25	2110	d			. .		
17	17.07.1980	06.03	M3/1B	S12E06	2562	b	CIR ?	IS/LE	18.07.1980	18	-80
18	30.03.1981	00.49	M3/2N	N13W74	2993	b	?	Bz¡-5	31.03.1981	17	-67
19	10.04.1981	16.55	X2/3B	N09W40	3025	b	MC ?	IS	12.04.1981	15	-311
20	24.04.1981	14.00	X5/2B	N18W50	3049	b	MC ?	IS	26.04.1981	08	-95
21	08.05.1981	22.52	M7/2B	N09E37	3099	b	CIR ?	IS/LE	10.05.1981	21	-137
22	13.05.1981	04.25	X1/3B	N11E58	3106	a	IS	IS	16.05.1981	06	-119
23	20.07.1981	13.29	M5/1B	S26W75	3204	a	IS		23.07.1981	07	-89
24	07.08.1981	19.16	M4/2B	S10E24	3257	d			.		
25	07.10.1981	23.08	X3/1B	S19E88	3390	a	MC ?	IS	10.10.1981	13	-116
26	09.12.1981	18.54	M5/3B	N12W16	3496	d			. .		
27	30.01.1982	23.58	X1/3B	S13E19	3576	d			. .		
28	03.06.1982	11.46	X8/2B	S09E72	3763	d			. .		
29	06.06.1982	16.37	X12/3B	S11E26	3763	a	CIR ?	IS/LE	09.06.1982	01	-66
30	09.07.1982	07.42	X9/3B	N17E73	3804	a	MC ?	IS	11.07.1982	12	-64
31	22.07.1982	17.34	M4/0F	N29W86	3804	b	RSI ?		24.07.1982	16	-75
32	04.09.1982	04.00	M4/3N	N11E30	3886	b	MC ?	IS	05.09.1982	21	-289
33	22.11.1982	18.28	M7/1N	S11W43	3994	d			. .		
34	26.11.1982	02.53	X4/2B	S11W87	3994	d			. .		
35	07.12.1982	23.54	X2/0B	S14W81	4007	d			. .		

Table 2
Continuation of Table 1.

Solar flares						Corre-	Interplanetary events				D_{st}
NN	Date	Time UT	Import. x/opt.	Coord.	NN region	lation	SW type	Bound.	Date	Time UT	nT
36	15.12.1982	02.02	X12/2B	S10E24	4026	c	no data	Bz¡-5	16.12.1982	11	-106
37	19.12.1982	16.24	M9/2B	N10W75	4022	b	no data	Bz¡-5	21.12.1982	05	-101
38	25.12.1982	07.52	X2/1B	S14E31	4033	d			. .		
39	03.02.1983	06.19	X4/3B	S19W08	4077	c	no data		04.02.1983	22	-172
40	17.02.1984	23.01	X2/2B	0	0	d			. .		
41	14.03.1984	03.34	M2/2B	S12W42	4433	d			. .		
42	25.04.1984	00.05	X13/3B	S12E43	4474	b	no data		26.04.1984	20	-71
43	22.05.1984	15.03	M6/2B	S09E24	4492	d			. .		
44	31.05.1984	11.42	M1	S09W90	4492	d			. .		
45	21.01.1985	23.50	X4/2B	S08W38	4617	d			. .		
46	24.04.1985	09.35	X1/3B	N06E27	4647	a	?	Bz¡-5	28.04.1985	10	-98
47	09.07.1985	02.04	M2/1B	S16W36	4671	a	no data	Bz¡-5	11.07.1985	18	-65
48	06.02.1986	06.25	X1/3B	S04W06	4711	c	MC ?	LE	07.02.1986	16	-307
49	14.02.1986	09.29	M6/1B	N01W76	4713	d			. .		
50	04.05.1986	10.07	M1	N06W90	4717	c	MC ?	LE	05.05.1986	12	-94
51	07.11.1987	20.14	M1	N31W90	4875	d			. .		
52	02.01.1988	21.45	X1/3B	S34W18	4912	a	no data		06.01.1988	19	-80
53	30.06.1988	09.06	M9/2B	S16E22	5060	d			. .		
54	23.08.1988	18.04	M2/EPL	N24E90	5125	d			. .		
55	12.10.1988	05.11	X2/2N	S20W66	5175	d			. .		
56	07.11.1988	11.05	M3/1N	S17W47	5212	c	?	Bz¡-5	08.11.1988	14	-63
57	13.11.1988	23.09	M3/1N	S23W27	5227	d			. .		
58	15.12.1988	05.05	X1/1N	N27E59	5278	b	?	Bz¡-5	17.12.1988	05	-77
59	04.01.1989	17.53	M4/1N	S20W60	5303	d			. .		
60	06.03.1989	14.05	X15/3B	N35E69	5395	a	IS		08.03.1989	18	-100
61	17.03.1989	17.44	X6/2B	N33W60	5395	a	no data		21.03.1989	07	-68
62	23.03.1989	19.48	X1/3B	N18W28	5409	b	no data		27.03.1989	23	-87
63	09.04.1989	01.05	X3/4B	N35E29	5441	c	IS		13.04.1989	22	-100
64	04.05.1989	11.15	M5/2N	S20W36	5464	a	IS		07.05.1989	06	-90
65	22.05.1989	00.37	M5/2B	S21E16	5497	b	no data		26.05.1989	23	-66
66	29.06.1989	21.27	M3/2B	N26W60	5555	d			. .		
67	25.07.1989	08.44	X2/2N	N25W84	5603	d			. .		
68	12.08.1989	14.27	X2/2B	S16W37	5629	c	MC ?	IS	14.08.1989	00	-145
69	03.09.1989	14.32	X1/1B	S18E16	5669	c	no data		04.09.1989	06	-67
70	12.09.1989	08.14	M5/EPL	S18W79	5669	a	no data	IS	15.09.1989	02	-124

Table 3
Continuation of Table 1.

Solar flares						Corre-	Interplanetary events				D_{st}
NN	Date	Time UT	Import. x/opt.	Coord.	NN region	lation	SW type	Bound.	Date	Time UT	nT
71	29.09.1989	11.33	X9/EPL	S26W90	5698	d			.		
72	19.10.1989	12.58	X13/4B	S27E10	5747	b	no data		24.10.1989	09	-74
73	15.11.1989	06.59	X3/3B	N11W26	5786	a	no data		17.11.1989	21	-266
74	25.11.1989	23.55	X1/2N	N30E05	5800	d			. .		
75	30.11.1989	12.29	X2/3B	N26W59	5800	a	no data		02.12.1989	04	-85
76	19.03.1990	05.08	X1/2B	N31W43	5969	b	CIR ?	IS/LE	21.03.1990	00	-134
77	28.03.1990	07.51	M4/2N	S04W37	5988	b	CIR ?	IS/LE	30.03.1990	06	-187
78	04.04.1990	13.38	M7/0N	N22E72	6007	d			. .		
79	15.04.1990	03.02	X1/2B	N32E57	6022	a	no data		17.04.1990	13	-113
80	21.05.1990	22.19	X5/2B	N35W36	6063	d			. .		
81	24.05.1990	20.51	X9/1B	N33W78	6063	a	no data		27.05.1990	08	-87
82	12.06.1990	05.41	M6/2B	N10W33	6089	b	MC ?	IS	14.06.1990	03	-93
83	30.07.1990	07.36	M4/2B	N20E45	6180	d			. .		
84	31.01.1991	02.30	X1/2B	S17W35	6469	c	no data		01.02.1991	23	-73
85	25.02.1991	08.19	X1/2N	S16W80	6497	d			. .		
86	22.03.1991	22.47	X9/3B	S26E28	6555	c	no data		24.03.1991	10	-298
87	02.04.1991	23.27	M6/3B	N14W00	6562	b	no data		04.04.1991	20	-83
88	13.05.1991	01.44	M8	S09W90	6615	b	no data		14.05.1991	17	-74
89	04.06.1991	03.52	X12/3B	N30E70	6659	c	no data		09.06.1991	19	-73
90	15.06.1991	08.21	X12/3B	N33W69	6659	a	IS ?		17.06.1991	11	-70
91	28.06.1991	06.26	M6	N30E85	6703	d			. .		
92	07.07.1991	02.23	X1/2B	N26E03	6703	c	CIR ?	IS/LE	08.07.1991	18	-194
93	10.07.1991	12.28	M3/2N	S22E34	6718	a	no data		13.07.1991	15	-183
94	25.08.1991	01.15	X2/2B	N25E64	6805	d			. .		
95	29.09.1991	15.33	M7/4B	S21E32	6853	a	no data		02.10.1991	03	-164
96	27.10.1991	05.48	X6/3B	S13E15	6891	a	MC ?	IS	30.10.1991	23	-196
97	30.10.1991	06.34	X2/3B	S08W25	6891	d			. .		
98	06.02.1992	10.48	M4/2B	S13W10	7042	a	MC ?	IS	08.02.1992	15	-201
99	15.03.1992	01.54	M7/3B	S14E29	7100	d			. .		
100	08.05.1992	15.46	M7/4B	S26E08	7154	c	no data	IS	09.05.1992	19	-288
101	25.06.1992	20.14	X3/2B	N09W67	7205	c	no data		01.07.1992	03	-89
102	03.08.1992	07.06	M4/1N	S09E68	7248	c	MC ?	IS	04.08.1992	14	-77
103	30.10.1992	18.16	X1/2B	S22W61	7321	a	no data		02.11.1992	06	-70
104	12.03.1993	18.15	M7/3B	S00W51	7440	a	no data		15.03.1993	16	-90
105	20.02.1994	01.41	M4/3B	N09W02	7671	c	MC ?	IS	21.02.1994	09	-144

Table 4
Continuation of Table 1.

Solar flares						Corre-	Interplanetary events				D_{st}
NN	Date	Time UT	Import. x/opt.	Coord.	NN region	lation	SW type	Bound.	Date	Time UT	nT
106	19.10.1994	21.27	M3/1F	N12W24	7790	a	no data		23.10.1994	06	-71
107	20.10.1995	06.07	M1/0F	S09W55	7912	d			. .		
108	04.11.1997	05.58	X2/2B	S14W33	8100	a	MC	IS	06.11.1997	22	-110
109	20.04.1998	10.21	M1/EPL	S43W90	8194	a	CIR	IS/LE	23.04.1998	18	-69
110	02.05.1998	13.42	X1/3B	S15W15	8210	c	MC	IS	04.05.1998	03	-205
111	06.05.1998	08.09	X2/1N	S11W65	8210	a	?	Bz¡-5	09.05.1998	15	-63
112	24.08.1998	22.12	X1/3B	N30E07	8307	c	CIR	IS/LE	26.08.1998	07	-155
113	23.09.1998	07.13	M7/3B	N18E09	8340	b	MC	IS	24.09.1998	23	-207
114	30.09.1998	13.50	M2/2N	N23W81	8340	d			. .		
115	20.01.1999	20.04	M5	N27E90	0	d			. .		
116	03.05.1999	06.02	M4/2N	N15E32	8525	d			. .		
117	04.06.1999	07.03	M3/2B	N17W69	8552	d			. .		
118	17.02.2000	20.35	M1/2N	S29E07	8872	d			.		
119	06.06.2000	15.25	X2/3B	N20E18	9026	b	CIR	IS/LE	08.06.2000	09	-85
120	10.06.2000	17.02	M5/3B	N22W38	9026	d			. .		
121	14.07.2000	10.24	X5/3B	N22W07	9077	c	CIR	LE	15.07.2000	15	-300
122	22.07.2000	11.34	M3/2N	N14W56	9085	d			. .		
123	12.09.2000	12.13	M1/2N	S17W09	Filam	c	CIR	IS/LE	17.09.2000	16	-172
124	16.10.2000	07.28	M2	N04W90	9182?	d			. .		
125	08.11.2000	23.28	M7/mu	N00-10	9212	, d			. .		
		.		W75-80	13,18				. .		
126	24.11.2000	05.02	X2/3B	N20W05	9236	b	CIR	LE	29.11.2000	05	-117

Table 5
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	132	$Kp > 5$	Wang et al. (2002)
	20	132	$Kp > 7$	
5	35	125	$Dst < -60$	Yermolaev and Yermolaev (2003a)
	40	125	$Dst < -50$	Yermolaev and Yermolaev (2003b)
			II. CME → Magnetic cloud, Ejecta	
1	63	8	Earth-directed halo-CME	Cane et al (1998)
			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	19	1273 E	$Kp > 5_-$, Solar minimum	Richardson et al. (2001)
	63	1188 E	$Kp > 5_-$, Solar maximum	
6	82	34 MC	$Dst < -50$	Wu and Lepping (2002)
			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	96	27	$Dst < -100$	Zhang et al. (2003)
			V. Storm → Magnetic cloud, Ejecta	
1	73	37	$Kp > 7_-$	Gosling et al. (1991)
2	25	?	$Dst(corr)$	Vennerstroem (2001)
3	33	618	$Dst < -60$	Yermolaev and Yermolaev (2003a)
	25	414	$-100 < Dst < -60$	
	52	204	$Dst < -100$	
			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)
			VII. Flare → SSC, Storm	
1	35-45	4836	$\geq M0$	Park et al. (2002)
2	32	653	$\geq M5$	Yermolaev and Yermolaev (2003a)
			VIII. Storm → Flare	
1	59	116	$Kp > 7_-$	Krajcovic and Krivsky (1982)
2	20	204	$Dst < -100$	Yermolaev and Yermolaev (2003a)
3	88	25	$Dst < -250$	Cliver and Crooker (1993)