Geoeffectiveness and efficiency of CIR, sheath, and ICME in generation of magnetic storms

Y. I. Yermolaev,[1] N. S. Nikolaeva,[1] I. G. Lodkina,[1] and M. Y. Yermolaev[1]

Received 5 September 2011; revised 25 March 2012; accepted 28 March 2012; published XX Month 2012.

[1] We investigate the relative role of various types of solar wind streams in generation of magnetic storms. On the basis of the OMNI data of interplanetary measurements for the period of 1976–2000, we analyze 798 geomagnetic storms with $Dst \leq -50$ nT and five various types of solar wind streams as their interplanetary sources: corotating interaction regions (CIR), interplanetary coronal mass ejection (ICME) including magnetic clouds (MC) and ejecta, and a compression region sheath before both types of ICME (SHE_{MC} and SHE_{Ej}, respectively). For various types of the solar wind we study the following relative characteristics: occurrence rate; mass, momentum, energy and magnetic fluxes; probability of generation of a magnetic storm (geoeffectiveness); efficiency of the process of this generation; and solar cycle variation of some of these parameters. Obtained results show that in spite of the fact that magnetic clouds have lower occurrence rates and lower efficiency than CIR and sheath, they play an essential role in generation of magnetic storms due to higher geoeffectiveness of storm generation (i.e., higher probability to contain large and long-term southward IMF Bz component). Geoeffectiveness for all drives is at the smallest during a solar cycle minimum and increases at other phases of the cycle.

Citation: Yermolaev, Y. I., N. S. Nikolaeva, I. G. Lodkina, and M. Y. Yermolaev (2012), Geoeffectiveness and efficiency of CIR, sheath, and ICME in generation of magnetic storms, *J. Geophys. Res.*, *117*, AXXXXX, doi:10.1029/2011JA017139.

1. Introduction

[2] One of the key issues of solar-terrestrial physics is investigation of mechanisms of energy transfer from the solar wind into the magnetosphere and of excitation of magnetospheric disturbances. As has been discovered by direct space experiments in the beginning of 1970s, the basic parameter leading to magnetospheric disturbances is negative (southward) Bz component of the interplanetary magnetic field (IMF) (or electric field $Ey = Vx \times Bz$) [*Dungey*, 1961; *Fairfield and Cahill*, 1966; *Rostoker and Falthammar*, 1967; *Russell et al.*, 1974; *Burton et al.*, 1975; *Akasofu*, 1981].

[3] Numerous investigations demonstrated that IMF in the undisturbed solar wind lies in the ecliptic plane (i.e., Bz is close to zero) and only disturbed types of the solar wind streams can have a considerable value of IMF Bz. The interplanetary coronal mass ejection (ICME) with a compression region sheath before it and the compression region between slow and fast solar wind streams (corotating interaction region (CIR)) belong to such types of solar wind streams (see reviews and recent papers, for instance, by *Tsurutani et al.* [1988], *Tsurutani and Gonzalez* [1997], *Gonzalez et al.* [1999], *Yermolaev and Yermolaev* [2002], *Huttunen and Koskinen* [2004], *Echer and Gonzalez* [2004], *Yermolaev and Yermolaev* [2006], *Borovsky and Denton* [2006], *Denton et al.* [2006], *Huttunen et al.* [2006], *Yermolaev et al.* [2007a, 2007b, 2007c], *Pulkkinen et al.* [2007a, 2007b], *Zhang et al.* [2007], *Turner et al.* [2009], *Xu et al.* [2009], *Yermolaev et al.* [2010a, 2010b, 2010c, 2010d, 2011], *Nikolaeva et al.* [2011, 2012], *Alves et al.* [2011], *Echer et al.* [2011], *Gonzalez et al.* [2011], *Guo et al.* [2011], *Mustajab and Badruddin* [2011], and references therein).

[4] Experimental results have shown that the magnetospheric activity induced by different types of interplanetary streams is different [*Borovsky and Denton*, 2006; *Denton et al.*, 2006; *Huttunen et al.*, 2006; *Pulkkinen et al.*, 2007a; *Plotnikov and Barkova*, 2007; *Longden et al.*, 2008; *Turner et al.*, 2009; *Despirak et al.*, 2009, 2011; *Guo et al.*, 2011].

[5] This fact indicates that it is necessary to take into account the influence of other (in addition to IMF Bz and electric field Ey) parameters of the solar wind, dynamics of parameter variation, and different mechanisms of generating the magnetospheric disturbances at different types of the solar wind streams. Several recent papers analyzed separately CIR, sheath and body of ICME and compared them with each other [*Huttunen and Koskinen*, 2004; *Yermolaev and Yermolaev*, 2006; *Huttunen et al.*, 2006; *Yermolaev et al.*, 2007a, 2007b, 2007c; *Pulkkinen et al.*, 2007a; *Yermolaev and Yermolaev*, 2010; *Yermolaev et al.*, 2010a, 2010b, 2011; *Alves et al.*, 2011; *Despirak et al.*, 2011; *Nikolaeva et al.*, 2011, 2012; *Guo et al.*, 2011].

[1]Space Plasma Physics Department, Space Research Institute, Russian Academy of Sciences, Moscow, Russia.

Corresponding Author: Y. I. Yermolaev, Space Plasma Physics Department, Space Research Institute, Russian Academy of Sciences, Prof. 84/32, Moscow 117997, Russia. (yermol@iki.rssi.ru)

0148-0227/12/2011JA017139

[6] The papers mentioned above are devoted to studying a response of the magnetosphere to interplanetary drives, and they use the word *geoeffectiveness* to designate this link. It should be noted that in the literature the *geoeffectiveness* is a double meaning term [see *Yermolaev and Yermolaev*, 2006, 2010]. In one case, *geoeffectiveness* implies a probability with which a selected phenomenon can cause a magnetic storm, i.e., the ratio between the number of events K^j of a chosen stream type *j* (MC, CIR etc.) resulting in a magnetic storm with $Dst < Dst_0$ and the total number of this type events N^j: $P^j = K^j/N^j$. In the other case, *geoeffectiveness* implies the 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 *Dst* index and the southward IMF *Bz* component. To avoid ambiguity of the term *geoeffectiveness* we will use below the term *geoeffectiveness* for a designation of probability of relation between the phenomena and the term *efficiency* for a designation of efficiency of process relating phenomena.

[7] Magnetospheric activity induced by different interplanetary drivers depends on the following parameters: (1) occurrence rate of these drivers near the Earth, (2) occurrence rate of corresponding geoeffective conditions in these drivers, and (3) ability (efficiency) of these conditions in various drivers to induce magnetospheric disturbances. Only several of these parameters for separate types of storm drivers have been estimated in the literature.

[8] The occurrence rate of magnetic clouds (MC) is analyzed in a great number of works, but only in several papers their authors compare occurrence rates of several types of the solar wind streams. For instance, occurrence rates of MC and ejecta are compared by *Cane and Richardson* [2003], *Richardson and Cane* [2004], and *Lepping and Wu* [2010]; occurrence rates of MC and SHE_{MC} by *Huttunen et al.* [2005]; and occurrence rates of CIR, ejecta and SHE_{Ej} by *Dmitriev et al.* [2005] and *Jian et al.* [2008]. In the present work we simultaneously consider the occurrence rates of 5 interplanetary drivers: CIR, MC, ejecta, SHE_{MC} and SHE_{Ej} (as well as combinations of them ICME = MC + ejecta and sheath = SHE_{MC} + SHE_{Ej}) during 1976–2000.

[9] Numerous papers are devoted to investigations of geoeffectiveness in generation of magnetic storm. Many works study geoeffectiveness of magnetic clouds, while geoeffectiveness of other phenomena is studied rather poorly (see, for example, recent reviews and papers by *Yermolaev and Yermolaev* [2006, 2010] and *Alves et al.* [2011]). So, one of the main aims of this paper is to investigate geoeffectiveness of various interplanetary drivers and to compare them to each other.

[10] Efficiencies of various interplanetary drivers vary with the type of solar wind streams and may be estimated as the ratio of measured energy output to estimated energy input (see, for example, papers by *Turner et al.* [2009], *Yermolaev et al.* [2010c], and references therein). In our previous and present investigations we use *Bz* (*Ey*) and magnetospheric indices *Dst*, *Dst** (pressure corrected *Dst*), *Kp* and *AE* as "input" and "output" of the storm generation processes for the estimation of efficiency of interplanetary drivers.

[11] In the present work we simultaneously consider for the first time the entire set of these parameters (occurrence rate (section 3.1), geoeffectiveness (section 3.2) and efficiency (section 3.3.)) for the magnetic storms generated by 5 types of interplanetary drivers (CIR, MC, ejecta, SHE_{MC} and SHE_{Ej}). In addition, in the present work we include (1) comparative characteristics of mass, momentum, energy and magnetic field fluxes for various drivers (section 3.1); (2) numerical estimations of efficiency of various geomagnetic activity for various drivers (section 3.3); and (3) solar cycle variation of parameters.

2. Methods

[12] When the types of solar wind streams were classified, we used the OMNI database (see http://omniweb.gsfc.nasa.gov [*King and Papitashvili*, 2005]) for interval 1976–2000, available world experience in identification of solar wind streams and the standard criteria for the following parameters: velocity *V*, density *n*, proton temperature *T*, ratio of thermal to magnetic pressure (β parameter), ratio of measured temperature to temperature calculated on the basis of average "velocity–temperature" relation *T*/*Texp* [*Lopez*, 1987], thermal pressure and magnetic field. This method allows us to identify reliably 3 types of quasi-stationary streams of the solar wind (heliospheric current sheet (HCS), fast streams from the coronal holes, and slow streams from the coronal streamers), and 5 disturbed types (compression regions before fast streams (CIR), and interplanetary manifestations of coronal mass ejections (ICME) that can include magnetic clouds (MC) and ejecta with the compression region sheath (SHE_{MC} and SHE_{Ej}) preceding them). In contrast with ejecta, MCs have lower temperature, lower ratio of thermal to magnetic pressure (β parameter) and higher, smooth and rotating magnetic field [*Burlaga*, 1991]. In addition, we have included into our catalog direct and reverse shocks, and the rarefaction region (region with low density) [*Yermolaev et al.*, 2009], but these types of events are not analyzed in this paper. The method and results of identification of several types of solar wind streams (fast, slow, CIR and CME which includes sum of MC, ejecta, SHE_{MC} and SHE_{Ej}) have been recently confirmed by *Thatcher and Muller* [2011].

[13] In order to calculate yearly averaged values of various parameters, we have taken into consideration that the OMNI database contains gaps of the data from 0 to 50% of the time of a year. This procedure has been made under the assumption that occurrence rate of a given type of the solar wind streams during each year is similar both in intervals of available data and in data gaps. If during a chosen year *i* the number of events of selected solar wind type N_i has been registered in interval of existing data t_{di}, the normalized number of the given solar wind type N_i^* in this year was defined by multiplication of occurrence rate of the given solar wind type N_i/t_{di} by the total duration of year t_{yi}, i.e., $N_i^* = (N_i/t_{di}) * t_{yi}$. The normalized number of solar wind events is used only for studying the time variations in occurrence rate of various types of streams (Figure 1 and solid circles in Figure 2), while the measured number of events is used to calculate plasma and IMF parameters (Figure 3) and geoeffectiveness and efficiency of types of events (Figures 4 and 5 and open circles and crosses in Figure 2). When we analyzed durations of different types of the solar wind streams, we selected intervals of the types of

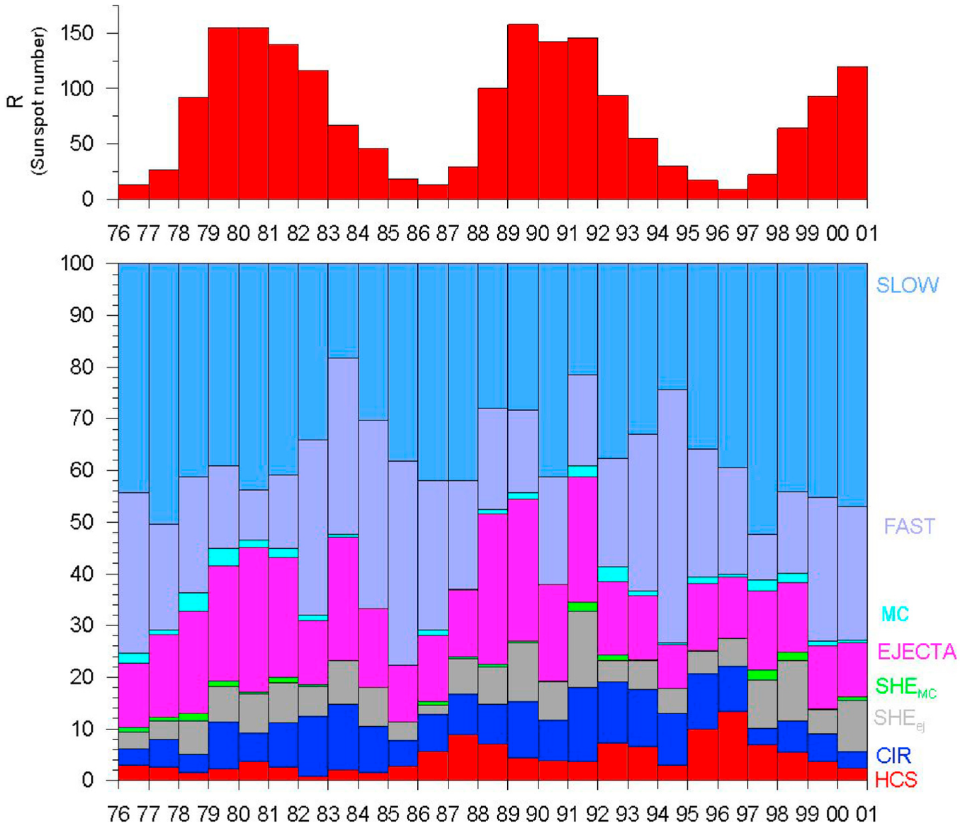

Figure 1. (top) Yearly average values of sunspots and (bottom) yearly average distributions of times of observations for different types of solar wind (percent).

streams which have not data gaps at both edges of the intervals.

[14] Specified types of the solar wind streams were put in correspondence to all magnetic storms for which measurements of the parameters of plasma and magnetic field in the interplanetary medium were available. This was done using the following algorithm. If the moment of a minimum in the *Dst* index from the list of magnetic storms falls within the time interval of a solar wind event or is apart from it by no more than 2 h interval, the corresponding solar wind type is ascribed to this storm. It should be noted that, according to the results of analysis of 64 intense ($Dst < -85$ nT) magnetic storms in the period 1997–2002, the average time delay between *Dst* peak and southward IMF *Bz* component is equal to ~2 h [*Gonzalez and Echer*, 2005]. Similar results were obtained in papers by *Yermolaev et al.* [2007a, 2007c]. Thus, 2 h correspond to the average time delay between the *Dst* peak of an intense magnetic storm and the associated peak in the southward IMF *Bz* component. Analysis of the data showed that less 5% of points of the storm main phase were measured during such 2 h interval between the last point of solar wind stream and *Dst* peak.

[15] In order to investigate the dynamic relation between development of parameters in interplanetary sources and in the magnetospheric indices we apply the method of double superposed epoch analysis (DSEA) [*Yermolaev et al.*, 2010c, 2010d]. Two reference times are used in this method: we put together the time of storm onset (time "0") and time of *Dst* index minimum (time "6"), the data between them we compress or expand in such a way that durations of the main phases of all magnetic storms are equal to each other. This DSEA method allows us to simultaneously study interplanetary conditions resulting in the beginning and end of magnetic storms as well as dynamics (temporal variations) of parameters during the main phase for storms with different durations.

3. Results

[16] Obtained results are presented in this section devoted to (1) observational statistics of various types of solar wind streams, (2) probability of magnetic storm generation by these interplanetary drivers, and (3) efficiency of magnetic storm generation by various drivers.

3.1. Occurrence Rate of Different Types of Solar Wind Streams

[17] In order to estimate geoeffectiveness of different types of solar wind streams it is necessary to have a total list of these types of streams during a sufficiently large time interval and with sufficiently large statistics. Measured and normalized numbers per year, average durations, temporal parts in total times of observations, as well as average values and their standard deviations of several plasma and magnetic field parameters for various solar wind types have been presented in our publications [*Yermolaev et al.*, 2009, 2010a, 2010b, 2010c, 2010d, 2011]. It should be noted that both types of compressed regions (CIR and sheath), as well as

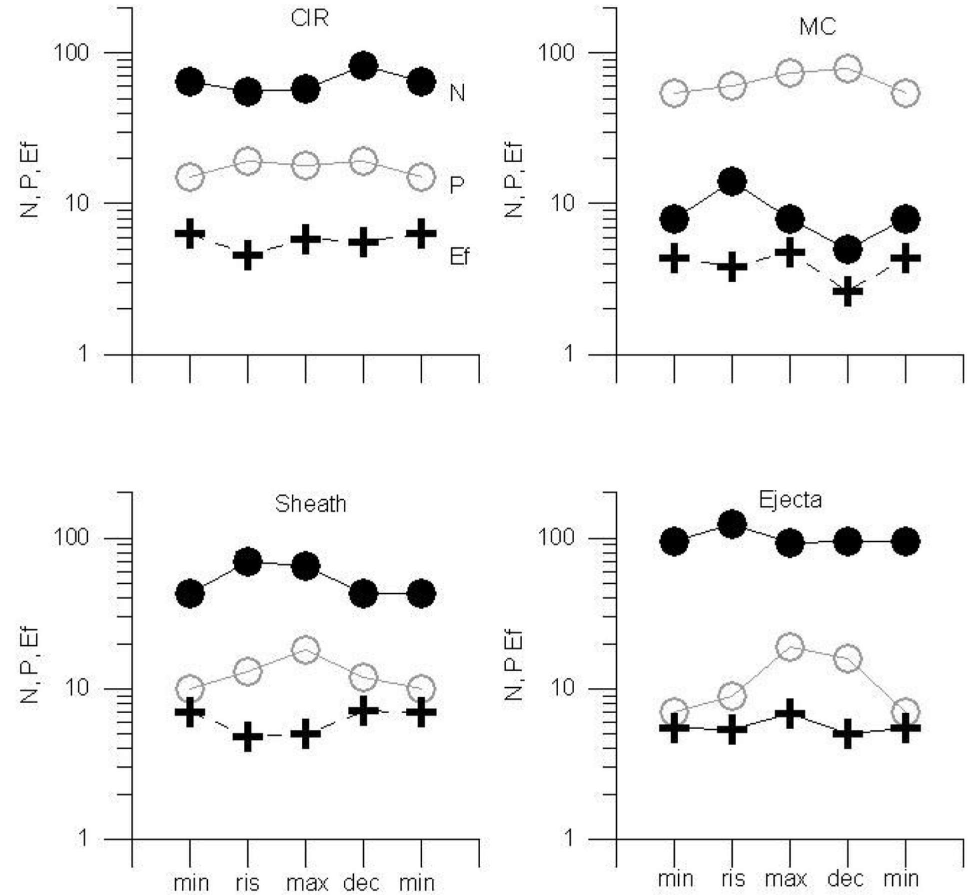

Figure 2. Solar cycle variations of yearly number of events (N, solid circles), probabilities (geoeffectiveness) (P, open circles), and efficiency of magnetic storm generation (Ef, crosses) for CIR, sheath, MC, and ejecta.

both types of sheath before MC and ejecta (SHE_{MC} and SHE_{Ej}), have very close values of parameters, while the parameters for 2 types of ICME (ejecta and MC) are different. In Figure 1 (top) we present yearly average values of sunspot numbers, and in Figure 1 (bottom) we present yearly average distributions of times of observations for different types of solar wind streams. Data for different types of streams are shown by various color columns (see designation on the right of the figure) with height proportional to percentage of observation time. On the average the quasi-steady types of solar wind streams (fast, slow and HCS) contain about 60% of all solar wind observations near the Earth (see Table 1) but the time of disturbed types of streams decreases down to 25% during solar minimum and increases

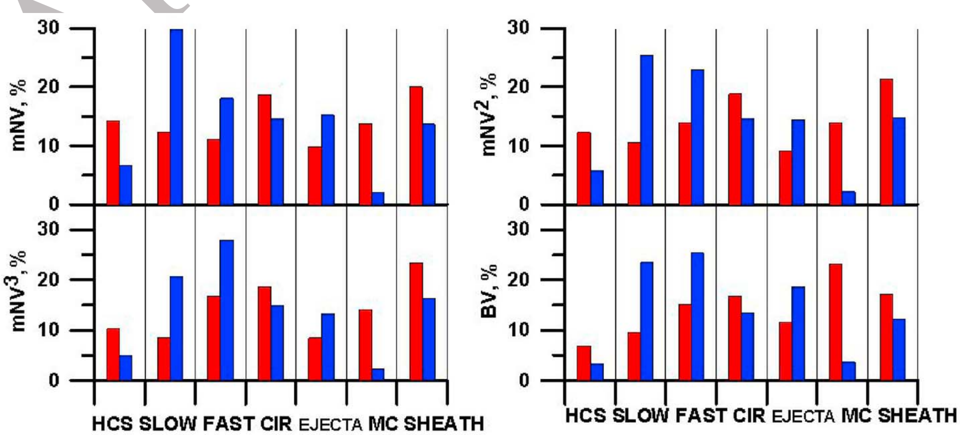

Figure 3. Average values (red) and integrated values (blue) mass (*nmV*), momentum (*nmV*^{2}), energy (*nmV*^{3}), and magnetic (*BV*) fluxes for different types of solar wind streams.

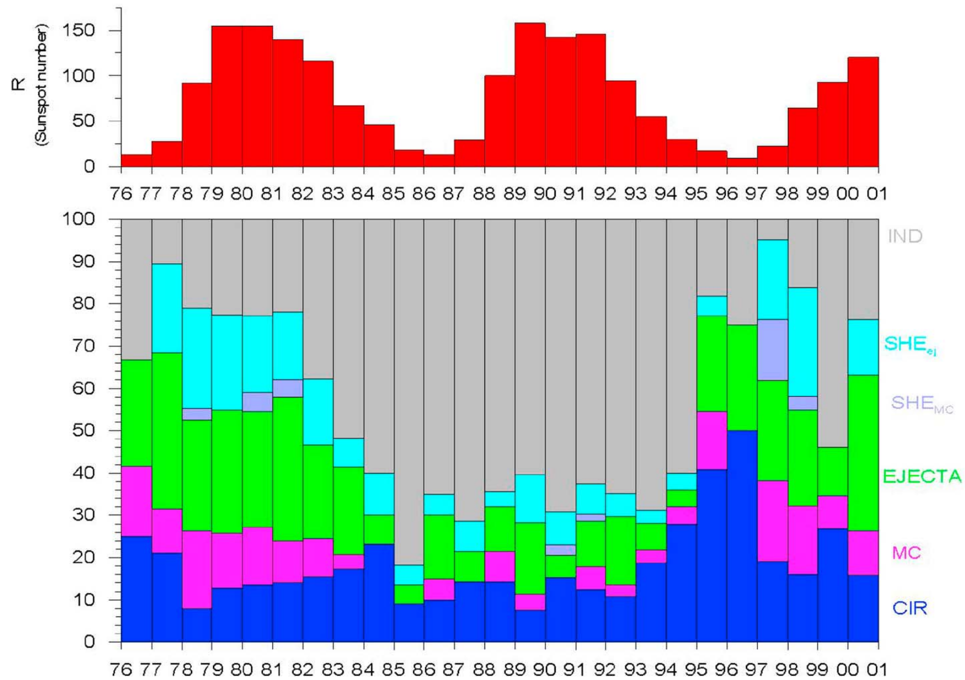

Figure 4. (top) Sunspot number and (bottom) year-averaged distributions of magnetic storms with $Dst < -50$ nT over types of their interplanetary drivers (percent).

up to 50% during solar maximum. To increase statistics in comparison with yearly averaging we made selection of data over four phases of the solar cycle: minimum, rising, maximum and declining phases. For the same purpose we combined two types SHE_{MC} and SHE_{Ej} and considered the common type sheath. Solid circles in Figure 2 show annual numbers of disturbed types of the solar wind (CIR, sheath, MC and ejecta) during four phases of the solar cycle. CIR

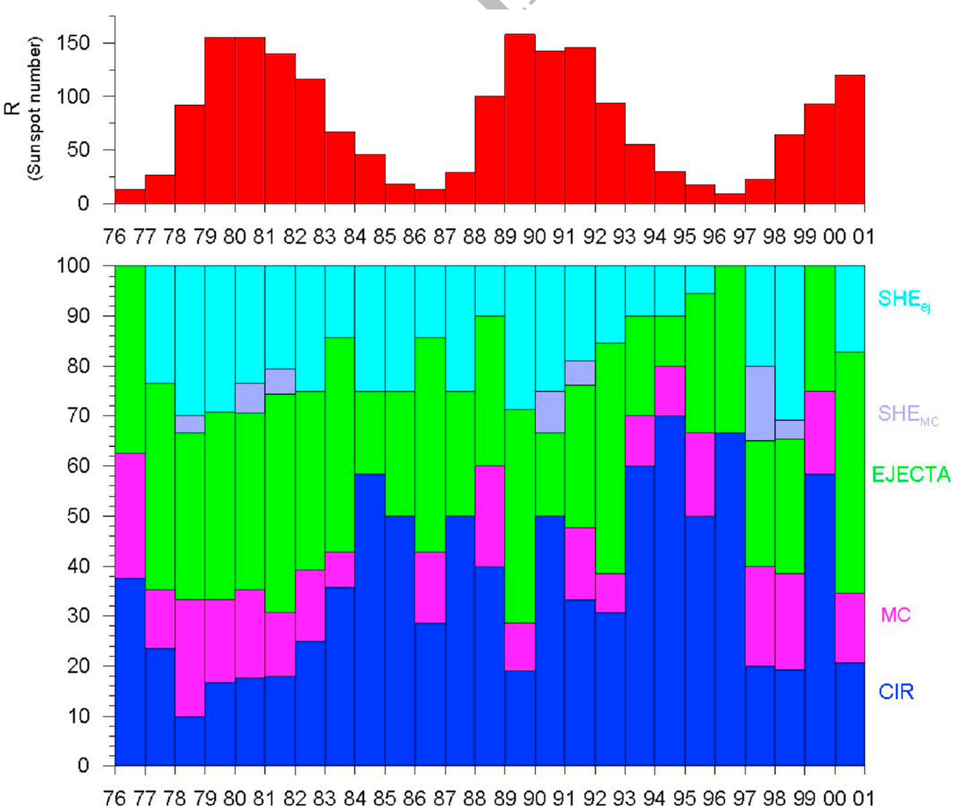

Figure 5. The same as in Figure 4 when IND storms were excluded from analyses.

Table 1. Time Observation of Different Types of Solar Wind Streams During 1976–2000

Types of Solar Wind	Time Observations (%)
Slow	31 ± 7
Fast	21 ± 8
HCS	6 ± 4
CIR	10 ± 3
Ejecta	20 ± 6
MC	2 ± 1
Sheath before ejecta	8 ± 4
Sheath before MC	0.8 ± 0.7

has maximal number of events during declining phase, sheath during rising phase and maximum, and ICME (MC and ejecta) during rising phase of the cycle.

[18] Various types of the solar wind streams transport different values of mass, momentum, energy and magnetic field from the Sun to the Earth. To estimate contribution of all types of streams to this process we calculate two sorts of parameters for each stream type: average parameters and parameters integrated over time of observation of corresponding stream type $\int adt$. Figure 3 shows distributions (percentage) of average values (red columns) and integrated values (blue columns) of mass (nmV), momentum (nmV^2), energy (nmV^3), and magnetic (BV) fluxes for different types of the solar wind streams. High average values for mass, momentum, and energy fluxes are observed in compressed regions CIR and sheath and magnetic flux in MC, but their integrated values are higher in steady types of streams (fast and slow) than in disturbed types of streams. In the following sections of the paper we will analyze how the occurrence rate of different types of streams and mass, momentum, energy and magnetic field transferred by these streams influence generation of magnetic storms.

3.2. Geoeffectiveness of Interplanetary Drivers

[19] For the entire period of time 1976–2000, 798 moderate and strong magnetic storms with the intensity $Dst \leq -50$ nT were observed on the Earth (see Figure 4). But only for 464 magnetic storms (i.e., for 58% of all magnetic storms) corresponding events were found in the solar wind. The sources of other 334 magnetic storms (i.e., of 42% of 798 storms, grey columns in Figure 4) are indeterminate (IND type of streams), and this fact is mainly connected with the lack of data on plasma and interplanetary magnetic field which makes impossible to identify the solar wind type for magnetic storm intervals. Figure 5 presents the distribution of storms for the case when we excluded IND storms from analysis.

[20] Analysis of data in Figures 1 and 5 allows us to compare the number of each type of solar wind streams with the number of magnetic storms induced by these types of streams and to calculate a probability (geoeffectiveness) of generation of magnetic storms by each types of these interplanetary drivers (see Table 2). The values of geoeffectiveness for MC and MC with sheath (MC + SHE_{MC}) are high and close to each other, while this value for ejecta with sheath (ejecta + SHE_{Ej}) is significantly higher than for ejecta without sheath. The values of geoeffectiveness for sheath before MC (SHE_{MC}) and before ejecta (SHE_{Ej}) are close to each other, but lower than for CIR.

[21] Small statistics of the annual numbers of solar wind streams in Figures 1 and 5 does not allow us to clearly see solar cycle variations in geoeffectiveness of various drivers. Nevertheless larger statistics for solar cycle phases in Figure 2 (open circles) shows that all types of the solar wind streams have the lowest geoeffectiveness during the solar minimum.

3.3. Efficiency of Interplanetary Drivers

[22] One of important problems of connection between interplanetary conditions and magnetospheric processes is the dependence of magnetospheric activity on temporal evolution of solar wind plasma and IMF parameters including Bz and Ey. Using the DSEA method [*Yermolaev et al.*, 2010c], we found qualitative consistency between time evolution of cause (Bz and Ey) and time evolution of effect (Dst, Dst* (pressure corrected Dst), Kp and AE indices) for the main phase time interval as dependence of indices on integral value of sources, for example, Dst^i. *vs.* $Ey(\sum)^i = \int_0^{t^i} Ey(\tau)d\tau = \sum_0^i Ey^k$, $i = 0, .., 6$; $k = 0, .., i$.

[23] Dependencies of Dst (or Dst*) on the integral of Bz (or Ey) over time are almost linear and parallel for different types of drivers. This fact can be considered as an indication that time evolution of the main phase of storms depends not only on current values of Bz and Ey, but also on their prehistory. The differences between these lines are relatively small ($|\Delta Dst| < 20$ nT). Nevertheless we can make the following comparisons. For various drivers we approximated data near the central parts of dependencies by linear functions and using these linear functions we calculated values of Dst (or Dst*) at fixed values of integral of Bz and integral of Ey ($\int_0^t Bz(\tau)d\tau = -30$ h*nT and $\int_0^t Ey(\tau)d\tau = 12$ h*mV/m).

Table 2. Probability of Generation of Magnetic Storms With $Dst \leq -50$ nT (Geoeffectiveness) for Different Types of Solar Wind Streams During 1976–2000

Types of Solar Wind	Number of Observations of Interplanetary Events	Number of Storms Induced by This Type of Event	Part From Identified Storms (%)	Geoeffectiveness
CIR	717	145	31.2	0.202
Sheath before MC	79	12	2.6	0.142
Sheath before ejecta	543	84	18.1	0.155
MC with sheath	79	50	13.4	0.633
MC without sheath	22	12	2.6	0.545
Ejecta with sheath	543	115	24.8	0.212
Ejecta without sheath	585	46	9.9	0.078

Table 3. Ratio of Magnetospheric Indices to Integrated IMF *Bz* and *Ey* Fields[a]

Solar Wind Type	*Dst*/*Bz*	*Dst**/*Bz*	*Kp*/*Bz*	*AE*/*Bz*	*Dst*/*Ey*	*Dst**/*Ey*	*Kp*/*Ey*	*AE*/*Ey*
CIR	2.4	2.8	0.18	22.7	5.0	6.8	0.45	56.8
Ejecta	2.6	2.6	0.17	22.0	6.1	6.8	0.43	53.8
MC	1.9	2.1	0.17	22.3	4.3	4.9	0.42	54.2
Ejecta+MC	2.3	2.6	0.17	21.8	5.3	6.0	0.42	53.3
Sheath	2.4	3.0	0.20	24.3	4.9	6.3	0.46	57.9
IND	2.9	2.6	0.18	24.0	6.5	6.1	0.44	48.9

[a]Ratio at fixed values of $\int_0^t Bz(\tau)d\tau = -30$ h*nT and $\int_0^t Ey(\tau)d\tau = 12$ h*mV/m. Dimensions of coefficients: [*Dst*/*Bz*, *Dst**/*Bz*, *AE*/*Bz*] = nT/(h*nT), [*Kp*/*Bz*] = 1/(h*nT), [*Dst*/*Ey*, *Dst**/*Ey*, *AE*/*Ey*] = nT/(h*mV/m), and [*Kp*/*Ey*] = 1/(h*mV/m).

The ratio of these calculated values of *Dst* (or *Dst**) indices to the fixed values of integrated *Bz* (or *Ey*) is a quantitative estimation of the process efficiency (see values *Dst*/*Bz*, *Dst*/*Ey*, *Dst**/*Bz* and *Dst**/*Ey* in Table 3). It should be noted that *Nikolaeva et al.* [2012] found integrated *Ey* threshold for generation of magnetic storms with $Dst \leq -50$ nT and the used value of integral of $Ey = 12$ h*mV/m is located near this threshold (i.e., the used interval of integral of *Ey* contains data for almost all magnetic storms). The value $\int_0^t Bz(\tau)d\tau = -30$ h*nT was recalculated from threshold value for *Ey*. Taking into account that differences in "efficiency coefficients" for various drivers are mathematically significant when they differ more by than 10% (i.e., 0.25 nT/(h*nT) for *Bz* and 0.5 nT/(h*mV/m) for *Ey*), it is possible to note that (1) dependencies of *Dst* (or *Dst**) on the integral of *Bz* (or *Ey*) are higher in CIR, sheath and ejecta than in MC (i.e., efficiency of MC for the process of magnetic storm generation is the lowest one) and (2) efficiency of CIR, sheath and ejecta are closed to each other. Dependencies of *Kp* (and *AE*) on integral of *Bz* (and *Ey*) are nonlinear (there is the saturation effect for *AE* index) and nonparallel. Nevertheless we made the same procedure for them as for *Dst* and *Dst** indices and calculated estimations of efficiency for different drivers. Efficiency for *Kp* and *AE* indices is higher for CIR and sheath than for MC and ejecta.

[24] Figure 2 (crosses) presents the solar cycle variation in efficiency of magnetic storm generation *Ef* (value *Dst*/*Ey* in Table 3) for four interplanetary drivers. Variations in efficiency for CIR, sheath and ejecta are small in comparison with data deviation, and minimum of *Ef* for MC during the declining phase of the solar cycle may be connected with small statistics of MC observations. Nevertheless, it is possible to indicate that CIR has *Ef* minimum during the rising phase, sheath during the rising and maximum phases, and ejecta has *Ef* maximum during the maximum phase.

4. Discussion and Conclusions

[25] The amount of the Sun's energy flowing into the magnetosphere and causing magnetospheric disturbances, is defined by the following processes and relations: (1) relative occurrence rate of disturbed types of solar wind streams (interplanetary drivers of magnetic storms), (2) typical values of plasma and field parameters in these types of streams, (3) probability of magnetic storm generation (geoeffectiveness) for these drivers (i.e., probability of occurrence of the southward IMF *Bz* component in these drivers), and (4) efficiency of physical process of magnetic storm generation for various drivers.

[26] On the basis of OMNI data for 1976–2000 we estimated and compared for the first time the entire set of these processes and relations for main set of interplanetary drivers of magnetic storms (CIR, MC, ejecta, SHE_{MC} and SHE_{Ej}).

[27] The results of our identification of solar wind streams [*Yermolaev et al.*, 2009] were partially compared with tabulated data of various events presented on the websites http://star.mpae.gwdg.de and http://lempfi.gsfc.nasa.gov, as well as with the ISTP Solar Wind Catalog on the website http://www-spof.gsfc.nasa.gov/scripts/sw-cat/Catalog- events.html and presented in papers by *Cane and Richardson* [2003], *Richardson and Cane* [2004], *Huttunen et al.* [2005], *Dmitriev et al.* [2005], *Alves et al.* [2006], *Koskinen and Huttunen* [2006], *Echer et al.* [2006], *Zhang et al.* [2007], *Jian et al.* [2008], *Lepping and Wu* [2010], and *Thatcher and Muller* [2011]. This comparison showed a good agreement in more than 90% of events. It is important to note that, unlike numerous papers where solar wind identifications were made for selection of only one or two stream types, we realized this approach with a single set of criteria to eight large-scale stream types and five types from them are analyzed in this paper as drivers of magnetic storms. The obtained statistical characteristics and distributions of the solar wind and IMF parameters in various types of the streams well agree with previously obtained results.

[28] During the full time from 1976 to 2000 the different types of the solar wind were observed: MC for $2 \pm 1\%$, ejecta for $20 \pm 6\%$, sheath before ejecta for $8 \pm 4\%$, sheath before MC for $0.8 \pm 0.7\%$, and CIR for $10 \pm 3\%$ of the total observation time. About 53% of the entire observation time fell on the fast and slow solar wind (21.5% and 31.5% of time, respectively) (see Figure 1 and Table 1) [*Yermolaev et al.*, 2010a, 2010b]. The numbers of sheath, MC and ejecta events have maximum during rising and maximum phases of the solar cycle, while CIR has maximum during declining phase (Figure 2). Our new results show that large values of mass, momentum and energy are transported from the Sun to the Earth by CIR and sheath, and of magnetic field by MC (see Figure 3).

[29] The probabilities that conditions in the interplanetary space allow the solar wind to input energy to in magnetosphere and generate magnetic storm with $Dst \leq -50$ nT are about 55% for MC (63% for MC with sheath), about 20% for CIR, about 8% for ejecta (21% for ejecta with sheath) and 15% for sheath (see Table 2). Because of different occurrence rates of various solar wind streams it was found that 35% of storms were generated by ejecta with/without sheath, 31% by CIR and 24% by MC with/without sheath (about 20% by sheath before MC and ejecta). Taking into account dependence of numerical estimation on the used method of data analysis, the values of geoeffectiveness obtained by us for MC and ejecta (both with sheath and without sheath) are in a good agreement with previous result (see review by *Yermolaev and Yermolaev* [2010]). Our estimation of CIR geoeffectiveness (about 20%) is lower than that obtained early by *Alves et al.* [2006]. Geoeffectiveness of sheath, MC and ejecta has maximum during the maximum and declining phases of the solar cycle, CIR has minimum during the minimum phase (Figure 2).

[30] The numerical estimations made in this work show that efficiency of MC for the process of magnetic storm generation (for *Dst* and *Dst** indices) is the lowest one, and efficiency for *Kp* and *AE* indices is higher for CIR and sheath than for MC and ejecta. Higher efficiency of the process of magnetic storms generation by sheath than MC are discussed in several papers [*Huttunen and Koskinen*, 2004; *Huttunen et al.*, 2006; *Yermolaev et al.*, 2007a, 2007b, 2007c, 2010d; *Pulkkinen et al.*, 2007a; *Turner et al.*, 2009; *Guo et al.*, 2011]. Our results confirm this conclusion. These data give evidence in favor of the hypotheses of considerable effect of density (and the dynamic and thermal pressures) and its variations, and IMF variations on the magnetospheric activity [see, e.g., *Borovsky and Funsten*, 2003; *D'Amicis et al.*, 2007; *Khabarova and Yermolaev*, 2008; *Weigel*, 2010; and references therein].

[31] Figure 2 shows that there is no solar cycle correlation between geoeffectiveness and efficiency for different types of the solar wind streams. This fact gives evidence in favor suggestion that geoeffectiveness (probability) of all types of streams is connected with solar and interplanetary processes, but not with magnetospheric ones.

[32] Thus obtained results show that despite the low occurrence rate and low efficiency of magnetic clouds they play an essential role in generation of magnetic storms due to high geoeffectiveness of storm generation (i.e., high probability to contain large and long-term southward IMF *Bz* component). Geoeffectiveness of CIR and sheath are lower, but they are compensated by higher occurrence rate and efficiency.

[33] **Acknowledgments.** The authors are grateful for the opportunity to use the OMNI database. The OMNI data were obtained from GSFC/SPDF OMNIWeb (http://omniweb.gsfc.nasa.gov). This work was supported by the Russian Foundation for Basic Research, projects 07–02–00042 and 10–02–00277a, and by Program 15 of the Physics Department of the Russian Academy of Sciences (OFN RAN) and Program 22 of Presidium of the Russian Academy of Sciences.

[34] Masaki Fujimoto thanks the reviewers for their assistance in evaluating this paper.

References

Akasofu, S.-I. (1981), Energy coupling between the solar wind and the magnetosphere, *Space Sci. Rev.*, *28*, 121–190, doi:10.1007/BF00218810.
Alves, M. V., E. Echer, and W. D. Gonzalez (2006), Geoeffectiveness of corotating interaction regions as measured by *Dst* index, *J. Geophys. Res.*, *111*, A07S05, doi:10.1029/2005JA011379.
Alves, M. V., E. Echer, and W. D. Gonzalez (2011), Geoeffectiveness of solar wind interplanetary magnetic structures, *J. Atmos. Sol. Terr. Phys.*, *73*, 1380–1384.
Borovsky, J. E., and M. H. Denton (2006), Differences between CME-driven storms and CIR-driven storms, *J. Geophys. Res.*, *111*, A07S08, doi:10.1029/2005JA011447.
Borovsky, J. E., and H. O. Funsten (2003), Role of solar wind turbulence in the coupling of the solar wind to the Earth's magnetosphere, *J. Geophys. Res.*, *108*(A6), 1246, doi:10.1029/2002JA009601.
Burlaga, L. F. (1991), Magnetic clouds, in *Physics of the Inner Heliosphere II:Particles, Waves, and Turbulence*, *Phys. Chem. Space*, vol. 20, edited by R. Schwenn and E. Marsch, Springer, New York.
Burton, R. K., R. L. McPherron, and C. T. Russell (1975), An empirical relationship between interplanetary conditions and *Dst*, *J. Geophys. Res.*, *80*, 4204–4214.
Cane, H. V., and I. G. Richardson (2003), Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–2002, *J. Geophys. Res.*, *108*(A4), 1156, doi:10.1029/2002JA009817.
D'Amicis, R., R. Bruno, and B. Bavassano (2007), Is geomagnetic activity driven by solar wind turbulence?, *Geophys. Res. Lett.*, *34*, L05108, doi:10.1029/2006GL028896.
Denton, M. H., J. E. Borovsky, R. M. Skoug, M. F. Thomsen, B. Lavraud, M. G. Henderson, R. L. McPherron, J. C. Zhang, and M. W. Liemohn (2006), Geomagnetic storms driven by ICME- and CIR-dominated solar wind, *J. Geophys. Res.*, *111*, A07S07, doi:10.1029/2005JA011436.
Despirak, I. V., A. A. Lubchich, A. G. Yahnin, B. V. Kozelov, and H. K. Biernat (2009), Development of substorm bulges during different solar wind structures, *Ann. Geophys.*, *27*, 1951–1960.
Despirak, I. V., A. A. Lubchich, and V. Guineva (2011), Development of substorm bulges during storms of different interplanetary origins, *J. Atmos. Sol. Terr. Phys.*, *73*, 1460–1464.
Dmitriev, A. V., N. B. Crosby, and J.-K. Chao (2005), Interplanetary sources of space weather disturbances in 1997 to 2000, *Space Weather*, *3*, S03001, doi:10.1029/2004SW000104.
Dungey, J. W. (1961), Interplanetary magnetic field and the auroral zones, *Phys. Rev. Lett.*, *6*, 47–48.
Echer, E., and W. D. Gonzalez (2004), Geoeffectiveness of interplanetary shocks, magnetic clouds, sector boundary crossings and their combined occurrence, *Geophys. Res. Lett.*, *31*, L09808, doi:10.1029/2003GL019199.
Echer, E., W. D. Gonzalez, and M. V. Alves (2006), On the geomagnetic effects of solar wind interplanetary magnetic structures, *Space Weather*, *4*, S06001, doi:10.1029/2005SW000200.
Echer, E., W. D. Gonzalez, and B. T. Tsurutani (2011), Statistical studies of geomagnetic storms with peak $Dst < -50$ nT from 1957 to 2008, *J. Atmos. Sol. Terr. Phys.*, *73*, 1454–1459.
Fairfield, D. H., and L. J. Cahill Jr. (1966), The transition region magnetic field and polar magnetic disturbances, *J. Geophys. Res.*, *71*, 155–169.
Gonzalez, W. D., and E. Echer (2005), Study on the peak *Dst* and peak negative *Bz* relationship during intense geomagnetic storms, *Geophys. Res. Lett.*, *32*, L18103, doi:10.1029/2005GL023486.
Gonzalez, W. D., B. T. Tsurutani, and A. L. Clúa de Gonzalez (1999), Interplanetary origin of geomagnetic storms, *Space Sci. Rev.*, *88*, 529–562.
Gonzalez, W. D., E. Echer, B. T. Tsurutani, A. L. Clúa de Gonzalez, and A. Dal Lago (2011), Interplanetary origin of intense, superintense and extreme geomagnetic storms, *Space Sci. Rev.*, *158*, 69–89, doi:10.1007/s11214-010-9715-2.
Guo, J., X. Feng, B. A. Emery, J. Zhang, C. Xiang, F. Shen, and W. Song (2011), Energy transfer during intense geomagnetic storms driven by interplanetary coronal mass ejections and their sheath regions, *J. Geophys. Res.*, *116*, A05106, doi:10.1029/2011JA016490.
Huttunen, K. E. J., and H. E. J. Koskinen (2004), Importance of postshock streams and sheath region as drivers of intense magnetospheric storms and high-latitude activity, *Ann. Geophys.*, *22*, 1729–1738, doi:10.5194/angeo-22-1729-2004.
Huttunen, K. E. J., R. Schwenn, V. Bothmer, and H. E. J. Koskinen (2005), Properties and geoeffectiveness of magnetic clouds in the rising, maximum and early declining phases of solar cycle 23, *Ann. Geophys.*, *23*, 625–641.
Huttunen, K. E. J., H. E. J. Koskinen, A. Karinen, and K. Mursula (2006), Asymmetric development of magnetospheric storms during magnetic clouds and sheath regions, *Geophys. Res. Lett.*, *33*, L06107, doi:10.1029/2005GL024894.
Jian, L. K., C. T. Russell, J. G. Luhmann, R. M. Skoug, and J. T. Steinberg (2008), Stream interactions and interplanetary coronal mass ejections at 0.72 AU, *Sol. Phys.*, *249*, 85–101, doi:10.1007/s11207-008-9161-4.
Khabarova, O. V., and Y. I. Yermolaev (2008), Solar wind parameters behavior before and after magnetic storms, *J. Atmos. Sol. Terr. Phys.*, *70*, 384–390, doi:10.1016/j.jastp.2007.08.024.
King, J. H., and N. E. Papitashvili (2005), Solar wind spatial scales in and comparisons of hourly Wind and ACE plasma and magnetic field data, *J. Geophys. Res.*, *110*, A02209, doi:10.1029/2004JA010649.
Koskinen, H. E. J., and K. E. J. Huttunen (2006), Geoeffectivity of coronal mass ejections, *Space Sci. Rev.*, *124*, 169–181, doi:10.1007/s11214-006-9103-0.
Lepping, R. P., and C.-C. Wu (2010), Selection effects in identifying magnetic clouds and the importance of the closest approach parameter, *Ann. Geophys.*, *28*, 1539–1552, doi:10.5194/angeo-28-1539-2010.
Longden, N., M. H. Denton, and F. Honary (2008), Particle precipitation during ICME-driven and CIR-driven geomagnetic storms, *J. Geophys. Res.*, *113*, A06205, doi:10.1029/2007JA012752.
Lopez, R. E. (1987), Solar cycle invariance in solar wind proton temperature relationships, *J. Geophys. Res.*, *92*, 11,189–11,194.
Mustajab, F., and Badruddin (2011), Geoeffectiveness of the interplanetary manifestations of coronal mass ejections and solar-wind stream–stream interactions, *Astrophys. Space Sci.*, *331*, 91–104, doi:10.1007/s10509-010-0428-5.
Nikolaeva, N. S., Y. I. Yermolaev, and I. G. Lodkina (2011), Dependence of geomagnetic activity during magnetic storms on the solar wind parameters for different types of streams [in Russian], *Geomagn. Aeron.*, *51*, 51–67. [*Geomagn. Aeron.*, Engl. Transl., *51*, 49–65.]

Nikolaeva, N. S., Y. I. Yermolaev, and I. G. Lodkina (2012), Dependence of geomagnetic activity during magnetic storms on the solar wind parameters for different types of streams: 2. Main phase of storm, *Geomagn. Aeron.*, *52*, 31–40. [*Geomagn. Aeron.*, Engl. Transl., *52*, 28–36.]

Plotnikov, I. Y., and E. S. Barkova (2007), Nonlinear dependence of *Dst* and *AE* indices on the electric field of magnetic clouds, *Adv. Space Res.*, *40*, 1858–1862.

Pulkkinen, T. I., N. Partamies, K. E. J. Huttunen, G. D. Reeves, and H. E. J. Koskinen (2007a), Differences in geomagnetic storms driven by magnetic clouds and ICME sheath regions, *Geophys. Res. Lett.*, *34*, L02105, doi:10.1029/2006GL027775.

Pulkkinen, T. I., N. Partamies, R. L. McPherron, M. Henderson, G. D. Reeves, M. F. Thomsen, and H. J. Singer (2007b), Comparative statistical analysis of storm time activations and sawtooth events, *J. Geophys. Res.*, *112*, A01205, doi:10.1029/2006JA012024.

Richardson, I. G., and H. V. Cane (2004), The fraction of interplanetary coronal mass ejections that are magnetic clouds: Evidence for a solar cycle variation, *Geophys. Res. Lett.*, *31*, L18804, doi:10.1029/2004GL020958.

Rostoker, G., and C.-G. Falthammar (1967), Relationship between changes in the interplanetary magnetic field and variations in the magnetic field at the Earth's surface, *J. Geophys. Res.*, *72*, 5853–5863.

Russell, C. T., R. L. McPherron, and R. K. Burton (1974), On the cause of magnetic storms, *J. Geophys. Res.*, *79*, 1105–1109.

Thatcher, L. J., and H.-R. Muller (2011), Statistical investigation of hourly OMNI solar wind data, *J. Geophys. Res.*, *116*, A12107, doi:10.1029/2011JA017027.

Tsurutani, B. T., and W. D. Gonzalez (1997), The interplanetary causes of magnetic storms: A review, in *Magnetic Storms*, *Geophys. Monogr. Ser.*, vol. 98, edited by B. T. Tsurutani et al., pp. 77–89, AGU, Washington, D. C.

Tsurutani, B. T., W. D. Gonzalez, F. Tang, S. I. Akasofu, and E. J. Smith (1988), Origin of interplanetary southward magnetic fields responsible for major magnetic storms near solar maximum (1978–1979), *J. Geophys. Res.*, *93*(A8), 8519–8531.

Turner, N. E., W. D. Cramer, S. K. Earles, and B. A. Emery (2009), Geoefficiency and energy partitioning in CIR-driven and CME-driven storms, *J. Atmos. Sol. Terr. Phys.*, *71*, 1023–1031.

Weigel, R. S. (2010), Solar wind density influence on geomagnetic storm intensity, *J. Geophys. Res.*, *115*, A09201, doi:10.1029/2009JA015062.

Xu, D., T. Chen, X. X. Zhang, and Z. Liu (2009), Statistical relationship between solar wind conditions and geomagnetic storms in 1998–2008, *Planet. Space Sci.*, *57*, 1500–1513.

Yermolaev, Y. I., and M. Y. Yermolaev (2002), Statistical relationships between solar, interplanetary, and geomagnetospheric disturbances, 1976–2000, *Cosmic Res., Engl. Transl.*, *40*(1), 1–14.

Yermolaev, Y. I., and M. Y. Yermolaev (2006), Statistic study on the geomagnetic storm effectiveness of solar and interplanetary events, *Adv. Space Res.*, *37*(6), 1175–1181.

Yermolaev, Y. I., and M. Y. Yermolaev (2010), Solar and interplanetary sources of geomagnetic storms: Space weather aspects, *Izv. Russ. Acad. Sci. Atmos. Oceanic Phys., Engl. Transl.*, *46*(7), 799–819.

Yermolaev, Y. I., M. Y. Yermolaev, I. G. Lodkina, and N. S. Nikolaeva (2007a), Statistic investigation of heliospheric conditions resulting in magnetic storms, *Cosmic Res., Engl. Transl.*, *45*(1), 1–8.

Yermolaev, Y. I., M. Y. Yermolaev, I. G. Lodkina, and N. S. Nikolaeva (2007b), Statistic investigation of heliospheric conditions resulting in magnetic storms: 2, *Cosmic Res., Engl. Transl.*, *45*(6), 461–470.

Yermolaev, Y. I., M. Y. Yermolaev, N. S. Nikolaeva, and L. G. Lodkina (2007c), Interplanetary conditions for CIR-induced and MC-induced geomagnetic storms, *Bulg. J. Phys.*, *34*, 128–135.

Yermolaev, Y. I., N. S. Nikolaeva, I. G. Lodkina, and M. Y. Yermolaev (2009), Catalog of large-scale solar wind phenomena during 1976–2000, *Kosm. Issled.*, *47*(2), 99–113. [*Cosmic Res.*, Engl. Transl., *47*(2), 81–94.]

Yermolaev, Y. I., N. S. Nikolaeva, I. G. Lodkina, and M. Y. Yermolaev (2010a), Relative occurrence rate and geoeffectiveness of large-scale types of the solar wind, *Kosm. Issled.*, *48*(1), 3–32. [*Cosmic Res.*, Engl. Transl., *48*(1), 1–30.]

Yermolaev, Y. I., N. S. Nikolaeva, I. G. Lodkina, and M. Y. Yermolaev (2010b), Large-scale solar wind structures: Occurrence rate and geoeffectiveness, *AIP Conf. Proc.*, *1216*, 648–651.

Yermolaev, Y. I., N. S. Nikolaeva, I. G. Lodkina, and M. Y. Yermolaev (2010c), Specific interplanetary conditions for CIR-, sheath-, and ICME-induced geomagnetic storms obtained by double superposed epoch analysis, *Ann. Geophys.*, *28*, 2177–2186.

Yermolaev, Y. I., I. G. Lodkina, N. S. Nikolaeva, and M. Y. Yermolaev (2010d), Statistical study of interplanetary condition effect on geomagnetic storms, *Kosm. Issled.*, *48*(6), 499–515. [*Cosmic Res.*, Engl. Transl., *48*(6), 485–500.]

Yermolaev, Y. I., I. G. Lodkina, N. S. Nikolaeva, and M. Y. Yermolaev (2011), Statistical study of interplanetary condition effect on geomagnetic storms: 2. Variations of parameters, *Cosmic Res., Engl. Transl.*, *49*(1), 21–34.

Zhang, J., et al. (2007), Solar and interplanetary sources of major geomagnetic storms ($Dst < -100$ nT) during 1996–2005, *J. Geophys. Res.*, *112*, A10102, doi:10.1029/2007JA012321.