A Unified View of the Influences of the IMF B_y on Geomagnetic Activity*

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The correlation between the solar wind parameters and geomagnetic activity represented by several indices is utilized to examine the effects of the azimuthal component of the interplanetary magnetic field on solar wind-magnetosphere coupling. It is suggested that the $|B_y|$ dependence of geomagnetic activity can be expressed by using the theoretical equation of the dayside reconnection. It is emphasized that the influence of B_y on different indices varies significantly. The seasonal variations of the B_y dependence of the AL index is discussed in the light of the viscous-like interaction hypothesis.

1. Introduction

It is well known that geomagnetic disturbances occur in close association with variations in the interplanetary magnetic field (IMF) and the solar wind. Many studies have emphasized that the southward component of the IMF (B_z) is the principal parameter that governs geomagnetic activity (e.g., ARNOLDY, 1971; BURTON *et al.*, 1975; NAKAI *et al.*, 1986). This feature is widely interpreted according to the dayside reconnection model, first postulated by DUNGEY (1961), in which southward field lines of the IMF merge with northward field lines of the magnetosphere at the subsolar point, and then transport the connected field lines to the nightside. Much evidence, however, suggests that not only interplanetary field lines pointing to the south but also to other directions can merge with geomagnetic field lines. Several theoretical arguments have also dealt with the magnetic merging for the IMF having various angles (GONZALEZ and MOZER, 1974; SONNERUP, 1974; HILL, 1975). The function of $\sin^n(\theta/2)$ has often been used empirically to represent the influence of the azimuthal component, B_y , of the IMF on geomagnetic activity, where θ indicates the angle between interplanetary field lines and geomagnetic north; KAN and LEE (1979) chose $n=2$, and PERREAULT and AKASOFU (1978) chose $n=4$.

The influences of B_y on magnetic disturbances in the polar cap were first investigated by SVALGAARD (1968). Since then, many workers have endeavored to reveal the convection pattern in the polar cap and the auroral zone (e.g., FRIIS-CHRISTENSEN, 1986; and references therein). In particular, the dayside convection pattern has been investigated in detail under various conditions of the IMF and of the solar wind. When the IMF is oriented southward and is relatively stable, the ion

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convection is directed toward dawn or dusk in the cusp region, depending on whether B_y is positive or negative, respectively.

WILCOX (1968), BERTHELIER and GUERIN (1973), and YOSHIZAWA (1984) examined the north-south asymmetry of magnetic activity in the subauroral latitudes and found that regardless of the season, magnetic activity in the northern hemisphere is higher than that in the southern hemisphere when B_y is negative, and lower when B_y is positive. On the other hand, AOKI (1977) suggested that the magnitude of the subauroral disturbance depends on the season due to the seasonal change in the tilt angle of the earth's dipole axis. Using the a_m index (the average of the northern and southern subauroral activities), Aoki showed that a_m with $B_y > 0$ is higher than that with $B_y < 0$ during winter, and lower during summer. The intensity of the westward electrojet (AL) has the same tendency, even more noticeably. MURAYAMA *et al.* (1980) sorted AL according to the tilt angle of the earth's dipole and suggested that AL depends almost linearly on B_y , with the slope of the B_y dependence changing systematically from positive to negative as the tilt angle changes from negative to positive.

Thus, B_y seems to control geomagnetic activity in a complex manner. It is crucial to gain a comprehensive understanding of the B_y effect on geomagnetic activity. The purpose of the present paper is to unify the correlation works on the influence of the IMF B_y . First, we will deal with the $|B_y|$ dependence of geomagnetic activity in the light of theoretical predictions. Next, we will discuss the influence of the earth's tilt angle on the B_y dependence of geomagnetic activity, focusing on how the differences between indices serve as indicators of different parts of the ionospheric plasma convection in high latitudes.

2. $|B_y|$ Dependence of Geomagnetic Activity

HILL (1975) calculated the dissipative component of the electric field, E_j , for a plane magnetopause model separating the sheath field B_{SH} and the geomagnetic field B_G , where j stands for the direction of the sheet current. Two field lines are separated with an angle θ measured clockwise from the geomagnetic field to the transverse component of the magnetosheath field viewed from the sun. Assuming that the j component of the field is unchanged across the boundary, E_j is represented as

$$E_j = V_A B_{SH} f(\theta), \quad (1)$$

where V_A is the Alfvén velocity in the magnetosheath, and

$$f(\theta) = \begin{cases} \frac{(\alpha - \cos\theta)^2}{(1 + \alpha^2 - 2\alpha\cos\theta)} & \text{for } \alpha > \cos\theta \\ 0 & \text{for } \alpha \leq \cos\theta. \end{cases} \quad (2)$$

Here α is the ratio of B_{SH}/B_G . It is empirically accepted that the transverse component of the IMF B_t multiplied by the solar wind speed V principally controls geomagnetic activity. For simplicity, assuming the following equations,

$$B_{SH} = (4B_t B_G)^{1/2} \quad (\text{CROOKER } et al., 1982),$$

$$B_G^2/8\pi = \rho V^2 \quad (\text{SPREITER } et al., 1966),$$

and $\rho_{SH} \propto \rho$ (Rankine-Hugoniot equation), Eq. (1) yields

$$E_j = \delta B_t V f(\theta), \quad (3)$$

where ρ , V , and B_t are the solar wind density, the solar wind speed, and the transverse component of the IMF, respectively, and δ is a constant. Therefore, assuming that the transverse component of the IMF does not rotate when it passes through the bow shock, Eq. (3) can predict the electric field along the reconnection line on the basis of the solar wind parameters outside the bow shock. Next, we will examine the θ dependence of several kinds of observations in the light of the predictions derived from Eqs. (2) and (3).

2.1 The AL and AU indices

The θ dependence of AL is shown in Fig. 1 for $-10^\circ \leq T < 10^\circ$. Since the solar wind speed dependence of the AL index is not linear, but approximately proportional to V^2 , AL values are normalized by $B_t(V/400)^2$ (MURAYAMA and HAKAMADA, 1975). The AL index and the solar wind parameters for 1978 and 1979 are used, assuming a 1-hour delay in the auroral zone response to the solar wind condition. The numerator of the ordinate is the AL index reduced by -40 nT, which is the average value of AL when $B_z > 5$ nT. To avoid the saturation of AL by the large southern component of the IMF, and also to avoid extreme fluctuations in the averages of normalized AL for small B_t , data used in Fig. 1 are restricted to those with $2 \leq B_t < 6$ nT. Bars attached at each point indicate the standard errors of averages. Solid lines indicate Eq. (2) with α of 0.4, 0.5 and 0.6. Since a typical value

Fig. 1. Averages of normalized AL are plotted as a function of θ for $2 \leq B_t < 6$ nT and $-10^\circ \leq T < 10^\circ$. A "base line" of -40 nT was subtracted before normalizing AL . The solid lines indicate the theoretical predictions by using Eq. (2) with α of 0.4, 0.5, and 0.6. Bars attached to each data point indicate the standard errors of averages. The solar wind speed V is normalized by 400 km/s.

of α is ~ 0.5 , the data points agree very well with the theoretical predictions. Consistent with this, BARGATZE *et al.* (1986) suggest that the θ dependence of the AL index is successfully represented by $\sin^4(\theta/2)$; note that the curve of $\sin^4(\theta/2)$ is quite similar to Eq. (2) with α of 0.5. Figure 2 shows the θ dependence of AU in the same format as Fig. 1. When α is 0.6, the theoretical prediction agrees well with observations.

Fig. 2. Same as Fig. 1 but for averages of $(AU-40)/B_t V$. $B_t V$ is in the unit of mV/m.

2.2 The polar cap potential drop

The results of three recent works on the θ dependence of the polar cap potential drop measured by polar-orbiting satellites are listed in Table 1 (REIFF *et al.*, 1981; WYGANT *et al.*, 1983; DOYLE and BURKE, 1983). The table presents the correlation coefficients between the potential drop and the solar wind parameters in the two lines at the top of the table. Note that $B_z V$ and $\sin^2(\theta/2)$ are equivalent to Eq. (3) with α of 0 and 1, respectively. The numbers of data points utilized in each work are also shown. Consistent with the results for AL and AU , WYGANT *et al.* (1983)

Table 1. Correlation coefficients between the polar cap potential drop and the solar wind parameters.

Models	$\sin^2(\theta/2)$		$\sin^4(\theta/2)$			—		Data points
	$B_t V$	$B V$	$B_t V$	$B_t V^2$	$B^2 V$	$B_z V$	$B_s V$	
(1)		0.81					0.81	33
(2)	0.59		0.74			0.69		35
(3)	0.77	0.74		0.59	0.63	0.71	0.73	68
(4)	0.82	0.58		0.80	0.66	0.83	0.82	25

The values listed above are obtained from (1) REIFF *et al.* (1981), (2) WYGANT *et al.* (1983), (3) DOYLE and BURKE (1983), using data points with standard deviations of IMF $\sigma \geq 1$ nT, and (4) the same as (3) but for $\sigma = 1$ nT.

suggest that $[B_t V \sin^4(\theta/2)]$ has a higher correlation coefficient than either $[B_t V \sin^2(\theta/2)]$ or $[B_z V]$. Unfortunately, Doyle and Burke do not present a result for the case in which $B_t V \sin^4(\theta/2)$ is used. Reiff *et al.* suggested that the highest correlation coefficient (0.87) is obtained when Eq. (3) is used.

2.3 The tail-lobe field

The field intensity of the magnetic lobe in the near-earth magnetotail is governed not only by the interplanetary field but by dynamic and static pressures of the solar wind. NAKAI *et al.* (to be published) examined the lobe field measured by ISEE 1 for 1978 and 1979, and suggested that the lobe field intensity B_L at the radial distance of $20 R_E$ is expressed by

$$B_L^2/8\pi = P_D^{0.5} \Psi + P_s, \quad (4)$$

where P_D and P_s are the solar wind dynamic and static pressures, respectively, and Ψ stands for influences on the lobe field from the interplanetary field and geomagnetic activity represented, for example, by the AE index. The lobe field strength principally increases with increasing AE , but sometimes decreases in association with the onset of a substorm (FAIRFIELD, 1986; and references therein). If one defines Ψ as

$$\Psi = (B_L^2/8\pi - P_s)/P_D^{0.5}, \quad (5)$$

the influences of P_D and P_s can be removed from the lobe field strength. One-hour values of Ψ were calculated by using the same data set that used in NAKAI *et al.* (to be published). Averages of $(\Psi - 3 \times 10^{-10})/B_t V$ are plotted as a function of θ for $B_t V \geq 1$ mV/m in Fig. 3. Although deviations in data are mainly rather large due to

Fig. 3. The θ dependence of the lobe field strength. Ψ is defined by Eq. (5). The solid lines indicate Eq. (2) with α of 0.5 and 0.6.

the depression of the lobe field from substorm occurrences, each point agrees well with the theoretical prediction resulting from using Eq. (2) with α of 0.5 or 0.6.

2.4 The PC index

VENNERSTRØM and FRIIS-CHRISTENSEN (1987) examined the relationship between magnetic variations in the central polar cap, the *PC* index, and the IMF B_y and B_z . They suggested that the effect of $|B_y|$ on the *PC* index is considerably less than the effect of $|B_z|$ in the theoretical expression, $B_t \sin^2(\theta/2)$. They estimate the ratio

$$\left(\frac{\Delta NPC}{\Delta B_y} \middle| \frac{\Delta NPC}{\Delta B_z} \right) \quad (6)$$

for $B_z = -1$ nT and $B_y = 3$ nT, and get ~ 0.3 , where *NPC* is the *PC* index corrected for changes in conductivity by UT hour and month. The same ratio using Eq. (3) is

$$\left(\frac{E_j}{\Delta B_y} \middle| \frac{E_j}{\Delta B_z} \right) = 0.30 \quad (7)$$

for $B_z = -1$ nT, $B_y = 3$ nT, and $\alpha = 0.6$. Therefore, the B_y dependence of the *PC* index is consistent with those of other indices described above.

In summary, the θ dependence of observations mentioned above can be represented by using Eq. (2). The most favorable values of α , however, seem to be different for different observations. Regression analyses were performed to search

Fig. 4. Correlation coefficients between the four different indices (*AL*, *AU*, Φ , and Ψ) and $B_t V f(\theta)$. The abscissa is α , which is the shaping factor of Hill's equation, $f(\theta)$. Φ and Ψ indicates the polar cap potential drop and the lobe field strength (see Eq. (5)), respectively.

for them by assuming an equation $X = aB_t V f(\theta) + b$, where X stands for AL , AU , the polar cap potential drop Φ , and the lobe field Ψ . Figure 4 shows the correlation coefficients as functions of α . The data points of the polar cap potential drop were obtained using Table 1 in DOYLE and BURKE (1983). Correlations for AU and the polar cap potential drop (Φ) are maximized at $\alpha=0.8$, while AL and the lobe field (Ψ) show the maximum coefficients at lower values of α . Based on these features, it is suggested that the absolute value of B_y influences the dayside observations more strongly than the nightside observations.

3. Asymmetric Influence of B_y

The observation that geomagnetic activity is enhanced during equinox was first interpreted by BARTELS (1928) as resulting from the influence of the tilt angle T of the earth's dipole angle. BOLLER and STOLOV (1970) proposed that the Kelvin-Helmholtz instability is responsible for the tilt angle dependence. This hypothesis is supported by the result of analysis that the dependence of AL on the solar wind speed V varies with the tilt angle: that is, the dependence is steeper when the absolute value of the tilt angle is smaller (MAEZAWA and MURAYAMA, 1986). AOKI (1977) found that the AL index shows a different dependence on T for different signs of B_y . Further, the B_y - T dependence is explicitly shown by MURAYAMA *et al.* (1980). The B_y dependence of the AL index in different ranges of T with 7° in width is shown in Fig. 5 (after MURAYAMA *et al.*, 1980). The tilt angle is denoted by χ in this figure. The slopes of the regression lines change systematically from negative for $T > 0$ to positive for $T < 0$. It is also noticeable that the sign of the slopes changes at $T = 7 \sim 14^\circ$ rather than at $T = 0^\circ$.

The same effects of B_y and T are found in variations of the auroral oval size (NAKAI, 1987). The auroral oval expands and contracts dynamically in association with variations in auroral activity and the interplanetary magnetic field (KAMIDE and WINNINGHAM, 1977; HARDY *et al.*, 1981; NAKAI and KAMIDE, 1983). When the IMF is oriented southward, the oval size strongly depends on the minimum value of B_z during the southward excursion of the IMF (NAKAI *et al.*, 1986). Here, the oval size is indicated by using the auroral boundary index Λ (GUSSENHOVEN *et al.*, 1983), which represents the corrected geomagnetic latitude of the equatorward boundary of the auroral oval at midnight. Figure 6 shows that the auroral boundary index depends linearly on $B_z V$ for $B_z V > -4.5$ mV/m, where Λ denotes the auroral boundary index obtained within one hour of the occurrence of the minimum B_z . The solid line indicates a regression line expressed by

$$\Lambda \text{ (in degrees)} = 65.5 + 2.57 B_z V \text{ (mV/m)}. \quad (8)$$

The value of Λ decreases by 2.6° for every increase of 1 mV/m in the dawn-dusk electric field of the solar wind. Comparing this with the $B_z V$ dependence of the polar cap potential drop, the expansion (or contraction) of the auroral oval by 1° corresponds to an increase (or decrease) in the polar cap potential drop of about 5 kV. Figure 7 shows the B_y - T dependence of the oval size. The value of G presented in the figure is defined as

Fig. 5. The B_y dependence of AL is shown for different values of the tilt angle χ . The points indicate the averages of $AL/(B_S+0.5)V^2$ within intervals of width 2 nT in B_y (courtesy of T. Murayama).

$$G = (\Lambda_m - \Lambda)/(\Lambda_m - \Lambda_{\text{pred}}), \quad (9)$$

where Λ_m stands for the value of the auroral boundary index during quiet periods of auroral activity and is set at 69 CGL (MAKITA and MENG, 1984), and Λ_{pred} indicates the prediction of Λ derived by using Eq. (8). The numerator of G is the observed value of the equatorward shift of the auroral boundary from Λ_m , whereas the denominator is the predicted value of the shift assuming that the shift is independent of the IMF B_y . Thus, if the auroral oval is in fact dependent upon B_y , then the values of G will deviate systematically from unity corresponding to positive or negative value of B_y . In Fig. 7, the values of G averaged in each bin of B_y are plotted as a function of B_y , with circles and triangles indicating the averages with a tilt angle of $T \geq 10^\circ$ and $T < -10^\circ$, respectively. Solid and open symbols indicate the averages in the northern and southern auroral ovals, respectively. Although the standard errors of averages are large, the systematic changes in the B_y dependence are evident; the G value negatively (positively) depends on B_y when the tilt angle is positive (negative). It is important to note that the oval size in both hemispheres depends on B_y in the same sense. Table 2 shows the results of a double regression analysis for the data points with $B_z V > -4.5$ mV/m and $|B_y V| < 4.5$ mV/m, where the following equation is assumed:

Fig. 6. Averages of the auroral boundary index obtained within one hour of the occurrence of the minimum B_z are plotted as a function of $B_z V$, adapted from NAKAI (1987). The solid line indicates a regression line.

Fig. 7. Averages of $G = (69^\circ - \Lambda) / (69^\circ - \Lambda_{\text{pred}})$ are plotted as a function of B_y . Λ indicates the auroral boundary index. Circles and triangles show the averages with the tilt angle of $T \geq 10^\circ$ and $T < -10^\circ$, respectively. Solid and open symbols indicate the averages in the northern and southern hemispheres, respectively.

Table 2. Parameters of the least-squares fits $\Lambda = aB_yV + bB_zV + c$.

N/S	Seasons	a	b	c	$c.c.$	n
N	$T \geq 10^\circ$	0.42 ± 0.20	1.95 ± 0.28	64.7 ± 0.6	0.79	39
S	$T \geq 10^\circ$	0.58 ± 0.32	2.12 ± 0.51	65.6 ± 1.0	0.86	12
N	$T < -10^\circ$	-0.38 ± 0.22	2.78 ± 0.33	66.2 ± 0.7	0.80	43
S	$T < -10^\circ$	-0.43 ± 0.22	2.92 ± 0.36	65.8 ± 0.8	0.77	45

The letters N and S indicate the northern and southern ovals, respectively. The last two columns show the correlation coefficients and number of data points.

$$\Lambda = aB_yV + bB_zV + c.$$

The results confirms the north-south symmetry of the B_y dependence: That is, when the tilt angle is greater than 10° , the coefficient for B_yV is positive for both northern and southern ovals, and negative when the tilt angle is less than -10° .

Figure 8 shows the B_y dependence of the PC index (after VENNERSTRØM and FRIIS-CHRISTENSEN, 1987). The feature noticed first is that the normalized PC increases with increasing absolute values of B_y . A closer inspection, however, reveals that during winter the regression line is steeper when B_y is positive than when it is

Fig. 8. The B_y dependence of PC is shown for three different seasons. The solid lines indicate the regression made separately for $B_y < 0$ and $B_y > 0$. NPC is obtained by correcting PC for seasonal and local-time variations in conductivity. The points represent average values within interval of width 1 nT in B_y (from VENNERSTRØM and FRIIS-CHRISTENSEN, 1987).

negative, and vice versa during summer. Vennerstrøm and Friis-Christensen remarked that the $|B_y|$ effect is more pronounced in variations of PC than the asymmetric effect of B_y , while AL seems to depend almost linearly on B_y (see Fig. 5).

Here we reexamine the influences of B_y on AL and AU . Figures 9 and 10 show the averages of AL and AU , respectively, with $-4 \text{ nT} \leq B_z < -1 \text{ nT}$, as functions of B_y . The averages are normalized at $B_y=0$. The three panels in each figure are for different seasons of T : $T \geq 10^\circ$, $-10^\circ \leq T < 10^\circ$, and $T < -10^\circ$, from top to bottom. The solid lines indicate Eq. (2) with α of 0.6 when B_z is -2.5 nT . The middle panel in

Fig. 9. The B_y dependence of AL with $-4 \leq B_z < -1 \text{ nT}$ is shown for three different seasons of the tilt angle. A “base line” was subtracted before normalizing AL . The points indicate the averages of normalized AL in each bin of B_y . The averages are normalized at $B_y=0$. The solid line represents Eq. (2) with α of 0.6 when B_z is -2.5 nT .

Fig. 10. Same as Fig. 9 but for AU .

Fig. 9 shows that when B_y is positive, data points are fitted by Eq. (2), while AL is evidently lower than predictions when B_y is negative. The same tendency is more remarkable in the panel for $T < -10^\circ$. When T is greater than 10° , however, Eq. (2) can predict the results of observations with $B_y < 0$, but fails for positive B_y .

In Fig. 10, it is noticed that, different from AL , there seem to be no seasonal changes in the B_y dependence of AU . The averages of AU are higher (lower) than the predictions from Eq. (2) with α of 0.6, when B_y is negative (positive) (AOKI, 1977). The asymmetry of the B_y dependence of AU probably reflects the B_y effect of ionospheric convection at high latitudes. Although the characteristic changes in the

ionospheric convection pattern according to the sign of B_y have been observed in the polar cap, our results suggest that the sector structures of the IMF also influence the intensity and/or location of the return currents in the auroral zone.

4. Discussion

4.1 $|B_y|$ dependence of geomagnetic activity

In the second section the $|B_y|$ dependence of geomagnetic activity has been examined in the light of the theoretical model (HILL, 1975). Consequently, it is remarked that the observed $|B_y|$ dependence is represented reasonably well by Hill's equation with $\alpha \sim 0.6$, approximately equivalent to $\sin^4(\theta/2)$. The most suitable values of α tend to be larger for the nightside observations than for the dayside observations; i.e., the polar cap potential drop and AU fit the curve of Eq. (2) with α of ~ 0.8 , while the lobe field strength and AL fit most suitably when α is ~ 0.5 . This discrepancy yields evident differences between the values of dayside and nightside indices, particularly when θ is $\sim 90^\circ$: for example, when the IMF vector is parallel to the ecliptic plane ($\theta = 90^\circ$), using Eq. (2), the ratio of $f(\alpha=0.8)/f(\alpha=0.5)$ is calculated to be 1.95. REIFF and BURCH (1985) constructed a global B_y dependent model of convection for southward IMF conditions. A major feature of their model is the coexistence of three distinct types of convection cell; i.e., a "viscous cell", a "merging cell", and a "lobe cell". In the lobe cell, field lines are always open and circulate entirely within the lobe of the magnetotail, but connect to new interplanetary field lines during each convection cycle. The "viscous cell" consists of closed field lines mapping into the boundary layer and plasma sheet. The polar cap potential drop is defined as a total potential drop induced on these three cells. On the other hand, the increase in the lobe field strength is in proportion to the dawn-dusk electric field in the "merging cell". The "lobe cell" is expected to expand with increasing B_y component. It is, therefore, understandable that the influence of $|B_y|$ on the lobe field strength is less than those on the polar cap potential drop. The difference between the values of α for AL and AU is reasonable if one considers that the AU index is controlled mainly by the electric field in the duskside auroral zone, and that the AL index is enhanced in association with changes in the lobe field strength (FAIRFIELD, 1986).

SATO (1985) carried out a three-dimensional MHD simulation of the interaction between the solar wind and the magnetosphere. He set up a rectangular box initially filled with the dipole magnetic field. Another field embedded in plasma (i.e., the solar wind) comes into the simulation system to merge with the dipole field with an arbitrary angle θ . Figure 11 (after SATO, 1985) shows the eroded magnetic flux (ΔF) of the dipole field as a function of θ . The solid circles represent the data points obtained by the simulation. Assuming steady erosion, the flux erosion is proportional to the dissipative component of the electric field E_j . Thus, it is possible to compare the result of the MHD simulation with observations. A distinct difference between the results of the MHD simulation and the geometrical model is that the reconnection does not occur for $\theta < \cos^{-1}(\alpha)$ in the geometrical model, while in the MHD simulation it can take place even for this case, although the reconnection rate is very small (SATO, 1985). This difference arises from the fact that in the simulation the magnetosheath field is compressed to a certain amplitude so that it can merge

Fig. 11. Transferred (eroded) magnetic flux obtained by a three-dimensional reconnection simulation is shown as a function of θ . For comparison, $\sin(\theta/2)$ and $\sin^2(\theta/2)$ curves are plotted (from SATO, 1985).

with the geomagnetic field, while the geometrical model does not incorporate the compression effect. Figure 11 shows that the flux erosion is roughly proportional to $\sin(\theta/2)$ for $\theta > 90^\circ$, and decreases drastically for $\theta < 90^\circ$. It is noted that the θ dependence of geomagnetic activity decreases more steeply with decreasing θ for $\theta > 90^\circ$ than the MHD simulation indicates. This discrepancy is probably due to the following two reasons. First, since the width of the simulation area is $8 R_E$ in the east-west direction centered at the noon meridian, the length of the reconnection line is limited not by the physical conditions but by the width of the simulation system when θ is equal or nearly equal to 180° . Secondly, the results of the simulation are dependent upon the assumption made about the physical conditions under which the magnetic reconnection occurs. For example, SATO (1985) assumes the anomalous resistivity created when the current density is greater than a threshold density of the current j_c . As values of j_c become larger, the magnetosheath field should be more compressed to reconnect with the geomagnetic field. Thus the j_c values would govern the results of the simulation. This implies, however, that a correlation study of the solar wind-magnetosphere coupling system should provide useful restrictions for determining the various parameters to be used in a future three-dimensional MHD simulation.

4.2 Asymmetric influence of B_y

As shown in Fig. 9, when B_y is positive (negative) in winter (summer), the values of AL are proportional to the dayside reconnection rate predicted by using Eq. (3), whereas they are considerably suppressed when B_y has the opposite sign. It is also noted that the difference between the average of AL and the prediction increases with increasing $|B_y|$. The same, but more obscure, influences of B_y and T are also observed in variations of the PC index and auroral boundary index as described in the previous section. The causes of the asymmetric B_y dependence are discussed below.

The PC index depends directly on the dawn-dusk electric field in the central polar cap, and the auroral boundary index is controlled by the electric field in the duskside auroral zone (NAKAI *et al.*, 1986). Thus, it is inferred that the polar cap potential drop would show the same tendency as to the B_y - T dependence. Unfortunately, the previous studies of the polar cap potential drop (REIFF *et al.*, 1981; WYGANT *et al.*, 1983; DOYLE and BURKE, 1983) are short of the data points to examine the influences of B_y and T : the data set utilized by Doyle and Burke includes 68 data points, but it comprises data with $B_y > 0$ and $T < 0$ mostly. If the asymmetric B_y dependence of the polar cap potential drop is observed, it supports the aspect that the B_y - T dependence of the auroral boundary index and PC index results from the dayside reconnection process. Note that even if this is the case, there still remains the question of why is there no indication of the seasonal variations in the B_y dependence of AU .

HEELIS (1984) discussed the cause of the B_y - T effect in terms of the dayside reconnection model. He studied a bulk data set from the AE satellites and presented an ionospheric convection model in the dayside high latitudes. A pronounced feature of the model is that, regardless of sector polarity, the "throat" of the antisunward convection is located at prenoon. Heelis suggested that this was caused by the dayside reconnection which takes place predominantly in the prenoon sector for both signs of B_y . Heelis suggested that the dawnside preference of the reconnection results from the antiparallel reconnection between the complete vector magnetic fields of the interplanetary medium and the earth. This model predicts a displacement of the "throat" to the postnoon side when the IMF is in the orthogarden hose orientation. FRIIS-CHRISTENSEN (1986) shows an example of convection velocity vectors in the dayside northern hemisphere from the Greenland magnetometer chain during an interval of orthogarden hose orientation of the IMF ($B_x < 0$ and $B_y < 0$). The expected displacement of the "throat", however, is not seen in this example. NAKAI (1987) suggested the alternative that the dawnside preference of the reconnection results from the clockwise rotation of the magnetospheric plasma convection which carries the magnetic flux into the prenoon sector from the tail (YASUHARA *et al.*, 1983; GUSSENHOVEN *et al.*, 1983). This model assumes that the dayside reconnection depends partially on the intensity of the return flux: That is, when the IMF is southward, the enhanced return flux intensifies the reconnection rate. These hypotheses should be examined further by using various observations to establish the physical process of the dawnside preference.

Since when $T > 0$, the northern cusp region tilts toward the sun, the field lines of the toward IMF can merge with earth's field lines at the dawnside of the northern cusp region, and those of the away IMF merge at the duskside. Then, assuming the dawnside preference, geomagnetic activity is higher when the IMF is oriented toward than when it is oriented away (CROOKER *et al.*, 1985). This situation is suggested to be responsible for the asymmetric B_y dependence of the PC index and auroral boundary index. On the other hand, VENNERSTRØM and FRIIS-CHRISTENSEN (1987) argued that if the dayside reconnection process is the unique cause of the asymmetric B_y dependence of AL , a more significant influence should appear in the PC index, which is considered to be a more direct measurement of the dayside interaction than the AL index. According to their indication, we do not ascribe the asymmetric B_y dependence of AL to the dayside reconnection process.

The changes of the convection pattern in the polar cap and auroral zone according to the signs of B_y are one possible cause of the asymmetric B_y dependence of AL . HOLT *et al.* (1987) deduced the convection velocity of the ion drift at high latitudes from Millstone Hill radar observations. Figures 12(a), 12(b) and 12(c) show the average convection velocity over $55^\circ \leq \Lambda \leq 75^\circ$ during summer, equinox, and winter, respectively, for $2 \leq K_p \leq 4$, when the IMF is away (after HOLT *et al.*, 1987). During summer the average of AL with $B_y < 0$ is significantly larger than that during winter (MURAYAMA *et al.*, 1980). However, there seems to be no seasonal changes in the nightside drift speed, except that the exit of the flux tube is located at 22.5 MLT, 23 MLT, and 23.5 MLT during summer, equinox, and winter, respectively. (Note that the exit of the flux tube is seen at $\sim 21:00$ MLT in the diagrams of convection patterns calculated from magnetic variations observed by the magnetometer chain at Greenland during summer (FRIIS-CHRISTENSEN *et al.*, 1985).) KAMIDE and VICKREY (1983) showed that the increase in the westward electrojet is accomplished mainly by the increase in the electric conductivity (KAMIDE and VICKREY, 1983). Therefore, the changes in the nightside convection pattern are likely to influence weakly, if at all, the intensity of the westward electrojet.

Recently the viscous-like interaction between the solar wind and the magnetosphere has attracted the close attention of many workers (BOLLER and STOLOV, 1970; EASTMAN and HONES, 1979; SCKOPKE *et al.*, 1981; MIURA, 1984; BURCH *et al.*, 1985; REIFF and BURCH, 1985). MAEZAWA and MURAYAMA (1986) showed that

Fig. 12(a). Average drifts observed during summer from Millstone Hill between January 1979 and August 1981 when $2 \leq K_p \leq 4$ and the IMF is away from the sun (from HOLT *et al.*, 1987).

Fig. 12(b). Same as for Fig. 12(a) but for equinox data.

Fig. 12(c). Same as for Fig. 12(a) but for winter data.

the enhancement of AL during equinox results from the increasing efficiency of the V dependence. This fact strongly supports the hypothesis that the viscous-like interaction is responsible for the equinoctial peaks of AL and the K index (BOLLER and STOLOV, 1970). MAEZAWA and MURAYAMA (1986) also found that the efficiency of the solar wind speed is higher in midnight and early morning sectors than in the evening sector. The local time sectors of the high efficiency of the solar wind speed correspond to the sectors in which the electric conductivity is the most dominant parameter to determine the intensity of the westward electrojet (KAMIDE and VICKREY, 1983). Accordingly, it is inferred that the viscous-like interaction controls the precipitating electron flux in the midnight and early morning sectors.

We examine the solar wind dependence of AL by dividing the data set into eight groups according to the earth's tilt angle, the IMF B_z , and B_y . Figures 13(a) and 13(b) show the V dependence of AL when $T < -10^\circ$ and $T \geq 10^\circ$, respectively. The upper panel is for the data with $-2 \text{ nT} \leq B_z < 0$, and the lower one is for the data with

Fig. 13(a). The V dependence of AL for $T \geq 10^\circ$. The upper and lower panels show the averages of AL with $-2 \text{ nT} \leq B_z < 0$ and $-5 \text{ nT} \leq B_z < -2 \text{ nT}$, respectively. Solid and open circles indicate the data points with $B_y < 0$ and $B_y \geq 0$, respectively. The regression lines are also shown by solid lines.

$-5 \text{ nT} \leq B_z < -2 \text{ nT}$. Solid and open circles indicate the averages of AL with $B_y < 0$ and $B_y \geq 0$, respectively, in each bin of V . The regression equations are represented by solid lines, which can be expressed as $AL = a(V - V_c)$, where a and V_c are constants. With a close inspection of the figures, it is seen that the B_y dependence of AL arises from the differences in V_c depending on the signs of B_y ; for example, when $T < -10^\circ$ and $-5 \text{ nT} \leq B_z < -2 \text{ nT}$, the values of V_c are 230 km/s and 147 km/s for $B_y < 0$ and $B_y \geq 0$, respectively. Figure 14 shows the occurrence distributions for AL with $B_y < 0$ (solid line) and $B_y \geq 0$ (dashed line) when the solar wind speed and B_z are in the ranges of $300 \text{ km/s} \leq V < 400 \text{ km/s}$ and $-5 \text{ nT} \leq B_z < -2 \text{ nT}$, respectively, and $T < -10^\circ$. If we assume that the occurrence probability can be represented by using the rate of data with $AL < -100 \text{ nT}$, we obtain a probability of 40% for $B_y < 0$ and 76% for $B_y \geq 0$. Thus, we see that when B_y is positive, substorms occur more frequently than when B_y is negative. One possible interpretation for the V_c value in the viscous-like interaction hypothesis is as follows: when the solar wind speed

Fig. 13(b). Same as for Fig. 13(a) but for $T < -10^\circ$.

Fig. 14. Occurrence distributions for AL with $300 \text{ km/s} \leq V < 400 \text{ km/s}$ and $-5 \text{ nT} \leq B_z < -2 \text{ nT}$ when $T < -10^\circ$. The solid and dashed lines indicate the distributions for $B_y < 0$ and $B_y \geq 0$, respectively.

exceeds V_c , the viscous-like interaction commences.

The influences of the IMF B_y and earth's tilt angle on the configuration of the magnetotail have been observed recently. When the earth's tilt angle is large, the cross-section of the neutral sheet warps so that it displaces toward the summer hemisphere near the aberrant x axis and is located in the winter hemisphere near the flanks (MURAYAMA, 1966; RUSSELL and BRODY, 1967; FAIRFIELD, 1980; GOSLING *et al.*, 1986). The influences of the IMF B_y are observed to correlate positively with the magnetotail B_y component (FAIRFIELD, 1979; LUI, 1984; TSURUTANI *et al.*, 1984). Besides, at distant magnetotail the neutral sheet twists about the magnetotail axis in response to the IMF B_y (RUSSELL, 1972; COWLEY, 1981, 1984; BRECHT *et al.*, 1981; SIBECK *et al.*, 1985). Although the distortions of the tail field due to the composite effect of these B_y and T influences are not revealed yet, it is speculated that the asymmetric suppression of AL is caused by such field distortions.

5. Summary

The influences of the IMF B_y component on several different types of observations have been examined to reconcile the inconsistencies in earlier interpretations. For this purpose, the B_y dependence of the AL , AU , and PC indices and the auroral boundary index, polar cap potential drop, and lobe field strength have been utilized.

1) The influences of the IMF $|B_y|$ on geomagnetic activity can be reasonably represented by using a theoretical equation derived on the basis of the geometrical model of the dayside reconnection (HILL, 1975).

2) The influences of $|B_y|$ on the lobe field strength and AL seem to be less than those on the polar cap potential drop, PC , and AU . This difference can be accounted for in terms of Reiff and Burch's convection model.

3) The asymmetric B_y dependence of the PC index and auroral boundary index is considered to result from the dawnside preference of the magnetic reconnection.

4) When the IMF B_y is positive (negative) in winter (summer), the B_y dependence of AL can be represented by using Hill's equation, while the values of AL are much lower than the predictions of the Hill's equation when the IMF B_y is in the opposite sectors. This is consistent with MURAYAMA *et al.* (1980).

5) The suppression of AL values does not result mainly from the dayside reconnection process. The viscous-like interaction between the solar wind and the magnetosphere appears to be responsible for this suppression.

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