ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2010, Vol. 46, No. 7, pp. 799–819. © Pleiades Publishing, Ltd., 2010.
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Solar and Interplanetary Sources of Geomagnetic Storms: Space Weather Aspects

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Abstract—The current notions of the solar–terrestrial relations responsible for the transport of solar disturbances and for the generation of magnetic storms on the Earth are briefly reviewed. The probability of generating magnetic storms by different solar and interplanetary phenomena is quantitatively estimated. The efficiencies of generating magnetic storms by different types of solar wind streams are compared.

Keywords: magnetic storms, flares, coronal mass ejections, magnetic clouds.
DOI: 10.1134/S0001433810070017

INTRODUCTION

With advances in technical potentialities and with our extended knowledge of nature, it is becoming more and more evident that space factors affect not only different space- and ground-based technological systems [Lilensten, 2007; *Plazmennaya Geliogeofizika* (*Plasma Heliogeophysics*), 2008], but they also significantly affect biological objects, including the human organism [*Plazmennaya Geliogeofizika* (*Plasma Heliogeophysics*), 2008]. When studying the influence of space factors, the term "*space weather*" often implies a combination of phenomena that are physically rather heterogeneous; therefore, in every particular case, the use of this term needs a more precise definition. In fact, a new scientific field—solar–terrestrial relations—has been formed. In the framework of this direction, all possible interactions between helio- and geo-physical phenomena are studied. Figure 1 schematically shows the structure of solar–terrestrial relations.

It is almost impossible to find a systematic description of the basic principles of this scientific field in any domestic or foreign publication, because it is both inter- and multidisciplinary and includes the elements of a number of sciences. These elements are most often presented in the specialized literature on one or another of scientific field and often fall through the cracks in regards to the specialists of related directions. A more detailed description of the problems related to the solar–terrestrial relations can be found in the above-mentioned monograph [*Plazmennaya Geliogeofizika* (*Plasma Heliogeophysics*), 2008] and in the encyclopedia edited by R.A. Syunyaev [*Fizika Kosmosa* (*Space Physics*), 1986], which is still of actual although it was published 20 years ago. It is important to note that both books are published in Russian, which makes them accessible to Russian researchers.

We think that, before proceeding with our basic results, we should give a brief popular description of some basic elements of the system under consideration. In our opinion, such a description will give even laymen a better insight into what follows. In addition, there is no commonly accepted terminology, which presents some difficulties in discussing the problems of the solar–terrestrial relations. To denote the described processes and phenomena, we use abbreviations taken from the scientific literature in English.

1. BASIC TERMS AND DEFINITIONS

When speaking about solar–terrestrial relations, it is necessary to emphasize that there are two channels of energy transfer from the Sun to the Earth: *electromagnetic* and *corpuscular radiations*. The former is considered basic: it is through this channel that most solar energy is transferred to the Earth (about 1.37 kW per every square meter of the land surface). This energy flux lies mainly within both visible and infrared wavebands and is characterized by its steadiness; its variations do not exceed fractions of percent, and, therefore, it is referred to as a *solar constant*. Reaching the Earth in over 8 min, this flux, which is absorbed mainly by the atmosphere and the land surface, plays an important role in atmospheric weather.

The electromagnetic radiation within both X-ray and ultraviolet bands significantly varies during the development of active processes occurring on the Sun. The energy fluxes within the indicated bands are extremely small: even when, during the strongest solar flares, the X-radiation flux increases by three orders of magnitude, the total energy flux remains six orders of magnitude smaller than the solar constant. In this case, it should be remembered that the indicated radiations are almost completely absorbed by the Earth.

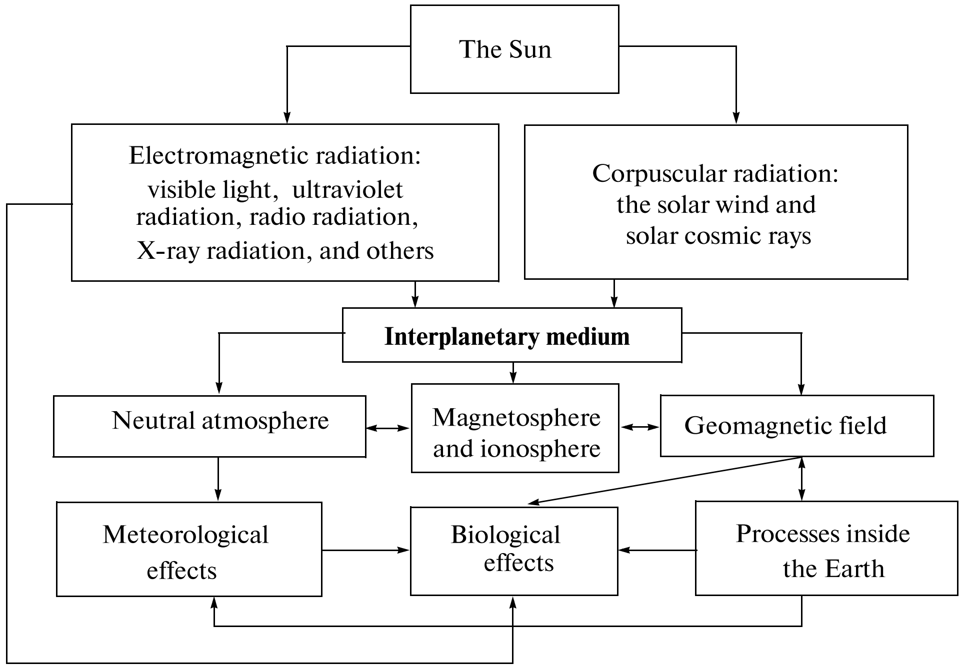

Fig. 1. Structure of solar–terrestrial relations.

The latter channel—corpuscular radiation—is dominant in "*space weather*", and it is precisely this channel which will be considered below.

Corpuscular radiation consists of solar wind and cosmic rays. In recent years it has been common practice to call cosmic rays *energetic particles*. This name better reflects their physical nature, because cosmic rays are charged particles (electrons, protons, and ions) accelerated to very high (often relativistic) velocities. These particles are of *galactic* or *solar* origin. The former particles are born outside the solar system. On average, their occurrence on the Earth's orbit is less frequent than the occurrence of particles of solar origin. An increase in the Sun's activity results in a decrease in the flux of these particles. During active processes occurring on the Sun (flares, destruction of arcs, coronal ejections, etc.) and in the interplanetary medium (mainly on shock waves), energetic particles of solar origin accelerate.

Basically, accelerated particles are radiation that can penetrate into bodies and destroy the molecules of both animate and inanimate natures. Fortunately, the Earth's surface is safely protected by the magnetosphere and the atmosphere. However, during space and even airplane transarctic flights, energetic particles may be hazardous to people and electronic devices. It is under the influence of radiation that most instruments installed aboard spacecrafts fail to operate. For example, in October–November 2003, some malfunctions of the instrumentation installed aboard the SOHO and ACE spacecrafts were associated with this reason [Veselovsky et al., 2004].

The temperature of the solar corona's plasma amounts to 2×10^6 K, and, as a result, this plasma cannot be completely confined by the Sun's gravitational field, "escapes" to the interplanetary space, and fills the heliosphere with itself. Although almost the entire solar system is within the solar corona, plasma that is more than a few solar radii away from the Sun and that has characteristics significantly different from those of the plasma at the corona's base is usually called *solar wind*. Having a mean velocity of 400 km/s, the solar wind reaches the Earth over 2–5 days. In this case, its density in the Earth's orbit amounts to a few ions per 1 cm^3, which is impracticable under the conditions of ground-based experimental installations. Nevertheless, solar wind has a profound effect on the energy transfer from the Sun to the Earth's magnetosphere and its outer layers.

Slow changes that occur in the system under consideration and that are characterized by the time on an order of months and more are sometimes called "space climate." If they are eliminated from consideration, the dynamic portion remains, which is characterized by rapid deviations from an averaged pattern that is the subject of investigation in studying space weather.

We will restrict ourselves to a description of only a small part of the given scheme—the transfer of disturbance from the Sun to the Earth's magnetosphere through the solar wind. In this case, most attention will be concentrated on recent results obtained from studies of the sources of the strongest magnetospheric disturbances (magnetic storms on Earth).

In recent years, in heliobiophysics that concerns the problems associated with the influence of space-weather factors on biological objects, including human beings, studies of the role of magnetic storms have taken on greater importance. In this direction, significant results have already been obtained [Villoresi et al., 1994; Gurfinkel', 2004; Zenchenko and Breus, 2008; and Kleimenova et al., 2008] and ways have been outlined to decrease the risk of serious consequences for people through taking preventive measures with the approach of magnetic storms. However, the number of similar investigations carried out thus far is insufficient, mainly because they are complex and interdisciplinary and require definite knowledge in the related scientific areas. In particular, these investigations were limited to a comparison with the very fact of the occurrence of magnetic storms. Currently, there are no serious comparisons of biological responses to magnetic storms with their properties and origin, because such comparisons require knowledge of magnetic storms and their sources. Heliobiophysicists are, as a rule, not very aware of the Sun's physics and solar–terrestrial relations. Their use of indices of geomagnetic activity and their classification according to activity level are formal and not always physically justified. This paper intended for a wide circle of readers has been written by us to clarify a number of questions related to the origin and character of geomagnetic storms, classification of the geomagnetic-activity indices, and to the adequate use of these indices in solving different applied problems.

From the preceding, it follows that the study of solar and interplanetary sources of geomagnetic storms remains an relevant and important problem of space weather and its numerous applications. Our general notion of the sources of storms has not changed over many years: the basic source of magnetospheric disturbances is the negative (southward) *Bz*-component of the interplanetary magnetic field (IMF), because, in this case, the magnetosphere becomes open and energy from the solar wind can arrive in the magnetosphere and result in magnetic storms. The IMF usually lies within the ecliptic plane and does not contain any of the *Bz* components; only the disturbed types of the solar wind can contain the IMF *Bz*-component, including the southward one.

According to current views, there are two basic chains (scenarios) of energy transfer from the Sun to the magnetosphere. (Since the terminological difficulties of the above-described scientific field have already been noted, below we will give the English names of each process and phenomena and use the abbreviations derived from their English names). Scenario 1: solar disturbance (solar flare and coronal mass ejection (CME)) ⟶ interplanetary CME (ICME, ejecta, and magnetic cloud (MC)), including the IMF southward *Bz* component, ⟶ magnetic storm. Scenario 2: coronal holes that form high-speed solar wind streams ⟶ interaction of a high-speed flow with the preceding low-speed flow and the formation of the IMF compression and deformation region (corotating interaction region (CIR)), which includes the IMF southward *Bz* component ⟶ magnetic storm. Although the mechanisms of energy transfer have been studied over many years and, by now, a significant volume of both experimental and theoretical data has been accumulated (see, for example, [Lilensten, 2007; Schwenn, 2006; Pulkkinen, 2007] and their references), this problem has yet to be finally solved.

On the one hand, the investigations that were carried out include a long chain of spatial regions with different physical processes, they are of interdisciplinary character, and they require the joint efforts of scientists of different specialities. On the other hand, among the regions known to us, there are some zones on which we have no experimental data and we can only propose hypotheses for their interrelations. For example, there are data on the Sun and circumsolar space obtained with the remote sensing methods and there are data obtained from direct measurements in the near-Earth space; however, there are almost no data on the region between the circumsolar and near-Earth spaces for lack of measurements in this region. We also know almost nothing about the thin fronts of a bow shock and the magnetopause because the motion of these boundaries is too fast with respect to the satellite. Therefore, in this paper, we will not consider regions for which experimental data are available; they are discussed in detail in the special literature. We will focus our attention on the "interface" between these regions, which is usually absent in the special literature.

In our previous papers [Yermolaev and Yermolaev, 2003b, 2006; Yermolaev et al., 2005a], it was shown that the quantitative relations between different phenomena depend strongly on the methodical approaches used. Therefore, problems related to the influence of the quantitative determinations of phenomena and ways to compare them on the estimates of correlation between these phenomena will be discussed in the following sections. Then, some estimates of correlations established on the basis of a large body of observational data will be given. Finally, it will be shown that, in most cases, the generation of magnetic storms is characterized not only by the IMF southward *Bz* component but also by a certain behavior of other solar-wind parameters. This allows us to suggest that the magnetic storms induced by a disturbed plasma-compression region before ejecta/MC (sheath), MC, and CIR can be generated through different physical mechanisms.

It should be noted that there is a double meaning of the word *geoeffectiveness*. In one case, geoeffectiveness implies a probability with which one or another phenomenon can cause a magnetic storm, i.e., the ratio between the number of events of a chosen type resulting in a magnetic storm and the total number of these events. In the other case, geoeffectiveness implies the

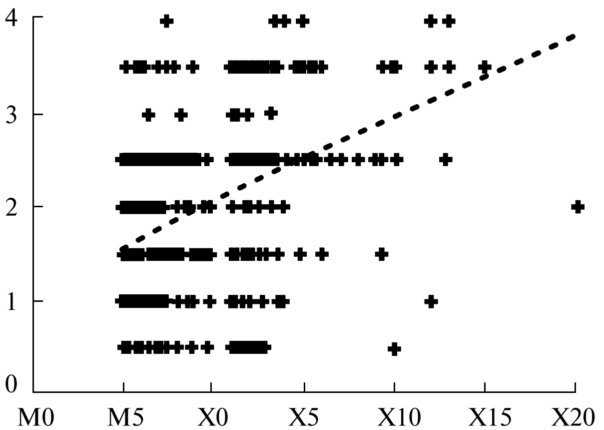

Fig. 2. Ratio between the optical (vertical axis) and X-ray (horizontal axis) values (classes) of solar flares. 643 flares of class M5 and higher observed in 1976–2000 have been analyzed [Yermolaev and Yermolaev, 2003b, 2006]. The dashed line denotes the linear approximation of the given data.

efficiency of storm generation by unambiguously interrelated phenomena, i.e., the ratio between the "output" and "input" of a physical process, for example, between the values of the D_{st} index and the IMF southward Bz component.

2. PHENOMENA ON THE SUN

Data on phenomena occurring on the Sun are of specific character. Unlike the data on interplanetary and magnetospheric phenomena obtained from in situ measurements of their parameters, data on solar phenomena are obtained from remote (ground-based or near-Earth space-based) measurements of the solar atmosphere within different frequency ranges of electromagnetic waves. The frequency of radiation is determined by conditions in the radiating volume of plasma (mainly, by its concentration), and, generally speaking, the measurements taken in different frequency ranges yield the characteristics of the Sun's different regions. Determining the dynamics of a solar phenomenon, including its spatial motion (especially along the line of sight) is a complicated and ambiguous problem, because, in this case, different phenomenon components whose characteristics and locations vary in time must be measured by different instruments. In this case, it is assumed that the results of measurements with different instruments can be used in studying one and the same phenomenon.

Solar flares were first measured within the optical wave band with ground-based instruments, and it is on the basis of optical observations that solar flares were classified (see, for example, [Krajcovic and Krivsky, 1982]). However, the orbital observations of the Sun within the X-ray band (which are impossible for ground-based measurements) were made possible with the advent of the space age; the X-ray flares were classified on the basis of (GOES) satellite measurements (see http://www.ngdc.noaa.gov/stp/GOES/goes.html). The optical and X-ray emissions are formed at different stages of solar flares and in their different regions. Thus, the flare values (classes) determined with two different methods are of different physical natures.

The ratios between the optical and X-ray values of solar flares are given in Fig. 2 for the period 1976–2000. All flares with X-ray values of M5 and higher, which are usually treated as candidates for the sources of interplanetary and magnetospheric disturbances, are shown [Yermolaev and Yermolaev, 2003b, 2006]. Figure 2 clearly shows that there is correlation only in a statistical sense, because some events can simultaneously have a high optical class and a low X-ray class and vice versa.

Over a long period of time, all disturbances within the solar wind and the Earth's magnetosphere were associated only with solar flares. Figure 3 (on the left) shows all X-ray flares of both high (M) and extreme (X) classes (gray and black squares, respectively). To make the flares, whose lengths were from a few minutes to a few dozen minutes, distinguishable in Fig. 3, their durations were increased up to 6 h in plotting the graph. Figure 3 (on the right) shows both average ($-50 > D_{st} > -100$ nT) and strong ($D_{st} < -100$ nT) magnetic storms (gray and black squares, respectively); their durations in the graph correspond to those observed in reality. The numbers of the days of the sun's Carrington rotations (about 27 days) are plotted along the abscissa axis, and the years from 1976 to 2000 are plotted as ordinates. On the whole, on the time scales of the Sun's several rotations, a good correlation is observed between solar and magnetospheric events. However, in most cases, the attempts to relate concrete events to one another prove to be ineffective; this will be discussed in more detail in Section 4.

In the early 1970s, one more powerful solar phenomenon—CME—was revealed with white-light coronagraphs installed aboard spacecrafts. Over a long period of time, the CMEs were studied only by individual researchers and were almost neglected in considering the chain of the solar–terrestrial relations. However, after the publication of Gosling's paper in 1993, the situation changed, and now the CMEs are treated as the single cause of all interplanetary and geomagnetic disturbances, although both the physical phenomena (flares and CMEs) are closely interrelated (see, for example, discussions in [Harrison, 1996; Cliver and Hudson, 2002; and Yashiro et al., 2005].

A large body of CME data was obtained with a LASCO coronagraph on board the SOHO spacecraft (http://cdaw.gsfc.nasa.gov/CME_list/). When studying the geoeffectiveness of CMEs (unlike flares that can be observed on the solar disc), a very important problem is to determine the location of their source on the solar disc and, first of all, answer the question of what side of the solar disc their source is located on visible or back side. CMEs are observed in two-dimen-

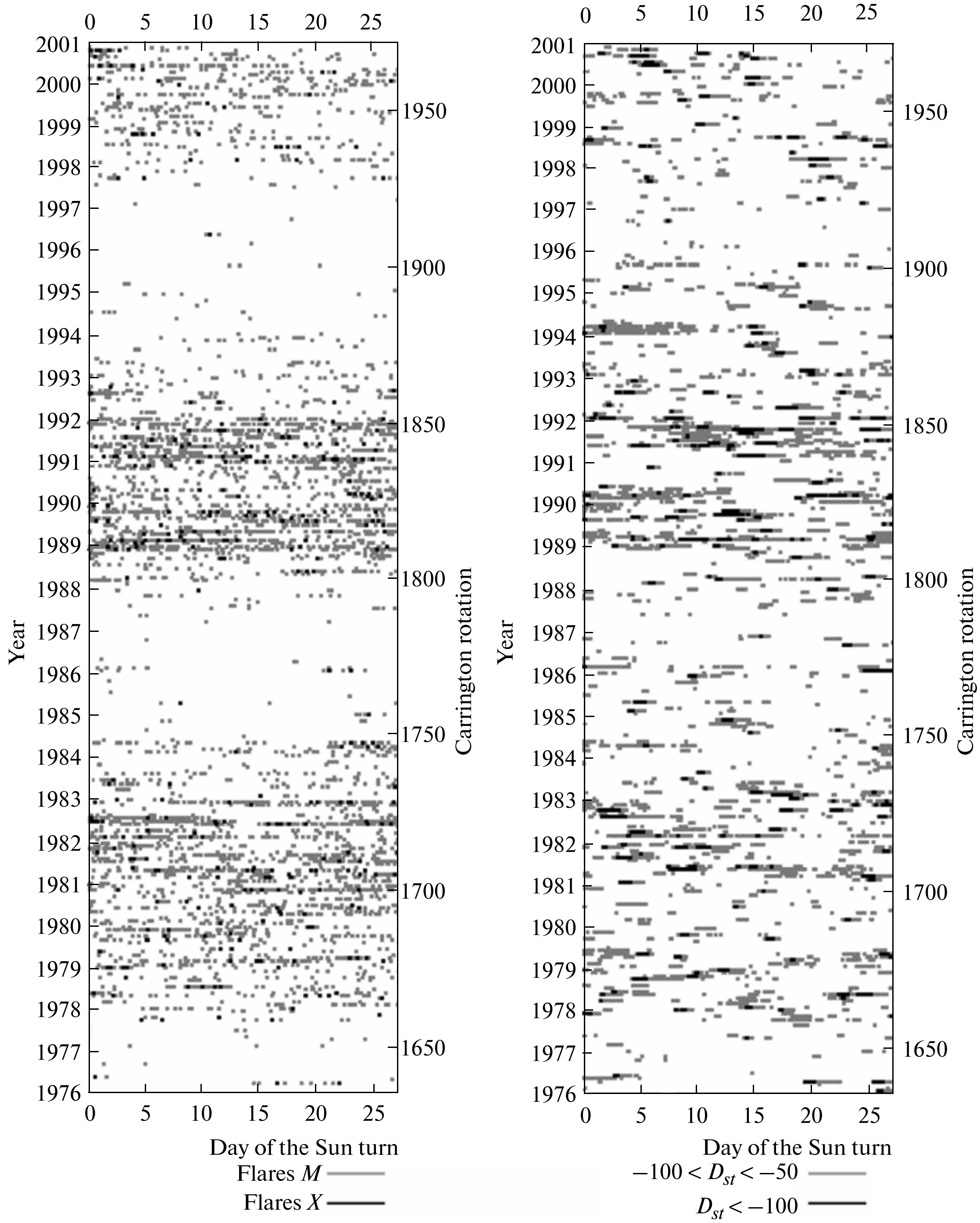

Fig. 3. Time variations in solar flares (on the left) and magnetic storms (on the right) for the period 1976–2000.

sional images in which the Sun is "cut out" of the viewing field of coronograph due to its occulting disc. To solve this problem, the results of observations of CMEs in the white light outside the solar disc are compared with the results of observations of other solar phenomena, such as flares, ultraviolet and X-ray dimmings, ultraviolet luminosities, both ultraviolet and X-ray posteruptive arcades, etc., on the solar disc in different wavebands. Such a comparison between the results of observations in the white light and ultraviolet band is shown in Fig. 4 [Gopalswamy, 2002]. Thus, it should be remembered that the CME location determined with the above-indicated method is not an experimental fact but a hypothesis, because, for this purpose, researchers have to use the results of measurements taken (i) with different instruments; (ii) on

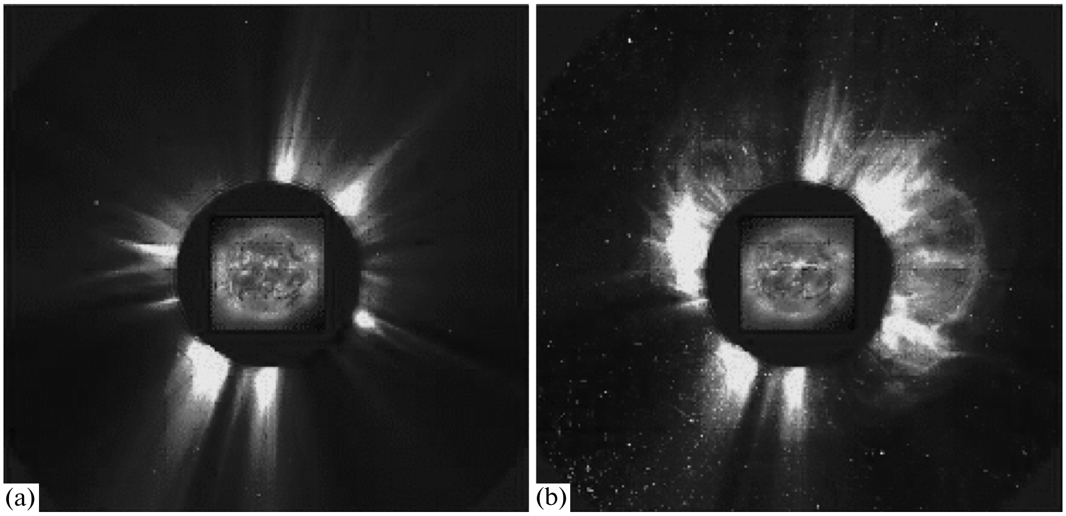

Fig. 4. Superposition of the images of CME moving toward the Earth on July 14, 2000 (the Bastille Day event) in the white light (SOHO/LASCO, SOHO/EIT). The background in the form of "white snow" (on the right) results from a bombardment of the SOHO detectors by energetic particles associated with solar activity [Gopalswamy, 2002].

different frequencies; (iii) in different spatial regions; and, finally, (iv) at different times. Therefore, the location of the CME source on the solar disc can only statistically be considered on the basis of images obtained within other wavebands. There are experimental facts that some CMEs lead to direct measurements of ejecta/MC (interplanetary CME) and magnetospheric disturbances, but they do not have any apparent features on the Sun's visible disc [Zhang et al., 2003]. If such CMEs are neglected, then, on the basis of only solar observations, they can be included in the list of CMEs on the invisible side of the Sun and can lead to wrong conclusions about the CME geoeffectiveness [Yermolaev, 2008].

Unlike flares and CMEs, coronal holes are sufficiently stable solar structures that can exist for several 27-day solar rotations. Coronal holes have an open configuration of the magnetic field which allows the corona to form fast solar wind streams (Fig. 5).

Table 1.

Quasistationary types	
Type 1	Heliospheric current sheet
Type 2	Slow wind from coronal streamers
Type 3	Fast wind from coronal holes
Disturbed types	
Type 4	Compressed solar wind streams (compression region between slow and fast flows (CIR) and compression region before MC and ejecta (sheath))
Type 5	Interplanetary CME (MC and ejecta)
Type 6	Rarefaction region

3. INTERPLANETARY PHENOMENA

The classification of large-scale events in the interplanetary medium arose with the advent of the space age and is developing now as knowledge of and data on the solar wind and its sources on the Sun accumulate. Although the classification methods are developing rapidly enough now, a general idea of the types of solar wind has not changed significantly. According to a large body of observational data, there are six basic types of large-scale solar wind streams (Fig. 6, Table 1).

Among the types given in Table 1, only two types 4 and 5 are geoeffective, because they can include the long southward IMF *Bz* component [Gosling and Pizzo, 1999; Gonzalez et al., 1999; Crooker, 2000; and Bothmer, 2004].

An analysis of literature shows that there is no one method for identifying interplanetary phenomena; different researchers use different sets of parameters and different numerical criteria in analyzing these phenomena. For example, to identify a magnetic cloud, the available methods may include from two to ten parameters (see, for example, [Yermolaev and Yermolaev, 2003b] and the references from this paper). In the literature, there are several lists of ICMEs (MC and ejecta) [Cane and Richardson, 2003; Zhang et al., 2004; and Echer et al., 2005] and one list of CIRs [Alves et al., 2006], but there are no lists of other types of solar wind streams or lists that simultaneously include different types of streams. We have prepared a list of all the above-indicated types of solar wind streams for 1976–2000 on the basis of the OMNI catalog of solar-wind measurement data (see [Yermolaev et al., 2009] and the site ftp://ftp.iki.rssi.ru/pub/omni/catalog/).

The authors of a large number of papers treat different types of solar wind as isolated events and neglect

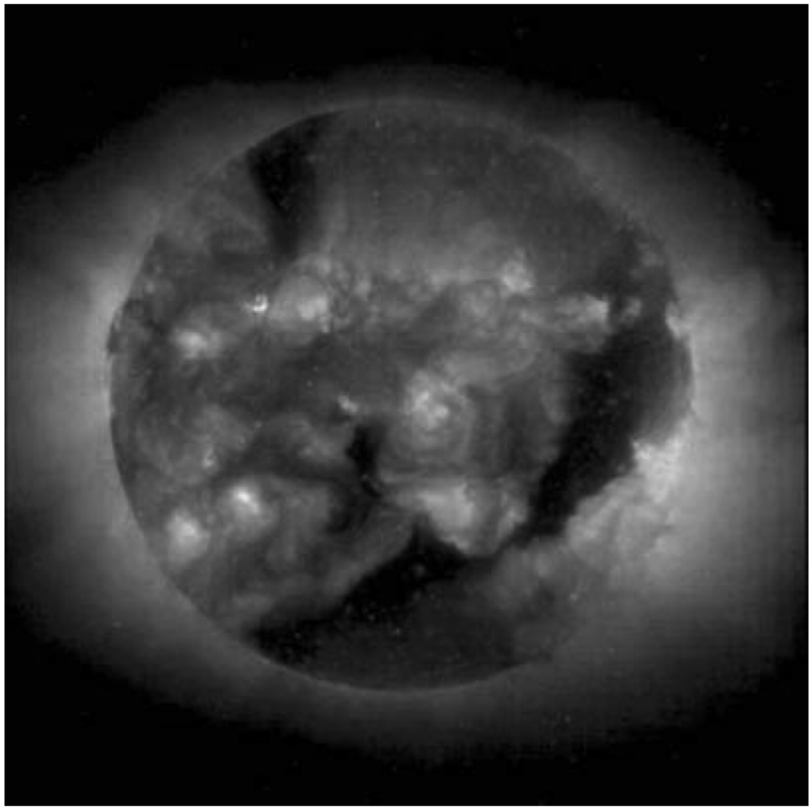

Fig. 5. The SOHO/EIT image of the lower corona: the light regions correspond to active zones and the dark regions correspond to coronal holes [http://www.lmsal.com/YPOP/ProjectionRoom/latest/eit/full/eit284-128.gif].

their interaction. In most cases, this assumption is justified, because the sizes of the above-listed disturbed types of phenomena in the Earth's orbit (1 AU) amount to no more than a few tenths of a percent of 1 AU and do not have time to significantly change or dissipate. However, interactions of CMEs in the vicinity of the Sun [Gopalswamy et al., 2001, 2002] and of magnetic clouds in the vicinity of the Earth (see, for example [Burlaga et al., 2001; Berdichevsky et al., 2003; Gonzalez-Esparza et al., 2004; Farrugia et al., 2006a] and references there in) were noted. In a number of papers, it is shown that some strong magnetic storms, for example, such as the events on March 31, 2001, with $D_{st} = -387$ nT; on April 11–13, 2001, with $D_{st} = -271$ nT [Wang et al., 2003]; on October 28–30, 2003, with $D_{st} = -363$ nT [Veselovsky et al., 2004, Skoug et al., 2004]; on November 20, 2003, with $D_{st} = -472$ nT [Yermolaev et al., 2005a, Gopalswamy et al., 2005]; and on November 8–10, 2004, with $D_{st} = -373$ nT [Yermolaev et al., 2005b], were generated by interacting magnetic clouds. Recently, in studying the interplanetary conditions for the 1995–2003 magnetic storms [Farrugia et al., 2006b], it was found that "a rather large number of our significant events (6 out of 16) consisted of interacting ICMEs/MCs that formed complex ejecta." Other authors [Xie et al., 2006] have studied 37 long-lived geomagnetic storms observed in 1998–2002 with $D_{st} < -100$ nT, which are associated with CMEs, and found that 24 of them were caused by a succession of CMEs and that the number of interacting magnetic clouds was from 2 to 4. This result can be

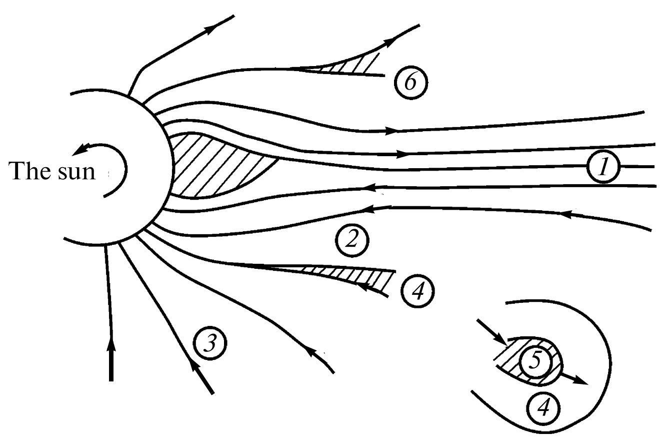

Fig. 6. Schematic representation of the large-scale types of solar wind: (*1*) heliospheric current sheet; (*2*, *3*) slow and fast streams from coronal streamers, and coronal holes, respectively; (*4*) compressed plasma (at the boundary between fast and slow flows (CIR) and before the leading edge of a "piston" (sheath)); (*5*) "piston" (magnetic clouds (MCs) and "pistons" (ejecta)); and (*6*) rare plasma at the front of slow and fast flows of solar wind.

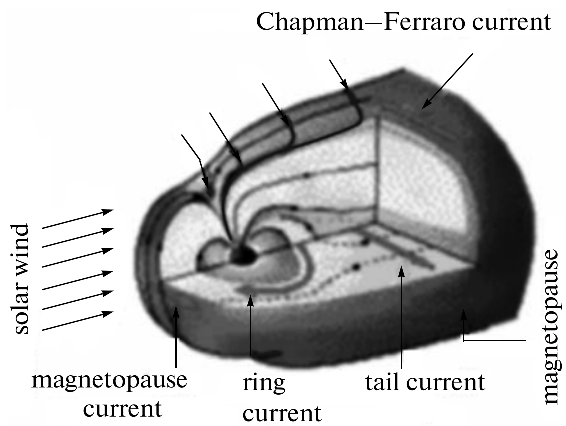

Fig. 7. Structure of the Earth's magnetosphere. The solar wind compresses the geomagnetic field on the subsolar side. The magnetopause within which the Chapman–Ferraro current flows is formed where the pressures are equal. Both tail and ring currents are also shown.

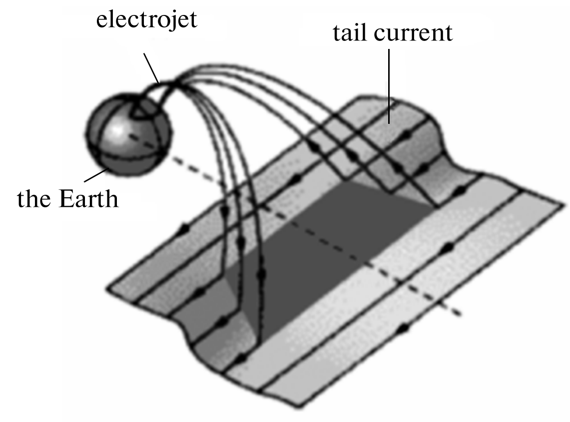

Fig. 8. Scheme of electrojet formation during a magnetic substorm when electric current starts to flow through the Earth's ionosphere.

explained by a compression of magnetic clouds resulting in the formation of complex structures (complex ejecta) that simultaneously have the features of both magnetic cloud and a sheath (below, it will be shown that a sheath is more efficient in generating storms than the body of a magnetic cloud).

4. MAGNETOSPHERIC PHENOMENA

The solar-wind plasma and the plasma in the vicinity of the Earth are practically ideal conductors of electric current. Therefore, in accordance with the laws of magnetic electrodynamics, the outer plasma of the solar wind and the IMF cannot closely approach the Earth because of its strong magnetic field. The interaction of the solar wind and the IMF with the Earth's plasma and magnetic dipole results in the formation of a cavity (*magnetosphere*) at the boundary (*magnetopause*) of which the plasma and field (of both outer and inner origins) pressures are balanced. This magnetopause in the subsolar region is moved to a distance of about 6×10^4 km away from the Earth (Fig. 7).

As a first approximation, the magnetosphere is impenetrable for the outer plasma of the solar wind, which can change only the form of the magnetopause in accordance with its pressure-balance condition. However, in fact, the situation is more complicated. When the IMF has a component that is parallel to the Earth' magnetic dipole (the IMF southward component), in the region of contact of the oppositely directed interplanetary and terrestrial magnetic fields, the condition of ideal plasma conductivity is violated and a magnetic-field erosion occurs. The plasma of the solar wind and its transported energy enter the magnetosphere. This process is called the *threshold* (*trigger*) *mechanism*. According to the rate of energy arrival, there are three possible scenarios of the magnetosphere's reactions.

(1) When the rate of energy arrival is lower than or equal to the rate of stationary energy dissipation within the magnetosphere, its form does not change; no significant changes are observed in the magnetosphere, i.e., the magnetosphere remains undisturbed.

(2) When the rate of energy arrival exceeds that of stationary dissipation, a portion of energy leaves the magnetosphere through a "quasistationary channel," which results in its recovery. The role of such a channel is played by magnetic substorms (the processes of releasing magnetic energy accumulated in the magnetosphere through tail-current connection (Fig. 7) along the magnetic lines through the ionosphere in the night region of the polar oval). The newly-formed current is called an "electrojet" (Fig. 8). The most impressive substorms—auroras—result from a bombardment of atmospheric neutral atoms by accelerated (along the magnetic force lines) particles in the tail of the magnetosphere. The magnetosphere can, for a long time, release excess energy into the polar regions of both of the Earth's hemispheres in the form of substorms with a periodicity of about 3 h.

(3) When the rate of energy arrival significantly exceeds the rate of both stationary and quasistationary dissipations, global changes occur in both magnetospheric and ionospheric current systems, which are accompanied by strong disturbances of the Earth's magnetic field; this is called a magnetic storm. The basic contribution to the magnetic field's changes is made by the *ring current* located in the geomagnetic-equator region (Fig. 7). Therefore, unlike magnetic substorms during which magnetic-field disturbances are observed in the polar regions, during magnetic storms, the magnetic field varies also in low latitudes in the vicinity of the equator. During strong storms,

Fig. 9. Scheme of the location of two networks of ground-based stations whose data are used in determining the indices D_{st} (circles) and K_p (triangles). The asterisks denote the location of the magnetic poles, and the solid line denotes the geomagnetic equator.

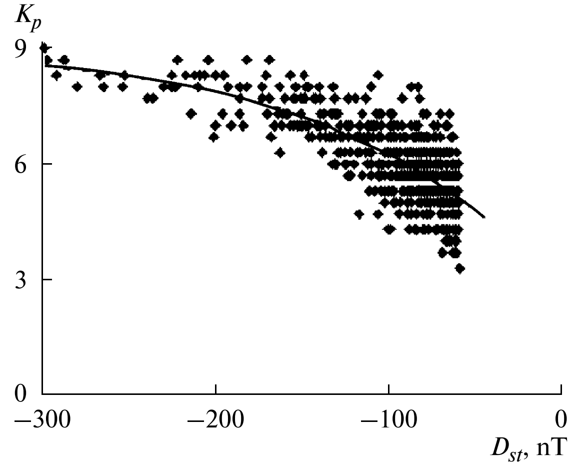

Fig. 10. Relation between the extreme values of the indices K_p and D_{st} for 611 magnetic storms with $-300 < D_{st} < -60$ nT for 1976–2000. The solid line denotes the approximation of the data presented [Yermolaev and Yermolaev, 2003b].

auroras can descend by 20°–30° to the equator of the polar regions and can be observed in the low latitudes, like, for example, on October 30, 2003.

Thus, magnetospheric disturbances result from rapid changes in the current systems existing in the Earth's magnetosphere and ionosphere or from the formation of new current systems. It is important to note that the ring-current variations during storms significantly the exceed electrojets that occur during substorms. However, because the ring current is located far from the Earth's surface (unlike the electrojet, which almost reaches the ionospheric and atmospheric lower layers), during magnetic storms, variations in the Earth's magnetic field are of a global character (except for small regions in the vicinity of the magnetic poles) and amount to no more than 500 nT at the most. During substorms, the variations in the magnetic field are of a local character and can amount to 1–3 × 10^3 nT (it should be remembered that the Earth's constant field amounts to about 30–50 × 10^3 nT; i.e., in any case, we are dealing with variations that do not exceed a few percent, which is significantly smaller than the fields of technogenic origin).

The magnetospheric state is described by a number of different indices calculated on the basis of ground-based measurements of the magnetic field [Mayaud, 1980]. Since the results obtained at different networks of magnetic stations are used to construct these indices, the latter include the responses of different magnetospheric and ionospheric current systems. Figure 9 shows the location of two networks of ground-based stations whose data are used to calculate the indices D_{st} and K_p that are most often used to describe magnetic storms.

On the one hand, it is possible to assume that, if the magnetic-storm statistics are sufficient, there must be a correlation between the extreme values of different indices. Such an analysis was made for 1085 magnetic storms during the period 1957–1993 [Loewe and

Table 2. Classification of magnetic storms on the basis of the D_{st} index measured in 1957–1993 [Loewe and Prolss, 1997]

Storm class	Number of storms	Percent	D_{st}, nT	$\langle D_{st}\rangle$	⟨ap⟩	$\langle K_p\rangle$	$\langle AE\rangle$, 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

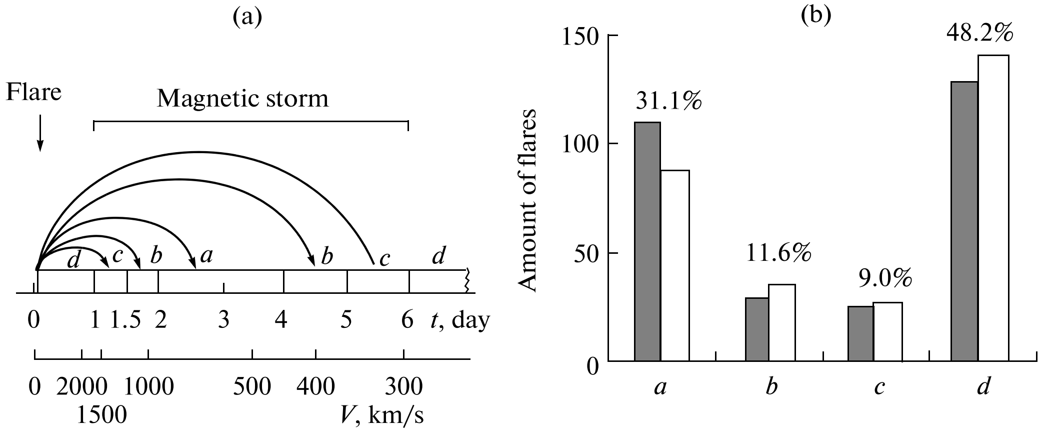

Fig. 11. (a) Scheme of establishing correspondence between flares and storms for different time windows *a*, *b*, *c*, and *d* (the window length is given in days on the horizontal line, and the scale under this line shows the mean velocity of motion of disturbances from the Sun to the Earth in km/s. (b) The amount of western (gray columns) and eastern (white columns) strong solar flares that result in storms with a (*a*) high, (*b*) mean, or (*c*) low probability, as well as those that (*d*) do not result in storms. Their portion from the total amount of flares falling within the corresponding window is given in % [Yermolaev and Yermolaev, 2003a].

Prolss, 1997] (see Table 2). On the other hand, such results may create the illusion that the magnetospheric indices are interchangeable. However, even the first attempts to analyze real data show that the behavior of different indices is not identical during one and the same event. For example, on October 24, 2003, 15:00–23:00 UT [Veselovsky et al., 2004], at high values of K_p, the index D_{st} remained at undisturbed level.

Figure 10 shows the relationship between the extreme values of the indices K_p and D_{st} for 611 magnetic storms ($-300 < D_{st} < -60$ nT) for 1976–2000 [Yermolaev and Yermolaev, 2003b]. A wide scatter of data is explained by the fact that the indices K_p and D_{st} are measured in different geomagnetic latitudes and are sensitive to different current systems (magnetospheric phenomena): auroral electrojet (magnetic substorms) and ring current (magnetic storms). Thus, in order to study the relation between magnetic storms and different phenomena and to eliminate auroral phenomena from analysis, it is necessary to use the D_{st} index. In studying the influence of the auroral electrojet on different systems, it is better to use the special *AE* index. The index K_p is sensitive to both phenomena and does not allow the influence of each of the current systems to be individually studied.

To correctly use the indices of geomagnetic activity in related disciplines (including heliobiophysics), it is necessary to have a general idea of the principles of constructing geomagnetic indices, their physical meaning, their interdependence, and the ranges of their values which correspond to different levels of geomagnetic activity. A familiarity with the data presented in this paper (Figs. 7, 8; Table 2) will provide additional insight into some of these problems. More detailed information can be found in [Mayaud, 1980; Loewe and Prolss, 1997].

5. CORRELATION BETWEEN DIFFERENT EVENTS OF “SPACE WEATHER”

A lack of strong evidence of the cause–effect relation between the phenomena under study is customary in solar–terrestrial physics. The only experimental fact is that the one event was observed after the other during a time window previously specified. As a rule, any additional information on the phenomena is not direct in studying the relations between them. Let us consider the flare–magnetic storm relation as an example (Fig. 11). In this case, the time windows are determined by the mean speed of the movement of disturbances from the Sun to the Earth (the corresponding scale is shown in Fig. 11a). The windows *a*, *b*, *c*, and *d* correspond to the intervals for which it is assumed that the flare–storm relation has a high, mean, low, and zero probability, respectively. Figure 11b shows the probability of storm generation after flares on the Sun’s both western and eastern hemispheres. The total probability of storm generation by solar flares is assessed at about 40% [Yermolaev and Yermolaev, 2003a]. Only two levels of probability (related and unrelated events) are used in many studies, and, in this case, the fact that the relation between the events is of probabilistic character is neglected.

The methods of identifying and classifying the solar (CMEs and solar flares), interplanetary (CIRs, sheaths, ejecta, and others), and geomagnetospheric (magnetic storms) phenomena have been described above. In addition to the ambiguity associated with different approaches to the classification of these phenomena, there is an ambiguity associated with different methods of comparing them in two spatial regions. If two phenomena with the sets *X*1 and *X*2 are chosen for analysis and the correspondences between these phenomena are found for the number of phenomena

$X12$, the probability of the process $X1 \longrightarrow X2$ is usually determined as the ratio $X12/X1$, which differs from the probability $X2 \longrightarrow X1$ equal to $X21/X2 = X12/X2$. The values of $X1$ and $X2$ correspond to different phenomena, are obtained according to different criteria, and can have different meanings (for example, it follows from Fig. 3 that the number of solar flares of class M and higher is approximately one order of magnitude larger than the number of moderate and strong magnetic storms). Hence, the geoeffectiveness determined in different studies depends on the direction of an analysis of the process. If we take into consideration that, in some studies, set $X2$ is not specified previously (before the start of analysis), i.e., the rules (or criteria) of choosing the phenomena for set $X2$ are not established initially but are selected during the study, the ambiguity of calculating the geoeffectiveness can be increased additionally.

Because in analyzing this chain of solar–terrestrial physics, a two-stage process (the Sun–solar wind and the solar wind–magnetosphere) is studied, data on the interplanetary medium make it possible to increase the accuracy of the estimate of the whole chain. Let us assume that there are sets of data on the Sun ($X1$ and $Y1$), the interplanetary medium ($Y2$ and $Z1$), and the magnetosphere ($X2$ and $Z2$) for which the probabilities of the processes $X1 \longrightarrow X2$ ($X12/X1$), $Y1 \longrightarrow Y2$ ($Y12/Y1$), and $Z1 \longrightarrow Z2$ ($Z12/Z1$) are estimated. In this case, it is natural to assume that the probability of the complete process must be close to the product of the probabilities of individual stages; i.e., $X12/X1 = (Y12/Y1)(Z12/Z1)$. In particular, this implies that the geoeffectiveness (in the sense of probability) of the complete process cannot be higher than the geoeffectiveness of each of the stages of $X12/X1 \le Y12/Y1$ and $X12/X1 \le Z12/Z1$. For example, the geoeffectiveness of solar events cannot exceed that of interplanetary events. Published data contain enough material to make such an analysis; its results will be demonstrated below.

It is important to note that many authors often call values obtained with quite other methods the geoeffectiveness of phenomena. As was noted above, in the strict sense of the word, the geoeffectiveness (as a probability) of solar and interplanetary phenomena is a portion (percent) of the corresponding sets of solar and interplanetary phenomena resulting in a magnetic storm of certain intensity.

The most common error is that some authors use the method of backward event tracing: first, they take the list of magnetic storms and then extrapolate them backward to the interplanetary medium or to the Sun in order to find corresponding phenomena. This method is important because it allows one to find phenomena (candidates) that can be treated as the causes of the studied magnetic storms in the interplanetary medium and on the Sun. However, this method does not allow one to determine the geoeffectiveness (probability) of these phenomena. Phenomena of different classes (if only they fall within the time window under analysis) are often treated as candidates, and this is one of the main reasons for disagreement among results obtained by many authors.

As was noted in the Introduction, a study of the flare–magnetic storm relation and, generally, the relation between the events occurring on the Sun and in the interplanetary space is very important for heliobiophysics, because geomagnetic disturbances on the Earth are predicted on its basis. This study gives information necessary to develop preventive measures and, sometimes, to save patients with a cardiovascular pathology from fatal outcomes [Gurfinkel', 2004]. Improving the prediction of geomagnetic disturbances on the basis of solar observations, which will be discussed in the next section, is of fundamental importance for heliobiophysics.

6. RESULTS AND DISCUSSION

With the preceding taken into account, data published by different authors have been analyzed and some results on the geoeffectiveness of solar and interplanetary phenomena have been obtained in the context of two different interpretations of geoeffectiveness: as the probability of the generation of magnetic storms and as the efficiency of their generation. These results are discussed individually in the following subsections.

6.1. Geoeffectiveness (Probability) of Different Phenomena

The published results on the geoeffectiveness of CMEs, solar flares, and interplanetary phenomena were selected with consideration for event tracing (forward or backward) and for the pairs of phenomena under analysis: CME ⟶ storm; CME ⟶ MC, ejecta; MC, ejecta ⟶ storm; storm ⟶ MC, ejecta; MC, ejecta ⟶ CME; storm ⟶ CME; flare ⟶ storm; and storm ⟶ flare. The results of this selection are given in Table 3 and schematically shown in Fig. 12. Table 3 differs from the previous publications [Yermolaev and Yermolaev, 2003b, 2006; Yermolaev et al., 2005a] in the inclusion of a number of recent papers and the additional process CIR ⟶ storm [Alves et al., 2006]. The entry "CME ⟶ storm" in Table 3 implies that the CME list with the numbers of analyzed cases (indicated in column 3) is used as an initial set of data. CMEs are compared with magnetic storms whose values are determined by the indices given in column 4 of Table 3. Thus, the data published were classified into six (I–VI) groups of phenomena comparison: three spatial regions and two directions of tracing (Table 3). Groups II, III, IV, and V combine magnetic clouds and ejecta (including sheaths and bodies) that are close to each other in origin and physical characteristics; however, in the column "The number of cases," symbols MC and E correspond to

Table 3. Correlation between solar, interplanetary, and magnetospheric phenomena

No.	%	Number of cases	Index values, comments	Sources of data
1	*2*	*3*	*4*	*5*
I: CME ⟶ storm				
1	50	38	K_p	Webb et al., 1996
2	71	7	$D_{st} < -50$	Crooker, 2000; Webb et al., 2000; Li et al., 2001
3	35	40	$K_p > 6$	Plunkett et al., 2001
4	45	20	$K_p > 5$	Berdichevsky et al., 2002
5	35–92	?	$D_{st} < -50$	Webb, 2002
6	45	132[a]	$K_p > 5$	Wang et al., 2002
	20	132[a]	$K_p > 7$	
7	35	125[a]	$D_{st} < -60$	Yermolaev and Yermolaev, 2003a
	40	125[a]	$D_{st} < -50$	Yermolaev and Yermolaev, 2003b
8	64	70[b]	$D_{st} < -50$	Zhao, Webb, 2003
	71	49[c]	$D_{st} < -50$	
9	58	12[c]	$D_{st} < -50$	Moon et al., 2005
10	42	218[a]	$D_{st} < -50$	Yermolaev and Yermolaev, 2006
11	40	305[b]	$D_{st} < -50$	Kim et al., JGR, 2005
12	71	229[b]	$D_{st} < -50$	Gopalswamy et al., 2007
[a] denotes halo CMEs directed toward the Earth, [b] denotes halo CMEs on the Sun's visible side, [c] denotes halo CMEs in the center of the Sun's visible side				
II: CME ⟶ magnetic clouds, ejecta				
1	63	8	Halo-CME toward the earthward	Cane et al., 1998
2	60–70	89	Halo-CME toward the earthward	Webb et al., 2001
3	80	20	Halo-CME	Berdichevsky et al., 2002
4	50–84	181	All CMEs	Schwenn et al., 2005
	53–90	154	All CMEs toward the earthward	
	59–93	91	Earthward full halo CME	
III: magnetic clouds, ejecta ⟶ storm				
1	44	327E	$K_p > 5\_$	Gosling et al., 1991
2	67	28MC	$D_{st} < -60$	Gopalswamy et al., 2000
				Yermolaev and Yermolaev, 2002
3	63	30MC	$D_{st} < -60$	Yermolaev et al., 2000
4	57	48MC	$D_{st} < -60$	Gopalswamy et al., 2001
				Yermolaev and Yermolaev, 2003b
5	19	1273E	$K_p < 5\_$; Solar minimum	Richardson et al., 2001
	63	1188E	$K_p < 5\_$; Solar maximum	
6	82	34MC	$D_{st} < -50$	Wu and Lepping, 2002a
7	73	135MC	$D_{st} < -50$	Wu and Lepping, 2002b
8	50	214E	$D_{st} < -50$	Cane and Richardson, 2003
	43	214E	$D_{st} < -60$	
9	76	104MC + E	$D^*_{st} < -30$	Zhang et al., 2004
	56	104MC + E	$D^*_{st} < -50$	
	34	104MC + E	$D^*_{st} < -100$	
10	77	149MC	$D_{st} < -50$	Echer and Gonzalez, 2004; Echer et al., 2005
IV: storm ⟶ CME				
1	100	8	$K_p > 6$	Brueckner et al., 1998
2	83	18	$K_p > 6$	St. Cyr et al., 2000; Li et al., 2001
3	94	?	?	Srivastava, 2002
4	96	27	$D_{st} \leq -100$	Zhang et al., 2003
5	83	23	$D_{st} \leq -100$	Watari et al., 2004
6	100	10	$-100 < D_{st} < -200$	Srivastava and Venkatakrishnan, 2004
	83	54	$D_{st} < -100$	

Table 3. (Contd.)

1	2	3	4	5
	V: storm ⟶ magnetic clouds, ejecta			
1	73	37	$K_p > 7$	Gosling et al., 1991
2	67	12	$D_{st} < -50$	Webb et al., 2000
3	25		D_{st} (corr)	Vennerstroem, 2001
4	19	1273E	$K_p > 5_-$, Solar minimum	Richardson et al., 2001 (GRL)
	12	833	$5_+ > K_p > 5_-$	
	22	352	$6_+ > K_p > 6_-$	
	45	62	$7_+ > K_p > 7_-$	
	88	26	$K_p > 8_-$	
	63	1188E	$K_p > 5_-$, Solar maximum	
	50	670	$5_+ > K_p > 5_-$	
	70	341	$6_+ > K_p > 6_-$	
	92	99	$7_+ > K_p > 7_-$	
	100	78	$K_p > 8_-$	
5	33	618	$D_{st} \le -60$	Yermolaev and Yermolaev, 2002
	25	414	$-100 \le D_{st} \le -60$	
	52	204	$D_{st} \le -100$	
6	32	90	$-100 < D_{st} \le -50$	Huttunen et al., 2002
	21	100	$7_- > K_p > 5$	
	76	21	$-200 \le D_{st} \le -100$	
	38	21	$7_- > K_p > 8$	
7	70	30	$D_{st} \le -100$	Watari et al., 2004
8	24	150	$D_{st} \le -50$, 1978–1982	Li and Luhmann, 2004
	31	58	$D_{st} \le -100$	
	70	10	$D_{st} \le -200$	
	32	187	$D_{st} \le -50$, 1995–2002	
	46	63	$D_{st} \le -100$	
	75	8	$D_{st} \le -200$	
9	29	271	$D_{st}^* < -30$	Zhang et al., 2004
	VI: magnetic clouds, ejecta ⟶ CME			
1	67	49E	Any CME	Lindsay et al., 1999
2	65	86E	Any CME	Cane et al., 2000
	42	86E	Earthward Halo-CME	
3	82	28MC	Any CME	Gopalswamy et al., 2000
4	50–75	4MC	Halo-CME	Burlaga et al., 2001
	40–60	5E	Halo-CME	
5	56	193E	Any CME	Cane and Richardson, 2003
6	48	21MC	Halo-CME	Vilmer et al., 2003
	VII: flare ⟶ storm			
1	44	126	$>M0$ + SEP (Solar Energetic Particles)	Yermolaev and Yermolaev, 2002
2	40	653	$>M5$	Yermolaev and Yermolaev, 2003a
3	33	571	>3 (optics)	Ivanov and Miletskii, 2003
4	44	746	$>M5$	Yermolaev and Yermolaev, 2006
	VIII: flare ⟶ SSC			
1	35–45	4836	$>M0$	Park et al., 2002
	IX: storm ⟶ flare			
1	59	116	$K_p > 7_-$	Krajcovic, Krivsky, 1982
2	88	25	$D_{st} \le -250$	Cliver and Crooker, 1993
3	20	204	$D_{st} \le -100$	Yermolaev and Yermolaev, 2003a
	X: CIR ⟶ storm			
1	33	727	$D_{st} \le -50$	Alves et al., 2006

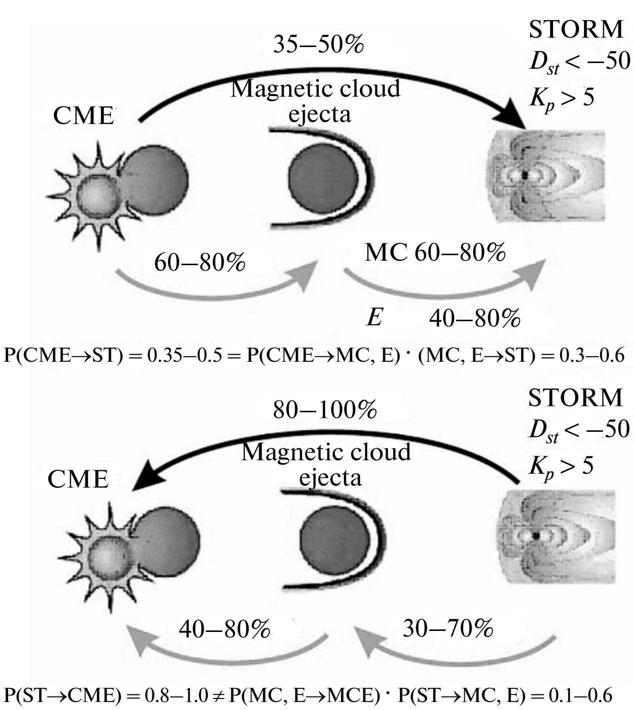

Fig. 12. Schematic representation of the correlation between CME, MC/ejecta, and magnetic storms for the forward (top) and backward (bottom) tracings of the phenomena. The numerical values of correlation are given above the corresponding arrows. The probabilities for both one- and two-step tracings are shown under each of the fragments [Yermolaev et al., 2005; Yermolaev and Yermolaev, 2006].

magnetic clouds and ejecta, respectively. Table 3 also includes data on the following groups of phenomena comparison: flare ⟶ storm (group VII), flare ⟶ storm sudden commencement (SSC) (group VIII), storm ⟶ flare (group IX), and CIR ⟶ storm (group X).

An analysis of the publications on the CME ⟶ storm process allows one to conclude that, for magnetic storms with $K_p > 5$ ($D_{st} < -50$ nT), the geoeffectiveness of halo-CMEs directed toward the Earth amounts to 40–50% at sufficiently high statistics (from 38 to 305 CMEs) and the values obtained in [Webb, 2002; Zhao and Webb, 2003; and Gopalswamy et al., 2007] prove to be overestimated (see below). The results of an analysis of the backward tracing for group VI (storm ⟶ CME) are in good agreement with each other (83–100%), but they reflect a low CME geoeffectiveness; they demonstrate that it is easy to find a probable candidate for the source of a storm among CMEs occurring on the Sun (this is not surprising, because the frequency of CME observations is a few times higher than that of magnetic-storm recordings).

An analysis of the sequence of the two-step forward tracing for groups II (CME ⟶ magnetic clouds, ejecta) and III (magnetic clouds, ejecta ⟶ storm) makes it possible to estimate the probability of the complete CME ⟶ storm process as a product probability, and, for magnetic clouds, we obtain (0.60–0.70)(0.57–0.82) = 0.34–0.57, which is close to the above-mentioned result (40–50%) for the one-step CME ⟶ storm process (group I) and is lower than the estimates obtained in [Zhao and Webb, 2003; Gopalswamy et al., 2007]. For ejecta, this approach yields a smaller value. An analysis of the two-step backward tracing for groups V (storm ⟶ magnetic clouds, ejecta) and VI (magnetic clouds, ejecta ⟶ CME) does not allow a high value (83–100%) to be obtained for the complete process (storm ⟶ CME), because, in this case, the product probability yields (IV) (0.25–0.73)(0.42–0.82) = 0.11–0.60. Thus, the results of comparison between the one- and two-step processes for the forward tracing (CME ⟶ storm) are in good agreement, while, for the backward tracing, the two-step process is a few times smaller than the one-step process. This implies that the values of the processes (storm ⟶ magnetic clouds, ejecta), (magnetic clouds, ejecta ⟶ CME), and (storm ⟶ CME) are not the geoeffectivenesses (probability) of the processes describing the "cause ⟶ effect" sequence.

Although the "effectiveness" (probability) of storm generation in [Webb et al., 2000; Webb, 2002; Zhao and Webb, 2003; Gopalswamy et al., 2007] refers to the forward tracing of I (CME ⟶ storm) and is lower than that for the backward tracing of IV (storm ⟶ CME), the results obtained in the indicated papers (1) exceed estimates obtained in other studies of this process; (2) exceed the values obtained for the second step, i.e., for process III (except for [Wu and Lepping, 2002a,b; Echer and Gonzalez, 2004; Echer et al., 2005]); (3) are close to the value obtained for the first step, i.e., process II; and (4) exceed the estimates obtained for two-step process II: III = (0.6–0.8)(0.2–0.8) = 0.1–0.6. Thus, the geoeffectiveness estimates obtained in [Webb et al., 2000; Webb, 2002; Zhao and Webb, 2003; Gopalswamy et al., 2007] are apparently overestimated. As was noted above (Section 2), there is a probability that some CMEs directed toward the Earth could inaccurately be referred to the CMEs on the Sun's back side [Zhang et al., 2003]; it is possible that this methodical error was made in analyzing data from a number of individual papers [Yermolaev, 2008].

In our recent studies, we [Yermolaev and Yermolaev, 2002, 2003a] performed the forward tracing of the events (flare ⟶ storm) and assessed the geoeffectiveness (probability) of 653 strong solar flares of the X-ray class higher than $M5$ and that of 126 weaker solar flares of the X-ray class higher than $M0$, but which were accompanied by an increasing flux of energetic particles in the vicinity of the Earth. For magnetic storms with $D_{st} < -60$ nT, the geoeffectiveness (probability) amounted to 40% in the former case and 44% in the latter case. If backward tracing (storm ⟶ flare) is performed and a list of strong magnetic storms with $D_{st} < -100$ nT is taken, only 20% of the indicated flares can be the sources of such storms. Similar investigations were carried out earlier. For example, in [Krajcovic and Krivsky, 1982], the backward tracing (storm ⟶ flare) was analyzed for strong solar flares of the optical class and it was shown that, in 1954–1976, 59% of possible sources were found for 116 storms with $K_p > 7$. In [Cliver and Crooker, 1993], the backward tracing (storm ⟶ flare) showed that, for the 25 strongest magnetic storms ($D_{st} < -250$ nT) during 1957–1990, flares that could be treated as candidates for storm sources were found in at least 22 cases (88%).The high values of geoeffectiveness (probability) obtained in [Krajcovic and Krivsky, 1982; Cliver and Crooker, 1993], in addition to the backward tracing of events, can be associated with the fact that, in these papers, even weak flares were treated as possible candidates for storm sources (see the ratio between the frequencies of flares and storms in Fig. 3), while only strong flares were used in our analysis.

A comparison of the (flare ⟶ SSC) events (i.e., not with magnetic storms but with their precursors), which are often observed a few dozen minutes before the start of the main phase of a magnetic-storm, was made in [Park et al., 2002] for 4836 flares of the class higher than *M*1 for 1975–1999. The results of this comparison showed that the estimate of geoeffectiveness (probability) amounts to 35–45% for a time delay (waiting "window") of 2–3 days and 50–55% for a longer window. This result is close to the above-discussed geoeffectiveness of flare ⟶ storm, although it was obtained for SSCs but not for storms.

To assess the probabilities from the practical point of view, let us compare the probabilities of magnetic-storm generations by solar and random events. To this end, if we take the value of the waiting window and the mean period between storms during disturbed years, we will obtain 35% [Yermolaev and Yermolaev, 2003b]. This implies that, currently, the probability of predicting magnetic storms on the basis of solar data only slightly exceeds the probability of prediction based on randomness.

Thus, the reliability of predicting magnetic storms on the basis of interplanetary phenomena and direct measurements of solar-wind parameters (see, for example, http://www.iki.rssi.ru/sw.htm) is sufficiently high (60–80% and 90–95%, respectively). In addition, the parameters of the solar wind and the IMF make it possible to calculate the values of magnetospheric disturbances. The reliability of prediction on the basis of solar phenomena is low; a predictable magnetic storm can be estimated according to the class of solar flare only after the record of its associated CME moving toward the Earth (i.e., halo CME). For example, the close algorithms of predicting magnetic storms on the basis of observations of solar flares and CMEs (or CME-related preceding shock-wave and radio bursts of types IV and II, respectively) are proposed in [Song et al., 2006; and Valach et al., 2007].

The prediction made without consideration for CME data is basically of a random character and of no practical significance. The quality of such a prediction should be improved in two directions: (1) to take into consideration a quantitative description of interrelations between the parameters of flare and CME and (2) to increase the probability of predicting interactions between CME and the Earth's magnetosphere.

6.2. Efficiency of Storm Generation by Different Phenomena

As was noted above, magnetic storms are generated mainly by the following types of solar wind: ICME, including sheath and the ICME body (MC/ejecta), and CIR [Vieira et al., 2004; Huttunen and Koskinen, 2004; Yermolaev et al., 2005c; Yermolaev and Yermolaev, 2006]. In [Yermolaev and Yermolaev, 2002], it is shown that the time variations in the portion of storms induced by CIR and ICME have two maxima (minima), each over the solar cycle and change in antiphase. On the other hand, there are experimental data on differences in storms generated by sheath, MC, and CIR [Borovsky and Denton, 2006; Denton et al., 2006; Pulkkinen et al., 2007b]. The ratios between extreme values (peak-to-peak analysis) Bz–D_{st} and Ey–D_{st} ($Ey = VxBz$ is the electric field of the solar wind during the IMF southward Bz-component) are given in some papers individually for CIR- and MC-induced storms. When considering these data simultaneously (Figs. 13, 14), one can see that, against the background of an evident scatter in experimental points, there are no significant differences in dependencies for different sources of storms. These results were obtained without selecting sheaths and MCs, and since the conditions of sheaths and CIRs are close to each other (both types are formed due to the compression and deformation of slow and fast flows), this approach could mask differences in the dependences under consideration. To verify if there is such a possibility, we calculated the dependences Bz–D_{st} and Ey–D_{st} individually for CIR, sheath, and MC; however, against the background of wide data scattering, we also found no significant differences [Yermolaev et al., 2007b]. Therefore, differences in storms induced by CIRs, sheaths, and MCs can be associated not with the peak values of Bz and Ey, but with other solar-wind plasma and field parameters and their dynamics.

For 623 magnetic storms with $D_{st} < -60$ nT, which were recorded in 1976–2000, we analyzed the effects of the solar-wind and IMF parameters and their variations individually for CIRs, sheaths, and MCs on the basis of the OMNI database (with calculated additional physical parameters) [Yermolaev et al., 2007a, b]. For this analysis, we used the method of the superposition of epochs (the start time of storm was taken as the start of the epoch). The differences in the time profiles of the solar-wind and IMF parameters for CIR (121 storms), sheath (22 storms), and MC

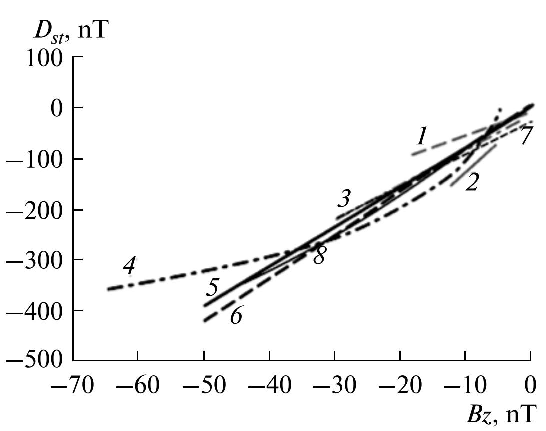

Fig. 13. Correlation dependences between the index D_{st} and the Bz component for different types of solar wind according to data obtained by different authors for CIR (*1*) [Alves et al., 2006], (*2*) [Richardson and Cane, 2005], and (*3*) [Yermolaev et al., 2007b], as well as for sheath + MC (*4*) [Naitamor, 2005], (*5*) [Wu and Lepping, 2002b, 2005], (*6*) [Richardson and Cane, 2005], (*7*) [Yermolaev et al., 2007b], and (*8*) [Yurchyshyn et al., 2004].

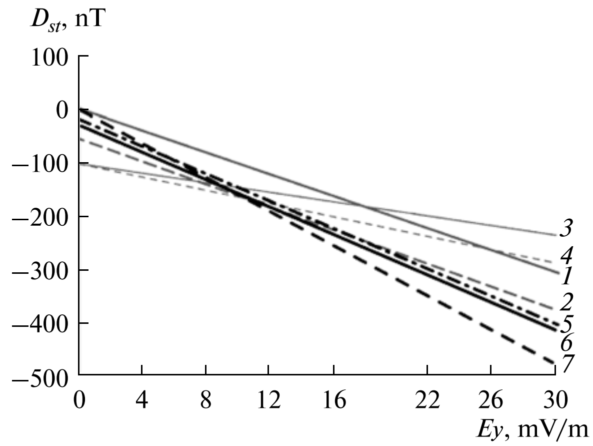

Fig. 14. Correlation dependences between the index D_{st} and the Ey component for different types of the solar wind according to data obtained by different authors for CIR (*1*) [Alves et al., 2006] and (*2*) [Yermolaev et al., 2007b] and for sheath + MC (*3*) [Srivastava and Venkatakrishnan, 2004], (*4*) [Kane, 2005], (*5*) [Wu and Lepping, 2005], (*6*) [Yermolaev et al., 2007b], and (*7*) [Wu and Lepping, 2002b].

(113 storms) are shown in Fig. 15, where 367 storms for which full datasets were absent in the OMNI database (about half the total observation period) are denoted as "unknown," which did not allow the types of the solar wind to be unambiguously identified. In the left column, the following parameters are given: density N, velocity V, dynamic pressure P_{dyn}, proton temperature T, ratio between measured and calculated (on the basis of velocity) temperatures T/T_{exp}, and the index D_{st}. In the left column, the following parameters are presented: the ratio between thermal and magnetic pressures β; B, Bx, By, and Bz—the magnitude and geocentric solar magnetospheric (GSM) components of the IMF; and the index K_p. The curves obtained from averaging over different types of solar wind differ in color. The variability of all the parameters for different types of the solar wind is sufficiently high, and, in some case, the differences between the points of the averaged curves are less noticeable than the variances of the corresponding parameters, which suggests that this is a tendency rather than a proven fact. Nevertheless, a noticeable divergence of the curves during measurements for many hours suggests a number of definite conclusions [Yermolaev et al., 2007a, b].

(1) Although the behavior of the solar-wind parameters during magnetic storms is markedly different for different types of solar wind, the IMF Bz component for all wind types turns southward 1–2 h before the start of magnetic storm and, 2–3 h after its start, reaches its minimum; simultaneously, both density and dynamic pressure increase.

(2) Although the IMF Bz component's lower values are observed in MCs, the smallest mean of the index D_{st} is reached in sheaths. Thus, the generation of a storm is more efficient during sheaths than during the arrival of the MC's body probably due to the higher values and variations of the pressure and magnetic field.

(3) The fact that nkT, T/T_{exp}, and β parameter in CIR and sheath have higher values than in MC is in agreement with the physical nature of these types of solar wind and supports the correctness of their selection.

7. CONCLUSIONS

At first, let us briefly review the basic principles of solar–terrestrial physics related to the sources and causes of magnetic storms on Earth.

(1) The source of magnetic storms on Earth is the large (>5 nT) and long-lasting (more than 2 h) southward ($Bz < 0$) component of the IMF, which makes the magnetosphere "open" for an enter of solar-wind energy.

(2) In the stationary solar wind, the Bz-component is small or quite absent; therefore, all magnetic storms are associated with the disturbed types of the solar wind.

(3) There are two chains of solar–terrestrial relations which result in magnetic storms: (1) CME ⟶ MC + its preceding compression region (sheath) with $Bz < 0$ ⟶ magnetic storm, and (2) coronal hole ⟶ high solar wind forms a compression region with the $Bz < 0$ ⟶ magnetic storm.

(4) Only the solar flares that are associated with CMEs can be treated as candidates for the solar sources of magnetic storms. Most flares do not have any cause–effect relation with magnetic storms.

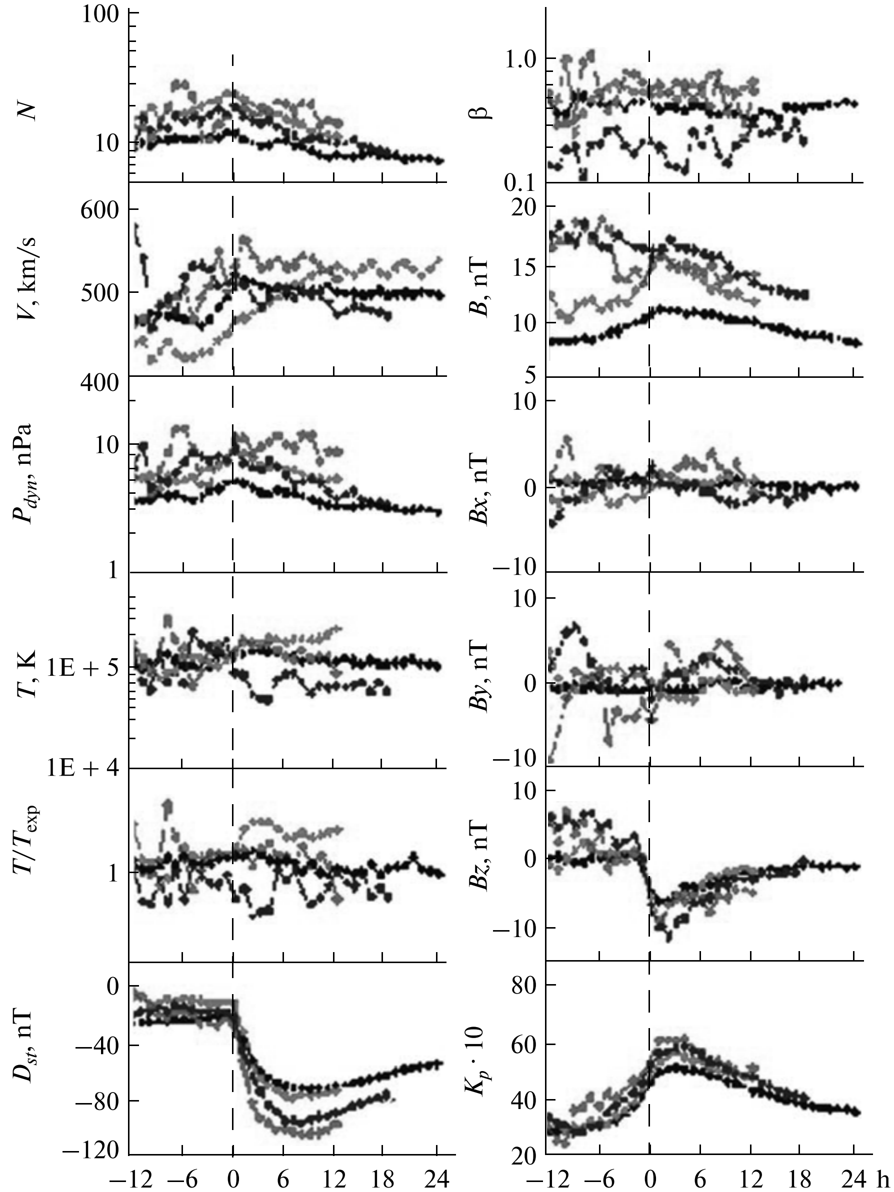

Fig. 15. Behavior of the parameters of the plasma and magnetic field of the solar wind for magnetic storms generated by different types of solar wind during 1976–2000: CIR (green curves), sheath (red curves), MC (blue curves), and "unknown" (black curves) [http://arxiv.org/abs/physics/0603251; Yermolaev et al., 2007]. The epoch superposed analysis method with the "zero" time corresponding to the first one-hour point of a rapid decrease in the D_{st} index was used for an analysis of the OMNI database. The time from the start of epoch is plotted on the horizontal axes, h. (See the text to identify the parameters in both left and right columns.)

(5) With an increase in the negative *Bz* component or energy arriving in the magnetosphere, magnetic substorms (auroral electrojets) occur first (at lower values) and then (at higher values) magnetic storms (ring-current disturbances) occur together with substorms. Auroral electrojets exert influence locally (in the auroral night region), and storms exert influence globally (within a broad band outside the auroral regions).

(6) The most faithful indicator of magnetic storms on Earth is the index D_{st}; the indicator of substorms is the *AE* index. The index K_p is sensitive to both storms and substorms and does not allow their influences to be separated.

(7) The term "geoeffectiveness" has two different meanings: (1) *probability*, i.e., a portion (percent) of one or another of the phenomena that have the cause–effect relations with magnetic storms (in this case, it is necessary to use the methods of the forward tracing from the phenomenon to the storm and not the reverse); and (2) *the efficiency of storm generation* by different phenomena that have the cause–effect relations with storms, i.e., a comparison between the "output" and "input" of the process.

An analysis of publications on the geoeffectiveness of solar and interplanetary phenomena and the results obtained allowed us to conclude the following:

(i) The geoeffectiveness estimate depends on the methods of identifying and classifying phenomena and on the methods and directions of searching for correlations between phenomena (backward tracing does not yield geoeffectiveness estimates).

(ii) The geoeffectiveness (the probability of magnetic-storm generation) for CME and flares amounts to 40–60%, which only slightly exceeds the probability of random processes.

(iii) The prediction of magnetic storms on the basis of solar observations may contain a substantial percentage of "false alarms."

(iv) The geoeffectiveness of ICME (sheath + MC) amounts to 60–80%.

(v) The geoeffectiveness of CIR amounts to 20–35%.

(vi) No significant differences were found in the peak-to-peak dependences of D_{st}–Bz and D_{st}–Ey for magnetic storms generated by MC, Sheath, and CIR, although there are differences in their development.

(vii) The minimum Bz-component of the IMF is observed in MC, and the minimum D_{st} index is observed in sheath; i.e., the efficiency of the physical process of storm generation during sheath is higher than during MC. This is possibly due to the higher level of field and pressure variations for sheath.

ACKNOWLEDGMENTS

We are grateful to researchers who work with SOHO, GOES, and other satellites, as well as at ground-based stations, and those who developed the OMNI database for the opportunity to use these data in our studies.

This study was supported by the Russian Foundation for Basic Research (project no. 07-02-00042) and by the Department of Physical Sciences, Russian Academy of Sciences, Program 15 "Plasma Processes in the Solar System."

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