Interplanetary conditions for CIR-induced and MC-induced geomagnetic storms

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Abstract

We present a comparison of conditions in the interplanetary space during geomagnetic storms which are generated by 2 types of large-scale interplanetary phenomena - corotating interaction region (CIR) and magnetic cloud (MC or interplanetary coronal mass ejection, ICME). We select also 2 geoeffective parts of MC - compressed region ahead of leading edge of MC (Sheath) and the body of MC. Superposed epoch analyses of interplanetary parameters during 1976-2000 are used separately (1) for 2 epoch zero times: start and end of main phase of geomagnetic storms and (2) for 4 categories of solar wind: CIR (121 storms), Sheath (22), MC (113), and "uncertain"(367). Though the greatest southward IMF component is observed, on the average, in magnetic clouds, the strongest storms are generated by Sheath (but not body of MC). In spite of large differences of parameters in various types of solar wind, the turning of IMF exerts primary control over start and end of a magnetic storm.

Key words: Solar flares, Coronal mass ejections, Geomagnetic storms, Space weather
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1 Introduction

After the experimental discovery that southward turn of interplanetary magnetic field (IMF) leads to magnetic storms at the Earth (Fairfield and Cahill,

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1966; Russell et al., 1974; Burton et al., 1975), the conditions in the solar wind (SW) resulting in magnetic storms are a subject of long and intensive investigations. Numerous studies showed that magnitude and features of magnetic storms depends not only on current values of IMF and SW parameters but also on temporal evolution of them. Therefore the superposed epoch analyses allowing the investigation of the average behaviour of these parameters was used in a number of papers (see Table 1).

The main difference of these papers is the time which was chosen as the epoch zero time. If onset time is chosen, the parameters before zero time allow one to investigate the reasons for the beginning of the main phase of a storm. If time of minimum Dst index is chosen, it is possible to similarly investigate the reasons for the termination of the main phase and the beginning of recovery phase of a storm. However, some researchers often tried to investigate the reason for onset using the second approach (Maltsev et al., 1996; Loewe and Prolss, 1997; Zhang et al., 2006), but this is unjustified because duration of the main phase lasts from 2 till 15 hours (Vichare et al., 2005; Gonzalez and Echer, 2005; Yermolaev et al., 2006), and inside of an interval with duration of several hours the parameters measured before and after onset are averaged simultaneously.

On the other hand, in many papers it was noted, that magnetic storms are generated basically by several types of solar wind: magnetic cloud (or ICME) including Sheath and body of MC (ICME) and corotating intereaction region (CIR) (see, for instance, Vieira et al. (2004); Huttunen and Koskinen (2004); Yermolaev et al. (2005); Yermolaev and Yermolaev (2006); Alves et al. (2006); Borovsky and Denton (2006) and references therein). Particularly, Huttunen and Koskinen (2004) showed that the largest fraction of 53 storms with Dst $<$ -100 nT during 1997-2002 was caused by a sheath region. Some papers present results of several kinds of data selection, but not over types of solar wind, and over other parameters, for example (Zhang et al., 2006), over a phase of solar cycle or a magnitude of magnetic storm. In this case, the result of averaging strongly depends on the real proportion between different types of solar wind included in the processed dataset rather than the parameters used for such a selection. In a paper by Miyoshi and Kataoka (2005) a selection on types of solar wind (CIR and MC including both body of MC and Sheath before it) has been made. According to numerous papers (see, for example, Crooker et al. (1999); Gosling et al. (1999); Lynch et al. (2003); Lepping et al. (2005); Yermolaev et al. (2006)) durations of CIR and MC on the average are about 1 day and, as a rule, do not exceed 2 days. Nevertheless the authors of paper by Miyoshi and Kataoka (2005) published Fig.1 where they presented several SW parameters categorized into three groups during time interval from -3 up to +5 days relative to minimum of Dst index, that is, for a time interval of 8 days. We believe that, taking into account the possible durations of CIR and MC types of solar wind, it is possible to calculate the parameters for maximum 4-day (from -2 up to +2 days) interval with correct data processing procedure.Therefore there are serious doubts that calculations in the paper by Miyoshi and Kataoka (2005) have been executed correctly.

In this paper we study interplanetary conditions resulting in magnetic storms on the basis of the OMNI dataset and use superposed epoch analyses of interplanetary parameters during 1976-2000 separately (1) for begining and end of main phase of geomagnetic storms and (2) for 4 categories of solar wind: CIR (121 storms), Sheath (22), Magnetic cloud (113), and "uncertain"(367).

2 Results

Figs.1 and 2 present results of processing of OMNI data for 623 magnetic storms with Dst < -60 nT during 1976-2000 which were obtained by superposed epoch method with 2 different epoch zero times: Dst storm onset and Dst minimum, respectively. Time profiles of SW and IMF parameters are shown separately for CIR, Sheath and MC. We designated as "uncertain" also storms for which there were not full set of measurements or the type could not be defined unambiguously. Methods of SW type classification are similar to ones described in reviews by Wimmer-Schweingruber et al. (2006) and Tsurutani et al. (2006) and references therein. Details of method used and several preliminary results may be found in papers by Yermolaev and Yermolaev (2002) and Yermolaev et al. (2005, 2006). Figs. 1 and 2 show similar parameters: (Left column) n - density, V - velocity, Pdyn - dynamic pressure, T - proton temperature, T/Texp - ratio of measured proton temperature to calculated temperature Texp using velocity V (Lopez and Freeman, 1986), Dst index, (Right) β - ratio of thermal to magnetic pressure, B, Bx, By and Bz - magnitude and GSM components of IMF and Kp index. Curves for different types of solar wind are presented by different symbols/color.

Average durations of Sheath, CIR and MC in our database are 9 ± 4, 20 ± 8 and 28 ± 12 hours, respectively. So, the durations of lines in the figures for Sheath and CIR are restricted by -12 till +12, for MC -12 till +18 and for "uncertain" type -12 till +24 hours. Nevertheless the errors of SW and IMF parameters may increase at the ends of (-12,+12) interval for the Sheath because of decrease in statistics. The variability of data for all parameters and for all types of solar wind is large, and therefore the Table 2 represents average values of their dispersions (standard deviations) in the most disturbed and interesting part: from -12 till +12 hours relative to onset. In cases discussed below the distinctions between curves are mathematically significant but they are less than corresponding dispersions, and in this case it is necessary to consider these distinctions as a tendency rather than a proven physical fact.

Fig.1. shows that the main phase of the "averaged storm" lasts about 8 hours and the time difference between minimum Bz and minimum Dst is about 6 hours while in Fig.2 there is no clearly defined main phase of the "averaged storm" and the time difference between minima Bz and Dst is only 1-2 hours, although in both cases the decrease in Dst index began in 1-2 hours after southward return of Bz component.

We discuss briefly the additional information arising from the selection of data based on SW types, and also the advantages of zero time choice. First of all, one can see in Fig.1 that although the largest souhward IMF component is observed in the body of MC the strongest storms as defined both by Dst (and corrected Dst* - not shown here) and Kp indexes were generated by the Sheath and not by the body of magnetic cloud. The highest value near onset is reached for density in the CIR and for velocity and Pdyn in the Sheath. It is interesting that in the Sheath near 6 hours before onset the large values (and variability, not shown here) of density and Pdyn are observed.

The magnitude of magnetic field B reaches a maximum near the beginning of storms (in 1-2 hours after onset) for "uncertain" type and CIR, and it has a decreasing shape within the limits of figure for Sheath and MC. The behavior of IMF Bz component has been described above. Bx and By components have no tendency near the beginning of a magnetic storm, since on the average they change near zero. But unique feature is observed for Sheath in an interval from -6 till +1 hours when the average of the By component is near -5 nT.

On the other side, comparison of Figs. 1 and 2 shows significant differences due to choice of zero time. For example, Fig. 1 demonstrates that the maxima of density n and of magnitude of magnetic field B for "uncertain" type and CIR are observed at storm onset, but Fig.2 does not allow one to make the same conclusions. For both choices of zero time there are significant differences in T/Texp and β, for CIR and Sheath, on one hand, and MC, on the other hand.

3 Discussion and Conclusions

The analysis of interplanetary conditions for 623 magnetic storms with Dst < -60 nT for the period 1976-2000 was made on the basis of the OMNI dataset. The analysis was carried out by the method of superposed epoch with two choices of zero times equal to time of the beginning of storm and the minimum Dst index and separately for parameters in CIR, Sheath and MC (or ICME). We obtained the following results.

1) The behaviour of solar wind parameters during magnetic storms essentially

differs for various types of solar wind. However for all types of solar wind we observed the occurrence of southward IMF Bz component for 1-2 hours prior to the beginning of a storm (with achievement of Bz minimum in 2-3 hours after the beginning of storm) and the increase of density and dynamic pressure of the solar wind.

2) Though the most minimum values of the IMF Bz component are observed in body of MC, the most minimum values of Dst index are reached in Sheath. Thus, the greatest magnetic storms are on the average raised during Sheath rather than during the passage of the body of a MC, probably, due to higher values of magnitude and variation of density and velocity (as well as combinations of these parameters - pressure and electric field VBz) in the Sheath. This result confirms the conclusion about high occurrence rate of strong magnetic storms during the Sheath obtained with the less statistics and for shorter time interval by Huttunen and Koskinen (2004).

3) Higher values of the parameters nkT, T/Texp and β are observed in the CIR and Sheath and lower values in the MC corresponding to physical essence of these types of solar wind and consistent with our selection of SW types.

4) The statement in paper by Lyatsky and Tan (2003) that IMF By component is negative before the beginning of a storm has proven to be true only for storms during the Sheath passage. Our results confirmed the hypothesis about compression of SW plasma before a storm by some "piston," discussed in paper by Lyatsky and Tan (2003). Our analyses showed that the role of the "piston" is played by the body of MC.

5) The unique and obvious reason for the termination of the main phase of storm is the northward turning of the IMF. Any variation of other parameters near to minimum Dst, apparently, does not play an important role.

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Table 1
List of results on interplanetary conditions of magnetic storms obtained by superposed epoch analysis

N	Number(Years)	Zero time	Selection	SW and IMF	Reference
1	538(1963-1991)	onset	No	B,Bx,By,Bz,V,T,n,Pdyn	Taylor et al. (1994)
2	120(1979-1984)	min Dst	No	Bz, n, V	Maltsev et al. (1996)
3	150(1963-1987)	Turning Bz	No	Bz,Pdyn	Davis et al. (1997)
4	305(1983-1991)	onset	No	Bz, Pdyn	Yokoyama and Kamide (1997)
5	1085(1957-1993)	min Dst	Dst	Bz, Pdyn	Loewe and Prolss (1997)
6	130(1966-2000)	onset	No	B,Bx,By,Bz,$\|Bx\|$, $\|By\|$, $\|Bz\|$,	
				V,n,Pdyn	Lyatsky and Tan (2003)
7	623(1976-2000)	onset	SW types[a]	B,Bx,By,Bz,V,T,n,Pdyn,	
				nkT, β, T/Texp	Yermolaev et al. (2005, 2006)
8	78(1996-2004)	min Dst	SW types[b]	B,Bz,dB/B,V,T,n,	Miyoshi and Kataoka (2005)
9	549(1974-2002)	min Dst	Yes[c]	B,Bx,By,Bz,$\|Bx\|$, $\|By\|$, $\|Bz\|$,	
				Bs, VBs,V,n,T,Pdyn	Zhang et al. (2006)

[a] - (1) CIR, (2) Sheath and (3) MC; [b] - (1) CIR and (2) MC (Sheath + MC body);
[c] - (1) moderate storm at solar minimum, (2) moderate storm at solar maximum, (3) strong storm at solar minimum, and (4) strong storm at solar maximum.

Table 2
Standard deviations of solar wind and IMF parameters (averaging in interval from -12 till +12 hours)

SW type	B nT	Bx nT	By nT	Bz nT	Tp kK	N cm^{-3}	V km/s	Kp	Dst nT	β	T/Tex	NkT nPa	Nv^2 nPa
Unknown	3.6	5.2	6.0	4.6	150	8.1	111	13.1	29	0.57	1.23	0.033	3.2
CIR	4.7	6.7	7.4	6.2	213	12.5	102	14.3	32	0.73	1.51	0.045	4.2
Sheath	5.6	5.2	9.0	7.1	133	11.8	88	13.5	36	0.61	1.00	0.036	7.7
MC	6.6	7.1	11.0	8.0	138	9.7	128	13.9	37	0.28	0.87	0.029	5.5

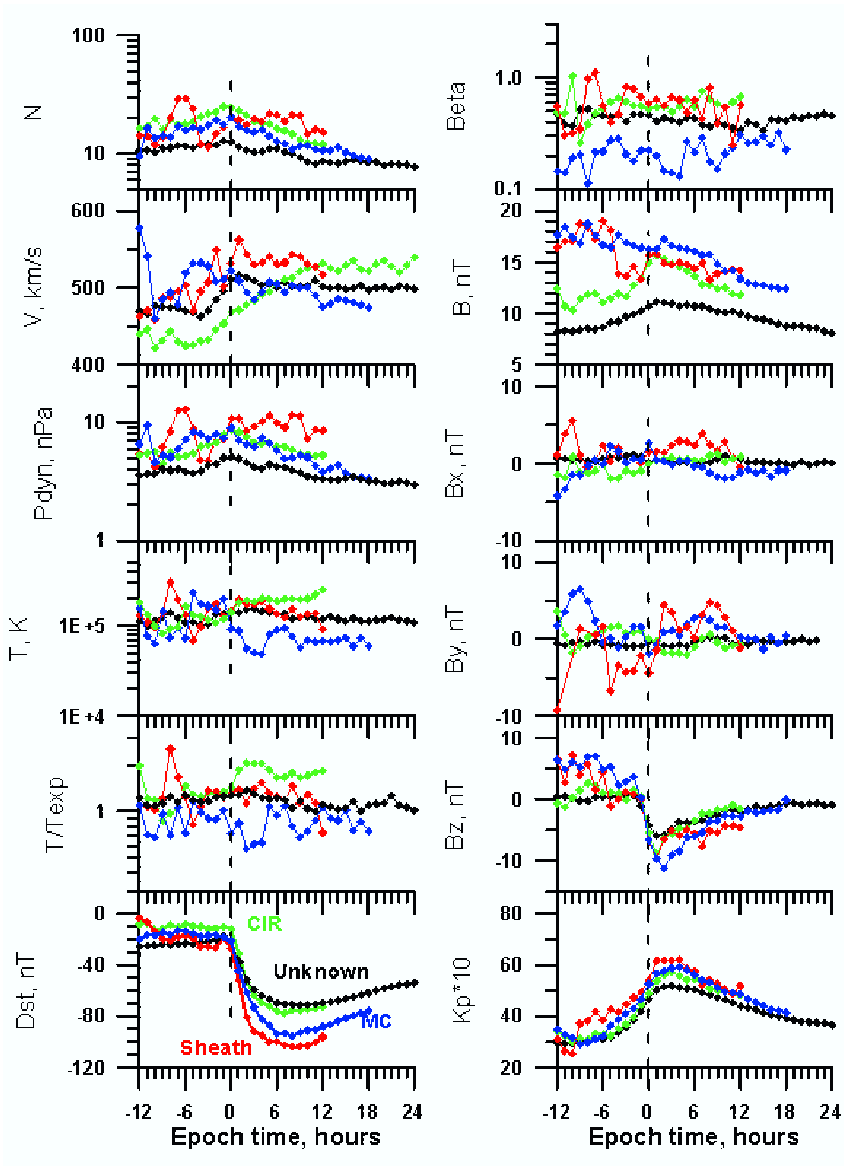

Fig. 1. Behavior of plasma and IMF for magnetic storms generated by CIR (green, 121 storms), Sheath (red, 22), MC (blue, 113) and "uncertain" (black, 367) types of solar wind during 1976-2000 obtained using OMNI dataset by superposed epoch method with zero time chosen as first 1-hour point of abrupt drop of Dst index.

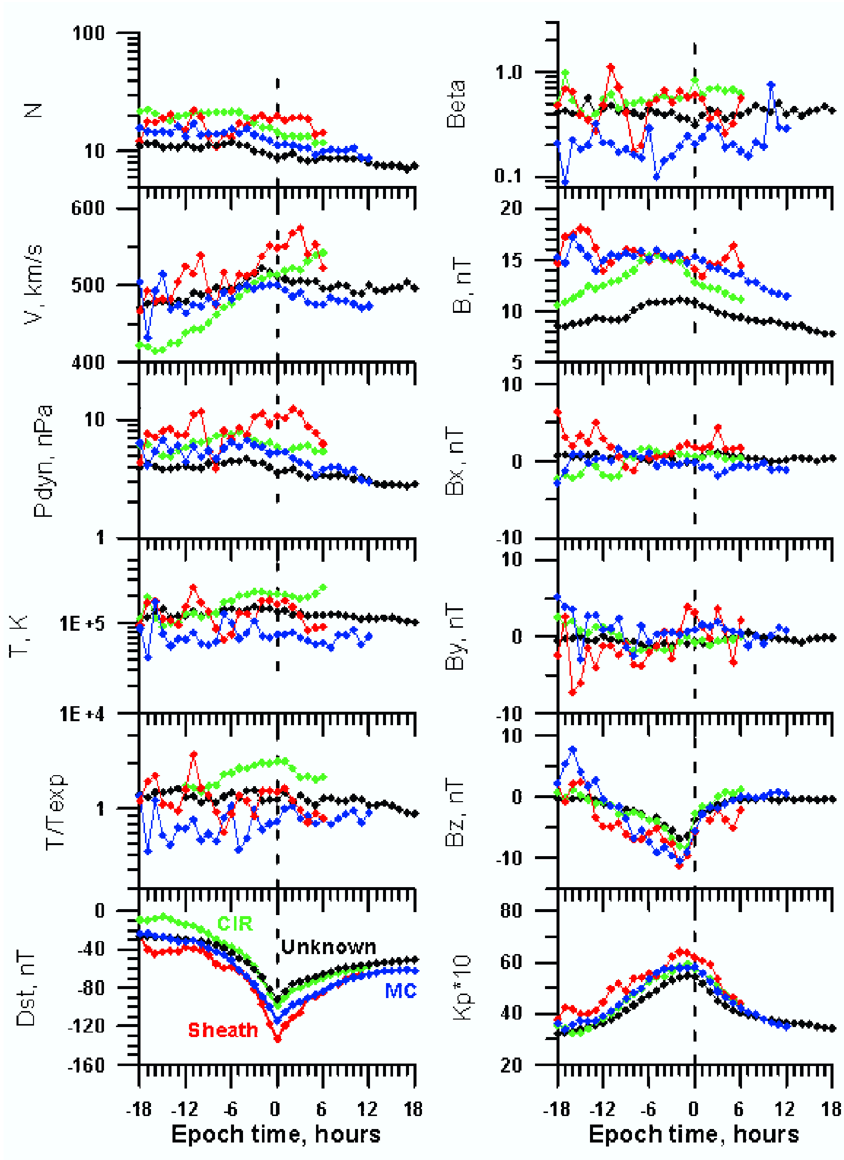

Fig. 2. The same as in Fig.1 obtained by superposed epoch method with zero time chosen as minimum of Dst.