OCCURRENCE RATE OF MAGNETIC SUBSTORMS DURING THE NORTHWARD IMF

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Abstract: The occurrence rate of magnetic substorms during the northward IMF was investigated statistically. The number of the substorm onsets was counted by searching the Pi2 magnetic pulsations on the rapid-run magnetograms from three mid-latitude stations. Main results obtained are as follows: (1) The occurrence rate during the northward IMF is rather high and decreases with time after the northward turning of the IMF. This indicates that the southward IMF before the northward turning has an important effect over more than several hours and causes a significant portion of the substorms during the northward IMF. (2) The condition where a substorm can be easily triggered comes with a period of three or four hours. Some oscillation in the plasma sheet may play an essential role in triggering a substorm. (3) An example shows that the tail lobe magnetic field data do not reveal any increase of the strength before the onset of a substorm during the northward IMF. (4) Two different roles of the southward IMF for a substorm, *i.e.* magnitude control and excitation of triggering mechanism, should be distinguished.

1. Introduction

The occurrence of a substorm is strongly controlled by the interplanetary magnetic field (IMF) north-south component B_z. However, it has been pointed out that substorms can occur even in the period of northward IMF. NISHIDA (1971, 1972) showed that the *AE* index enhancement during the northward IMF tends to occur after the decrease of B_z holding the B_z positive. This tendency was interpreted as follows; since the IMF influences the magnetospheric structure under all conditions of B_z polarity, a decrease in B_z leads to an increase in the magnetotail magnetic flux and sets the condition for the substorm breakup (NISHIDA, 1972). AKASOFU (1975) and AKASOFU *et al.* (1973) concluded that $B_z<0$ is not always a necessary condition for triggering a substorm, and suggested that substorms can occur so long as an excess energy exists in the magnetosphere. KAMIDE *et al.* (1977) examined the dependence of a substorm-seeing probability on IMF-B_z of 1 h before and showed that the substorms can be observed for any value of the B_z, but that the substorm occurrence frequency has a strong dependence on B_z and the size of the auroral oval. They suggested that the triggering mechanism has something to do with an increase in the stored energy in the magnetotail. All of these authors interpret the occurrence of the substorms during the northward IMF from a viewpoint of energy accumulation in the magnetotail. However, a different interpretation may also be possible. For example, rather high occurrence probability of a substorm at positive B_z (KAMIDE *et al.*, 1977) may be due to the effect of the southward IMF several hours before.

After the southward turning of the IMF, the convection of the magnetospheric tail lobe plasma is excited with a time lag of about 10 min and is observed as an enhancement of DP2 current system (NISHIDA, 1968). At the same time, the magnitude of the tail lobe magnetic field starts to increase, that is, the magnetic flux in the magnetotail increases. Thinning of the plasma sheet may also occur because of the increased magnetic pressure and/or $E \times B$ plasma drift. After a while, the earthward convection of the plasma sheet plasma is believed to be enhanced and a dawn-to-dusk electric field develops in the neutral sheet.

After these complex processes, a substorm expansion phase starts. So it is not clear which process is essential for triggering a substorm so far as only the case of southward IMF is examined. Therefore, it is important to examine the relationship between the IMF-B_z and the substorm onset during the northward IMF when such a complexity is somewhat reduced.

The interplanetary magnetic field, particularly the north-south component B_z, is always in fluctuation. So, when we discuss a substorm during the northward IMF, it is important to take account of the time duration of the northward condition before the substorm onset, the magnitude of the southward component B_s of the IMF before the northward turning, and the magnitude of the northward component after the turning. The main purpose of this paper is to examine the occurrence rate of substorms during the northward IMF and its time variation after the turning. We expect from such an analysis to make clear the essential role of the southward IMF in the triggering mechanism of a substorm.

2. Selection of IMF Events

The IMF events examined in this paper satisfy the following conditions; the hourly value of B_z before the northward turning is less than -1.5 nT, *i.e.* the southward component $|B_s|$ is greater than 1.5 nT, and the northward condition after the turning lasts more than five hours holding the B_z greater than 2 nT. Hourly averaged data in the NSSDC IMF composite tape were used in GSM coordinate system.

Since we use hourly values, it is necessary to exclude such cases that the hourly averaged B_z is greater than 2 nT but the B_z fluctuates southward in the averaged period (*i.e.* 1 h) and has finite southward component B_s. The southward component of the IMF is calculated by eq. (1) from both the hourly averaged B_z, *i.e.* B_{z_0} in eq. (1), and the standard deviation of B_z, *i.e.* σ_z, assuming the Gaussian distribution (MURAYAMA, 1979);

$$B_s = \int_{-\infty}^{0} B_z \cdot (\sqrt{2}\sigma_z)^{-1} \exp[-(B_z - B_{z_0})^2/2\sigma_z{}^2] \mathrm{d}B_z. \tag{1}$$

When the $|B_s|$ exceeds 0.1 nT, we regard that the IMF is no longer in the northward condition.

Using the above criteria, 76 IMF events were picked up for the period from 1963 to 1974 (see Figs. 2a and 2b).

3. Detection of Substorm Onset

After the northward turning of the IMF, the auroral oval contracts and the magnitude of a substorm becomes small. So it is difficult to detect the onset of a substorm by the standard *AE* indices (AKASOFU, 1973) or by the mid-latitude positive bay.

On the other hand, SAITO *et al.* (1976) emphasized that the most practical method to identify accurately the onset of substorms is to use low-latitude Pi2 magnetic pulsations and cooperative monitoring of Pi2 at three low-latitude stations on three well-separated meridians is really effective in detecting most substorms. The one-to-one correspondence between substorms and Pi2's (SAITO *et al.*, 1976) is not yet fully confirmed because, to confirm such a relationship, all substorms and Pi2's must be detectable or the essential mechanism of a substorm and a Pi2 must be fully understood. So, in this paper, we assume the one-to-one relationship between substorms and Pi2's and regard the onset of a Pi2 as that of a substorm. The definition of the magnetospheric substorm by ROSTOKER *et al.* (1980) permits several Pi2 bursts in one magnetospheric substorm and only the first one of them as the indicator of the substorm onset. Each Pi2 burst is thought to coincide with a substorm intensification. However, it is not sure whether the essential mechanism operating at the onset of a substorm, *i.e.* the triggering mechanism of the expansion phase and the mechanism of the particle acceleration, differs or not from the mechanism operating at each substorm intensification. In addition, it is difficult in practice to determine the earliest Pi2 when the substorm is not isolated. Therefore, in this paper, we use the term 'substorm onset' for each Pi2 burst.

The rapid-run magnetograms at three mid-(or low-)latitude stations, *i.e.* Fredericksburg (FRD), Memambetsu (MEM) and Wingst (WNG), are used for the detection of a Pi2. Fig. 1 shows three examples of Pi2 that occurred during the northward IMF on 13 December 1966. In these examples, at least one magnetogram of three stations shows clear onset of Pi2 (noted as 'A' in Fig. 1) and the others do not show such clear onset (noted as 'B') or show no indication. However, clear Pi2 is not always detectable and there are many cases where less clear Pi2 only, class B in Fig. 1, is detected. When we pick up Pi2's from the rapid-run magnetograms, a small variation as in class B is also adopted as a Pi2. Some of them may not be Pi2

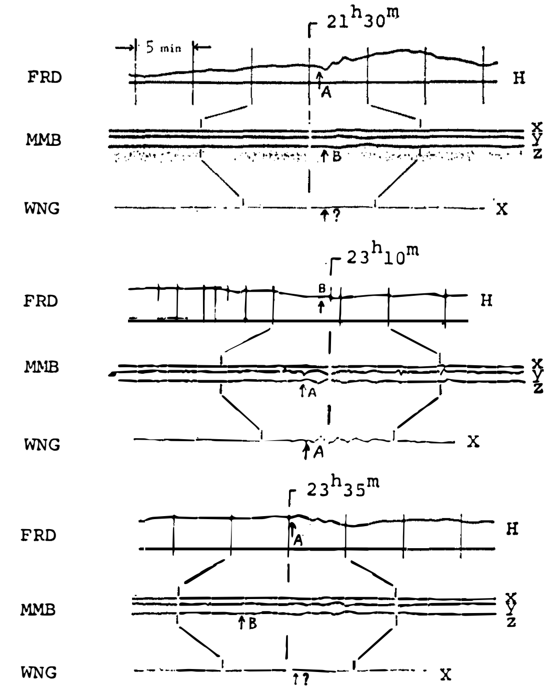

Fig. 1. Examples of the Pi2 pulsation on the rapid-run magnetograms from three mid-latitude stations; Fredericksburg (FRD), Memambetsu (MMB) and Wingst (WNG). Clear Pi2 is classified as A and less clear one is classified as B.

NO.	DATE	N.T.
1	63.11.29	23 UT
2	65. 7. 5	7 UT
3	65.10.31	6 UT
4	65.11.12	13 UT
5	65.11.29	4 UT
6	66. 7.27	15 UT
7	66. 8.30	22 UT
8	66. 9. 5	16 UT
9	66. 9. 6	13 UT
10	66. 9.23	18 UT
11	66.12.13	15 UT
12	66.12.14	4 UT
13	67. 1.14	9 UT
14	67. 1.26	13 UT
15	67. 1.29	7 UT
16	67. 2. 5	15 UT
17	67. 2. 6	3 UT
18	67. 2. 6	22 UT
19	67. 2. 8	13 UT
20	67. 2.23	0 UT
21	67. 3. 7	21 UT
22	67. 3.12	9 UT
23	67. 7.27	8 UT
24	67. 8.29	13 UT
25	67. 9. 7	16 UT
26	67. 9.17	17 UT
27	67.10. 6	3 UT
28	67.10. 7	1 UT
29	67.10.12	16 UT
30	67.11.23	13 UT
31	67.12.15	20 UT
32	67.12.27	15 UT
33	68. 1.20	19 UT
34	68. 1.26	16 UT
35	68. 2.13	16 UT
36	68. 3. 1	16 UT
37	68. 5.15	9 UT
38	68. 6. 7	17 UT

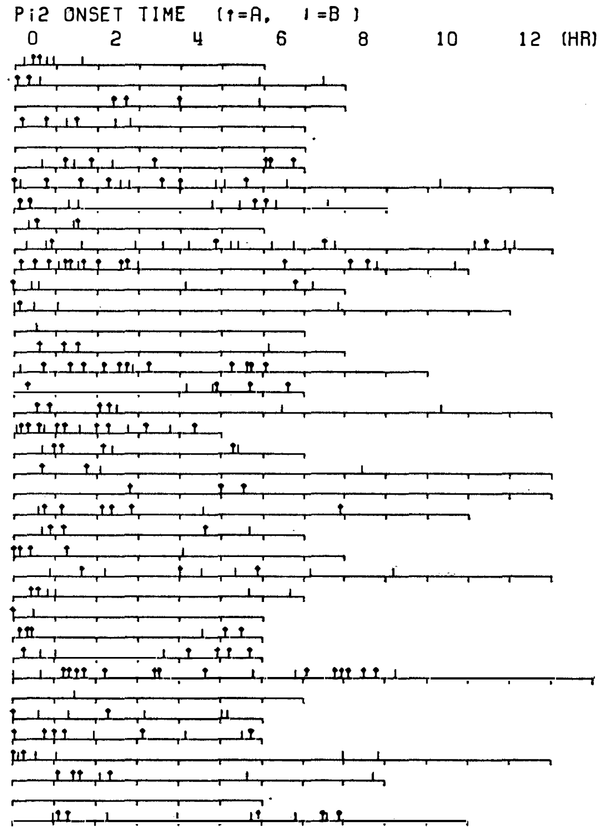

Fig. 2a.

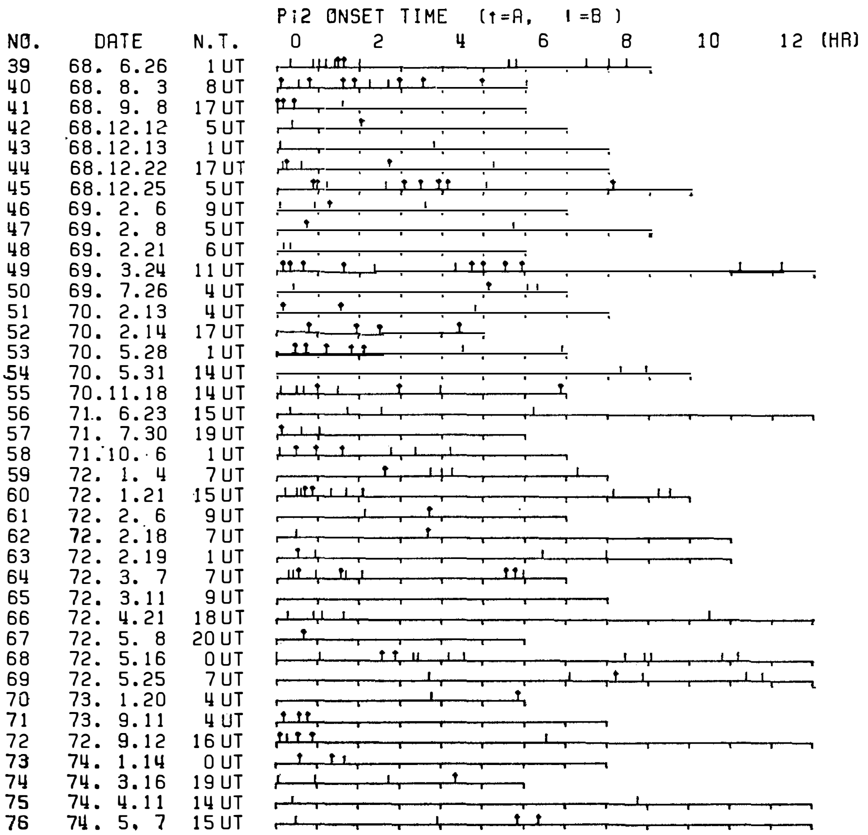

Fig. 2b.

Fig. 2. List of the northward turning events examined in this paper. Northward transition (N. T.) of the IMF occurred at some point in the interval denoted as zero. The horizontal axis is the period of the northward IMF. Short bar above the axis indicates the onset of a Pi2.

but Psc or Psi that originate from an abrupt change in the kinetic pressure of the solar wind. However, some mixture of Psc or Psi in our Pi2 list (Fig. 2) may not affect the results much, so far as we discuss the statistical nature of the substorm occurrence rate during the northward IMF. In practice, the Pi2's of class A and B are distinctly listed up. When at least one of three stations detects a Pi2 of class A, we regard that a substorm of class A starts. When there are only the Pi2 of class B, the class of the substorm is B. The time difference of Pi2 onsets among three stations within 5 min is disregarded and the earliest one is adopted as the onset of a substorm.

The list of 76 IMF events and the onset time of substorms in each event thus determined are shown in Fig. 2.

4. Results

Fig. 3 shows the averaged variation of the IMF-B_z and the AE indices (AU and

AL) for 66 IMF events where the *AE* indices are available. The origin of the time axis is at the northward turning of the IMF (with maximum 1 h error). Though the northward component B_z varies with hour considerably in the individual IMF event, the averaged variation after northward turning is rather constant (see the second panel). The average of the time derivative of B_z (dB_z/dt) for negative value also does not vary so much (top panel). The *AL* and *AU* indices decay rapidly in a few hours after the turning. Hence, when the substorm activity is measured by these indices, we are inclined to conclude that the effect of the southward IMF remains in the magnetosphere only for a few hours and the substorm activity during the northward IMF

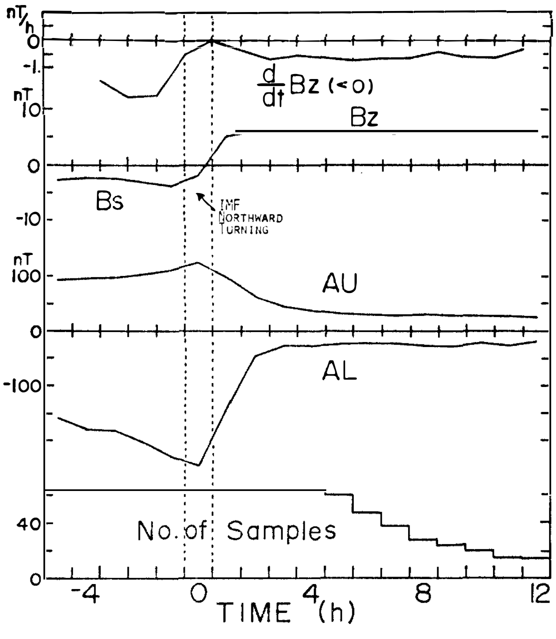

Fig. 3. Averaged variation of IMF-B_z and AE indices for 66 IMF events. The northward turning takes place at some point within the interval of zero hour. Top panel shows the average of negative change of B_z per an hour. When $dB_z/dt>0$ (i.e. positive change) we set $dB_z/dt=0$ in the calculation. B_s is the southward component of the IMF calculated by eq. (1) in the text.

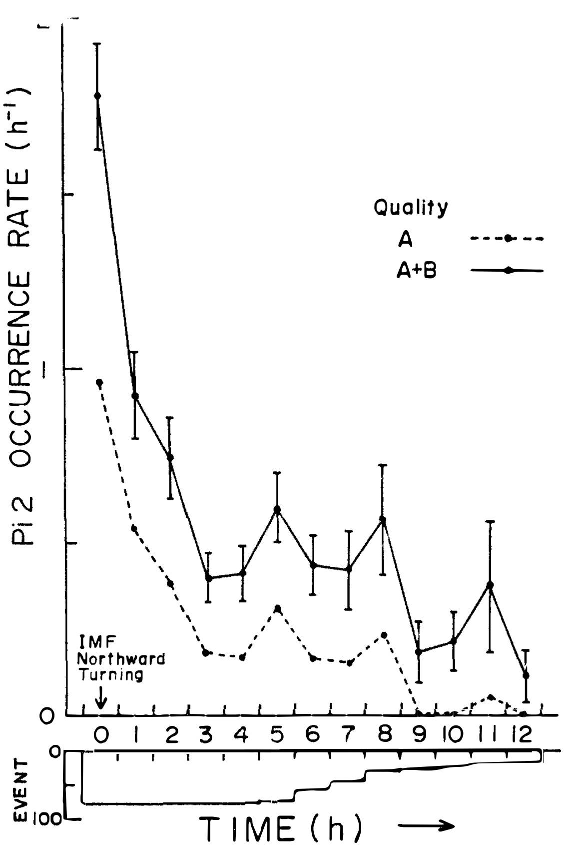

Fig. 4. Time variation of the Pi2 onset rate after the northward turning of the IMF. Solid line represents the rate of both class A and class B Pi2 (i.e. clear and less clear Pi2 respectively), and dotted line shows that of class A only. Vertical bar on the solid line denotes a sampling error (not shown for the dotted line).

is very low. However, as shown in the next paragraph, the occurrence frequency of substorms is rather high for several hours even after the northward turning, if a Pi2 pulsation is used as an indicator of a substorm onset. The rapid decay of *AE* indices probably comes from the contraction of the auroral oval (AKASOFU, 1973) and the decrease of the magnitude of a substorm, and may not come from the rapid decay of the onset frequency of the substorms.

Fig. 4 shows the time variation of the substorm occurrence rate measured by the Pi2 pulsations after the northward turning. Again, the origin of the time axis (*i.e.* at 0 h) is the time when the IMF turned northward during this one hour. The dotted line denotes the substorm occurrence rate calculated from the number of class A, *i.e.* the number of substorms defined by clear Pi2 onset, and the solid line denotes that calculated from the number of both class A and B, *i.e.* the number of substorms defined by the Pi2 onset which is not so clear is also included. Both the lines decrease with time for about 10 h, but not monotonously. The decrease of the occurrence rate after northward turning implies that the effect of the southward IMF before the northward turning remains for about ten hours on the average. The onset rate averaged from four to six hours after northward turning is about 0.5 per one hour for solid line or 0.2 for broken line, *i.e.* one substorm per two hours or per five hours. About one-third of the substorms are the multiple onset substorms if the substorms that start successively within 20 min are defined as the multiple onsets. The rate of the multiple onsets for all onsets also decreases with time after the turning similarly to the occurrence rate of substorms (not shown in Fig. 4). The decrease of the occurrence rate is not monotonous but wavy, and the period of the wave is about three or four hours. Remarkably, there is a valley of the rate for three to four hours after the turning. These results imply that the condition where a substorm can easily occur comes with a period of about three or four hours.

The magnitude of B_s before the northward turning is obviously related to the magnitude of the *AE* indices after the turning and also to the occurrence rate of substorms, though not so clear for the latter case as shown in the left panel of Fig. 5. In this figure, $<B_s>$ denotes the averaged value of B_s from three hours to zero hour before the turning, and the *AE* indices are averaged from two to five hours after the turning. The magnitude of B_z after the turning is scarcely related either to the magnitude of the *AE* indices or to the occurrence rate of the substorm except for the case of very strong northward IMF (*i.e.* $<B_z>$ greater than 8 nT) as shown in the right panel of Fig. 5. Here, $<B_z>$ denotes the averaged value of B_z from one to five hours after the turning, and *AE* indices are averaged from two to five hours after the turning. Both the occurrence rate and the *AE* indices are averaged from two to five hours. Both the occurrence rate and the *AE* indices for the case of very strong northward IMF are greater than those of the other cases. This result is the reverse of what is expected from the results of KAMIDE *et al.* (1977).

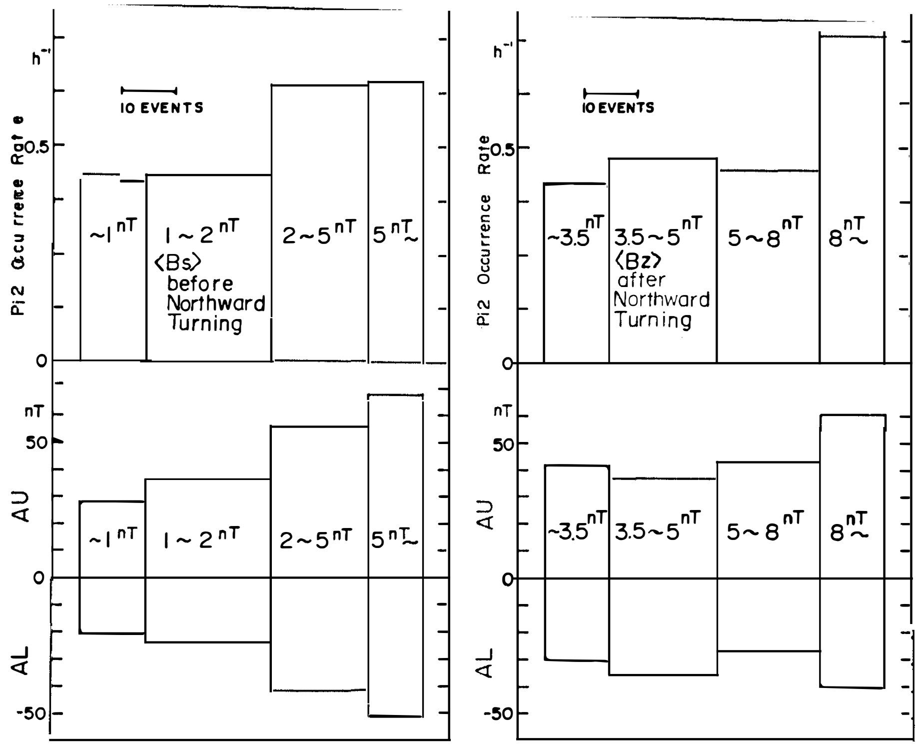

Fig. 5. The occurrence rate and the AE indices for various conditions of B_s before the northward turning (left panel) and B_z after the turning (right panel). $\langle B_s \rangle$ is an average of B_s over four hours before the northward turning and $\langle B_z \rangle$ is an average of B_z over five hours from 1 h to 5 h after the turning. The width of a column represents the number of the IMF events that satisfy the condition of the classification. The Pi2 occurrence rate and the AE indices were averaged from 2 h to 5 h after the turning.

5. Discussion

On the energy source of a substorm during the northward IMF, there are two ideas as mentioned in the first section. One of them ascribes the source to the excess energy in the magnetosphere which was accumulated during the southward IMF and still remains after the northward turning (AKASOFU, 1975; AKASOFU and LEPPING, 1977). The other ascribes it to the relative increase of energy input from the solar wind during the northward IMF; the increase of the magnetic energy in the magnetotail is assumed to result from the increased dayside reconnection rate due to the decrease of the northward component of the IMF (NISHIDA, 1972). If the substorm occurrence rate depends on the amount of the excess energy in the magnetosphere (KAMIDE *et al.*, 1977), our results, *i.e.* the occurrence rate decreases with time after the northward turning and scarcely depends on the intensity of the northward component (see Figs. 3 and 4), are consistent with the former. However, the above assumption may not be correct as shown in the next paragraph. KAMIDE *et al.* (1977) state that a substorm-seeing probability depends on the IMF-B_z and decreases with the increase of the northward component. Our result is apparently inconsistent with them, but the seeing probability of a substorm condition obtained by KAMIDE *et al.* (1977) (see Fig. 2 in their paper) also scarcely depends on the intensity of the B_z in the range of $B_z > 2$ nT, though that of the quiet time weakly depends on the B_z. It is suggested from our results that the dominant factor for the magnetosphere to reach the 'ground state' (ROSTOKER *et al.*, 1980) is not the magnitude of B_z but the length of time lapsed after the northward turning. The linear relationship between the southward component B_s before the turning and the *AE* indices after the turning is a natural consequence of the energy transfer from the solar wind which is strongly controlled by B_s, because the *AE* indices do not indicate the frequency of the substorm onsets but the magnitude of the substorm.

The wavy nature in the variation of the substorm occurrence rate (Fig. 4) suggests that the amount of the excess energy in the magnetosphere does not account for triggering a substorm, because the amount of the excess energy should decrease monotonously whenever a substorm starts. That is, the occurrence rate should also decrease monotonously with time if the triggering probability depends on the amount of the excess energy. The weaker dependence of the occurrence rate of the Pi2 than that of the *AE* indices on the magnitude of B_s (see the left panel of Fig. 5) also supports our suggestion. In other words, the significance of the southward IMF for energy transfer from the solar wind and for the excitation of the substorm triggering mechanism should be distinguished. The independence of the time lag of the substorm onset from the IMF southward turning on the intensity of the southward component after the turning (IYEMORI, 1980) may also be interpreted naturally if the above suggestion holds good. The wavy nature in the time variation with a period of about three or four hours suggests some periodic change probably in the plasma sheet. Such a periodic nature of the substorm occurrence was suggested previously from a statistical analysis of the geomagnetic indices (IYEMORI *et al.*, 1979) and from an analysis of the individual events (IYEMORI, 1979).

During the expansion phase of a substorm, it is believed that the cross-tail current interrupted by some mechanism is diverted into the polar ionosphere and flows as an auroral electrojet. However, the mechanism which leads to the interruption is not yet clear. The tearing mode instability with subsequent formation of the X-type neutral line is one of the influential mechanisms (SCHINDLER, 1975). Even this is in fact the case, the actual condition that leads to the instability is not yet specified from observation. One of the conditions for the instability to occur is the thinning of the plasma sheet. However, it is not yet known whether the thinning actually occurs or not before the substorm onset during the northward IMF. If the thinning of the plasma sheet before the expansion phase of a substorm is caused by the increase of the tail magnetic flux, our results suggest that the thinning of the plasma sheet is not the essential condition for substorm onset. The periodic increase of the substorm onset rate suggests that the condition for the instability is something which has an oscillatory nature. One of the possibilities is the oscillation of a cross-tail electric field which results from large inductance and capacitance of the plasma sheet, though the estimation by MURPHY (1978) shows the period of only a few tens of minutes. However, considering the turbulent nature of the plasma sheet (FRANK and ACKERSON, 1976), the period may be much longer because the equivalent capacitance of the turbulent plasma sheet becomes large. If this is the case, the condition of the instability may be an enhanced cross-tail electric field, and the enhanced electric field may result some macroscopic instability, *e.g.* ALFVÉN and CARLQVIST (1967) type, or some microscopic instability, *e.g.* BOWERS (1973) type, which leads to anomalous resistivity in the neutral sheet.

The tendency that a substorm is apt to occur after some decrease of B_z holding the B_z positive (NISHIDA, 1971, 1972) may be interpreted as follows: The solar wind electric field can penetrate into the magnetosphere even in the northward IMF (MAEZAWA, 1976) though it is weak. When the B_z decreases, the dusk-to-dawn electric field of the solar wind is weakened and helps the oscillation of the electric field in the plasma sheet, if the phase of the oscillation of the polarization current coincides with the decrease of B_z. In other words, if the B_z increases greatly and the phase coincides with the reverse phase of the oscillation, it also helps or excites the oscillation of the electric field or polarization current in the plasma sheet. The increase of the Pi2 occurrence rate under the condition of very strong northward IMF (right panel of Fig. 5) may be interpreted by this effect.

Only the Pi2 pulsation was used in this paper to define the onset of a substorm. The onsets of Pi2's are detected by the rapid-run magnetograms from three mid-latitude observatories. The wave forms of the Pi2's are considerably different from each other, and Pi2 and Psi (or Psc) pulsations are rather similar in the period and wave form and are confusing. The Psc is not so frequent because the SC (sudden commencement) is not so frequent, but the Psi is not so seldom. Therefore, some events in our list of Pi2's (see Fig. 2) may not be the physical Pi2 but the Psi. The tendency that the Pi2 occurrence rate increases under the condition of very strong northward IMF may partly be affected by the mixture of the Psi, since the strong IMF tends to accompany the large density regions, or in other words, a high kinematic pressure regions of the solar wind plasma. To distinguish a Pi2 from a Psi, the kinematic pressure change in the solar wind should be monitored or the polarization of the pulsation and its local time variation should be examined carefully. Instead of such a careful examination, we analyzed the 76 IMF events statistically, and some Psi's commingled with Pi2's in our list does not alter our conclusion.

So far, the relationship between the IMF conditions and the onset rate of substorms defined by the ground magnetograms was examined to discuss a substorm during the northward IMF. It is desirable to examine the condition of the magneto-

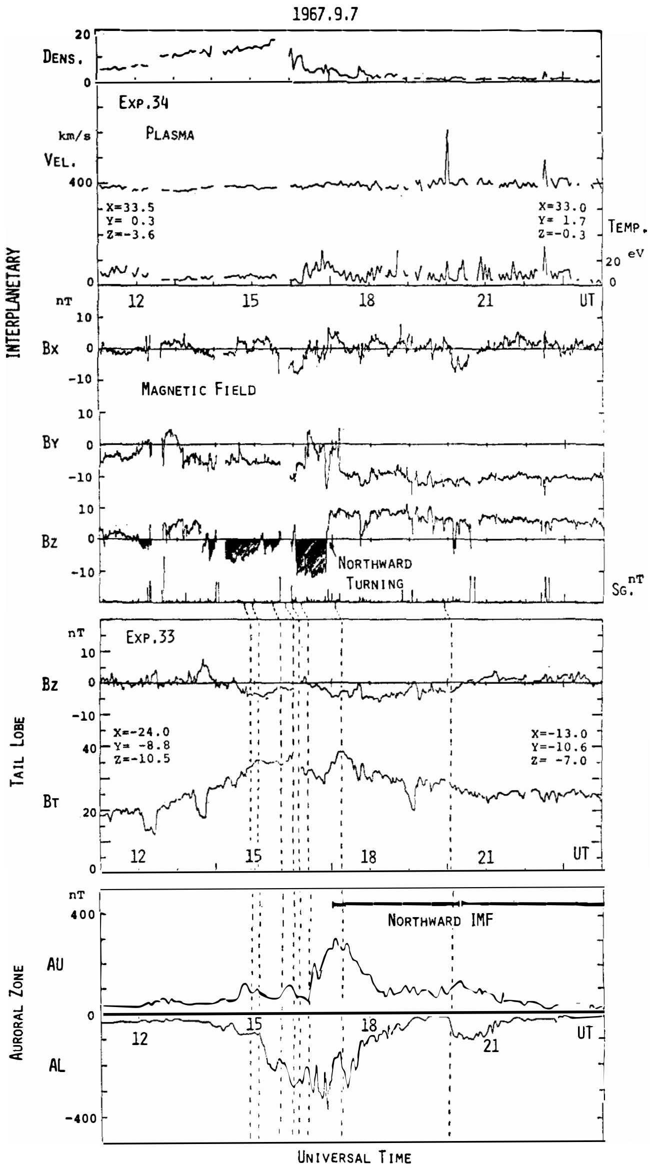

Fig. 6. An example which shows the tail lobe magnetic field variation around the onset of a substorm during the northward IMF. Solar wind plasma parameters, three components of the IMF, AL and AU indices of fine time resolution are also presented. B_t in the middle panel represents the total magnitude of the magnetic field in the tail lobe. X, Y and Z at the left and right sides in the middle panel are the satellite position (earth radius unit) in GSM coordinate system at the start and the end of this figure, respectively. Vertical dotted line represents the onset time of the Pi2. Sporadic decrease of B_t (for example, around 1215, 1340 and 1900 UT) may be the effect of the satellite encounter with a relatively dense plasma region and not the effect of a substorm. Note that the B_t before the onset at 2005 UT is fairly constant for about one hour in contrast with that before the onsets during the southward IMF.

tail where the essential process of the substorm is believed to take place. Fig. 6 shows the tail magnetic field variation with the interplanetary parameters and the *AE* indices for a northward turning event. In this event, a substorm onset is seen at 2005 UT when the IMF has been northward for about three hours. The solar wind plasma data do not show any particular change around the onset time. The tail lobe magnetic field strength B_t is fairly constant for about one hour before the time, and suddenly starts to decrease at the onset. In contrast with this onset, the tail lobe field data around the onset during the southward IMF or immediately after the northward turning show an increase and a decrease of the magnitude before and after the onset, respectively. Such field variations are seen at least three times in Fig. 6, *i.e.* around 1505, 1600 and 1715 UT. Therefore, this figure also suggests that the substorm during the northward IMF occurs without any increase of the tail field energy. That is, the amount of energy or its increase is not the essential condition for triggering a substorm The plasma motion in the plasma sheet around the substorm onset during the northward IMF should be examined in the future to make clear the triggering mechanism of a substorm.

6. Summary

The time variation of the substorm occurrence rate during the northward IMF was investigated statistically for 76 characteristic IMF events. A substorm onset as defined by an onset of the Pi2 pulsation though there is some ambiguity in practical determination of the Pi2 onset. The results of this investigation may be summarized as follows:

(1) The substorm occurrence rate decreases with time for about 10 h after the northward turning of the IMF. So, it is concluded that the effect of the southward IMF before the northward turning can remain for a fairly long time, *i.e.* more than several hours.

(2) The decrease of the onset rate is not monotonous but wavy with a period of three or four hours. This suggests that the amount of the energy stored in the tail magnetic flux does not play an essential role in triggering a substorm. The instability condition which leads to the onset of a substorm probably has an oscillating property with the above period. One possibility of the condition is an oscillation of the dawn-to-dusk electric field in the neutral sheet.

(3) An example of the tail lobe magnetic field was shown (see Fig. 6). The magnitude of the total field B_t before the onset of a substorm during the northward IMF does not show any increase, in contrast with the case during the southward IMF.

(4) Two different roles of the southward IMF for substorms should be distinguished; one is to govern the magnitude by controlling the energy transfer rate from the solar wind and the other is to excite the triggering mechanism of a substorm probably through the electric field which penetrated into the plasma sheet.

The behavior of the plasma sheet around the substorm onset during the northward IMF should be investigated in the future.

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