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Statistical Relationships between Solar, Interplanetary, and Geomagnetic Disturbances, 1976–2000: 3

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Abstract—In this paper we continue the analysis of the influence of solar and interplanetary events on magnetic storms of the Earth that was started in [9, 10]. Different experimental results on solar-terrestrial physics are analyzed in the study and the effects are determined that arise due to differences in the methods used to analyze the data. The classifications of magnetic storms by the K_p and D_{st} indices, the solar flare classifications by optical and X-ray observations, and the classifications of different geoeffective interplanetary events are compared and discussed. It is demonstrated that quantitative estimations of the relationships between two types of events often depend on the direction in which the events are compared. In particular, it was demonstrated that the geoeffectiveness of halo CMEs (that is, the percentage of Earth-directed coronal mass ejections that result in geomagnetic storms) is 40–50%. Higher values given in some papers were obtained by another method, in which they were defined as the probability of finding candidates for a source of geomagnetic storms among CMEs, and, strictly speaking, these values are not true estimates of the geoeffectiveness. The latter results are also in contrast with the results of the two-stage tracing of the events: first a storm—an interplanetary disturbance, and then an interplanetary disturbance—a CME.

INTRODUCTION

The investigation of the processes via which disturbances are transported from the Sun to the Earth by the solar wind is the most important element of the solar-terrestrial physics and, in particular, of its practical part, the “Space Weather” program (see reviews [1–3] and references therein). The number of publications on this problem grows steadily, and it is worth noting that a considerable divergence exists between quantitative estimates obtained when a general physical pattern was analyzed based on close general ideas about the physical mechanism of the solar impact on the Earth. For example, the estimates of the geoeffectiveness of so-called halo CMEs (coronal mass ejections that occupy most of the corona round the solar disk in a coronagraph image) give from 45% [4] to 96% [5]. As such an analysis incorporates a chain of various physical objects, which are investigated by different developing with time methods, the result can be strongly dependent on both the analysis methods used in each link of the chain and the efficiency of the relationships between individual links. In this connection, one of the purposes of this study is a comparison of the methods used to analyze data and a quantitative comparison of results obtained by different methods. Since in each of three regions (the solar atmosphere, solar wind, and the magnetosphere) the comparison of the methods is a subject of the corresponding field of knowledge, which is thoroughly analyzed in special literature, whereas the problem of relationships between the events in different regions is often beyond the scope of interests of the specialists, we try to fix our attention primarily on the analysis of the methods used to study relationships between the events in different links of the solar-terrestrial chain.

In our previous papers [6–10] we presented some results of the analysis of the influence of solar (flares and CMEs) and interplanetary (magnetic clouds, shock waves, and corotating interaction regions, CIR) events on geomagnetic disturbances. However, due to some reasons we could not give a sufficiently detailed discussion of instrumental aspects in these papers. We also could not make a comparison with some results obtained in this field in other papers including those published recently. We try to fill this gap in the present study. We also pay attention to the place of our study in the general pattern of solar–terrestrial physics.

1. DESCRIPTION OF GEOMAGNETIC DISTURBANCES

Geomagnetic disturbances arise due to sharp variations in the existing current system in the Earth’s magnetosphere and ionosphere or due to generation of new currents. This reconstruction of the current systems is preceded by the energy accumulation in the magnetosphere under the action of variations of the interplanetary medium and primarily of the interplanetary magnetic field (IMF). There are weak polar disturbances (substorms [11]) and strong global disturbances (magnetic storms [12, 13]) (see also [14, 15]). We shall mainly analyze the strong global magnetic field distur-

Table 1. Location of magnetic stations used to calculate the K_p and D_{st} indices

Magnetic station					Geographical coordinates		Magnetic coordinates
number	code	name	country	operation period	latitude	longitude	latitude
				K_p index			
1	LER	Lerwick	Scotland	1932–present time	60°08′	358°49′	62.0°
2	MEA	Meanook	Canada	1932–present time	54°37′	246°40′	61.8°
3	SIT	Sitka	USA	1932–present time	54°37′	246°40′	61.8°
4	ESK	Eskdalemuir	Scotland	1932–present time	55°19′	356°48′	57.9°
5	LOV	Lovö	Sweden	1954–present time	59°21′	17°50′	57.8°
6	AGN	Agincourt	Canada	1932–1969	43°47′	280°44′	54.4°
	OTT	Ottawa	Canada	1969–present time	45°24′	284°27′	56.1°
7	RSV	Rude Skov	Denmark	1932–1984	55°51′	12°27′	55.5°
	BFE	Brorfelde	Denmark	1984–present time	55°37′	11°40′	55.4°
8	ABN	Abinger	England	1932–1957	51°11′	359°37′	53.5°
	HAD	Hartland	England	1957–present time	50°58′	355°31′	54.0°
9	WNG	Wingst	Germany	1938–present time	53°45′	9°04′	54.2°
10	WIT	Witteveen	Netherlands	1932–1988	52°49′	6°40′	53.7°
	NGK	Niemegk	Germany	1988–present time	52°04′	12°41′	51.9°
11	CLH	Cheltenham	USA	1932–1957	38°42′	283°12′	49.4°
	FRD	Fredericksburg	USA	1957–present time	38°12′	282°38′	48.8°
12	TOO	Toolangi	Australia	1972–1981	–37°32′	145°28′	–45.8°
	CNB	Canberra	Australia	1981-present time	–35°18′	149°00′	–43.1°
13	AML	Amberley	New Zealand	1932–1978	–43°09′	172°43′	–47.0°
	EYR	Eyrewell	New Zealand	1978–present time	–43°25′	172°21′	–47.3°
				D_{st} index			
1	HER	Hermanus	South Africa	1941–present time	–34.40°	19.22°	–33.3°
2	KAK	Kakioka	Japan	1913–present time	36.23°	140.18°	26.0°
3	HON	Honolulu	USA	1902–1960	21.30°	201.90°	21.0°
	HON	Honolulu	USA	1960–present time	21.32°	201.98°	21.1°
4	SJG	San Juan	USA	1903–1965	18.38°	293.88°	29.9°
	SJG	San Juan	USA	1965–present time	18.01°	293.85°	29.9°

bances, which are generally called magnetic storms and which are associated mostly with intensification of the Earth's ring current. First (starting from 1932) global disturbance of the magnetosphere was described by the 3-h K_p index, which was determined by observations at a number of ground magnetic stations (see Table 1). Since later magnetic storms were shown to be mostly associated with the ring current flowing near the equator, the K_p index determined by mid-latitude station data proved to be inaccurate in describing magnetic storms. Therefore, in 1957 the interest to the D_{st} index suggested by Chapman in 1919 was revived again (for more details see the discussion in [16]). The index is defined from the data of equatorial magnetic stations (see the second part of Table 1). In some cases the so-called corrected D_{st} index is used. It is a difference between the initial D_{st} index and its part determined by the currents at the magnetopause surface and calculated from the measured dynamic pressure P_{dyn} of the solar wind: $D_{st}(\mathrm{corr}) = D_{st} + A\,P_{\mathrm{dyn}} + B = D_{st} - (0.02vn^{1/2} - 20\ \mathrm{nT})$, where v[km/s] is the velocity and n[cm^{-3}] is the density [17, 18]. In addition to the above-mentioned indices, other indices are also used to describe the state of the magnetosphere: AE, aa, A_p, and others [19]. They differ by the geographical location of the stations applied and by the method of data representation.

Since the classifications of magnetic storms applied in various studies differ both by the index type and by the chosen storm strength gradations, to compare the study results we had to find a quantitative relation between storms, characterized by different indices. As different sets of stations were used to construct the indi-

Table 2. Classification of magnetic storms on the basis of the D_{st} index using the 1957–1993 measurements [21. Loewe and Prolss, 1997]

Class	Number	%	D_{st}, nT	$\langle D_{st}\rangle$	$\langle ap\rangle$	$\langle K_p\rangle$	⟨AE⟩, nT
Weak	482	44	–30…–50	–36	27	4_o	542
Moderate	346	32	–50…–100	–68	48	5_o	728
Strong	206	19	–100…–200	–131	111	7_-	849
Severe	45	4	–200…–350	–254	236	8_+	1017
Great	6	1	<–350	–427	300	9_-	1335

ces, the responses to different magnetospheric/ionospheric current systems were included in them, and, strictly speaking, different physical systems associated with one global event, a magnetic storm, were analyzed. In this case, we cannot expect the identical index behavior during one and the same event (see, for example, [20]). However, we can assume that, given the sufficient statistics, the correlation between different indices can be found for the magnetic storm maximum. Such an analysis was performed, for example, for 1085 magnetic storms in 1957–1993 [21]. Its results are presented in Table 2. Since we analyzed the data for a different period, we repeated the comparison of the D_{st} and K_p indices for the period of 1976–2000 and obtained a rather close result. The minimum of the D_{st} index versus the maximum of the K_p index during magnetic storms is presented in Fig. 1. A good correlation with a rather large scatter with respect to the average line can be seen for these parameters. The linear dependence between these parameters (which is bounded by the values of D_{st} from –60 to –200 nT) is described by the formula $K_p = -0.023D_{st} + 3.9$, which allows one to compare the events classified by the D_{st} and K_p indices: D_{st} from –60 and –100 nT correspond to $K_p = 5_+$ and 6_+. On the whole, the dependence of the K_p index on the D_{st} index during magnetic storms is clearly nonlinear and must lie near $K_p = 0$ at $D_{st} = 0$. Thus, the formula obtained above can be used only within the indicated range of the D_{st} index. In some papers, where the classification by the K_p index was used, moderate storms were chosen based on the condition $K_p > 5$. This, on average, corresponds to the storms with $D_{st} < -50$ nT, which are weaker than those selected in our previous publications, with $D_{st} < -60$ nT [9, 10].

2. INTERPLANETARY EVENTS

The classification of events in the interplanetary medium started with the beginning of the space age. It is rapidly developing now, when one conception is quickly replaced by the other and new ideas arise while our understanding of physics of the solar corona and the interplanetary medium is improving at a high rate. We cannot review the whole history of this process and have to confine ourselves only to those events that are necessary for the comparison of the latest results in the investigation of the relationships between solar, interplanetary, and magnetospheric disturbances.

Historically, the solar wind was initially partitioned into stationary and nonstationary streams. Fast and slow streams were considered as stationary. The streams in the regions where streams with different velocities interact (CIR) and the streams generated by active processes on the Sun, interplanetary shock waves, and "pistons" [22–24], were regarded as nonstationary. The energy is transferred from the solar wind to the magnetosphere only if the interplanetary magnetic field (IMF) contains the component parallel to the Earth's magnetic dipole, that is, the negative (southward) component B_z of the IMF (see, for example, [25, 26] and references therein). Since the stationary streams of the solar wind contain the IMF lying mostly in the ecliptic plane, their geoeffectiveness is very low. Thus, in the problems of propagation of the solar effect to the Earth the main attention is given to the nonstationary events in the interplanetary medium.

The pistons were initially found as associated with the occurrence of noncorotating (that is, recorded with a period different from the 27-day period of the solar rotation) interplanetary shocks. These shocks were assumed to be generated in the case when some plasma

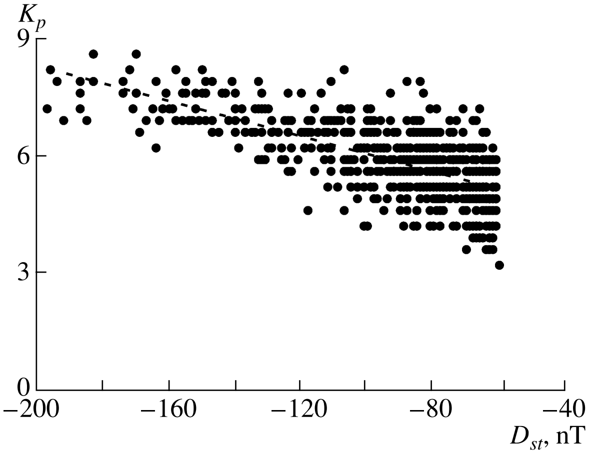

Fig. 1. Correlation between the D_{st} and K_p indices during geomagnetic storms in 1976–2000.

volume in the corona or in the interplanetary medium moves with a speed exceeding that of the ambient medium. Now this term is usually replaced by such terms as magnetic clouds, ejecta, and interplanetary CMEs (ICMEs). The magnetic clouds are often considered as a special case of the two other terms, which apparently can be regarded as synonyms. To identify these events it is usually assumed that certain conditions (in various combinations) are satisfied:

(1) Plasma (ion and electron components) is colder than the ambient medium;

(2) The magnetic field is stable (with a low level of fluctuations) and often slowly rotating;

(3) The ratio between thermal and magnetic pressures is low (parameter $\beta < 1$);

(4) The abundances of alpha particles and other minor ion components of the solar wind are high;

(5) There exist bidirectional streams of thermal electrons;

(6) There are bidirectional streams of high-energy protons (> 20 keV);

(7) The flux of high-energy ions (> 1 MeV) is reduced;

(8) There exist some unusual ionization states of the thermal plasma of the solar wind [27–31, 20].

It is usually assumed that the existence of the magnetic fields that are higher than those in the ambient plasma is a typical feature of magnetic clouds. Note that some of these characteristics are observed rather rarely, for example, singly ionized helium atoms, He^+, were observed only several tens of times during the entire space age [32, 33]. Quite often all these criteria are not satisfied simultaneously. Thus, even one and the same event can be differently defined by different authors depending on the criteria chosen. In this case, the identification of the interplanetary events can be ambiguous.

In a number of recent publications only the first criterion alone or in combination with other criteria is used to identify ejecta [31, 20]. In these papers the current proton temperature T_p is compared to the temperature T_{exp} that should correspond to the measured solar wind velocity v and is calculated by the formulas [34]:

$T_{\mathrm{exp}} = (0.031v - 5.1)^2$ at $v < 500$ km/s and $T_{\mathrm{exp}} = (0.51v - 142)$ at $v > 500$ km/s.

Low-temperature intervals with $T_p/T_{\mathrm{exp}} < 0.5$ are considered as the ejecta intervals [38, 20]. It is necessary to mention that the velocity is determined in the experiments rather accurately (with an error of not more than 2–3%), but the temperature is obtained with much greater error (30–50% depending on how it was determined). Thus, we must treat this method rather carefully, in particular, when comparing the results obtained using different instruments and on different spacecraft.

The identifications of interplanetary events by different methods were compared only in a few publications. This often makes a quantitative comparison of the results of different studies impossible. The authors of [35] examined the origin of 40 interplanetary shock waves, which were observed during the period from 1978 to 1983. They correlated the characteristics of plasma observed behind the shock front (so-called shock drivers) using 10 different criteria and found that the number of the criteria satisfied by the drivers varies from 0 to 10. If the drivers that can be thought to be ejecta are considered, the number of satisfied criteria increases considerably. Using the *Prognoz-7* satellite data for the period from November 1978 to June 1979, we determined in [36] 10 intervals for the matter ejected from the Sun. Only 7 of them were identified by the *ISEE-3* data [37] as the ejecta intervals, determined from bidirectional electron streams. The authors of [38] determined the intervals of the cold solar wind with $T_p/T_{\mathrm{exp}} < 0.5$ for the period of 1965–1991 and compared these intervals with observations of different events published by this time: bidirectional motions of thermal electrons and energetic particles, magnetic clouds, enhancements of helium density, interplanetary shock waves, and decreases of the flux of energetic ions. The obtained correlations (from 49% to 93%) formed the basis for a belief that these events could be considered as additional criteria of the presence of ejecta in the solar wind.

3. SOLAR EVENTS

If the data on magnetospheric indices and interplanetary events are obtained from measurements at the observation point, the data on solar events are received by the remote sensing (ground-based or near-Earth space-based) of the solar atmosphere in different frequency ranges of electromagnetic waves, and the signal obtained is an integral characteristic associated with the entire length of the line of sight. The frequency of emission is connected with conditions in the radiating plasma volume, and, generally speaking, the measurements held in different frequency ranges yield characteristics of different regions of the Sun. The problem of specifying the dynamics of the solar event (including its spatial motion), especially along the line of sight, is rather complicated and ambiguous, since it is assumed in this case that some parts of the event, whose characteristics and position are varying, are observed by instruments of one type while other parts are observed by instruments of another type, and these measurements performed by several instruments can be used to study one and the same event.

Solar flares were first detected in the optical range of wavelengths, and their classification was based on optical measurements (see for example [39]). However, with the advents of the space era, a permanent orbital X-ray control of the Sun was maintained on the *GOES* satellites, and the classification based on these measurements was developed (for more details see the site http://www.ngdc.noaa.gov/stp/GOES/goes.html). The optical and X-ray emissions are formed at different stages in different regions of the solar flare, as a result of different processes. Thus, the importances of flares determined by the two methods have different physical grounds. The relationship between optical and X-ray importances of solar flares for the interval of 1976–2000 is presented in Fig. 2, where the flares analyzed in our paper [10] and chosen by the X-ray importance M5 and higher are shown. This figure clearly shows that the correlation exists only in the statistical sense, because some events can have high optical importance and low X-ray importance and visa versa.

Even more complicated procedure must be applied if we want to study the motion of halo CMEs using measurements of the *SOHO* interplanetary observatory. The position of the disturbance taken for the CME's start is found on the disk with the help of UV measurements by the EIT instrument. The motion outside the disk is viewed in white light by the LASCO coronagraph, whose aperture masks (cuts from the field of view) the area equal in size to the solar disk. Two different frequency channels C2 and C3 allow the plasma to be investigated at a distance of 2–6 and 3–32 solar radii, respectively (see [40] and the site http://lasco-www.nrl.navy.mil). Thus, the above two instruments measure the radiation not only in different frequency ranges, but also in different spatial domains and at different times. This comparison is very important for solving a principal question whether the halo CME moves towards the Earth or in the opposite direction. However, the question of how strongly these two events measured by the two instruments are related, in our opinion, needs further studies.

4. COMPARISON OF DIFFERENT EVENTS

The said above allows one to estimate more critically the relationships between solar, interplanetary, and magnetospheric events that we and other authors have obtained. In addition to the above-mentioned ambiguity in the comparison of results, which is associated with different approaches to the event classification, the ambiguity also results from various methods used to compare two types of events. If two events with samples X1 and X2 were chosen for the analysis, and the number of events, for which the correspondence between the samples was established, is X12, then the ratio X12/X1 is usually considered as the "effectiveness" of the process X1 ⟶ X2. This value differs from the effectiveness of the inverse process, X2 ⟶ X1, which is equal to X21/X2 = X12/X2, because the samples X1 and X2 are determined by different criteria and can have different values. Thus, the effectiveness determined in different studies depends on the direction of the process analysis. If we take into account that sometimes the sample X2 is not fixed before the analysis, that is, initially a rule (or criteria) of selection of the events for the sample X2 was not preset, the ambiguity in defining the process effectiveness can increase additionally.

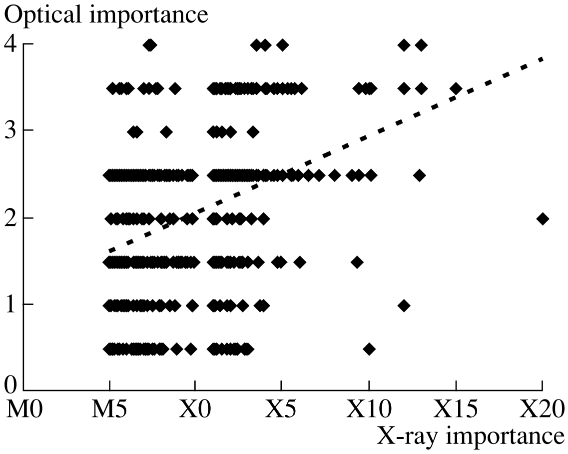

Fig. 2. Correlation between optical and X-ray indices during solar flares in 1976–2000.

As solar-terrestrial physics investigates the process consisting of two links, the Sun – the solar wind and the solar wind – the magnetosphere, the data on the intermediate link can improve the reliability of the estimates for the entire chain. Assume that we have data for the samples X1 and Y1 on the Sun, Y2 and Z1 in the interplanetary medium, and X2 and Z2 in the magnetosphere, and the effectivenesses of the processes X1 ⟶ X2, Y1 ⟶ Y2, and Z1 ⟶ Z2 were estimated as X12/X1, Y12/Y1, and Z12/Z1, respectively. It is natural to expect in this case that the effectiveness of the total process must be close to the product of the effectivenesses of each link, that is, X12/X1 = (Y12/Y1)(Z12/Z1). In particular, this means that the effectiveness of the total process cannot be higher than the effectivenesses of each link: X12/X1 ≤ Y12/Y1 and X12/X1 ≤ Z12/Z1. There are enough data for this analysis in published papers. However, such an analysis has not been made yet, and we perform it below.

It is important to mention that for the "geoeffectiveness" of one or another event the authors often take different values, obtained by different procedures. Strictly speaking, the geoeffectiveness of a solar or interplanetary event determines which fraction (percent) of one or another set of solar or interplanetary events, respectively, results in an occurrence of magnetic storms of a certain class. In other words, first solar or interplanetary events should be chosen using a certain rule; then each event followed by a magnetic storm should be investigated using a given algorithm. As an algorithm for comparing different events the delay time between the events is usually taken. This time must hit some predefined "window," which is either a typical range of the time of the event propagation between two points or is determined from some initial data.

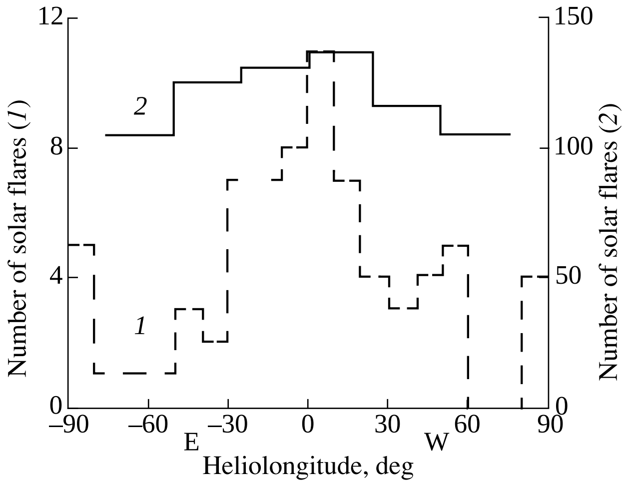

Fig. 3. Heliolongitude distribution of geoeffective flares based on the data for the period (curve *1*) of 1954–1976 [39] and (curve *2*) 1976–2000.

Quite often the analysis is made in the opposite direction: a list of storms is taken as the initial list, and the storms are extrapolated back to the interplanetary medium or to the Sun, where the appropriate event is looked for. This method does not determine the geoeffectiveness of solar or interplanetary events, but rather allows one to find in the interplanetary medium or on the Sun candidates for the cause of the magnetic storms in view. If we take into account that the events of various strengths are often considered to be such candidates (if the time of their occurrence suits), it becomes clear why the results of different studies diverse.

5. RESULTS OF ANALYSIS

We correlated the Flare ⟶ Storm events in our paper [10] and estimated the geoeffectiveness of 653 solar flares of X-ray importance M5 and higher, which in 32% of cases resulted in magnetic storms of with intensity $D_{st} < -60$ nT. If we try to correlate events in the opposite direction, Storm ⟶ Flare, and use a list of strong magnetic storms with $D_{st} < -100$ nT, only 20% of the flares from the given set can be considered as storm sources. In [39], the Storm ⟶ Flare relationship was analyzed based on a rather large set of solar flares (in optical importance). It was demonstrated that in 59% of 116 storms with $K_p > 7_-$, observed in 1954–1976, flares can be considered as their possible sources. The relation Storm ⟶ Flare was also analyzed in [41], where it was shown that for 25 severe magnetic storms with $D_{st} < -250$ nT, observed during the period of 1957–1990, at least in 22 cases (88%) a solar flare can be assumed to be a candidate for the storm source. In addition to the opposite direction of the event correlation, a high percent of the effectiveness in [39, 41] is apparently associated with the fact that even weak solar flares were considered as possible sources of storms, whereas in our study only strong flares were analyzed. It is worthwhile to note that the heliolongitudinal distributions of geoeffective flares are highly different in [39] and [10]. According to [39], the distribution, presented by curve *1* in Fig. 3, has a clear maximum near the central meridian and contains 61 out of total 78 geoeffective flares in the range from –50 to +50 degrees. According to our results [10], the distributions of geoeffective and nongeoeffective flares over the solar disk are nearly uniform. If we incorporate weaker flares into our analysis and consider the flares of importance M0 and higher in the similar way, then, as can be seen in curve *2* in Fig. 3, a small maximum near the central meridian arises and 509 out of 920 geoeffective flares appear within the range of heliolongitudes from –50° to +50°.

The results of correlating halo CMEs and different interplanetary events with magnetic storms for the last 12 years are presented in Table 3. Note first that we separated the results by the events examined and by the direction of correlation. For example, the notation "CME ⟶ Storm" means that the CME list was taken for the initial data set (the number of analyzed CMEs is given in the column "Number of events"), and the CMEs are correlated with magnetic storms, whose strength was determined by the index presented in the column "Notes". Thus, we summarized the published data on six types of the event correlation: I. CME ⟶ Storm; II. CME ⟶ Magnetic clouds, Ejecta; III. Magnetic clouds, Ejecta ⟶ Storm; IV. Storm ⟶ CME; V. Storm ⟶ Magnetic clouds, Ejecta; and VI. Magnetic clouds, Ejecta ⟶ CME. In types II, III, V, and VI we combined magnetic clouds and ejecta, which have close physical characteristics, but in the column "Number of events" (for processes III and VI) we gave the author identification by letters MC (Magnetic clouds) and E (Ejecta).

The geoeffectiveness of the CMEs is demonstrated by the correlation I. CME ⟶ Storm, which includes six datasets, and is equal to 35%–71% [42, 43, 4, 56, 57, 10]. The result of 71% was obtained in [43] with a comparatively low statistics of 7 events. It was later reproduced in papers [44, 45]. Other results, based on the statistics comprising from 38 to 132 CMEs, lie within the interval from 35% to 50% and agree well. Our result, obtained in [10] for magnetic storms with $D_{st} < -60$ nT is 35%. If weaker storms with $D_{st} < -50$ nT (this corresponds to $K_p > 5$ as in paper [4]) were included into the analysis, we would obtain the geoeffectiveness of the CMEs equal to ~40%. Thus, we can conclude that the geoeffectiveness of the halo CMEs for magnetic storms with $K_p > 5$ ($D_{st} < -50$ nT) is 40–50% for sufficiently high statistics from 38 to 132 CMEs.

If we consider the results of the analysis held in the opposite direction, IV. Storm ⟶ CME, we can see that for three datasets the values are from 83 to 100% at lower statistics from 8 to 27 events of quite strong magnetic storms with $K_p > 6$ and $D_{st} < -100$ nT [46, 47, 45, 5]. These results agree well with each other, but they

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

N	%	Number of events	Reference	Note
I. CME ⟶ Storm				
1	50	38	[42] *Webb et al.*, 1996	K_p
2	71	7	[43] *Webb et al.*, 2000; [44] *Crooker*, 2000; [45] *Li et al.*, 2001	$D_{st} < -50$
3	35	40	[56] *Plunkett et al.*, 2001	$K_p > 6$
4	45	20	[57] *Berdichevsky et al.*, 2002	$K_p > 5$
5	45	132	[4] *Wang et al.*, 2002	$K_p > 5$
	20	132		$K_p > 7$
6	35	125	[10] Yermolaev and Yermolaev, 2003	$D_{st} < -60$
	40	125	This paper	$D_{st} < -50$
II. CME ⟶ Magnetic clouds, Ejecta				
1	63	8	[48] *Cane et al.*, 1998	Earth-directed halo CMEs
2	60–70	89	[58] *Webb et al.*, 2001	Earth-directed halo CMEs
3	80	20	[57] *Berdichevsky et al.*, 2002	Halo CMEs
III. Magnetic clouds, Ejecta ⟶ Storm				
1	44	327 E	[50] *Gosling et al.*, 1991	$K_p > 5_-$
2		28 MC	[51] *Gopalswamy et al.*, 2000	
	67		[9] Yermolaev and Yermolaev, 2002	$D_{st} < -60$
3	63	30 MC	[6] Yermolaev *et al.*, 2000	$D_{st} < -60$
4		48 MC	[52] *Gopalswamy et al.*, 2001	
	57		This paper	$D_{st} < -60$
5	19	1273 E	[53] *Richardson et al.*, 2001	$K_p > 5_-$, Solar minimum
	63	1188 E		$K_p > 5_-$, Solar maximum
6	82	34 MC	[54] *Wu & Lepping*, 2002	$D_{st} < -50$
7	50	214 E	[60] *Cane and Richardson*, 2003	$D_{st} < -50$
	43	214 E		$D_{st} < -60$
IV. Storm ⟶ CME				
1	100	8	[46] *Brueckner et al.*, 1998	$K_p > 6$
2	83	18	[47] *St.Cyr et al.*, 2000; 45. *Li et al.*, 2001	$K_p > 6$
3	96	27	[5] *Zhang et al.*, 2003	$D_{st} \le -100$
V. Storm ⟶ Magnetic clouds, Ejecta				
1	73	37	[50] *Gosling et al.*, 1991	$K_p > 7_-$
2	67	12	[43] *Webb et al.*, 2000	$D_{st} < -50$
3	25		[20] *Vennerstroem*, 2001	D_{st}(corr)
4	33	618	[9] Yermolaev and Yermolaev, 2002	$D_{st} \le -60$
	25	414		$-100 \le D_{st} \le -60$
	52	204		$D_{st} \le -100$
VI. Magnetic clouds, Ejecta ⟶ CME				
1	67	49E	[55] *Lindsay et al.*, 1999	Any CME
2	65	86E	[49] *Cane et al.*, 2000	Any CME
	42	86E		Earth-directed halo CMEs
3	82	28MC	[51] *Gopalswamy et al.*, 2000	Any CME
4	50–75	4 MC	[59] *Burlaga et al.*, 2001	Halo CMEs
	40–60	5 E		Halo CMEs
5	56	193 E	[60] *Cane and Richardson*, 2003	Any CME

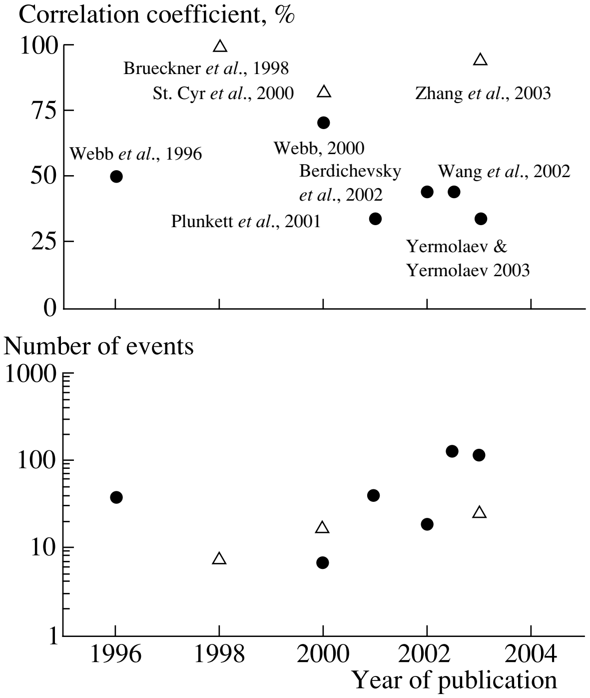

Fig. 4. The effectiveness of correlation between the events "CME → Storm" (dark circles) and "Storm → CME" (light triangles) according to different publications (upper panel) and observation statistics (lower panel).

indicate not the high geoeffectiveness of the CMEs, but the fact that among possible solar candidates for the source of strong magnetic storms CMEs can be found with a high probability. The difference between the results of correlation types I. CME → Storm (dark circles) and IV. Storm → CME (light triangles) is clearly seen in Fig. 4. The lower panel shows the statistics of the initial datasets, while the upper one presents the percent obtained in correlating the two types of events.

The analysis of correlations II (CME → Magnetic clouds, Ejecta) and IV (Magnetic clouds, Ejecta → CME) shows that the values of 60–70% are observed in the first case given a low statistics from 8 to 89 cases [48, 58]. In the second case, we have 42% for the statistics of 86 cases [49]. Other results were obtained for arbitrary CMEs, for CMEs determined not sufficiently clearly [51, 55, 57, 60], or with a low statistics [59] and must be treated carefully. It follows from the analysis of III (Magnetic clouds, Ejecta → Storm) that the correlation is somewhat higher (57–82%) for magnetic clouds [51, 9, 6, 54] than for ejecta (~40–50%, 44% [50], 50% [60], and 41% as the average of 19 and 63% [53]). The back tracing correlation V (Storm → Magnetic clouds, Ejecta) gives contradictory results: 73% [50] and 25% [20]. It should be emphasized here that in both cases storms and ejecta were determined in a different way and the corresponding statistics differ many times (50 months and 32 years, that is, by more than a factor of 7). Our estimates for magnetic clouds, obtained for the period of 1976–2000 for moderate and strong storms (33%), for moderate storms (25%), and for strong storms (52%) [9], are in good agreement with the results of [20].

By analyzing two subsequent steps in the processes II (CME → Magnetic clouds, Ejecta) and III (Magnetic clouds, Ejecta → Storm) we can estimate the probability of the total CME → Storm process as a product of probabilities. We obtain the value of (0.6–0.7) $\times$ (0.57–0.82) = 0.34–0.57) for magnetic clouds. This is close to the above-given results of 40–50% for the direct analysis of process I (CME → Storm). The analysis of the sequence of two steps V (Storm → Magnetic clouds, Ejecta) and VI (Magnetic clouds, Ejecta → CME) does not give high Storm → CME correlations (compare to 83–100% obtained for the direct process IV): (0.25–0.73) $\times$ 0.42 = 0.11–0.31.Thus, the results of two-stage and single-stage processes for the CME → Storm direction agree well. Meanwhile, for the opposite direction the two-stage process gives the estimate differing several times from that given by the single-stage process. This indicates that the methods used to analyze the processes Storm → Ejecta, Ejecta → CME, and Storm → CME need to be improved.

CONCLUSIONS

The methods used to analyze events on the Sun, in the interplanetary medium, and in the Earth's magnetosphere and the results of their application were compared based on the data of numerous publications. It was demonstrated that in addition to the methods applied in each region, the way of correlating the events in different regions is of great importance for the investigation of the entire chain of solar-terrestrial physics. To study the geoeffectiveness of solar and interplanetary events (that is, their ability to generate magnetic storms on the Earth), one must first select the events on the Sun or in the solar wind and then compare them to the event at the next stage of the chain. In this case the estimates of the CME impact on storms obtained both directly and by the multiplication of the probabilities of the two steps (CME–ejecta and ejecta–storms) turn out to close to each other and equal to 40–50% [4, 6, 9, 10, 42, 48, 50, 51, 56, 57, 60]. These results differ from those published in papers [46, 47, 5], where the value of 83–100% was obtained. However, the events were traced in the opposite direction in [46, 47, 5], and, thus, not the geoeffectiveness of the CMEs, but a possibility to find among CMEs appropriate candidates for the source of magnetic storms was estimated. The obtained coefficient of 83–100% is not confirmed by the two-stage analysis of the storm sources as the coefficients are 25–73% [50, 20] and ~40% [49] for the stages storm–ejecta and ejecta–CME, respectively, and each of them is less than the coefficient obtained by the direct analysis storm–CME. Thus, the methods suggested in [46, 47, 5] for the data analysis should be developed further in order to remove this contradiction.

The estimates of 40–50% obtained for the CME geoeffectiveness turned out to be close to the estimated geoeffectiveness of solar flares (~40%) [10] (similar to the case of CMEs the opposite tracing "storm–flare" results in higher estimates of 59% and 88% [39, 41]). As we demonstrated in [9], if solar processes and magnetic storms are distributed randomly, the correlation coefficient calculated formally can be 30–40%. This means that the estimated geoeffectiveness for both CMEs and solar flares can be largely referred to random processes. Therefore, the forecasts of the geomagnetic situation based on observations of solar events can give false alarms in many cases. Thus, we face a paradoxical situation when modern science in a retrospective review can successfully explain the origin of practically all strong geomagnetic disturbances, but cannot predict their occurrence reliably enough on the basis of solar observations. In order to improve the forecast reliability, it is necessary to make a subsequent analysis of solar data and to find characteristics that should allow us to find highly geoeffective events among CMEs and/or flares.

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