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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 – co-rotating 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 the leading edge of MC (Sheath) and the body of MC. Superposed epoch analyses of interplanetary parameters during 1976–2000 are used separately: (i) for 2 epoch zero times – start and end of main phase of geomagnetic storms, and (ii) 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 the 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.

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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 [1-3], the conditions in the solar wind (SW) resulting in magnetic storms are a subject of long and intensive investigations. It has been shown by numerous studies that magnitude and features of magnetic storms depend not only on current values of IMF and SW parameters but also on their temporal evolution. 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 is 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

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	Ref.
1	538 (1963-1991)	onset	No	B, B_x, B_y, B_z, V, T, n, $P_{\rm dyn}$	[26]
2	120 (1979-1984)	min Dst	No	B_z, n, V	[4]
3	150 (1963-1987)	turning B_z	No	B_z, $P_{\rm dyn}$	[27]
4	305 (1983-1991)	onset	No	B_z, $P_{\rm dyn}$	[28]
5	1085 (1957-1993)	min Dst	Dst	B_z, $P_{\rm dyn}$	[5]
6	130 (1966-2000)	onset	No	B, B_x, B_y, B_z, $\|B_x\|$, $\|B_y\|$, $\|B_z\|$, V, n, $P_{\rm dyn}$	[25]
7	623 (1976-2000)	onset	SW types[a]	B, B_x, B_y, B_z, V, T, n, $P_{\rm dyn}$, nkT, β, $T/T_{\rm exp}$	[12,13]
8	78 (1996-2004)	min Dst	SW types[b]	B, B_z, dB/B, V, T, n	[16]
9	549 (1974-2002)	min Dst	Yes[c]	B, B_x, B_y, B_z, $\|B_x\|$, $\|B_y\|$, $\|B_z\|$, B_s, VB_s, V, n, T, $P_{\rm dyn}$	[6]

[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.

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 [4-6], but this is unjustified because duration of the main phase lasts from 2 to 15 hours [7-9], and inside of an interval with duration of several hours the parameters measured before and after onset were 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, [10-15] and references therein). Particularly, Huttunen and Koskinen [11] 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 [6], 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 [16] 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, [9,17-20]) 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 [16] published Figure 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, i.e., 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 days (from -2 up to +2 days) interval with correct data processing procedure. Therefore, there are serious doubts that calculations in the paper [16] 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: (i) for beginning and end of main phase of geomagnetic storms, and (ii) for 4 categories of solar wind: CIR (121 storms), Sheath (22), Magnetic cloud (113), and "uncertain" (367).

2 Results

Figures 1 and 2 present results of processing of OMNI data for 623 magnetic storms with $Dst < -60$ nT during 1976–2000, which have been 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.* [21] and Tsurutani *et al.* [22] and references therein. Details of method used and several preliminary results may be found in papers [9,12,23]. Figures 1 and 2 show similar parameters: (Left column) n – density, V – velocity, P_{dyn} – dynamic pressure, T – proton temperature, T/T_{exp} – ratio of measured proton temperature to calculated temperature, T_{exp}, using velocity V [24], Dst index, (Right) β – ratio of thermal to magnetic pressure, B, B_x, B_y, and B_z – 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 to +12, for MC -12 to +18 and for "uncertain" type -12 to +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 to +12 hours relative to onset. In the cases discussed below the distinctions between curves are mathematically significant but they are less than corresponding dispersions,

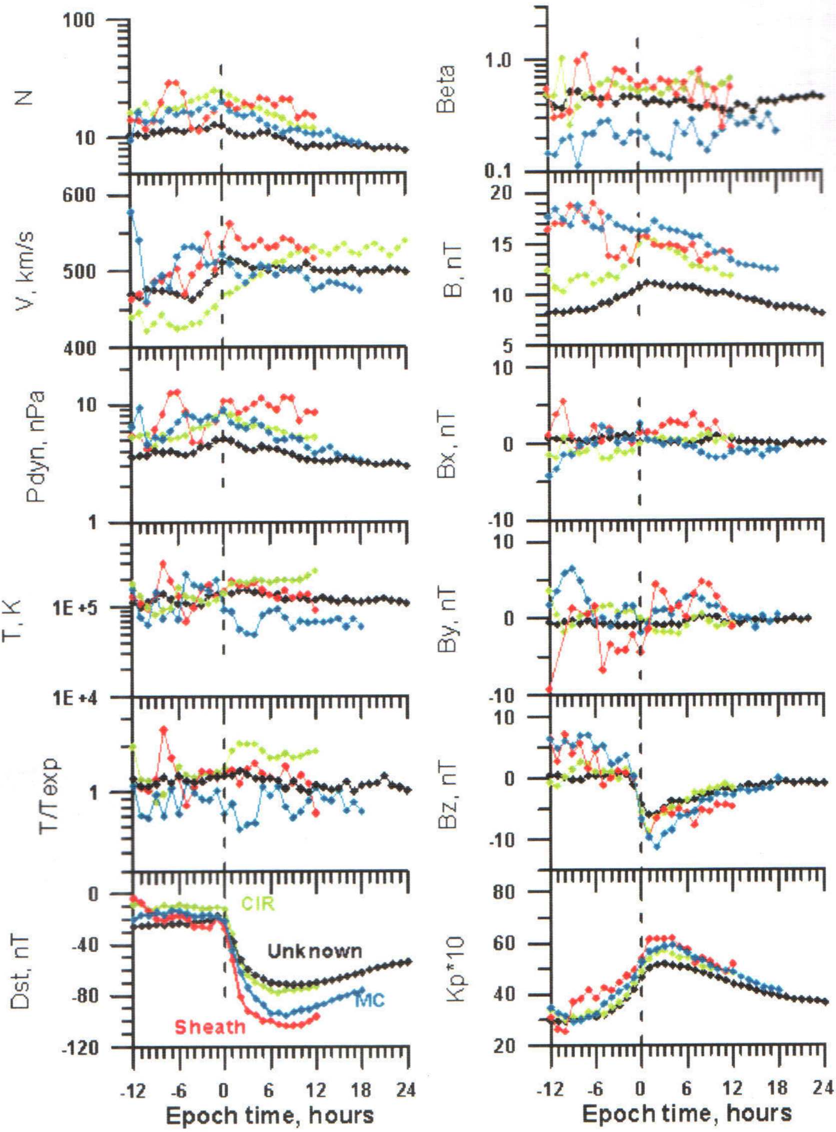

Figure 1. Behavior of plasma and IMF for magnetic storms generated by CIR (green, 121 storms), Sheath (red, 22), MC (blue, 113) and "uncertain" (black, 367) types of solar wind during 1976-2000 obtained using OMNI dataset by superposed epoch method with zero time chosen as first 1-hour point of abrupt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

and in this case it is necessary to consider the distinctions as a tendency rather than as a proven physical fact.

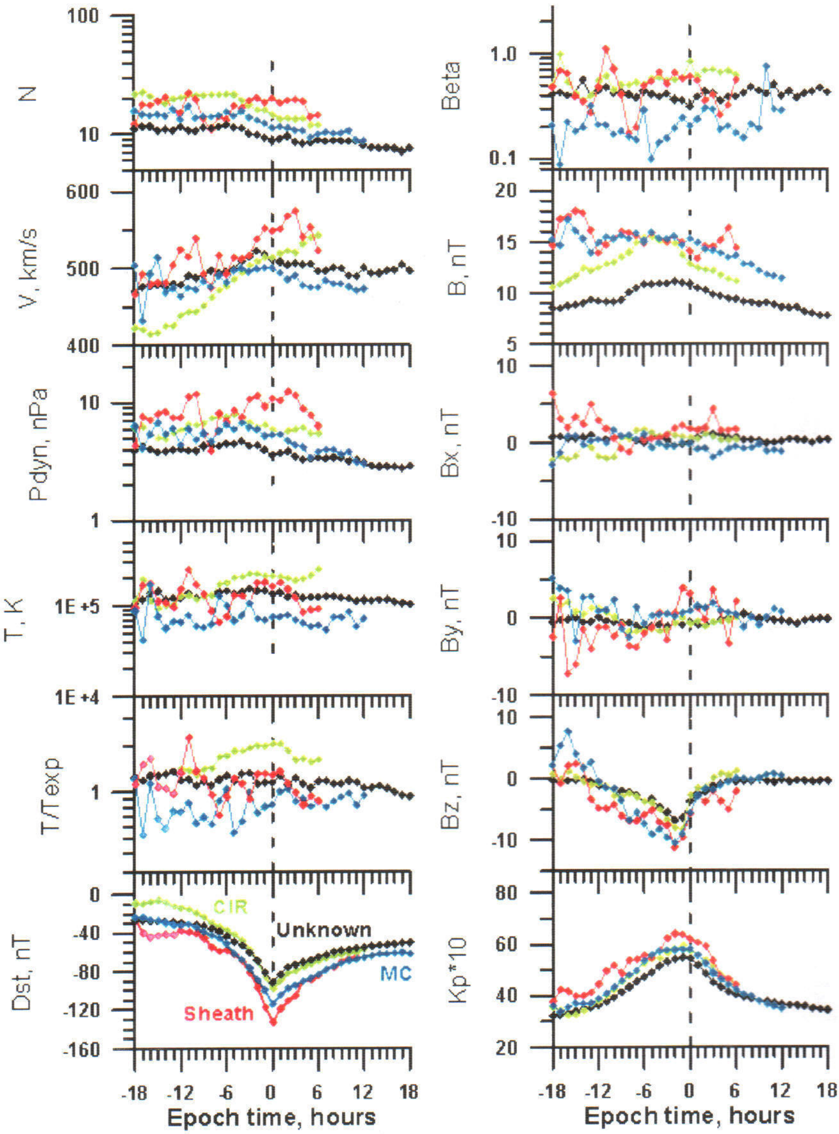

Figure 2. The same as in Figure l obtained by superposed epoch method with zero time chosen as minimum of Dst.

Figure l. shows that the main phase of the "averaged storm" lasts about 8 hours and the time difference between minimum B_z and minimum Dst is about 6 hours while in Figure 2 there is no clearly defined main phase of the "averaged storm", and the time difference between minima B_z and Dst is only

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

SW type	B nT	B_x nT	B_y nT	B_z nT	Tp kK	n cm^{-3}	V km/s	Kp	Dst nT	β	T/T_{exp}	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

1–2 hours, although in both cases the decrease in Dst index begins in 1–2 hours after southward return of the B_z 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 Figure 1 that although the largest southward 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 indices have been 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 P_{dyn} 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 P_{dyn} are observed.

The magnitude of magnetic field B reaches a maximum near the beginning of storms (in 1–2 hours after the 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 B_z component has been described above. B_x and B_y 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 to +1 hours when the average of the B_y component is near -5 nT.

On the other side, a comparison of Figures 1 and 2 shows significant differences due to the choice of the zero time. For example, Figure 1 demonstrates that the maxima of the density, n, and of the magnetic field magnitude, B, for the "uncertain" type and CIR are observed at storm onset, but Figure 2 does not allow one to make the same conclusions. For both choices of zero time there are significant differences in T/T_{exp} and β, for CIR and Sheath, on the 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 B_z component for 1–2 hours prior to the beginning of a storm (with achievement of B_z 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 B_z component are observed in the 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 the magnitude and variation of density and velocity (as well as combinations of these parameters – pressure and electric field VB_z) in the Sheath. This result confirms the conclusion made by Huttunen and Koskinen [11] about high occurrence rate of strong magnetic storms during the Sheath obtained with the less statistics and for shorter time interval.

3) Higher values of the parameters nkT, $T/T_{\rm exp}$ 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 the paper by Lyatsky and Tan [25] 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 [25]. 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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