Average characteristics of triggered and nontriggered substorms

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Received 12 March 2003; revised 2 February 2004; accepted 16 March 2004; published 17 July 2004.

[1] Magnetic field data from ground stations, geosynchronous orbit, and magnetotail are examined to study the response to substorm activity with and without apparent interplanetary magnetic field (IMF) perturbations. Global substorms are identified using a sudden, persistent decrease in the $\text{AL}$ index. The onset of this global expansion is taken to be the time of the Pi2 burst nearest to the beginning of the $\text{AL}$ decrease. IMF triggers were identified subjectively through visual scanning of the data. Both northward turnings of the IMF $B_z$ and decreases in the amplitude of the $B_y$ component were considered as possible triggers. Two different solar wind monitors were used in the investigation: IMP 8 in a circular orbit with a distance between $\sim 12$ and $\sim 35 \text{RE}$ from the Earth-Sun line and ISEE 2 in an elliptical orbit with a distance of only $\sim 5–10 \text{RE}$ from the Earth-Sun line. The results of superposed epoch analysis show that the temporal response from ground stations, geosynchronous orbit, and magnetotail are nearly identical for triggered (with apparent IMF perturbation) and nontriggered (without apparent IMF perturbation) substorms. It is therefore concluded that the nontriggered substorms are not a different form of activity than triggered substorms. However, we demonstrate that the magnitude of the response is different for the two types of substorms. By every measure considered, triggered substorms are systematically larger than nontriggered substorms. We interpret the fact that nearly 40% of all substorms cannot be associated with an IMF trigger as evidence that substorms are caused by an internal instability. However, the fact that so many appear to be triggered suggests that this internal instability is susceptible to external perturbations by the IMF. The fact that triggered substorms are larger than nontriggered substorms is counterintuitive, and we have no explanation for the observation. INDEX TERMS: 2788 Magnetospheric Physics: Storms and substorms; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2740 Magnetospheric Physics: Magnetospheric configuration and dynamics; 2744 Magnetospheric Physics: Magnetotail; KEYWORDS: IMF, substorm, triggering


1. Introduction

[2] An outstanding question in magnetospheric physics is whether substorms are always triggered externally by changes in the interplanetary magnetic field (IMF) or solar wind plasma or whether they sometimes occur spontaneously as a result of internal processes. Over the past decade, arguments have been made on both sides of this issue. Horwitz [1985] and McPherron et al. [1986] suggested that substorms usually appear to be initiated by an internal instability. However, Lyons [1995, 1996a, 1996b] argued that substorms must be triggered by external changes in the IMF and/or the solar wind. Specifically, Lyons [1996b] argued that events without apparent triggers were likely to be a nonsubstorm disturbance such as a convection bay [Pytte et al., 1978]. It should be noted that the term “northward turning” refers to a significant increase in the latitude angle of the IMF but not necessarily an increase to a positive value [Lyons, 1995].

[3] The objection raised by Lyons [1996b] that nontriggered events are really due to the $\text{DP} 2$ current system (convection) rather than the $\text{DP} 1$ current system (substorm expansions) has been examined recently. Henderson et al. [1996] have presented several examples demonstrating that nontriggered events do have substorm-like signatures on the ground and at geosynchronous orbit.

[4] However, several issues regarding IMF triggering were raised [Blanchard et al., 2000; Lyons, 1996a, 1996b; Lyons et al., 1997], including the importance of IMF $B_z$ as a potential trigger and the distance of the solar wind monitor from the Earth-Sun line. Lyons suggests that the closer the monitor is to the Earth-Sun line, the higher the chance to observe the IMF trigger. In order to resolve these issues, Hsu and McPherron [2003] established a substorm onset list to examine the occurrence
frequency of IMF triggered and nontriggered substorms. It was found that the inclusion of IMF $B_x$ as a potential trigger does not significantly change the statistics. The frequency of triggering is almost the same as found in the study by McPherron et al. [1986]. Furthermore, Hsu and McPherron [2003] found that the probability of detecting IMF triggering is not a function of distance to the Earth-Sun line. The probability of detecting an IMF trigger at substorm onset is almost the same anywhere from 5 to 35 $R_E$ with respect to the Earth-Sun line. Furthermore, at least 40% of all substorms occur without apparent IMF triggers.

While the study of Henderson et al. [1996] found clear examples of the existence of nontriggered substorms, the tail response during triggered and nontriggered substorms has not been investigated. The purpose of this paper is to establish statistically the differences in the tail behavior between triggered and nontriggered substorms. In pursuing this, we use the Hsu and McPherron [1996, 1998, 2002, 2003] substorm onset list consisting of nearly 8 months of data distributed over 2 years.

2. Substorm Onset List

In the Hsu and McPherron [1996, 1998, 2002, 2003] onset list the authors used two different databases to examine the statistical response of triggered and nontriggered substorms. The first list was obtained during spring of 1978 and 1979. The second was obtained during the fall of 1978 and 1979. Each of these data sets has its own advantages and disadvantages for the study. Readers are referred to Hsu and McPherron [2003] for a detailed description of the onset event selection and IMF triggering analysis statistics. We will only briefly describe the substorm onset event selection procedure below.

A substorm onset timing procedure was proposed by Hsu and McPherron [1996, 1998, 2002, 2003]. This procedure scans the $AL$ index from the auroral oval for any possible enhancement of the $AL$ index. Then high time resolution magnetometer data ($\Delta t < 3$ s) from either the Air Force Geophysics Laboratory (AFGL) [see Knecht, 1985; McPherron, 1982] or Institute of Geological Science (IGS) [see Stuart, 1982] magnetometer chains were analyzed. The north components from the entire chain of stations were band-pass filtered in the Pi2 band (period from 40 to 150 s). The filtered traces from each station were then stack plotted on the computer screen with resolution such that individual cycles of the Pi2 waveform could be resolved. At least three stations in the network must observe the event before it is added to the list. The earliest time of all the stations observing the event was taken as the Pi2 onset time and written to a digital file. In the final step the list of Pi2 onsets was associated with the list of sharp $AL$ onsets. Any $AL$ onset without a Pi2 onset within $\pm 20$ min was dropped. Similarly, any Pi2 onset without a corresponding negative bay in $AL$ was dropped. In the case of multiple Pi2 onsets near a single $AL$ onset, the closest Pi2 onset was taken as the main substorm onset.

This procedure has been shown to organize the variations in tail magnetic field [Hsu and McPherron, 1996, 1998]. A substorm onset timing example using the IGS chain is presented in Figure 1, where the vertical line indicates the substorm onset time determined by the substorm timing procedure.

3. Statistical Examination of IMF Triggering Using IMP 8 (Spring of 1978 and 1979)

This spring database covers the period from March to April in 1978 and 1979 when the ISEE 2 spacecraft passed through the tail. In this onset list the solar wind monitor is IMP 8, which has a nearly circular orbit around the Earth, and its distance to the Earth-Sun line varies between $\sim 15$ and $\sim 35 R_E$.

Hsu and McPherron [2003] used this spring onset list to examine the occurrence frequency of substorms during times when the IMP 8 spacecraft was in the solar wind. They were unable to find any particular location of
IMP 8 that has a higher probability of observing IMF triggering than any other location does. Furthermore, they found that the probabilities of triggered and nontriggered substorms are about equal for any distance from the monitor to the Earth-Sun line. On the basis of this result from Hsu and McPherron [2003] it is reasonable to study substorm events without regard to the location of the solar wind monitor. In this study we separate substorms into two classes: triggered and nontriggered. Triggered substorms refer to those having apparent IMF $B_z$ (the $z$ component of magnetic field) northward turnings close to substorm onset, while nontriggered substorms refer to those that do not. However, as noted by Hsu and McPherron [2003] and some earlier studies [Henderson et al., 1996; Lyons et al., 1997; McPherron et al., 1986], there are two types of nontriggered substorms, those with steady southward IMF $B_z$ and those with positive IMF $B_z$. Throughout this study those substorms associated with a steady southward IMF $B_z$ are referred to as “nontriggered substorms,” and those during northward IMF are referred to as “nontriggered substorms with positive IMF $B_z.””

3.1. Average IMF Properties for Triggered and Nontriggered Substorms

We begin by examining the difference in average IMF between triggered and nontriggered substorms. The superposed epoch traces for both classes of substorms are presented in Figure 2. The triggered substorms exhibit a clear minimum of IMF $B_z$ at the Pi2 main onset, while the other field components show no apparent change. The nontriggered class shows no apparent change in any component of the IMF. It is apparent that IMF $B_z$ is the only component that is consistently associated with substorm onsets.

Figure 2. Superposed traces of the four components of the IMF for triggered and nontriggered events. It is clear that only the $z$ component of the IMF $B_z$ is associated with substorm onsets. See color version of this figure in the HTML.

3.2. Average Response of the Tail for Two Classes

The superposed averages of the total lobe field for triggered and nontriggered substorms are presented in Figure 4 (bottom). In these averages the subclass with northward IMF at substorm onset is not included. It is evident that the overall temporal behavior of the tail magnetic field is similar for both classes of substorms. Both triggered and nontriggered substorms exhibit the same

Figure 3. The superposed IMF components for nontriggered substorms during positive IMF $B_z$. Obviously, IMF $B_z$ was positive most of the time around substorm onset. There are no obvious changes in any component near onset. See color version of this figure in the HTML.
response; i.e., $B_z$ and $B_t$ show extrema at Pi2 main onsets, a typical signature at substorm onset [e.g., Caan et al., 1978; McPherron et al., 1993]. These results demonstrate that the nontriggered substorms do not differ from triggered substorms in their overall behavior. However, there is an interesting difference in the magnitude of the changes in lobe field magnitude. The triggered substorms seem to have a larger increase in lobe field before onset and a larger decrease after onset than does the nontriggered class. The triggered class also has a stronger tail dipolarization than does the nontriggered class. See color version of this figure in the HTML.

[14] Another interesting result is that the times of extrema in $B_t$ and $B_z$ relative to main Pi2 onset for nontriggered substorms seem to occur several (∼3–5) minutes earlier than they do for triggered substorms. However, since the timing error is ∼1–2 min, it is possible that this difference

Figure 4. The superposed tail magnetic field for triggered (blue line) and nontriggered (green line) events. The overall temporal behavior is about the same for both classes. However, the triggered class has higher stored tail energy than does the nontriggered class. The triggered class also has a stronger tail dipolarization than does the nontriggered class. See color version of this figure in the HTML.

Figure 5. The superposed tail magnetic features for nontriggered substorms with positive IMF $B_z$. It can be seen that the energy growth and release and the dipolarization are weaker for these events. See color version of this figure in the HTML.

Figure 6. The superposed $AL$ index for triggered and nontriggered substorms. The triggered class seems to be stronger than the nontriggered class. The triggered class has a more obvious growth phase as well. See color version of this figure in the HTML.
is a statistical fluctuation. Figure 5 shows the temporal behavior of the tail field for nontriggered substorms with positive IMF $B_z$. It is clear that the dipolarization of tail $B_z$ and the energy release from tail $B_t$ are weaker than in either the triggered or nontriggered substorms (during southward IMF $B_z$). The curves suggest that tail energy storage ceased/C24\textsuperscript{30–40} min before the substorm onset, consistent with the observation that IMF $B_z$ turned northward about this time.

[15] The existence of substorms associated with positive IMF $B_z$ has been reported in the past. Akasofu [1975] and Akasofu et al. [1973] suggested that $B_z < 0$ is not always a necessary condition for substorm onset. Kamide et al. [1977] also reported that substorms could occur with rather high probability during positive IMF $B_z$. If so, a northward turning from a southward IMF $B_z$ is apparently not a necessary condition for substorm triggering.

### 3.3. Average Properties of the Ground Signature for Two Classes

#### 3.3.1. $AL$ Indices

[16] In Figure 6 we show superposed traces of the $AL$ index for both classes of events. Both curves show a sudden break in the $AL$ index at the main Pi2 onset, and the

Figure 7. The superposed Pi2 power for triggered substorms during spring of 1978 and 1979. The Pi2 power is defined as the sum of filtered horizontal component ($D$ and $H$). The first two capital letters indicate the ground station name, and the lowercase letter “p” indicates the Pi2 power. The break in slope of the $AL$ index and the sudden increase of Pi2 power are standard indicators of substorm onset. See color version of this figure in the HTML.

Figure 8. The superposed Pi2 power for nontriggered substorms during spring of 1978 and 1979. There is no evident difference between the superposed signatures for triggered and nontriggered events. See color version of this figure in the HTML.

Figure 9. The Pi2 power as a function of the $L$ value of IGS stations. It seems that the triggered class has stronger Pi2 signal power than the nontriggered class does, particularly near the plasmapause. The estimated $L$ value is from Stuart [1982]. See color version of this figure in the HTML.
recovery phase begins ~30 min after onset. However, there are two interesting differences. Triggered events have a more obvious growth phase and a stronger $AL$ response than nontriggered substorms. This result is consistent with the tail observations where we found that the lobe energy in the triggered substorm is higher than in the nontriggered events.

3.3.2. Pi2 Power

Figure 7 shows the superposed average horizontal power in the Pi2 frequency band calculated from IGS stations for triggered substorms. The superposed Pi2 power for nontriggered substorms is shown in Figure 8. A comparison of Figures 7 and 8 shows that the two classes of substorms cannot be distinguished by the pattern of the Pi2 response relative to the start of the Pi2. Thus these data also support the conjecture that “nontriggered events” are truly substorms just as the “triggered events” are. However, even though the temporal pattern of changes in Pi2 power for these two classes is the same, we find that the peak of Pi2 power for triggered events is slightly larger than it is for nontriggered substorms. This result is consistent with the results obtained above (sections 3.2 and 3.3.1) using the tail field and the $AL$ index. The maximum amplitude of the Pi2 signature from triggered events (Figure 7) and nontriggered events (Figure 8) as a function of estimated $L$ value (distance to the equatorial crossing of the magnetic field line) [from Stuart, 1982] is plotted in Figure 9. As can be seen, the maximum amplitude of Pi2 power for the triggered class has a very different latitude profile than the nontriggered class. On average, the maximum amplitude of Pi2 power in triggered events is higher than for the nontriggered events. This is especially true at high-latitude stations.

In Figure 10 the superposed AFGL Pi2 power for nontriggered events with positive IMF $B_z$ is presented. It is evident that the break in the $AL$ index and the onset of the Pi2 enhancement occur almost simultaneously, as they do with the other classes of events. The similarities between the signatures associated with these events and the other two event classes suggest they are all manifestations of the same type of event, i.e., substorms.

3.3.3. Geosynchronous Observations for Spring Data Set

We have also examined the response of the magnetic field at synchronous orbit using data from GOES 1, 2, and 3 satellites. During the spring season of 1978 and 1979,
Table 1. Comparison of the Properties of the Three Types of Events at Different Locations

<table>
<thead>
<tr>
<th>Substorm Features</th>
<th>Triggered</th>
<th>Nontriggered (IMF $B_z &lt; 0$)</th>
<th>Nontriggered (IMF $B_z &gt; 0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$AL$ sudden decrease</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>P12 power sudden increase</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Tail $B_t$ features(^a)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Tail $B_t$ features(^b)</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Geosynchronous flux return after onset</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

\(^a\)Flaring before onset and dipolarization after onset.

\(^b\)Increasing before onset and decreasing after onset.

[21] In summary, the only difference in the tail behavior between the triggered and nontriggered classes is the amplitude of the response. Triggered events are stronger than nontriggered events. Because of the similarities in behavior we conclude that all three classes are substorms. Our results therefore suggest that some substorms cannot be associated with northward turnings of the IMF measured by a single upstream monitor.

4. Statistical Examination of IMF Triggering Using ISEE 2 (Fall of 1978 and 1979)

[22] The ISEE 2 spacecraft was just in front of the subsolar region during the fall of 1978 and 1979. In contrast to the IMP 8 spacecraft that hardly ever sampled the subsolar region ($\sim 0–10 R_E$ from the Earth-Sun line), ISEE 2 spent most of the time there, and thus it provides an opportunity to further examine substorm triggering.

4.1. Average Ground and Geosynchronous Properties for Two Triggered and Nontriggered Substorms

[23] The superposed IMF curves from ISEE 2 are virtually the same as the IMP 8 results shown in Figures 2 and 3. In this study we also find a subset of nontriggered substorms that occurs during prolonged northward field. Such events appear to be completely inconsistent with the hypothesis that all substorms are triggered.

[24] The ground observations for the fall data set produce nearly the same results as the spring study. It is important to point out that we again find that the superposed $AL$ trace for nontriggered events is weaker than that for triggered events, as in Figure 6. For both triggered and nontriggered events we observe an enhancement of P12 activity at substorm onset similar to that shown in Figures 7 and 8.

[25] We have also examined synchronous magnetometer data for the fall data set, and we obtain essentially the same results as in the spring data set. Both panels in Figure 12 present the superposed $AL$ index and the synchronous $H$ component for the two types of substorms. The $AL$ plot makes it very clear that triggered substorms are stronger than the nontriggered substorms. The same behavior is evident in the synchronous $H$ component. Triggered substorms exhibit an immediate rapid increase that by the end of the plot is considerably stronger than the response of nontriggered substorms.

4.2. Comparison of Characteristics Between Triggered and Nontriggered Substorms

[26] The main advantage of using ISEE 2 data to study substorm triggering during the fall season is its location.

GOES 1 and 3 were located at 135°W geographic longitude while GOES 2 was located at 75°W geographic longitude. Here we consider only the $H$ component since an increase in this component (dipolarization) is generally taken as an indicator of flux return from the tail. Only events in the premidnight sector were used ($2100–2400$ LT) because of the well-known delays in synchronous response at earlier and later local times [Nagai, 1982]. The results are shown in Figure 11 (bottom). For comparison, Figure 11 (top) presents the superposed analysis of the $AL$ index for the subset of events used in the bottom panel. The behavior of the $AL$ index is similar to that described in section 3.3.1; the nontriggered substorms are weaker than the triggered substorms. Figure 11 (bottom) shows the behavior of the $H$ component at synchronous orbit. For both types of substorms, $H$ increases after the main onset, indicating flux returning to synchronous orbit. However, the nontriggered substorms exhibit smaller changes. In Figure 11 the dotted curve is the result for nontriggered substorms shifted upward to compare with the change for triggered substorms. Again, it appears that nontriggered substorms are weaker than triggered substorms.

3.4. Comparison of Characteristics Between Triggered and Nontriggered Events

[20] Table 1 summarizes the feature identified in the superposed epoch analysis of the $AL$ index, the P12 power, and the ISEE 2 tail magnetic field observations. Table 1 makes it abundantly clear that there is no difference in temporal behavior between these three classes of events. Each class has a P12 power increase and an $AL$ decrease at substorm onset, features that are typically associated with substorms. Of course, these $AL$ and P12 features are the phenomena required to satisfy our selection criteria, so we expect this result. More significant is the fact that all three classes are also associated with changes in the tail field that are characteristic of substorms, such as a growth and decay of a taillike field. The main feature that distinguishes these three classes of events is their association with the IMF. In the first class the IMF is southward and then turns northward at onset, i.e., appears to be triggered. In the second class the IMF is southward and remains southward through the onset and hence appears not to be triggered. The third class also appears not to be triggered but occurs during northward IMF. This third class of events is completely inconsistent with the hypothesis that the IMF must turn from southward to less southward or northward for a substorm to occur. The three classes also differ in the amplitudes of the responses of various parameters. Events during northward IMF are generally weak. In addition, triggered events appear to be stronger than nontriggered events during southward IMF.
Since the ISEE 2 spacecraft is very close to the subsolar region in the fall, it is extremely unlikely that IMF hitting the subsolar point will be missed by the monitor. Unfortunately, these observations have disadvantages; that is, we do not have the associated tail observation as we did in the spring study. Table 2 provides a comparison of the characteristics between triggered and nontriggered events.

5. Summary and Conclusions

[27] The initial objective of this study was to examine the Lyons’ conjecture that auroral zone disturbances labeled nontriggered substorms are not really substorms. To this end, we utilized magnetic data from different locations, including the AL index, ground Pi2 pulsations, synchronous magnetometers, and the ISEE spacecraft in the tail. We have tried to show that there is no difference in temporal behavior between the two types of events. Also, to counter the argument that the IMP 8 spacecraft is not able to detect small-scale IMF structures [see Lyons et al., 1997] that hit the subsolar magnetopause, we utilized two different IMF monitors: IMP 8 in the spring of 1978 and 1979 and ISEE 2 in the fall of these years. In a separate paper [Hsu and McPherron, 2003] we showed that there is no difference in the probability of triggering at any location in the IMP 8 orbit when proper account is taken for the time the spacecraft spends in each radial bin orthogonal to the Earth-Sun line. However, because of the tilt of its orbit in spring of 1978 and 1979, IMP 8 hardly ever sampled the region inside of 12 R_E, and it is possible that the triggering probability increases within these distances as suggested by L. R. Lyons (private communication, 1997). Fortunately, in fall of 1978 and 1979, ISEE 2 (apogee at 23 R_E) was in the solar wind upstream of the bow shock and covered exactly this region. The fraction of triggered substorms identified in the ISEE data set was statistically identical to that found everywhere in the IMP 8 orbit. We therefore conclude that substorms without triggers are not due to the monitor failing to detect IMF triggers close to the Earth-Sun line.

[28] To examine whether there is a difference in behavior between triggered and nontriggered substorms, we performed a superposed epoch analysis on several important substorm variables. We found that the tail lobe magnetic field strength and Bz behave as expected from previous reports; all of the substorms (triggered and nontriggered) show an accumulation of energy in the tail lobes prior to onset and a release of this energy following onset. These features suggest that during southward IMF Bz, magnetic flux is added to the tail lobe, increasing the lobe magnetic pressure and stretching the tail magnetic field. At substorm onset, tail reconfiguration begins, and the energy stored in the lobe is released. Our new results are consistent with many previous reports [Caan et al., 1978; Hsu and McPherron, 1996, 1998; McPherron, 1992; McPherron et al., 1993].

[29] We also found that the AL index behaves in the same way for triggered and nontriggered substorms. A growth phase in which AL gradually decreases before onset is followed by a rapid drop of several hundred nanotesla over 15–30 min after onset. Subsequently, AL recovers over an interval of 90 min or more. Note that this behavior in AL is assured by our selection criteria, which required that there be a sharp break in the slope within ±20 min of a Pi2 onset. However, the sharpness of this signature in the superposed results suggests that most of the sharp breaks in AL were simultaneous with the Pi2 onset used to precisely time the event.

[30] A superposition of the Pi2 index from multiple stations also suggests that there is no difference in the temporal behavior of the two types of substorms. In both types of events, there is a midlatitude Pi2 burst of 7–15 min duration whose onset and association with a break in AL is our marker of the main onset of the substorm.

[31] Finally, we examined the H component at synchronous orbit when the spacecraft were in the premidnight

| Table 2. Comparison of the Properties of the Three Types of Events at Different Locations |
|----------------------------------------|-----------------|-----------------|-----------------|
| Substorm Features | Triggered (IMF Bz < 0) | Nontriggered (IMF Bz > 0) |
| AL sudden decrease | yes | yes | yes |
| Pi2 power sudden increase | yes | yes | yes |
| Geosynchronous flux return after onset | yes | yes | yes |
sectors. For both types of substorms we find the $H$ component decreases before the main Pi2 onset and increases afterward. This phenomenon is generally referred to as dipolarization and is thought to be the consequence of magnetic flux transported from the tail lobe after substorm onset. We have also checked the $V$ and $D$ components. In essence, these components show clear dipolarization in the magnetic field, consistent with the $H$ component.

Our conclusion from this part of our study is that both types of events are substorms and that the conjecture that nontriggered substorms are actually pseudobreakups or convection bays is not supported by the data. However, it is noted that auroral streamer [Sergeev et al., 1999, 2000] and poleward boundary intensification [Lyons et al., 1999; Zesta et al., 2000] can cause Pi2 pulsation and auroral current perturbation, which are used in this study to identify substorm onset. Given that either auroral streamer or poleward boundary intensification has a lifetime of \( \sim 10 \) min, it is unlikely that our substorm list is due to either one of these auroral perturbations because our substorm identification procedure requires a much longer activity time of \( \sim 30 \) min.

We have also found and described in a separate report [Hsu and McPherron, 2003] that the identification of non-triggered substorms is unlikely to be a result of the location of the IMF monitor. The triggering probability at ISEE 2 immediately upstream of the subsolar bow shock is statistically identical to that found everywhere in the IMF 8 orbit. Roughly 40% of all substorms appear to be nontriggered. However, it is noted that IMF spatial structure can be oriented over a large range of angles relative to the Sun-Earth direction from time to time. It is thus possible that some small-scale IMF perturbation can hit the magnetopause but not be detected by a single spacecraft (ISEE 2 or IMF 8). A further study to examine the triggering hypothesis and IMF perturbation scale by using more than one solar wind monitor is needed.

It is also important to note that in both our data sets \( \sim 10\% \) of the nontriggered substorms occurred during a prolonged northward IMF and there is no indication of a further northward turning at the time of the onset. An example of one such event is presented in Figure 13. The occurrence of a significant negative bay in $AL$ during a prolonged interval of northward IMF is obvious. Note also that the radial component of the magnetic field at synchronous orbit \((V_{\text{eo}})\) increases in magnitude. Since GOES is above the magnetic equator, the magnetic field should have a negative projection on the $V$ axis that becomes more negative during a growth phase. In this case it becomes less negative consistent with the absence of convection driven by a southward IMF. Such events appear to be incompatible with the Lyons [1996a, 1996b, p. 13,011] hypothesis that “most, and perhaps all, expansions are triggered by IMF changes” [Lyons, 1996a, 1996b; Lyons et al., 1997]. In these cases, the IMF was already northward and was presumably not driving magnetospheric convection through dayside reconnection. For these events we also found that the temporal behavior of all our indicators was the same as it is for triggered substorms. However, as might be expected, the events were systematically weaker than either of the types of substorm that occur during southward IMF. Perhaps the substorms that occurred during northward IMF were driven by residual energy stored in the tail lobe by previous southward IMF since the lobe field decreased in these events just as it does during southward IMF. Another possibility is that a single spacecraft may misidentify a possible IMF structure that can cause substorm onset. Lyons et al. [1997] provided an example where the IMF was northward at one IMF measurement location while typical substorm triggering IMF structure was observed simultaneously at another location. A further analysis by using more than one solar wind monitor is needed to investigate issues such as how often this missing identification can occur and what the scale size of the IMF trigger structure is. These issues have important implications for the understanding of substorm dynamics.

Perhaps the most important conclusion from this work is that there appears to be a quantitative difference between triggered and nontriggered substorms. Triggered substorms are stronger by every measure we examined than nontriggered substorms. Furthermore, triggered substorms have more obvious growth phases than nontriggered substorms do. This result appears to contradict our interpretation that substorm expansions are the consequence of the onset of an internal instability and that this instability is sometimes triggered by a change in the...
IMF. One would suppose that if there is no IMF trigger, then the amount of energy stored in the tail lobe would be larger when the expansion phase actually occurs. Also, growth phase effects should be more obvious since the standard substorm model [Baker et al., 1996] posits that plasma sheet thinning is the cause of reconnection in the tail. A prolonged growth phase should lead to larger tail field changes, larger changes at synchronous orbit, a stronger westward electrojet, and possibly more powerful Pi2s. Just the opposite is observed.

[15] L. R. Lyons (personal communication, 2003) has suggested that our observations are completely consistent with his hypothesis that all substorms are triggered. He postulates that the 40% of all substorms without apparent IMF triggers were actually triggered by structures with an extent transverse to the Earth-Sun line too small for our monitor to detect. He then argues that the structures must also be small in radial extent (duration in time) and amplitude of IMF \( B_z \). Therefore these structures do not transfer as much energy to the magnetosphere, and hence substorms produced by the unobserved northward turning will be smaller. Consequently, our nontriggered substorms will be smaller than our triggered substorms.

[36] Several studies have investigated the IMF structure by using multiple satellites [e.g., Collier et al., 1998; Richardson and Paularena, 2001]. Richardson and Paularena [2001] have shown that the scale length of IMF \( B_z \) transverse to the Earth-Sun line is \( \sim 45 R_E \) and the plasma moments have a scale length \( >70 R_E \). Collier et al. [1998] found a similar result of the transverse scale length IMF \( \sim 41 R_E \). It is thus possible that the upper limit of the transverse IMF structure is 40 \( R_E \). Furthermore, Hsu and McPherron [2003] found that the triggered (\( \sim 60% \)) and nontriggered (\( \sim 40% \)) substorm statistics are almost the same for ISEE 2 IMF trigger study (maximum transverse distance to the Earth-Sun line is \( \sim 7 R_E \) in their study) and for IMP 8 IMF trigger study (maximum transverse distance to the Earth-Sun line is \( \sim 40 R_E \)). Therefore we do not believe that previous studies of the scale of IMF structures support the view that a single monitor will miss 40% of the IMF triggers. It is more likely that solar wind structures are aligned radially or along the Parker spiral and are much longer along this direction than transverse to it. Richardson and Paularena [2001] found that the radial scale lengths are of the order of 400 \( R_E \). This suggests that time evolution of the solar wind (as indicated by the radial separation of the spacecraft) has a scale length larger than that for direction transverse to it. In addition, we know of no evidence in the literature that there is a correlation between the transverse scale of IMF structures and their duration and strength as required by Lyon’s hypothesis. However, we cannot reject this explanation because no one has yet determined the frequency with which two spacecraft do not see the same IMF trigger, nor has anyone examined the correlations between transverse scale, radial scale, and strength of the IMF \( B_z \).

[37] A possible interpretation of our results is that the criteria used in the definition of an IMF trigger create a systematic bias in the selection of trigger events. For example, the criterion that the increase in \( B_z \) must exceed a fixed value might result in selecting times of stronger IMF \( B_z \) and hence might result in stronger substorms. Future studies will be required to determine if such a bias exists.

[38] It is obvious that the onset of the expansion phase of a substorm is the result of an internal magnetospheric process. Also, it is obvious that this process is susceptible to external perturbation. It remains to be demonstrated that all substorms that appear to be nontriggered are actually caused by small-scale structures in the IMF. If it can be shown that some substorms are caused by the spontaneous onset of an internal instability, then it is perplexing that such substorms are weaker than those that are triggered by external perturbations.

[39] Acknowledgments. The authors would like to thank L. R. Lyons, the referees of this paper, and our colleagues at UCLA for their helpful suggestions and discussions in preparing this work. This research was funded by NASA NAG 5-11898 and NSF ATM 99-72069.

[40] Lou-Chuang Lee thanks Michael G. Henderson and the other reviewer for their assistance in evaluating this paper.

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