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Substorms under northward interplanetary magnetic field: Statistical study

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[1] It was recently noted that substorms can occur even under prolonged northward interplanetary magnetic field (IMF) conditions. Based on the substorm list obtained from the IMAGE spacecraft, we perform a statistical study on the features of substorms during northward IMF interval. The strength of the substorm is represented by the *AL* index decrease and the total intensity of the auroral bulge. Four main features have been found as follows: (1) Most substorms occur soon after a southward IMF, and intense substorms are more likely to occur for short duration of northward IMF period (2 ~ 5 h), whereas no intense substorms occur after prolonged northward IMF condition. (2) There is a positive correlation between the strength of the substorm and the two solar wind parameters (the IMF $|B_y|$ and the solar wind dynamic pressure P_d). (3) The average strength of the substorms during the storm period is much larger than that of the substorms during the period without storm. Meanwhile, nearly all strong storm time substorms occurred either during the intense storm period, or during the late main phase or the early recovery phase of the storm. (4) About half of substorms, either an increase or a decrease in the solar wind dynamic pressure, are found within 30 min preceding each onset time. Such features indicate that the energy stored in the magnetotail during a previous southward IMF period is the main energy source for substorms under northward IMF condition, especially for intense substorms, and both the IMF $|B_y|$ and the solar wind dynamic pressure play an important role in the energy accumulation during the northward IMF period.

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1. Introduction

[2] Substorms usually occur during southward interplanetary magnetic field (IMF) period, during which energy from the solar wind is accumulated in the magnetotail [e.g., *McPherron et al*., 1973]. However, a number of previous reports showed that substorms can occur under northward IMF conditions [e.g., *Akasofu et al*., 1973; *Lui et al*., 1976; *Kamide et al*., 1977; *Petrukovich et al*., 2000; *Wu et al*., 2002]. More recently, using high-resolution auroral and solar wind/IMF data, several studies reported that substorms may occur even under prolonged northward IMF conditions [*Wu et al*., 2002; *Miyashita et al*., 2011]. For example, *Wu et al*. [2002] first showed two substorms under a prolonged northward IMF condition (onset occurred after the northward IMF persisted for more than 15 h). *Lee et al*. [2010] reported several substorms observed under northward IMF conditions during the recovery phase of strong storms, and their strength was at least as large as that of typical substorms under moderately southward IMF conditions. *Miyashita et al*. [2011] showed successive substorm expansions (a series of 11 very weak to moderate substorms) occurred under prolonged northward IMF conditions (~19 h).

[3] Through careful examinations, previous studies have shown that the signatures observed by spacecraft and ground-based instruments, such as the auroral breakup, the enhancement of the westward auroral electrojet in the ionosphere and dipolarization in the magnetotail, are the same as those for typical substorms during southward IMF period [*Lee et al*., 2010; *Miyashita et al*., 2011]. This implies that the mechanism of the substorms under northward IMF conditions is basically the same as that of the typical substorms, and both reflect a process of energy release in the magnetotail.

[4] However, the energy sources for the substorms that occurred under northward IMF conditions are not clear yet. Two main possibilities were suggested. First, a large IMF $|B_y|$ may be an important factor in the dayside reconnection and the energy accumulation in the magnetotail [*Petrukovich et al*., 2000; *Lee et al*., 2010; *Miyashita et al*., 2011]. *Petrukovich et al*. [2000] showed that substorms occurred under large IMF $|B_y|$ conditions, and

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no substorms occurred for case of nearly due northward IMF without large $|B_y|$. Second, a preceding intense storm may be another important factor because of the large energy loading done by the preceding southward IMF B_z during the storm's main phase [*Akasofu*, 1975; *Lee et al.*, 2010; *Miyashita et al.*, 2011]. Recent statistical study showed that the energy stored in the magnetosphere is not always released fully during an intense storm, some of which can serve as an additional energy source for the later moderate storms or substorms [*Li et al.*, 2012].

[5] Although recent studies [*Lee et al.*, 2010; *Miyashita et al.*, 2011] have given clear examples of the substorms occurring during northward IMF interval, the results were obtained from individual or several cases. To our knowledge, the statistical response of the substorms for different upstream parameters has not been investigated, and the corresponding energy source is still an open question. The purpose of this work is to examine the statistical features of the substorms under northward IMF conditions, and discuss the energy sources on the basis of the statistical results.

2. Data Sets

[6] In this paper, we use the substorm onset list observed by IMAGE from May 2000 to December 2005 [*Frey et al.*, 2004; *Frey and Mende*, 2007]. The prime data source was the Wide-Band Imaging Camera (WIC) because of its better spatial resolution (with 256×256 pixels and bands between 140 and 180 nm). Some additional Spectrographic Imager 13 (SI-13) images (with 128×128 pixels and images OI 135.6 nm) were used whenever the WIC high voltage was not turned on or when they offered a better view. From the substorm list we can obtain some useful parameters of each substorm onset, such as the onset time, the geomagnetic location and the magnetic local time (MLT). For a more detailed description of the instrument on board the IMAGE spacecraft and the approach to determine the auroral substorm onset, please see *Frey et al.* [2004]. The IMF (in GSM coordinate) and solar wind conditions are analyzed using the OMNIWeb 1 min data set. Our analysis is limited to substorms occurring under northward IMF conditions, i.e., with IMF $B_z > 0$.

[7] In what follows, we take two parameters to represent the strength of the substorm. They are the decrease of the *AL* index (δAL) and the total intensity of the auroral bulge. The value of δAL is defined as the difference between the *AL* index before the onset and the minimum *AL* index after the onset. The total intensity of the auroral bulge is calculated at its maximum expansion phase by integrating the auroral luminosity if the intensity of the auroral bulge above a certain threshold. In this study, the threshold of the auroral luminosity is set to be one half of the maximum value of auroral luminosity, and the auroral luminosity is measured by counts, which represent the brightness of the aurora [*Frey et al.*, 2004].

[8] Substorms under northward IMF conditions are somewhat related to the solar wind conditions, such as the solar wind dynamic pressure P_d, the IMF P_y, and the epsilon parameter $\varepsilon = l_0^2 v B^2 \sin^4(\theta/2)$ (l_0 denotes the linear dimension of the effective cross-sectional area, v is the solar wind speed, B is the magnitude of IMF, and θ is the IMF clock angle) [*Akasofu*, 1981]. To clarify these relations, we calculate their average values over 2 h right before each substorm onset, denoted by $\bar{P_d}$, $\bar{B_y}$, and $\bar{\varepsilon}$, respectively, hereinafter. Meanwhile, whether a geomagnetic storm coexists also affects the properties of the substorm. Therefore, we divide substorm under northward IMF conditions into two subcategories. A substorm is referred to as "storm time substorm" if its onset occurs during a storm period in either the main phase or the recovery phase, and "nonstorm time substorm" if no storm takes place simultaneously with the substorm. In this study, the storm is identified if the minimum $Dst < -50$ nT.

2.1. Typical Substorm Events

2.1.1. Nonstorm Time Substorm Event

[9] We first show a nonstorm time substorm event under the northward IMF condition. From top to bottom, the solar wind and IMF parameters (the IMF B_z, B_y, and the solar wind dynamic pressure P_d) taken from the OMNIWeb site, the corresponding epsilon parameter ($\varepsilon = l_0^2 v B^2 \sin^4(\theta/2)$, the units of v and B are km/s and nT, respectively, and $l_0 = 7$ Re), the *AL* index and the *Dst* index for interval 0000 UT to 2000 UT on 14 June 2000 are shown in Figure 1. Two vertical dashed lines are drawn in Figure 1 to indicate the expansion onsets of two substorms, and the second (the right one) belongs to a nonstorm time substorm. It can be seen that the IMF B_z turned northward at ~1000 UT on 14 June 2000. Then the northward IMF B_z persisted for about 5 h when the substorm onset occurred at about 1501 UT. The magnitude of the IMF B_y, i.e., $|B_y|$, had moderate values (~5 nT) from 0800 to 1300 UT, and reached a larger value of 10 nT nearby the onset. The solar wind dynamic pressure was not very high, but showed a pulse-like increase just before the substorm onset. The ε parameter varied greatly from 0800 to 1300 UT, and then had moderate values (about 10^5), a little smaller than the value during the preceding southward IMF period.

[10] Global auroral images from WIC for this substorm event are shown in Figure 2. The images in Figure 2 show that brightening was first visible at 1501 UT at ~0000 to 0200 MLT. Such brightening indicates the onset of a substorm expansion. Then the region of enhanced aurora spread azimuthally and poleward over the next 20 min, forming a typical auroral bulge and reaching a maximum azimuthal coverage of ~5 h of MLT. Fading of the enhanced aurora was clear at 1531 UT. Correspondingly, the *AL* index for this event showed a clear decrease in Figure 1, from ~–50 nT to ~–220 nT. It can be also found that the *AL* index behaved in the same way as standard substorm under southward IMF conditions. The *AL* index decreased gradually in the growth phase until the substorm onset occurred, followed by a rapid drop over 15–30 min after the onset, and eventually recovered over an interval of more than 90 min.

[11] Notice that there was no storm during the event in terms of *Dst* index. Meanwhile, a substorm onset, identified by the global auroral images from WIC, occurred just before the IMF turning northward at about 0800 UT. This substorm persisted nearly 1 h, and ended at ~0900 UT. The relevant *AL* index also showed a great reduction, from ~–50 to –280 nT. After this event, geomagnetic activity kept quiet in terms of the *AL* index until the next substorm onset at 1501 UT. The auroral activity was also quiet as seen from the global auroral images available, except for the period from 0904 to 1359 UT, during which no data from the IMAGE satellite is available.

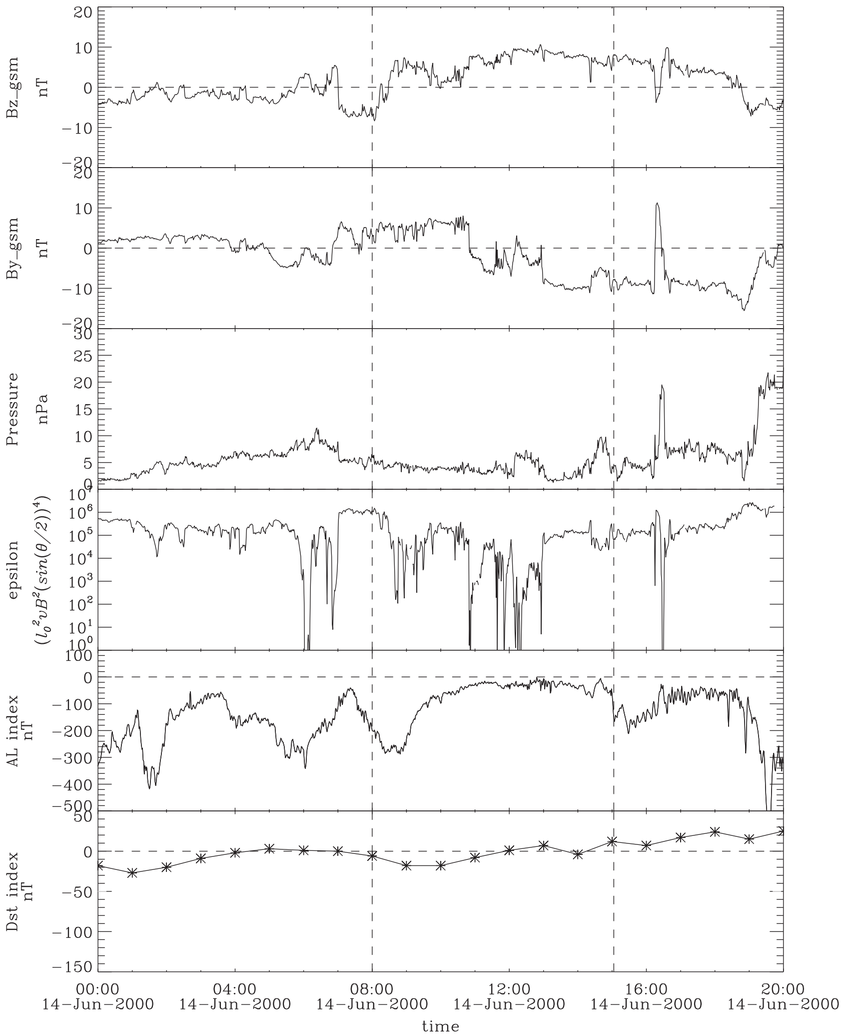

Figure 1. Substorms on 14 June 2000. From top to bottom, IMF B_z, B_y, solar wind dynamic pressure, epsilon parameter, *AL* index, and *Dst* index. The vertical dashed lines denote substorm onsets.

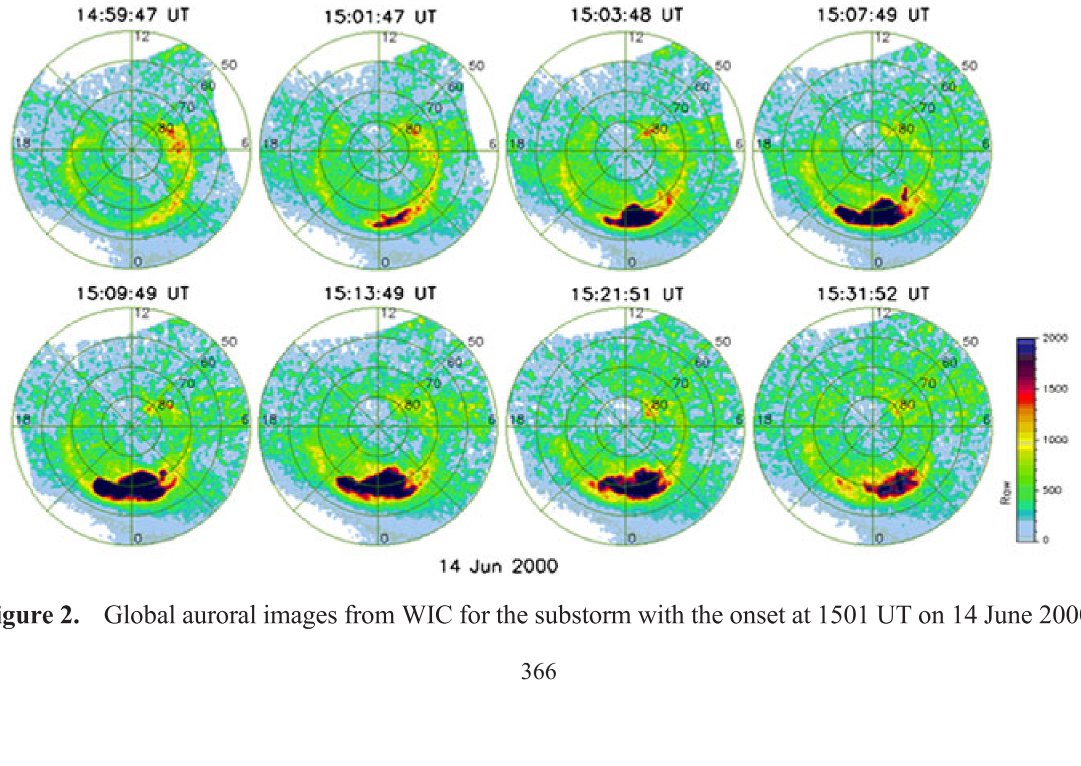

Figure 2. Global auroral images from WIC for the substorm with the onset at 1501 UT on 14 June 2000.

2.1.2. Storm Time Substorm Event

[12] *Lee et al.* [2010] showed several northward IMF substorms occurring during the recovery phase of storms. Similarly, we here show a storm time substorm event under a prolonged northward IMF condition. This event occurred at 1920 UT on 13 August 2000, after the northward IMF persisted for almost ~22 h. The solar wind and IMF parameters, as well as *AL* index and *Dst* index, are shown in Figure 3 in the same format as in Figure 1. The vertical dashed lines mark out the substorm onsets too. It can be seen that the IMF B_z turned southward for a very short time at 2130 UT on 12 August 2000, and then remained northward for at least 21 h before the onset (the second vertical line). The $|B_y|$ value was small (0 ~ 4 nT) from 0800 to 1920 UT, and the P_d had normal values (2 ~ 5 nPa) during the interval. The ε parameter was small from 0800 to 1600 UT ($\leq 10^4$), and then increased gradually to a moderate value ($\sim 10^5$). The profile of the *Dst* index showed that this event occurred during a recovery phase of a storm. The *Dst* index reached the minimum value (–235 nT) on 12 August 2000, and then recovered over the next two days.

[13] The top two panels of Figure 4 show the corresponding global auroral images of this event. Like usual substorms under southward IMF conditions, after breakup the auroral images showed a clear azimuthal and poleward expansions during the next 30 min. Correspondingly, the *AL* index decreased rapidly and clearly (from –30 nT to –100 nT). This event is much weaker than the event 20000614. On the other hand, it should be noted that the *AL* index varied greatly from about 0000UT to 0400UT on 13 August 2000 (still under northward IMF). *Liou et al.* [2004] pointed out that the *AL* decrease can be caused by a compression of the magnetosphere as well as by a substorm. Therefore, it is hard to determine whether the *AL* decrease at 0200UT, which is associated with a large enhancement of the solar wind dynamic pressure, is a substorm or the compression effect. However, it can be noted that there is a large decrease in *AL* at 0000UT occurring without increase of solar wind dynamic pressure. This indicated that (at least) an intense substorm occurred during the period, which was not observed by the Polar and the IMAGE satellites.

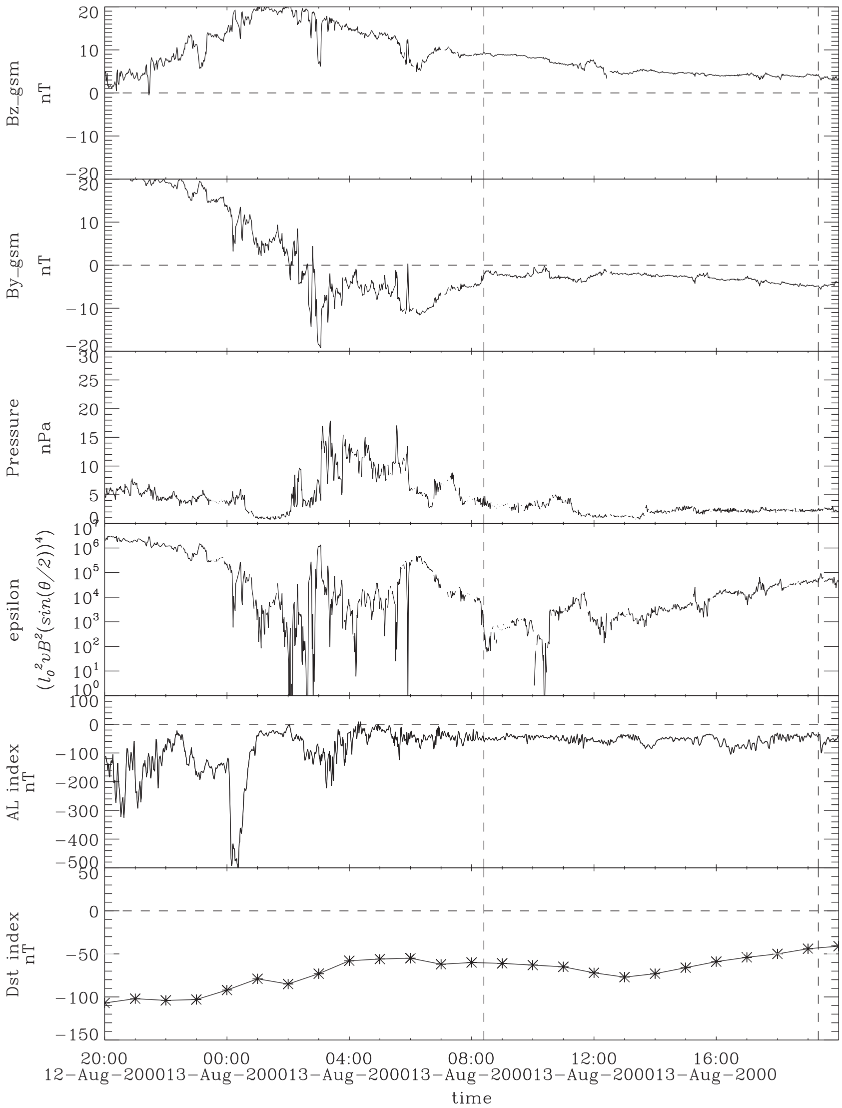

Figure 3. Same as Figure 1 but for substorms on 13 August 2000. The vertical dashed lines denote the substorm onsets.

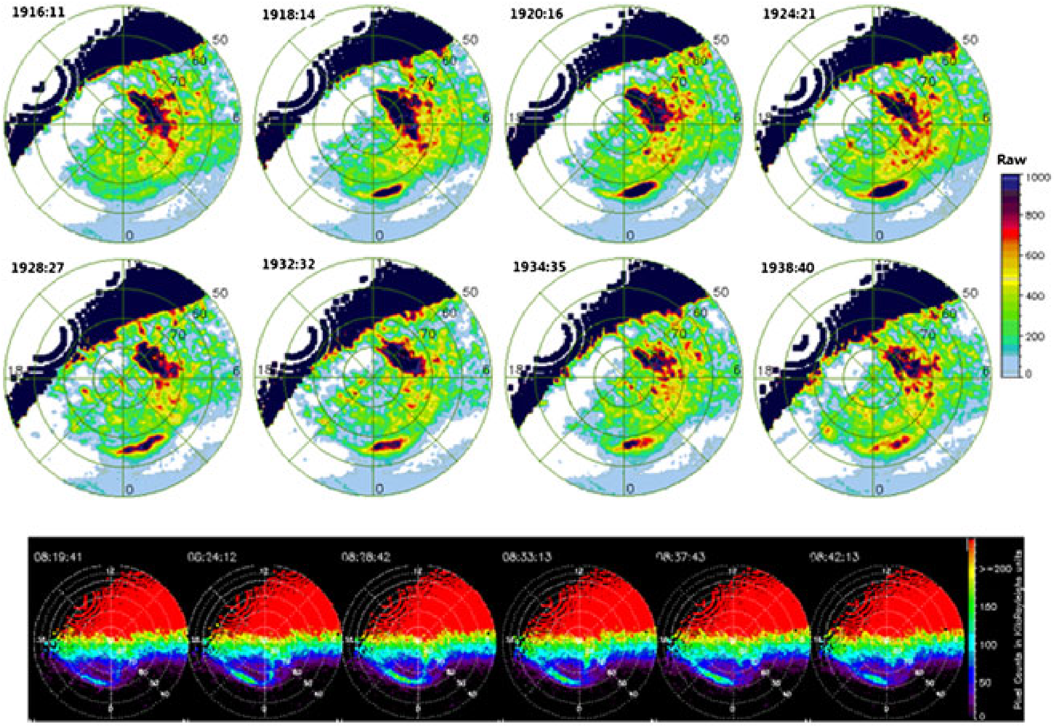

Figure 4. (top) Global auroral images from WIC for the substorm with the onset at 1920 UT on 13 August 2000. (bottom) Auroral images from Polar for substorm with the onset at 0819 UT on 13 August 2000.

[14] For this event, the data from IMAGE was only available from 1735 UT to 2035 UT. The data from Polar visible imaging system was available from 0600 UT to 1700 UT on 13 August 2000, and led to a ~0.5 h gap between the two series of data. It is found from the Polar observation that a substorm occurred between 0819 UT and 0850 UT (the first vertical line), which is shown in the bottom panel of Figure 4, then the ionosphere remained quiet for the following ~9 h (from 0850UT to 1700UT), and the geomagnetic activity kept quiet in terms of the *AL* index from 1700 UT to 1735 UT. Thus, the northward IMF has persisted for at least 10 h (from 0850 UT to 1920 UT) with no substorm occurring during the 10 h interval prior to that particular onset.

2.2. Statistical Examination

[15] In the present statistical study, we divide all substorms into three categories according to the duration of the northward IMF: (1) 2 ~ h, (2) 5 ~ h, and (3) > 10 h. The duration of the northward IMF is defined as the time interval during which the northward IMF persisted until a substorm onset was observed by IMAGE. Note that other substorms might occur during this interval but were missed by IMAGE, and this does not affect our definition of the duration of the northward IMF made above

[16] All substorms under northward IMF conditions are classified according to the duration of northward IMF based on the above criterion. Based on the list of substorm onsets observed by IMAGE spacecraft, which covers the period from May 2000 to December 2005, 72 events in total are identified, where four of them are observed by the instrument SI-13, the others are all observed by the instrument WIC. The results are listed in Table 1. The first row in Table 1 is the northward IMF duration. The second row is the total number of the substorms for different durations of the northward IMF period. The "storm" and "nonstorm" in the third row represent substorms occurring in the

Table 1. Substorms Under Northward IMF Conditions

	Duration (hours)					
	2 ~ 5		5 ~ 10		> 10	
	Total Number					
	45		17		10	
	Storm	Nonstorm	Storm	Nonstorm	Storm	Nonstorm
Number	16	29	4	13	2	8
$\bar{AL}$ (nT)	–236	–100	–160	–67	–105	–54
$\delta\bar{AL}$ (nT)	178	65	66	46	70	26
Total intensity	1.10e6	2.77e5	3.86e5	2.42e5	1.75e5	1.20e5
$\overline{\lvert GeomagLAT \rvert}$	64.1	67.1	64.5	68.3	64.1	67.8

presence and absence of magnetic storms respectively. The last four rows are the minimum *AL* index, the *AL* index decrease, the auroral total intensity and the geomagnetic latitude of the substorm onset, respectively, averaged among the associated substorm events.

[17] As shown in Table 1, 72 events in total are identified, including 22 storm time substorms and 50 nonstorm time substorms. When the duration of the northward IMF lies in between 2 and 5 h, 45 events in total are identified, including 16 storm time substorms and 29 nonstorm time substorms. As expected, the number of the identified substorms and the average values $|\bar{AL}|$ and $|\delta\bar{AL}|$ decrease with increasing duration of the northward IMF. The average values of the auroral total intensity show similar feature.

[18] Figure 5 gives the histogram of occurrence number depending on the duration with 1 h resolution. Here, each bar was divided into two cases: "storm time" case (black code) and "nonstorm time" case (gray code), and the right histogram is the occurrence number when the duration time is over 15 h. It can be seen that the distribution peaks at 2 h, and then falls rapidly, suggesting that substorms are more likely to occur just after preceding southward IMF conditions.

[19] Figures 6 and 7 both show the strength of the substorm, which is represented by $|\delta\bar{AL}|$ and the total intensity of the aurora respectively, versus different parameters. From Figures 6a to 6f, the parameters are $|\bar{B}_y|$, $\bar{P}_d$, the epsilon parameter ($\bar{\varepsilon}$), the sudden pressure change ($|dP_d|$), duration of the northward IMF and *–Dst*, respectively. Here the change (an increase or a decrease) of the solar wind dynamic pressure is taken to be larger than 1 nPa in 20 min, and any substorm onset with such a preceding P_d change within 30 min will be identified as a substorm associated with a pressure sudden change. $|\bar{B}_y|$, $\bar{P}_d$, and $\bar{\varepsilon}$ are the average values over the 2 h period right before the substorm onset, as mentioned in the last section. *Dst* is the value at the onset time. The circles and diamonds denote the storm time substorms and nonstorm time substorms, respectively. Here, four very weak events in Figure 7 are observed by the instrument SI-13. The solid lines denote the averaged substorm strength (δAL and the total intensity of the aurora) versus different parameters. The average windows are taken as follows: (1) 5 nT for $|\bar{B}_y|$, (2) 5 nPa for $\bar{P}_d$, (3) 4 nPa for dP_d, (4) 50 nT for *Dst*, (5) 1 for $\bar{\varepsilon}$. Because the events focused in short duration region, the average window for the duration of northward IMF differs between two parts: 2.5 h for the duration smaller than 10 h, and 10 h otherwise.

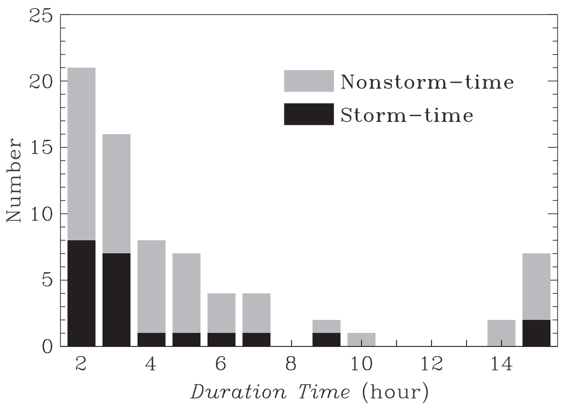

Figure 5. Histograms of the occurrence number depending on the duration of the northward IMF. The right histogram is the occurrence number for the duration time longer than 15 h.

2.2.1. Comparison of Properties Between Storm Time Substorms and Nonstorm Time Substorms

[20] First, we examine the differences between storm time substorms and nonstorm time substorms. It can be seen fromTable 1 that the average values of $|\bar{AL}|$, $|\delta\bar{AL}|$, and the averaged auroral intensity of the storm time substorm are all much larger than those of the nonstorm time substorm. Also, the average value of the geomagnetic latitude of the onset is more equatorward for the storm time substorm. It can be also seen from Figures 6f and 7f that the averaged values (solid lines) of δAL and the auroral intensity are both positively related to the value of *–Dst*.

[21] Figure 8 shows the occurrence distribution of the *Dst* value at the onset time and minimum *Dst* value of the storm (*MDst*). The *x* axis is the minimum *Dst* value of the storm, and the *y* axis is the ratio of the *Dst* value at the onset time to the minimum *Dst* value of the storm(*Dst*/*MDst*). When the value *Dst*/*MDst* goes to 1, it means that the onset is located in the late main or early recovery phase of a storm. The color codes in Figures 8a–8b represent the magnitude of δAL (the *AL* index decrease) and the total intensity of the auroral bulge, respectively. It can be seen that nearly all strong events are located at the upper right side in both panels, indicating that strong substorms are more likely to occur during intense storm period or during the late main or early recovery phase of the storm.

2.2.2. Role of the IMF $|B_y|$

[22] It can be seen from Figure 6a that when the IMF $|B_y|$ increases, the averaged value of the decrease of the *AL* index increases. Figure 7a shows that the averaged value of the total intensity of the auroral bulge also increases with the rising of the IMF $|B_y|$. Such features demonstrate that there is a positive correlation between the IMF $|B_y|$ and the strength of the substorm. This provides additional evidence that the large IMF $|B_y|$ plays an important role in the energy accumulation under northward IMF conditions. This is consistent with the results obtained by previous studies [*Lee et al.*, 2010; *Miyashita et al.*, 2011], and implies that the intensive substorms are more likely to occur under large IMF $|B_y|$ conditions.

2.2.3. Role of the Dynamic Pressure P_d

[23] The role of P_d is examined in Figures 6b and 7b. It can be seen from Figure 7b that there is a positive correlation between the averaged value of the total intensity of the auroral bulge and the magnitude of the solar wind dynamic pressure. However, the correlation between the solar wind dynamic pressure and the averaged δAL value is not good in Figure 6b. This difference may come from that the *AL* index is not a good parameter for substorm activity when the auroral oval is located at lower or higher latitudes from the *AL* stations. According to the auroral intensity result, we suggest that there is a positive correlation between the solar wind dynamic pressure and the strength of the substorm.

[24] According to recent work [*Liou et al.*, 2003; *Liou*, 2007], the substorm may be triggered by an increase or a decrease of the pressure. Therefore, the relation between

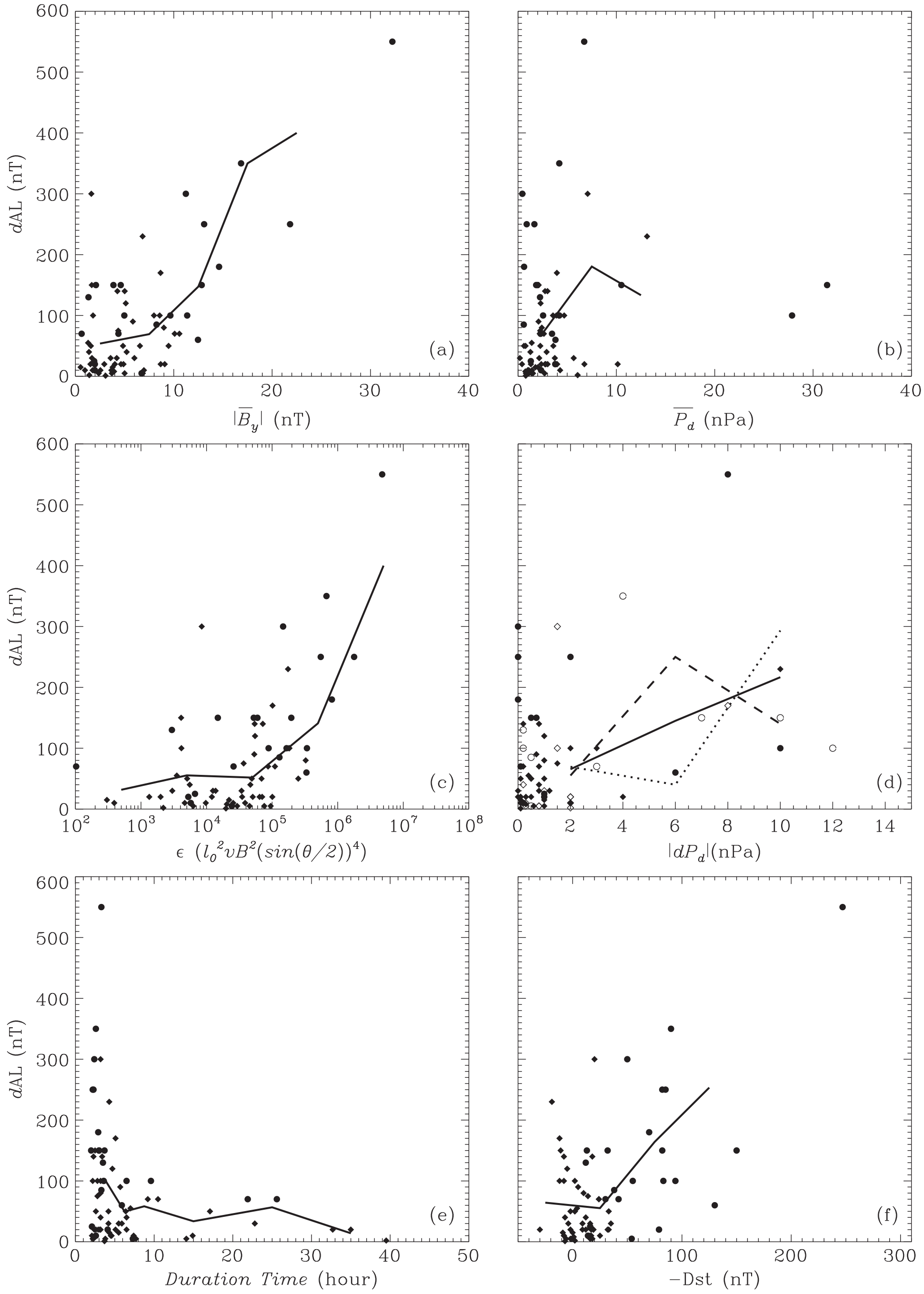

Figure 6. The decrease of the *AL* index (δAL) versus different parameters. (a)–(f) The parameters are $\left|\bar{B}_y\right|, \bar{P}_d$, the epsilon parameter ($\bar{\varepsilon}$), the sudden pressure change ($|dP_d|$), duration of the northward IMF, and the $-Dst$, respectively. Solid lines represent the averaged values versus different parameters. The black and white symbols in Figure 6d represent positive dP_d and negative dP_d, and the corresponding averages are plotted by dotted and dashed lines, respectively.

the sudden change of the dynamic pressure (an increase or a decrease) and the occurrence of substorms is checked too. The positive dP_d event and the negative dP_d event correspond to the compression and expansion of the magnetosphere, respectively. They may be different in substorm triggering, so they are treated separately. It is found that about half of the substorms (11 positive events and 16 negative events) are associated with the pressure sudden change, which is similar to the result of *Lee et al*. [2010]. Figures 6d and 7d give the relation between the sudden change of the dynamic pressure ($|dP_d|$) and the strength of substorms. The black and white symbols represent positive and negative events, respectively. The three different lines (dotted, dashed and solid) are the averages of positive events, negative events, and total events, respectively. It can be seen that the three average lines are similar to each other in Figure 7d. Similar to the results of Figures 6b and 7b, there is a positive correlation between the averaged

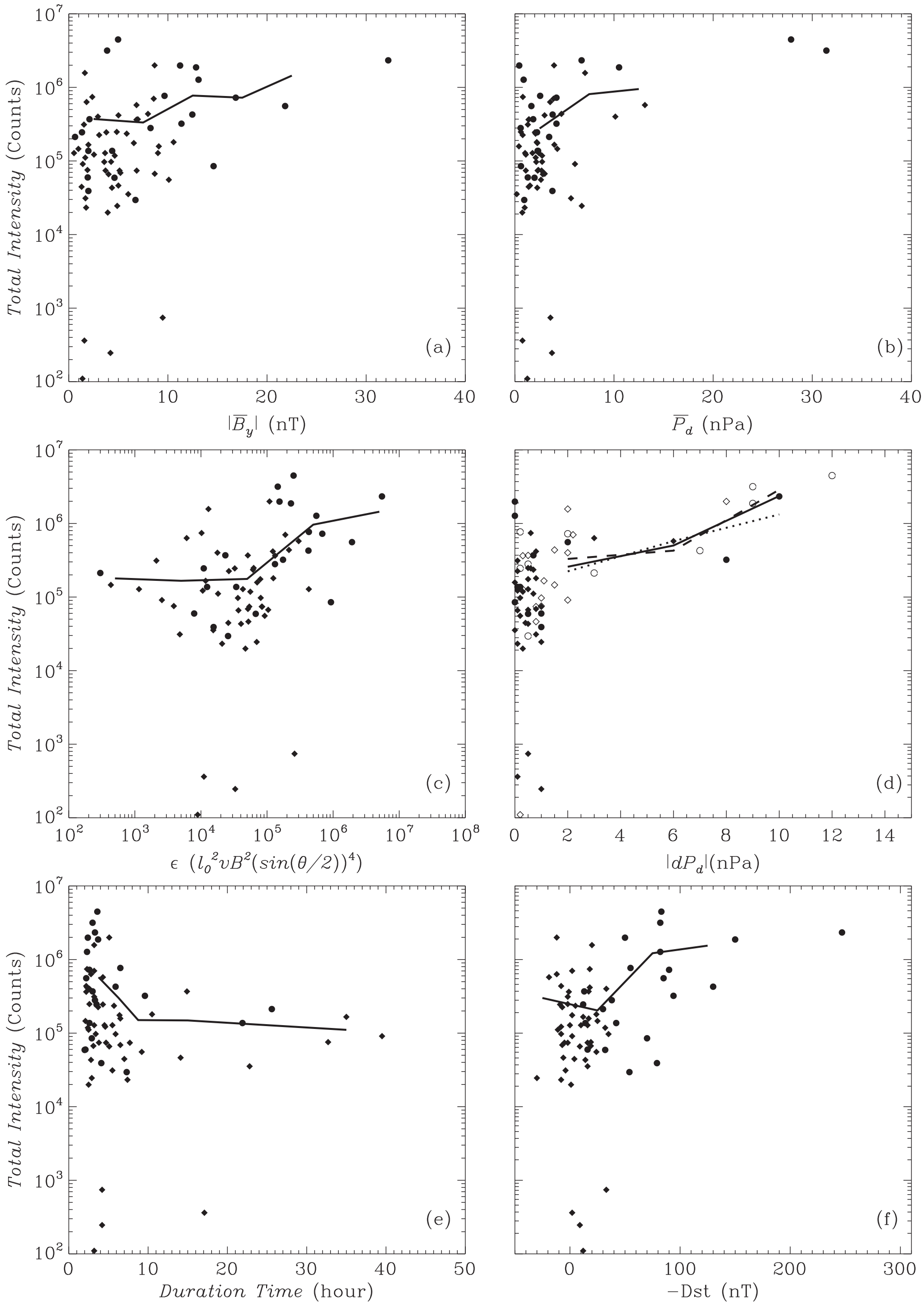

Figure 7. Similar to Figure 6, total intensity of the auroral bulge versus different parameters.

auroral total intensity and the magnitude of the sudden pressure change in Figure 7d, while the correlation between δAL and the pressure change is not good as shown in Figure 6d.

2.2.4. Effect of Northward IMF Duration

[25] It is well known that when the IMF turns from southward to northward, the topology of the magnetosphere will change from tail-like to more dipolar-like, and hence the energy stored in the tail will decrease with time through certain mechanisms, which may be substorms or other mechanisms. Consequently, the energy stored during the previous southward IMF will decrease with time, and the effect of the previous southward IMF will weaken. Therefore, to examine the effect of the previous southward IMF condition, the duration of the northward IMF is defined as the time interval during which the IMF persists northward prior to the substorm onset observed by IMAGE.

[26] Figures 6e and 7e show the effect of northward IMF duration on the two parameters (the *AL* index decrease and the total intensity of the auroral bulge). It can be seen that all strong events are located in short duration regions, and only several weak events are located in prolonged duration regions. The average lines in both figures show similar results. This demonstrates that there is a negative correlation between the strength of substorm and the duration of northward IMF.

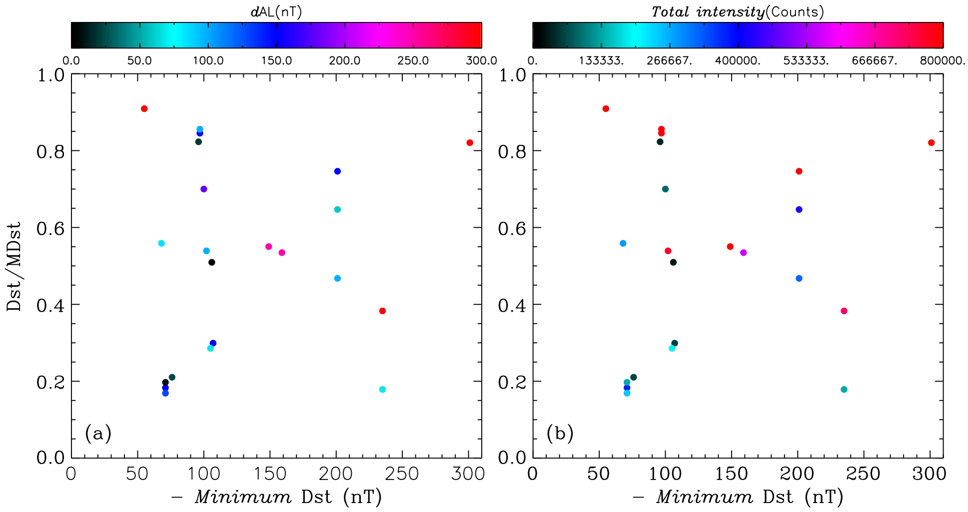

Figure 8. The occurrence distribution of the *Dst* value at the onset time and minimum *Dst* value of the storm. The *x* axis is the minimum *Dst* value of the storm, and the *y* axis is the ratio of the *Dst* value at the onset time to the minimum *Dst* value of the storm (*Dst/MDst*).

It should be noted that there is no intense substorm occurred under prolonged northward IMF conditions (about 6 h). Furthermore, so far as we know, substorm onsets under prolonged northward IMF conditions that have been published are all weak or at most moderate events. Such features demonstrate that there is no enough energy stored in the tail under prolonged northward IMF conditions or that the tail under prolonged northward IMF conditions cannot store enough energy for an intense substorm to occur.

2.2.5. Role of Other Parameters

[27] The strength of the substorm is related to the efficiency of energy transferred from the solar wind into the tail. Therefore, there should be a relation between the strength of the substorm and the energy coupling parameter such as the epsilon parameter by *Akasofu* [1981]. We have made a plot of δAL versus the epsilon parameter in Figure 6c and a plot of total intensity of the auroral bulge versus epsilon in Figure 7c. Both plots show that there is a rough positive relation between the strength of the substorm and the epsilon parameter.

[28] The polar cap boundary, which is usually defined as the poleward boundary of the aurora, is used to monitor the transfer of magnetic energy to the open tail. Therefore, the latitude location of the substorm onset may be an important parameter. Plots of δAL and auroral intensity versus geomagnetic latitude are shown in Figure 9. Solid lines are the averages, and the average window is 5°. It can be clearly seen from Figure 9b that the total intensity of the auroral bulge is much stronger when the substorm onset located in the equatorward side. While in Figure 9a, there is a similar relation between δAL and the latitude distribution except for three events located at lower latitudes. The three events may be located at lower latitudes from the *AL* stations, so that the *AL* index underestimates the strength of the substorm. That may also be why the correlation between the solar wind dynamic pressure and the δAL value is not clear. The averaged latitude for the substorm onsets is 66.5°, which is almost the same as the results (66.4°) of *Frey et al.* [2004].

3. Discussion and Summary

[29] In the preceding section we have discussed the substorms occurring under northward IMF conditions based

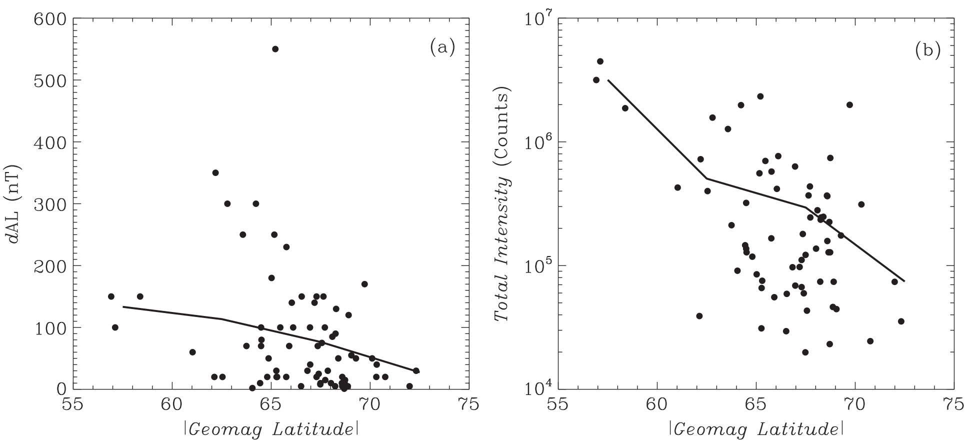

Figure 9. (a) δAL and (b) auroral intensity versus geomagnetic latitude of the substorm onset. The solid lines are the average lines.

on the substorm list identified by the IMAGE satellite. Using the high-resolution IMF and *AL* index data provided by the OMNIWeb site, and the *Dst* data provided by the Kyoto *Dst* index service, we have examined the features of the substorms and their relation to solar wind and IMF parameters. The duration of the northward IMF (defined as the time interval during which the IMF persisted northward prior to the substorm onset observed by IMAGE) is used to analyze the effect of a previous southward IMF, which is expected to be negatively related to the northward IMF duration. When the duration is short, previous southward IMF condition will play a more important role. When the duration is prolonged, the role of previous southward IMF condition will be weakened. The main features are summarized as follows.

[30] 1. When the duration of northward IMF is short (2 ~ 5 h), intense substorms, at least as intense as usual substorms under southward IMF conditions, can occur even under small IMF $|B_y|$ and dynamic pressure conditions. On the other hand, when the duration of the northward IMF is prolonged (> 6 h), the strength is much weaker, and no intense substorm occurs. Furthermore, most events occurred soon after a southward IMF.

[31] 2. There is a positive correlation between the strength of the substorm and the two solar wind parameters (the IMF $|B_y|$ and the solar wind dynamic pressure P_d). The strength of the substorm is positively related to the epsilon parameter too.

[32] 3. About ~30% of the substorms occurred during the storm period. The average strength of the substorms during the storm period is larger than that of the substorms during the period without storm. Also, the storm time substorm onsets are located more equatorward than the nonstorm time substorm onsets.

[33] 4. It is found that nearly all strong storm time substorms occurred either during the intense storm period, or during the main phase or the early recovery phase of the storm.

[34] 5. For nearly half of the substorms (27/72), either an increase or a decrease in the solar wind dynamic pressure is found within 30 min preceding each onset time. In particular, there is a positive correlation between the strength of the substorm and the magnitude of the sudden pressure change.

[35] It is generally believed that during substorm, explosive reconfiguration of the magnetosphere should occur due to the release of the energy supplied from the solar wind and stored in the magnetotail [e.g., *McPherron et al*., 1973]. *Akasofu* [1975] suggested that substorms can occur as long as there is enough magnetic energy in the tail, regardless of the sign of the IMF B_z component. Therefore, the key question is how the energy is accumulated during northward IMF periods. Two main possible mechanisms were previously suggested. First, excess energy in the tail during northward IMF may have been supplied during a previous southward IMF interval [*Akasofu*, 1975; *Lee et al*., 2010; *Miyashita et al*., 2011]. Second, there may be other efficient solar wind-magnetosphere coupling processes to accumulate energy in the magnetotail during northward IMF period, such as a large IMF $|B_y|$ [*Petrukovich et al*., 2000; *Lee et al*., 2010; *Miyashita et al*., 2011]. In the following, based on the above summaries of the observations together with recent studies, we first discuss the above two possibilities briefly, and then discuss another possible energy source (the high solar wind dynamic pressure), and finally try to find out which one is the main source.

[36] The successive substorm expansions during the prolonged northward IMF period indicated an energy input process under northward IMF conditions, and such process was suggested to be caused by a large IMF $|B_y|$ [*Petrukovich et al*., 2000; *Lee et al*., 2010; *Miyashita et al*., 2011]. Recently, global MHD simulation results also showed that the dayside reconnection of the closed field lines can take place when the IMF is not due northward [*Hu et al*., 2009]. The statistical positive correlation between the IMF $|B_y|$ and the strength of the substorm shows again that the IMF $|B_y|$ plays an important role in the energy accumulation during the northward IMF period. At the same time, we should also note that there is nearly no intense substorms under prolonged northward IMF conditions, which indicates that the energy transfer efficiency due to the IMF $|B_y|$ is much lower than that under southward IMF conditions.

[37] The storm-time intense substorm events during northward IMF period suggested that a certain amount of energy loaded by preceding southward IMF remains in the tail even under northward IMF conditions [*Lee et al*., 2010]. Our statistical results show that substorms occurring during the storm period are generally much stronger than those not associated with storm. Moreover, the strength of the substorm is negatively related with the duration of northward IMF, and most of the substorms occurred during short duration of northward IMF. These statistical features show again that the energy stored during a previous southward IMF interval is an important energy source for substorm under northward IMF condition.

[38] Another possible source for energy transfer is the high solar wind dynamic pressure. In ideal MHD, the field lines are tacitly assumed to be equipotential, and then the transpolar potential in the ionosphere can be considered to be a measure of the strength of the dayside reconnection [*Fedder et al*., 1991]. Recently, *Ober et al*. [2003] found that DMSP observed higher transpolar potentials when P_d was larger for southward IMF conditions. Using global MHD simulation, *Peng et al*. [2009, 2011] showed that the transpolar potentials increase monotonically with increasing P_d, leading to an enhancement of the auroral brightening for both southward and northward IMF conditions. Therefore, it can be seen that an increase of the solar wind dynamic pressure can enhance the energy transferring from solar wind to magnetosphere. Our statistical results show that there is a positive correlation between the strength of the substorm and the dynamic pressure. It demonstrates that the solar wind dynamic pressure also plays an important role in the energy accumulation during northward IMF period.

[39] It is also found that about half of the substorms are associated with a pressure sudden change (11 positive events and 16 negative events), and the positive change and negative change show similar behavior. The strength of the substorm is positively related to the magnitude of the sudden change, indicating that the sudden change of the dynamic pressure may play an important role in triggering a substorm under northward IMF.

[40] The statistical results show that almost all of the strong events occurred during short northward IMF periods,

and there is no intense substorm occurring under prolonged northward IMF condition. This indicates that (especially intense) substorms are more likely to occur just after the southward IMF turned northward. Meanwhile, nearly all strong storm time substorms occurred either during intense storm period or during the early recovery phase of the storm. Storm (or intense storm) period means a large previously stored energy, and the early recovery phase of the storm indicates again a short northward IMF duration. All these features demonstrate again that intense substorms are more likely to occur just after a preceding southward IMF condition, even if the IMF $|B_y|$ component and the solar wind dynamic pressure are very small. Hence, we can reasonably conclude that the energy stored in the magnetotail during a previous southward IMF period is the main energy source for substorms, especially for intense substorms. That is also why there is no intense substorm occurring under prolonged northward IMF condition.

[41] Finally, all the results show that the magnetotail can still contain a lot of magnetic energy for some time even after a northward turning of the IMF. *Akasofu* [1975] claimed that this time interval can range from 40 min to ~1 h after the northward turning of an IMF. *Lee et al.* [2010] conjectured that it is longer during storm times. Our statistical results show that (1) most substorms occurred during short duration of northward IMF (smaller than 6 h), (2) the averaged substorm strength decreased with the increase of duration of northward IMF, and no intense substorm occurred for long duration of northward IMF (larger than 6 h). Based on the above statistical results, the time interval can be as long as 6 h.

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