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

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Abstract.

We investigate 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 their interplanetary sources: corotating interaction regions (CIR), interplanetary CME (ICME) including magnetic clouds (MC) and Ejecta and compression regions Sheath before both types of ICME. For various types of solar wind we study following relative characteristics: occurrence rate; mass, momentum, energy and magnetic fluxes; probability of generation of magnetic storm (geoeffectiveness) and efficiency of process of this generation. Obtained results show that despite magnetic clouds have lower occurrence rate 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).

1. Introduction

One of key issues of the 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 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]. 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 CME (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, b, c]; *Pulkkinen et al.* [2007a, b]; *Zhang et al.* [2007]; *Turner et al.* [2009]; *Yermolaev et al.* [2010a, b, c, d, 2011]; *Nikolaeva et al.* [2011]; *Alves et al.* [2011]; *Echer et al.* [2011]; *Gonzalez et al.* [2011]; *Guo et al.* [2011]; *Mustajab and Badruddin* [2011] and references therein).

Experimental results showed 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]. 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 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, b, c; *Pulkkinen et al.*, 2007a; *Yermolaev and Yermolaev*, 2010; *Yermolaev et al.*, 2010a, b, 2011; *Alves et al.*, 2011; *Despirak et al.*, 2011; *Nikolaeva et al.*, 2011; *Guo et al.*, 2011].

Papers mentioned above are devoted studying of response of magnetosphere to interplanetary drives and use word *geoeffectiveness* for a designation of this link. It should be noted that there is a double meaning of the term *geoeffectiveness*. In one case, *geoeffectiveness* implies a probability with which selected 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 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. Below we will use 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.

A considerable quantity of papers is devoted investigations of geoeffectiveness in generation of magnetic storm. The great bulk of works studies geoeffectiveness of magnetic

clouds, and geoeffectiveness of other phenomena is studied rather poorly (see, for example, one of recent reviews by *Yermolaev and Yermolaev* [2006, 2010]; *Alves et al.* [2011]. So, one of the main aims of current paper is investigation of geoeffectiveness of various interplanetary drivers and comparison of them to each other.

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, paper by *Turner et al.* [2009]; *Yermolaev et al.* [2010c] and references therein). In our 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.

2. Methods

When the types of solar wind streams were classified, we used OMNI database (see http://omniweb.gsfc. nasa.gov [*King and Papitashvili*, 2004]) for interval 1976-2000 and available world experience in identification of solar wind streams and the standard criteria for 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 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 preceding them). In contract 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 such events (rare enough) as direct and reverse shocks, and the rarefaction region (region with low density) Rare but these types of events are not analyzed in this paper.

In order to calculate yearly averaged values, we have taken into consideration that the OMNI database contains gaps of the data from 0 to 50% time of year. This procedure has been made in the assumption that occurrence rate of given type of solar wind streams is similar both in intervals of data presence and in intervals of data gap. If during chosen year the number of events of selected solar wind type Ne has been registered in interval of data presence t_d the normalized number of the given solar wind type Ne^* in this year was defined by multiplication of occurrence rate of the given solar wind type Ne/t_d to total duration of year t_y, i.e. $Ne^* = (Ne/t_d) * t_y$. Normalized number of solar wind events is used only for studying the time variations in occurrence rate of various types of streams and measured number of events is used to calculate geoeffectiveness of types of events. When we analyzed durations of different types of solar wind streams, we selected intervals of types of streams which have not data gaps at both edges of the intervals.

Definite 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 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, c]. Thus, two hours 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.

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, d]. 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 is 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 main phase for storms with different durations.

3. Results

Obtained results are presented in 3 subsections 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

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 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 publication [*Yermolaev et al.*, 2009, 2010a, b, c, d, 2011]. It should be noted that both types of compressed regions (CIR and Sheath) have very close values of parameters while the parameters for 2 types of ICME (Ejecta and MC) are different. In figure 1 we present yearly average values of sunspots (top panel) and yearly average distributions of times of observations for different types of solar wind streams (bottom panel). Data for different types of streams are showed by various color columns (see designation on the right of the figure) with height proportional to percent 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 but time of disturbed types of streams decreases down to 25% during solar minimum and increases up to 50% during solar maximum.

Various types of solar wind streams transport different values of mass, momentum, energy and magnetic field from the Sun to the Earth. Figure 2 shows average distributions (percentage) of values (red columns) and total Sun's losses (parameters integrated over time, blue columns) mass, momentum, energy and magnetic fluxes for different types of 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 total

losses are higher in steady types of streams (Fast and Slow) than in disturbed types of streams. In following sections of the paper we will analyze how 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

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 3). But only for 464 magnetic storms (i.e., for 58% of all magnetic storms) corresponding various 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 3) are undeterminate, 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 4 presents distribution of storms when we excluded IND storms from analyses.

Analyses of data in Figures 1 and 4 allows us to compare number of each type of solar wind streams and number of magnetic storms induced by these types of streams and to calculate probability (geoeffectiveness) of generation of magnetic storms by each types of these interplanetary drivers (see Table 2). Though the statistics of annual numbers of solar wind streams is small, the available data speak in favour of suggestion that geoeffectiveness does not change essentially during solar cycle.

3.3. Efficiency of interplanetary drivers

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. We found a 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 time interval of "0"–"6" as depen-

dence of indices on integral value of sources, for example, $Dst^i.vs.Ey(\sum)^i = \int_0^{t^i} Ey(\tau)d\tau =$

$\sum_0^i Ey^k, i = 0, ..., 6; k = 0, ..., i.$

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 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 following comparisons. For various

drivers we approximated data near central parts dependencies by linear functions and

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) (see Table 3). It should be

noted that used value of integral of Ey is located near threshold of generation of magnetic

storms with $Dst \leq -50$ nT (i.e. used interval of integral of Ey contains data for almost all

magnetic storms) [*Nikolaeva et al.*, 2012]. Taking into account that difference in "efficiency

coefficients" for various drivers are mathematically significant when they differ more 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 process of magnetic storm

generation is the lowest one); (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.

4. Discussion and conclusions

The quantity of Sun's energy flowing in a magnetosphere and causing magnetospheric disturbances, is defined by 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 in magnetic storm generation (geoeffectiveness) for these drivers (i.e. probability of occurrence of southward IMF Bz component in these drivers), and

4. efficiency of physical process of magnetic storm generation for various drives.

On the basis of OMNI data during 1976–2000 we estimated and compared these processes and relations.

The results of our identification of solar wind streams were partially compared with tabulated data of various events presented on the websites http://star.mpae.gwdg.de/, http://lempfi.gsfc.nasa.gov/, and 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]; *Alves et al.* [2006]; *Koskinen and Huttunen* [2006]; *Echer et al.* [2006]; *Zhang et al.* [2007]. 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. The obtained sta-

tistical characteristics and distributions of the solar wind and IMF parameters in various types of the streams well agree with previously obtained results

During the full time from 1976 to 2000 the different types of the solar wind were observed: HCS for $6 \pm 4\%$, 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 fast and slow solar wind (21.5% and 31.5% of time, respectively) (see Figure 1 and Table 1). 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 2).

Probabilities that conditions in the interplanetary space allow to input solar wind energy to 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 different solar wind streams it was found that 35% 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 used method of data analysis , 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 one obtained early by *Alves et al.* [2006].

Our estimations show that efficiency of MC for 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 magnetic storms

generation process by Sheath than MC are discussed in several papers [*Huttunen and Koskinen*, 2004; *Huttunen et al.*, 2006; *Yermolaev et al.*, 2007a, b, c, 2010c; *Pulkkinen et al.*, 2007a; *Turner et al.*, 2009; *Guo et al.*, 2011]. Our results confirm this conclusion.

Thus obtained results show that despite 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). Geoeffectivenesses of CIR and Sheath are lower but they are compensated by higher occurrence rate and efficiency.

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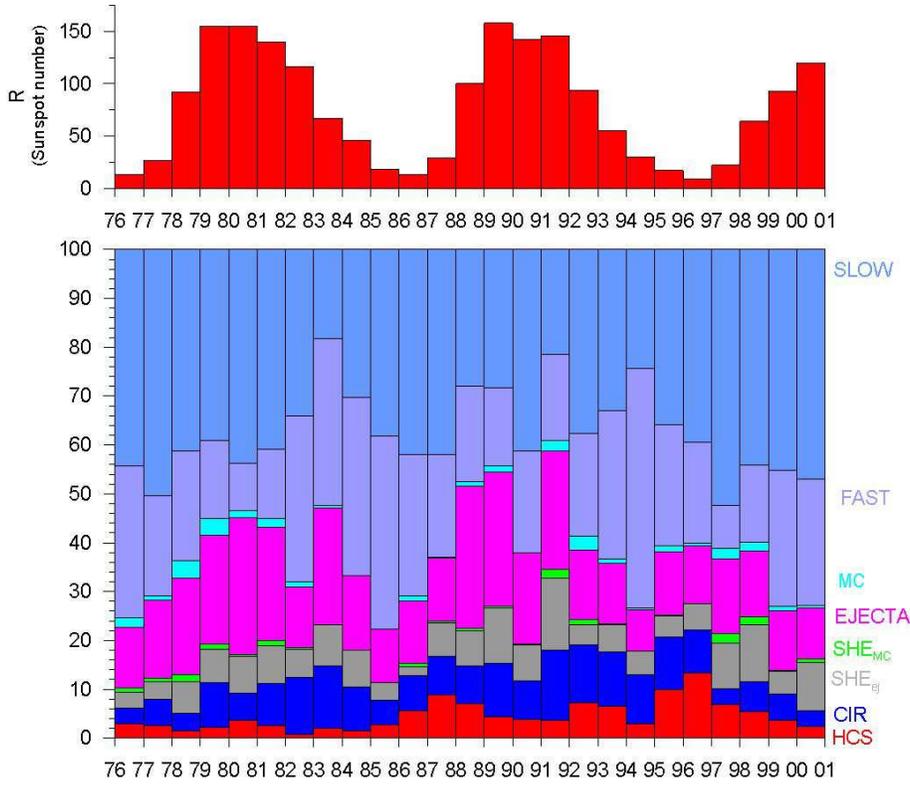
Figure 1.　Yearly average values of sunspots (top panel) and yearly average distributions of times of observations for different types of solar wind (%, bottom panel).
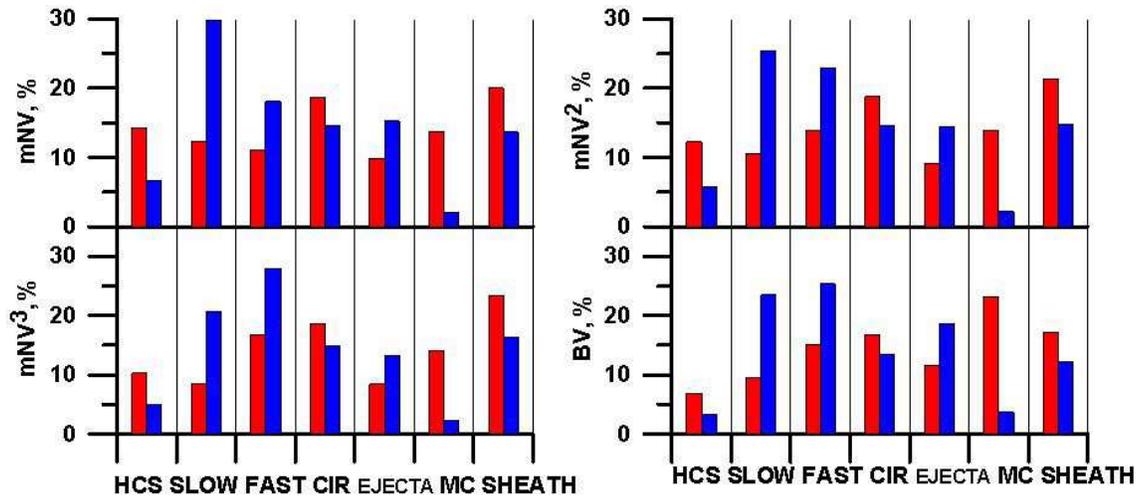
Figure 2.　Average values (red columns) and Suns losses (blue columns) mass, momentum, energy and magnetic fluxes for different types of solar wind streams (%).
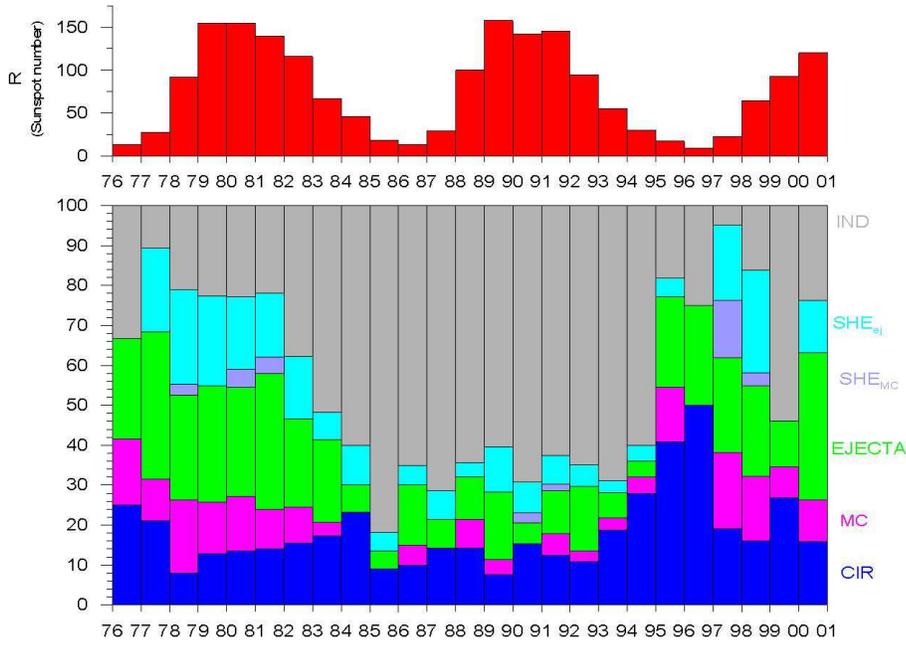
Figure 3. Sunspot number (top panel) and year-averaged distributions of magnetic storms with $Dst < -50$ nT over types of their interplanetary drivers (%, bottom panel).
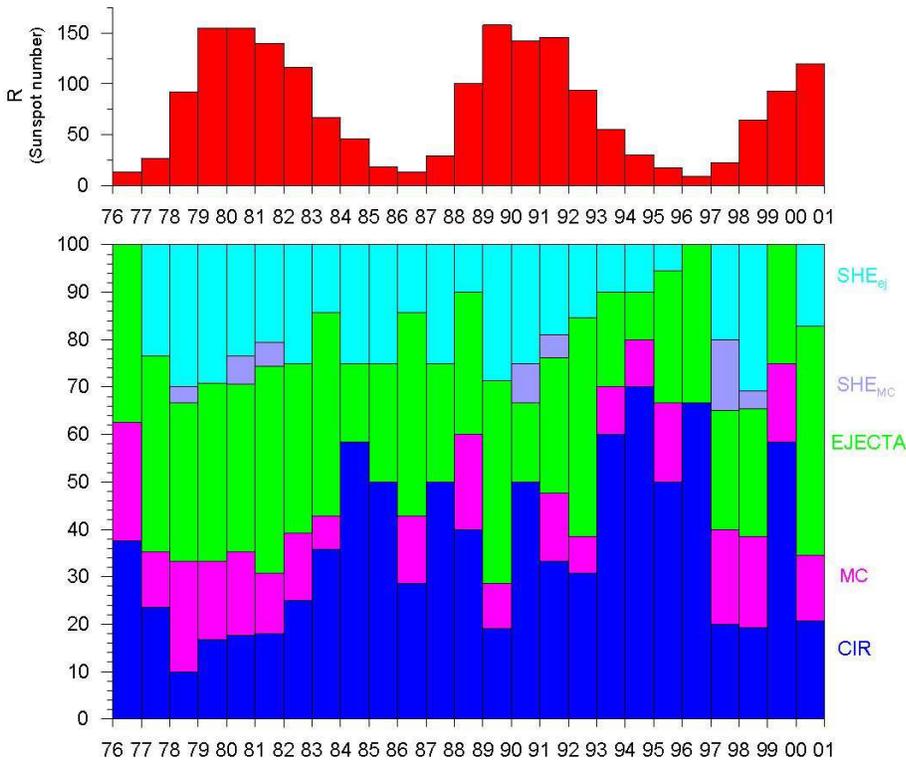
Figure 4. The same as in Figure 3 when IND storms was excluded from analyses

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

Table 2. Probability of generation of magnetic storms with $Dst \leq -50nT$ (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 events	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

(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) [a]

SW 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] 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$)$