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RELATIONSHIPS OF THE SOLAR WIND PARAMETERS WITH THE MAGNETIC STORM MAGNITUDE AND THEIR ASSOCIATION WITH THE INTERPLANETARY SHOCK

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ABSTRACT

It is investigated quantitative relations between the magnetic storm magnitude and the solar wind parameters such as the Interplanetary Magnetic Field (hereinafter, IMF) magnitude (B), the southward component of IMF (Bz), and the dynamic pressure during the main phase of the magnetic storm with focus on the role of the interplanetary shock (hereinafter, IPS) in order to build the space weather forecasting model in the future capable to predict the occurrence of the magnetic storm and its magnitude quantitatively. Total 113 moderate and intense magnetic storms and 189 forward IPSs are selected for four years from 1998 to 2001. The results agree with the general consensus that solar wind parameter, especially, Bz component in the shocked gas region plays the most important role in generating storms (Tsurutani and Gonzales, 1997). However, we found that the correlations between the solar wind parameters and the magnetic storm magnitude are higher in case the storm happens after the IPS passing than in case the storm occurs without any IPS influence. The correlation coefficients of B and $Bz_{(min)}$ are specially over 0.8 while the magnetic storms are driven by IPSs. Even though recently a Dst prediction model based on the real time solar wind data (Temerin and Li, 2002) is made, our correlation test results would be supplementary in estimating the prediction error of such kind of model and in improving the model by using the different fitting parameters in cases associated with IPS or not associated with IPS rather than single fitting parameter in the current model.

Key words : Solar wind, interplanetary shocks, magnetic cloud, interplanetary magnetic field, geomagnetic storms

I. INTRODUCTION

Monitoring of the solar wind plasma and magnetic field by spacecraft located at the Lagrangian L1 point which is about 230 Re (Earth's radius) upstream between the Sun and the Earth can forecast the geomagnetic disturbances in the Earth's magnetosphere, if the relationship between the solar wind disturbances and the geomagnetospheric responses is verified.

Gosling et al. (1991) found that 26 out of 27 (96%) magnetic storms of (Kp $\geq$ 6) were associated with either an IPS or a coronal mass ejection (CME) or both. With the analysis of the advanced solar coronagraph observation data, it is reported that the frontside Halo CMEs (HCMEs) are strongly associated with the IPSs and the magnetic storms (Webb et al., 2000; St Cyr et al., 2000). In addition, a strong association has been observed between Interplanetary CMEs (ICMEs), called as the magnetic clouds (MCs) defined by Burlaga et al. (1981), and the IPSs in lots of case studies (Lindsay et al., 1994; Tsurutani et al., 1995; Watari and Watanebe, 1998; Luhman, 1995; Lepping et al., 2001).

Some other groups of researchers made an effort to find the solar wind parameters determining the magnetic storm intensity and the physical mechanisms explaining both association between the IPS and the magnetic storm, and association between the IPS and the ICME. Gonzales and Tsurutani (1987) noticed that in order to create a intense ($Dst_{(min)}$ < -100 nT) magnetic storm, it is necessary to have long-duration southward IMF (Bz < -10nT) lasting more than three hours. Later, Tsurutani et al. (1992) also found that three out of the five largest storms ($Dst_{(min)}$ < -250 nT) during the period 1971-1986 were caused mainly by the shocked sheath field ahead of the CME. Gosling et al. (1991) suggested that the speed of the ICME relative to the ambient solar wind ahead was a major controlling factor for its ability to generate storms. However, Jurac et al. (2002) found a weak relationship between the shock speed and the storm intensity of correlation coefficient 0.41. Instead, they suggested that the angle between the shock front normal and the IMF direction might be able to forecast the intense magnetic storms.

In general, the associations found by case studies of a few intense magnetic storms may give us a hint how to figure out the causality relationship behind the phenomena, but can not help us to predict the storm intensity quantitatively. However, in order to predict the occurrence of the magnetic storm and its intensity quantitatively in the future space weather forecasting, it is

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TABLE 1.
THE STORM CLASSIFICATION DURING THE PERIOD FROM 1998 TO 2001 (GONZALES ET AL., 1994)

Storm class	$Dst_{(min)}$ range	B[a]	Bz[b]	$Bz_{(min)}$[c]	ΔDst[d]	ΔT[e]	w/ IPS[f]	w/o IPS[g]	N[h]
weak	-30∼-50	11.0	-1.78	-6.5	52	6.6	27	4	41
moderate	-50∼-100	12.0	-4.2	-9.4	72	7.7	29	25	54
strong	-100∼-200	17.0	-8.2	-15.5	119	8.6	20	11	31
severe	-200∼-350	31.6	-13.8	-31.8	248	6.1	10	1	11

(Remarks : [a] The mean value of IMF magnitude during the storm main phase, [b] The mean value of north-south component of IMF during the storm main phase, [c] The mean value of the minimum Bz during the storm main phase [d] The varied value of Dst index for main phase, [e] The duration time of the main phase, [f] The number of the magnetic storms driven by IPS, [g] The number of the magnetic storms without IPS, [h] The total number of the magnetic storms)

required to completely figure out the magnetic storm intensity response functions of the solar wind parameters controlling the storm. Thus, in this paper, our main focus is to determine the relationships between the solar wind parameters and magnetic storm intensity with statistical correlation test between the solar wind parameters and the Dst index as a proxy of geomagnetic effectiveness. We examine the relationships of many solar wind parameters such as the IMF magnitude (hereinafter, B), the north-south component of the IMF (hereinafter, Bz), and dynamic pressure (hereinafter, $P_{(dyn)}$) on the magnetic storms and their association with the IPS.

II. DATA AND METHOD

The storms selected using Dst index offered from WDC in Kyoto University. The Dst index is a proxy for the strength of the symmetric component of the ring current. Table 1 classified geomagnetic disturbances occurred from 1998 to 2001 on stepping to the solar maximum activity into four levels in the magnetic storm intensity scale suggested by Gonzales et al. (1994). ACE has a full coverage of the in situ solar wind observation data for that period of the time. Especially, we have utilized as a new magnetic storm intensity parameter ΔDst, which is the amount of Dst change during the magnetic storm main phase, to represent the strength of the storms instead of $Dst_{(min)}$. Since ΔDst and the $Dst_{(min)}$ have a good correlation with a correlation coefficient (r=0.9078), ΔDst could be considered as a new proxy for the magnetic storm intensity replacing the $Dst_{(min)}$. We only considered the magnetic storms which have the $Dst_{(min)}$ value less than -40 nT and ΔDst greater than 50 nT. It means that the chosen magnetic storms are roughly moderate storms or the stronger. We have identified total 113 magnetic storms as our data set. In the yearly occurrence, the numbers of the magnetic storms are respectively 26, 20, 36, and 31 from 1998 to 2001 in the yearly order. We recognized that the geomagnetic disturbances more frequently had occurred for two years, 2000 and 2001, and their associations with the IPS had increased because of more violent activities at solar maximum.

We analyzed the solar wind parameters from ACE observation data of hourly values in solar wind speed, proton temperature, proton density, magnetic field magnitude, and Bz component in the given period. We could identify the 189 forward IPSs discarding the revere shocks and the shocks with missing solar wind parameters data. During the same period of the magnetic storm events above the numbers of the IPSs are 30, 39, 54 and 66 each year and the 189 IPSs occurred in total.

III. RESULTS

(a) The Magnetic Storms Driven by the IPSs

We defined that the IPS and the magnetic storm is associated if the magnetic storm main phase starts in a couple of hours after the IPS is detected by the ACE. It was found that 63% (71 out of 113) of the magnetic storms were initiated with the IPSs simultaneously, or co-existed with IPSs in progress of the magnetic storms. The magnetic storm driven by IPS are stronger than the magnetic storm without any IPS as shown in Table 1. The most of the magnetic storms of $Dst_{(min)} < -100$ nT are the storms driven by IPSs. This shows that IPSs take an important role in generating intense storms.

It is five storms which were directly driven by interplanetary events as known as shock drivers of ICMEs such as MCs and Ejectas. Out of 71 magnetic storms driven by IPSs, IPS driven by High Speed Stream (HSS) initiated seven storms, IPS driven by ejecta generated ten storms, and Blast-wave type shock formed three storms as shown on the Figure 1. The IPSs driven by MC (51/71) are the most effective in forcing the magnetic storms.

Oh et al. (2002) demonstrated that most of IPSs driving the magnetic storms might be caused by MCs and Ejecta because the IPSs driven by MC have more stronger magnetic field, longer duration of shocked gas and relatively well-aligned magnetic structure than other IPSs driven by other shock drivers such as the

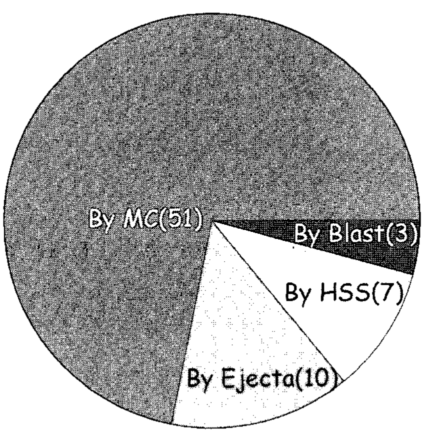

Fig. 1.— The IPS driven storm classification by the IPS drivers (total 71 storms).

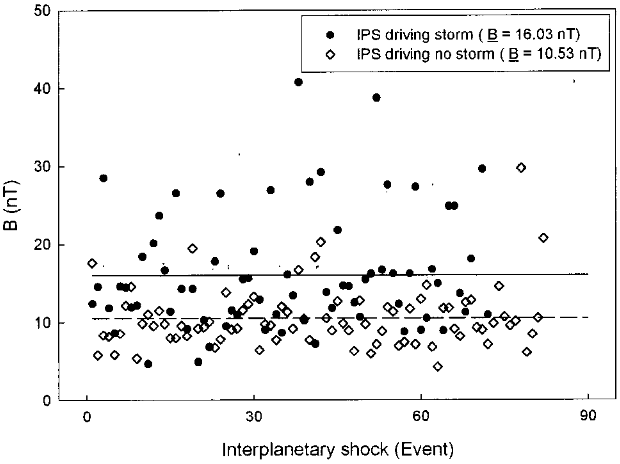

Fig. 2.— The distribution of the averaged B in the shock down stream region.

HSS. Thus IPSs driven by MC are the most dominant in driving the magnetic storms. Surely most of the IPSs were related with the any geomagnetic disturbances of very weak magnetic storms. However, the weak IPSs driven by the HSS are excluded in our data since they are associated with relatively much weaker magnetic storms than our selected moderate storm classification.

(b) The IPSs Driving the Magnetic Storms

It is found that only 37% of the IPSs (71/189) could drive the magnetic storms in our storm category (Oh et al., 2002). This suggests that there might exist a certain criteria for an IPS to overcome in order to drive a magnetic storm stronger than the moderate storms.

This result demonstrates that the IPS builds magnetic field in shocked gas region stronger enough to trigger a magnetic storm.

We arranged the 189 IPSs into two groups by whether it could drive the magnetic storm or not. We determined the physical properties of the post-shock region maintaining the characteristics of the IPS, so-called the shocked gas region or the sheath region. We calculated the solar wind parameters averaged over whole the main phase period in case the magnetic storm was initiated by the IPS, and over the first seven hours from the start of the shock in case the magnetic storm was not associated with the IPS.

The distribution of B, Bz, and $Bz_{(min)}$ averaged over the shock sheath region is respectively plotted on the Figure 2, 3, and 4. The IPSs driving storm are marked by (•) and the IPSs not-driving storm are marked by (◇). The horizontal solid line on each figure marks the mean value of IPSs driving storms, and the horizontal dashed line marks the mean value of IPSs not-driving storms. From these three figures, inspecting the physical properties in shocked gas region, the average IMF values of IPS driving storm (B = 16.03 nT, Bz = -5.63 nT, $Bz_{(min)}$ = -13.21 nT) are larger than the average values of IPS not-driving storm (B = 10.53 nT, Bz = 0.26 nT, $Bz_{(min)}$ = -4.07 nT), by the significant difference of over 5 nT, the average value of IMF magnitude at 1AU.

(c) The Factors Controlling the Magnetic Storm Intensity

In order to find out the factors generating the magnetic storms and to determine their strength, we examined the IMF magnitude B, the trend of IMF Bz (southward direction component), and the dynamic pressure, which are suggested as important major factors from many preceding investigations with special focus on the main phase, the period which determines the magnetic storm intensity.

The Figure 5, 6, and 7 are the plots of ΔDst versus the averaged B, the averaged Bz, and the minimum Bz, $Bz_{(min)}$ during the main phase, respectively, for two kinds of magnetic storm clans. One is the magnetic storm driven by IPS (marked by •), the other is the magnetic storm not-driven by IPS (symbolized by ◇). Some of these magnetic storms might be driven directly by the MC itself if the IPS driven by the MC is weak.

The Figure 5 tells that the storms whose ΔDst index are less than 200 nT occurred more frequently for four years in this solar maximum. From this plot of averaged B and ΔDst index, as the averaged IMF magnitude gets strong, the magnetic storm gets intenser. Also, the magnetic storm driven by IPS only could have stronger IMF during the main phase and the magnetic storm itself could be stronger over than the magnetic storm not-driven by IPS.

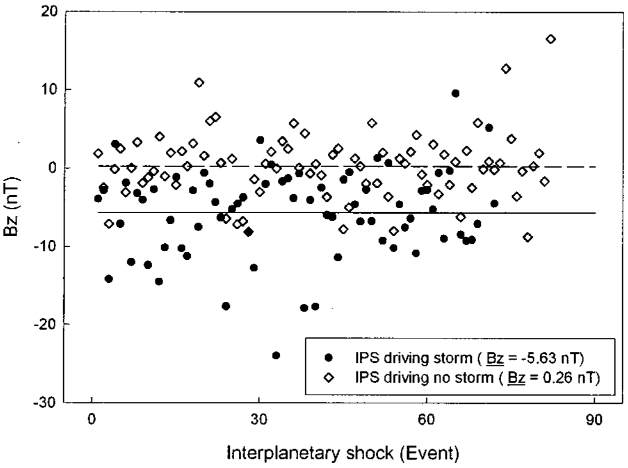

Fig. 3.— The distribution of the averaged Bz in the shock down stream region.

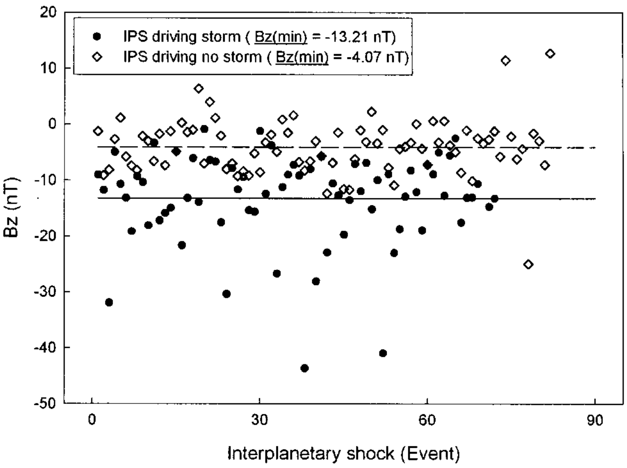

Fig. 4.— The distribution of the averaged $Bz_{(min)}$ in the shock down stream region

The Figure 6 shows that as the averaged value of Bz in the southward direction (negative Bz) gets larger, the magnetic storm gets intenser. This indicates the similarity with the result of many preceding investigations which examined the influence of Bz component on the storms (Gonzales and Tsurutani, 1987; Gonzales et al., 1994). The averaged value of Bz includes the duration of the southward IMF. Then the longer duration of the southward IMF makes the intenser magnetic storm.

The Figure 7 is the plot of the most southward IMF component, $Bz_{(min)}$, in the main phase versus the magnetic storm intensity. This also confirms indisputably the importance of southward Bz in generating and intensifying the magnetic storms. These results confirm that the enhanced magnetic field in the sheath region ahead of the CME can be also the main cause of the large storms (Tsurutani and Gonzales, 1997).

Plot of ΔDst and the averaged $P_{(dyn)}$ during the main phase on the Figure 8 shows the another strong correlation. The higher the solar wind dynamic pressure is in the main phase, the intenser the geomagnetic storm is. The correlation coefficients between the solar wind parameters (B, Bz, $Bz_{(min)}$ and $P_{(dyn)}$) and the magnetic storm intensity (ΔDst index) summarized on the Table 2. The notations of w/ IPS, w/o IPS and all mean respectively storm driven by IPS, storm not-driven by IPS and all storms. There are strong correlations between the above solar wind parameters and the magnetic storms intensity, especially in case of the storm driven by IPS.

The IPSs are accompanied by the strongly compressed IMF and the higher density solar wind plasma at faster speed in the sheath region. Thus they are more effective on the magnetic disturbances than any other interplanetary events. The capability to drive the magnetic storm can be determined by the characteristics of the region which maintains the shock's identity, i.e., just the shocked gas region. However, we can cautiously summarize that the magnetic storms are driven and gets intenser only while the duration of the IMF Bz in the shocked gas is longer and stronger in southward direction. This inference agrees very well with the interpretation that the IPS driving a magnetic storm has stronger IMF and larger southward component than the IPS driving no storm.

The magnetic storm generation is mainly attributed to the value of Bz in the southward direction. This component might be formed by directly the ejection of the magnetic structure from the Sun and by indirectly the interaction of the solar wind flows during the propagation of the IPSs or the fast solar wind. Only five magnetic storms are verified as driven by material eruption, such as ICME (MC) during the our four year period, supporting that the IPSs are more effective in

TABLE 2.
THE CORRELATION COEFFICIENT BETWEEN SOLAR WIND PARAMETERS AND ΔDST INDEX

solar wind		correlation	coefficient
parameters	w/ IPS[a]	w/o IPS[b]	all[c]
B	+0.807	+0.669	+0.804
Bz	-0.526	-0.443	-0.479
$Bz_{(min)}$	-0.818	-0.774	-0.813
P_{dyn}	+0.661	+0.352	+0.645

(Remarks : [a] The notation of w/ IPS means the magnetic storm driven by IPS., [b] The notation of w/o IPS means the magnetic storm without IPS., [c]The notation of all means the all storms.)

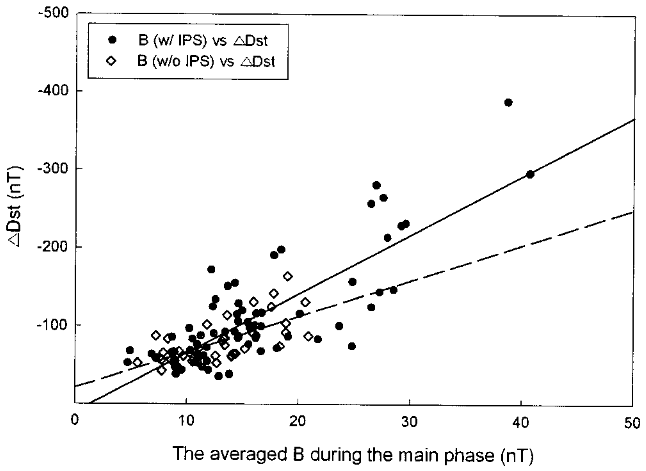

Fig. 5.— ΔDst versus $\overline{B}$, the averaged total IMF magnitude during the storm main phase.

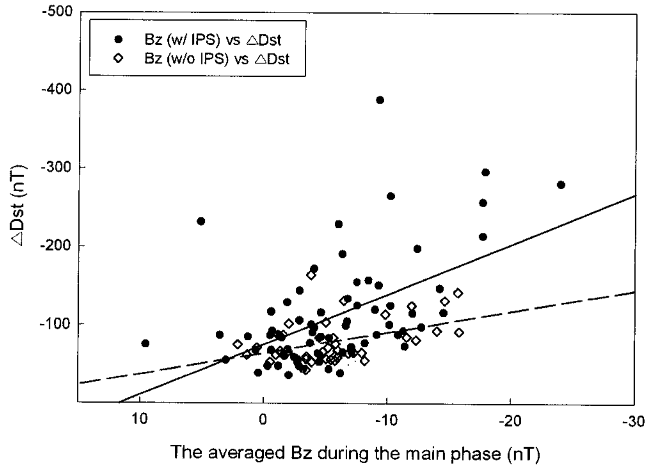

Fig. 6.— ΔDst versus $\overline{Bz}$, the averaged Bz component during the storm main phase.

generating the magnetic storms than the shock drivers themselves such as CMEs (Gosling et al., 1991). Usually the magnetic storm starts in one hour after the IPS is encountered by the spacecraft at L1 point, the IPS is associated with the storm rather than the MC, which has the transit time lag between the IPS and its driver MC itself about 12 hours.

Table 3.
The linear fit parameters of solar wind parameters (x) from the equation of $y = ax + b$

	a		b	
x	w/ IPS	w/o IPS	w/ IPS	w/o IPS
B	-7.546	-4.561	9.623	-21.415
Bz	6.428	2.684	-75.146	-64.242
$Bz_{(min)}$	6.932	4.847	-19.759	-26.859
P_{dyn}	-1.161	-0.470	-38.581	-62.461

From the Figure 5, 6, 7 and 8, we calculated the linear fit parameters and summarized at the Table 3 using the equation of $y = ax+b$. The variable x is solar wind parameter such as B, Bz, $Bz_{(min)}$, and P_{dyn}, and the variable y is ΔDst. In case of the storm driven by IPS, there are good relationship between the solar wind parameters and the storm intensity.

IV. SUMMARY AND CONCLUSION

The storms are selected from the geomagnetic disturbances occurred for four years from 1998 to 2001 since there is solar wind observation data with full coverage of during that period by ACE spacecraft at L1 point. The Dst index is used instead of Kp index as a proxy of the magnetic storm intensity. Total 113 magnetic storms were chosen with the selection criteria of the $Dst_{(min)}$ index less than -40 nT and ΔDst during the main phase more than 50 nT, which is introduced as a new parameter of the magnetic storm intensity. Statistically about 63% of the magnetic storms are driven by IPSs. However, only 37% of the IPSs can drive the magnetic storms. The magnetic storms are classified into two clans. One is driven by IPS and the other is not driven by IPS.

Out of the many solar wind parameters governing the intensity of the magnetic storm, the IMF magnitude B, Bz component, and the dynamic pressure are correlated with ΔDst during the main phase. The main phase of the storm driven by IPS is mainly associated

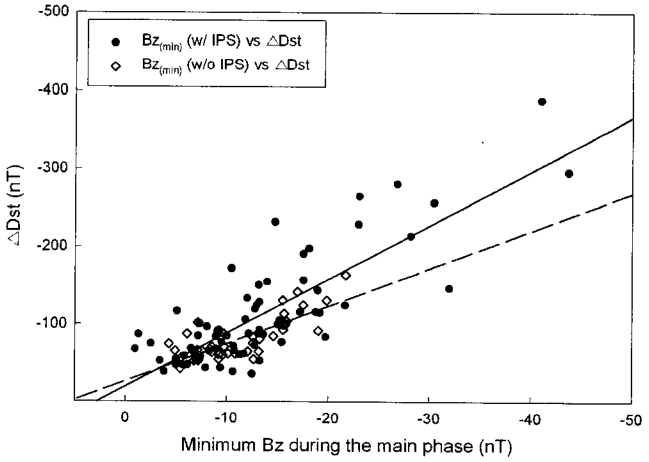

Fig. 7.— ΔDst versus $Bz_{(min)}$, the minimum Bz during the storm main phase.

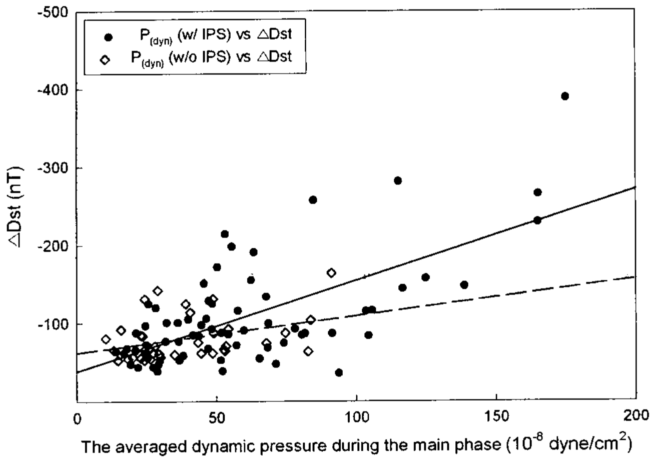

Fig. 8.— ΔDst versus $P_{(dyn)}$, the averaged dynamic pressure during the storm main phase.

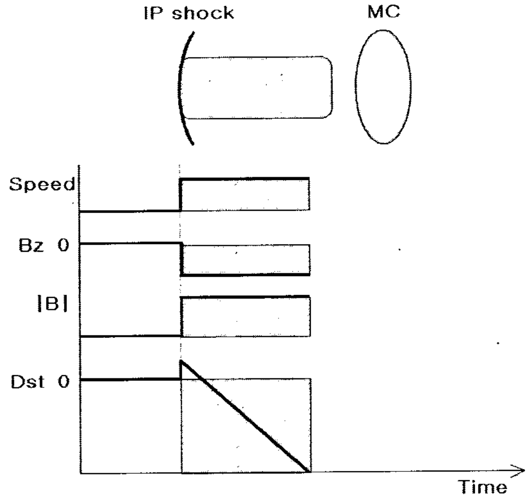

Fig. 9.— IPS-ICME (MC) pair structure and its relation with the magnetic storm.

with the region lasting the shock's characteristics in the sheath region. It favors the conclusion that especially Bz component among the solar wind parameters in the shocked gas region takes the most important role in generating the magnetic storms (Tsurutani and Gonzales, 1997).

As it regards that there exists a good correlation between the IPSs and the magnetic storms, the magnitude of the storm driven by IPS is more higher than that of the storm not driven by IPS. Since the IPS performs the role in informing of start point of storm, the storm can be forecasted in the observational view. The criteria of driving the storm for IPS is "IPS strength". Considering the IPS strength, we have to investigate the duration and the magnetic structure of shocked gas region maintaining the shock's identity, in addition to the magnetic field strength. This can be explained by the fact that the main phase of the storm driven by IPS is mostly set in the shocked gas region.

In addition, considering that the IPSs driving storms mostly are driven by MC, we may conclude that; first, IPSs driven by MC are stronger magnetic than any other IPSs, secondly, IPSs driven by MC are easy to define and to understand the shocked gas region, and thirdly, the IPS-shock driver, MC as an example, structure sketched on the Figure 9, that is, the magnetic properties (strength and structure) of the sheath region is relatively effective on driving the storm rather than IPS structure driven by an HSS or a blast-wave type shock.

To predict the occurrence of the magnetic storm and its intensity quantitatively in the space weather forecasting, it is necessary to figure out the quantitative relations between the solar wind parameters and the magnetic storm intensity. Even though recently a Dst prediction model based on the real time solar wind data (Temerin and Li, 2002) is coded, our correlation test results would be supplementary in estimating the prediction error of such kind of model and in improving the model by using the different fitting parameters in cases associated with IPS or not associated with IPS rather than single fitting parameter in the current model.

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