A statistical study of the spatial structure of interplanetary magnetic field substorm triggers and their associated magnetic response

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[1] 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. An apparent association between northward turnings of the IMF and substorm onset has been frequently demonstrated, but it is also found that not all substorms are triggered. Previous studies have shown that the ratio of triggered and nontriggered substorms is about 60/40. A surprising finding is that substorms classified as triggered exhibit a stronger response than nontriggered substorms. It has been suggested that this may be due to undetected small-scale structures in the IMF which presumably have weak driving fields of short duration and hence transfer less energy to the magnetosphere.

In this work we use a large database of 1978–1985 ISEE 2 and IMP 8 IMF observations to investigate whether small-scale structures occur frequently enough to account for the 40% nontriggered substorms. We find that the probability of observing IMF small-scale structures is less than 13%. This low probability (13%) does not match the occurrence frequency of 40% for nontriggered substorm onsets. It is thus unlikely that all nontriggered substorms can be attributed to small-scale IMF structures missed by an upstream monitor. Another interesting finding is that the small-scale IMF $B_z$ triggers do not seem to create significant AL response but the large-scale IMF $B_z$ triggers do. The median curve shows a sudden sharp drop of the AL index at the time the IMF trigger is expected to arrive at the magnetopause. This suggests that some substorms must be associated with the IMF triggers.


1. Introduction

[2] The possibility that substorms can be triggered by interplanetary shocks was first suggested by Heppner [1955]. A few years later, Schieldge and Siscoe [1970] suggested that substorms might be triggered because the authors believed that the substorm was an instability of the configuration of the magnetosphere, and because they thought that it might be sensitive to changes in solar wind dynamic pressure. Consequently, they and Kawasaki et al. [1971], studied the relation of bay onsets to storm sudden commencements (SSC) and sudden impulses (SI). Both studies found a positive correlation, 18.7% and 49% respectively and thus confirmed the suggestion made by Heppner [1955] that substorms can be triggered by a shock. Burch [1972] carried this work further demonstrating that triggering only occurred if the IMF had been southward for at least 1/2 h and the SSC amplitude exceeded 10 nT. A detailed statistical study of SSC and SI triggering of substorm expansions performed by Kokubun et al. [1977] found that negative bays followed large solar wind pressure changes 43% of the time. For 90% of these bay onsets AE had been previously disturbed and the IMF had been southward indicating that the magnetosphere must be preconditioned for an onset to be triggered. In a recent study, Zhou and Tsurutani [2001] also suggested that precondition is very important for the interplanetary shock to trigger substorms. As a matter of fact, 44% of all shocks trigger substorm if strong southward IMF $B_z$ existed before the shock arrival [Zhou and Tsurutani, 2001]. Parks et al. [1972] interpreted the initial triggering results as support for a substorm model in which the sudden compression altered the pitch angle distribution of electrons near synchronous orbit so that wave instabilities caused particle precipitation, changes in conductivity and the onset of the substorm expansion.

[3] Several years later, Caan et al. [1975] used a superposed epoch analysis to show that the onset of midlatitude positive bays and a peak in the tail lobe were correlated with a northward turning of the IMF. Hirshberg and Holzer [1975] performed a detailed analysis of an earlier study reported by Foster et al. [1971]. In this analysis Hirshberg and Holzer [1975] noted that the superposed epoch analysis
of isolated substorms done by Foster et al. had a minimum in IMF $B_z$ at the time of the onset of auroral zone negative bay. Caan et al. [1977] and Caan et al. [1975] reexamined the question of the association of the IMF with substorms using case studies. For a small set of 18 events they found that $\sim 60\%$ of the onsets could be associated with a substantial northward fluctuation or change in IMF $B_z$.

[4] Subsequently many authors noted that their substorm onsets were associated with northward turnings of the IMF [see, e.g., Pellinen et al., 1982; Rostoker et al., 1982]. However, as noted by Rostoker [1983] many of the events used by Caan, Rostoker, and other authors occurred during very disturbed times with multiple substorms and fluctuating IMF where it is hard to determine the uniqueness of triggers or the time of substorm onsets. Consequently, Rostoker [1983] chose three clear-cut examples of isolated substorms apparently triggered by northward turnings of IMF $B_z$. While the examples seem very convincing, Rostoker [1983] raised questions of whether isolated substorms display the same response to the solar wind as do substorms in more disturbed times. They therefore showed that a sequence of five transient northward turnings of $B_z$ in a 5-h interval was related to a corresponding sequence of onsets or intensifications of electrojet activity. They also pointed out that changes in the IMF $B_z$ component might play a role in triggering onset, and that some substorms apparently occur without external triggers of any kind. Similar conclusions were obtained by Dmitrieva and Sergeev [1983], who also found that for spontaneous onset substorms (no apparent trigger) there is a relation between the duration of the growth phase and rectified electric field (VBs) prior to the onset. Generally, triggered substorms occur earlier than predicted by this relation. Horwitz [1985] shows a number of examples of substorm expansions occurring during very quiet intervals of southward IMF that led him to conclude that substorms are an internal instability of the magnetosphere.

[5] McPherron et al. [1986] determined the frequency of occurrence of substorm triggering with a statistical study of 6 months of data. Visually scanning the IMF and AL index data they identified substorms with sharp onsets and associated them with the solar wind dynamic pressure and rectified electric field (VBs). They found that $44\%$ could be associated with either a northward turning or a fluctuation in the IMF $B_z$. About $30\%$ of the onsets occurred during steady southward IMF. In contrast, only $2\%$ of the substorms were associated with storm sudden commencements. Additional support for the $B_z$ triggering hypothesis was provided by Samson and Yeung [1986], who used a sophisticated method call generalized superposed epoch analysis to show near simultaneity of northward turnings and onset. However, Troshichev et al. [1986] reached a different conclusion claiming that northward turnings of $B_z$ are less important than a change of $B_y$ from positive to negative. We note, however, that their epoch zero for both case histories and superposed epoch analysis was the time the component changed sign, not the time it began the change.

[6] Lyons [1995] introduced a new theory for magnetospheric substorms. His theory requires a reduction in the magnetospheric convection electric field to create an azimuthal pressure gradient which then drives the substorm current wedge. Either a northward turning of $B_z$ or a reduction in $|B_y|$ will reduce convection and hence according to this theory, trigger a substorm. Lyons [1996a, 1996b] suggested that substorms that appear not to be triggered are not really substorms, but instead might be convection bays or poleward boundary intensifications. Thus Lyons suggests all substorms are triggered with the statement in his paper "these studies imply that most, and perhaps all, expansions are triggered by IMF changes" [Lyons, 1996b]. This extreme view immediately drew criticism, leading to several articles in Eos under the banner "Great Debates in Space Physics" [Lui, 1996; Lyons, 1996a; Spence, 1996]. Lui presents the view that expansion onset is an internal instability of a metastable system responding to an external perturbation. Lyons, on the other hand, argues that the expansion onset is a response to external changes. In support of his view he argues that previous reports of onsets during steady IMF $B_z$ did not use sufficiently accurate indicators of substorm onset, or that they ignored possible triggers such as IMF $B_z$, or that the events were not substorms. Finally he suggests that the IMF structures that cause substorms may either have spatial scales so small that they are missed by a monitor, or that they are improperly timed because of orientation and propagation of the IMF discontinuities in the solar wind.

[7] In response to Lyons objections Henderson et al. [1996] reexamined three examples from McPherron et al. [1986] with more and higher time resolution data. One of the three events was clearly associated with a change in $B_z$ as noticed by Lyons. The other two exhibited smooth traces in the 5-min data used by McPherron, but had high-frequency waves in the field components that could conceivably trigger substorms. As a consequence of this ambiguity the authors found six additional substorm onsets during extremely steady solar wind conditions. They demonstrate that these were classic substorms, and that no triggers were observed in the available data. Lyons et al. [1997] responded with an extremely detailed analysis of 20 carefully timed, classic substorms. They found that $14\%$ of the 20 could be associated with an IMF trigger. In addition they showed that the probability of triggering depended on the distance of the solar wind monitor from the Earth-Sun line, with $89\%$ probability of triggering when the monitor was at a distance $<30$ $R_e$, but only $50\%$ beyond this distance. Finally they made a statistical estimate of the probability of a chance association of IMF triggers with onset and concluded that it was less than $10^{-9}$. Blanchard et al. [2000] extended the work of Lyons et al. determining whether their IMF trigger criteria actually predict substorms. To reduce ambiguity they required that two spacecraft were in the solar wind close to the Earth-Sun line and that there was a strong northward turning. For ten such cases, they found substorms in five cases. They attribute three of the failures to a simultaneous increase in $|B_y|$, the other two cases were intervals of very weak southward IMF prior to the northward turning.

[8] Hsu and McPherron [2002] used IMP 8 and ISEE 2 solar wind observations to examine whether the apparent association of an increase in IMF $B_z$ and substorm onset might be due to chance. They found that the probability of having an association as high as observed is of order of $10^{-11} \sim 10^{-9}$. This gives strong support to the contention that at least some substorms are triggered by IMF northward.
Hsu and McPherron [2003] extended their study further to examine whether IMF $B_z$ is a significant factor for substorm triggering. It was found that the inclusion of IMF $B_z$ effect does not change the statistics of solar wind triggering significantly. The ratio between triggered substorm and nontriggered substorm is about 60:40. Furthermore, the probability of detecting IMF triggers is roughly stable from the Earth-Sun line to 35 $R_e$.

Russell et al. [1980] used solar wind data at the Earth and L1 without regard to the type of structure and found that the $B_z$ correlations varied from 0.0 to 1.0. Although the most probable correlation was 0.85, half of the time the correlation was less than 0.5. They also found that the ratio of expected delay to observed delay (time of peak correlation) was highly variable with errors from L1 as large as 30 min. They noted that often the structures arrived too early suggesting that they were propagating outward in the solar wind. A more detailed study of the L1 to Earth correlation was done by [Crooker et al., 1982] to determine how the correlation depends on the variability of the IMF as well as the spacecraft separation and solar wind speed. Confirming Chang and Nishida [1973] they found that poor correlations tend to occur when the spacecraft separation perpendicular to the Earth-Sun line exceeds 90 $R_e$. They also noted that poor correlations are associated with low IMF variance, and that a change to high variance improved the correlation. In contrast to Chang and Nishida they found no significant dependence on solar wind speed. Finally, they found that the correlation perpendicular to the IMF falls off within only 20 $R_e$ for low variance, and 50 $R_e$ for high variance.

The scale of IMF correlations was reexamined by Collier et al. [1998] using data from Wind and IMP 8, but near solar minimum, rather than solar maximum as done in the Russell and Crooker studies. They found that intervals of good correlation are only half as likely at solar minimum as they are at solar maximum. In addition they demonstrate that the error in the simple convective time delay can be expressed as $\Delta \tau \sim (d_1/d_0)r_{con}$ where $d_1$ and $d_0$ are respectively distances between the spacecraft perpendicular to, and parallel to, the Earth-Sun line. They point out that there is a high probability (relative to Gaussian) of obtaining very bad errors in timing. Finally, using Wind and IMP 8 they show that the probability of obtaining a high correlation falls rapidly with the perpendicular separation of the two spacecraft. Fitting an exponential they obtain a perpendicular scale length of 41 $R_e$.

The most thorough work to date on solar wind correlations is that of the MIT group who have studied both plasma and IMF correlations from a space weather perspective [Paularena et al., 1998; Richardson et al., 1998; Richardson and Paularena, 2001]. These authors have shown that plasma correlations are high using several day averages, but drop as the averaging interval decreases. Plasma correlations also begin to drop slowly as the radial separation exceeds $\sim$200 $R_e$. In their early work they could not find a significant dependence of the plasma correlations on perpendicular separation. The best predictor of high correlations of plasma properties is high variability in the density. From a comparison of calculated and observed time delays they conclude that most disturbance fronts are oriented halfway between perpendicular to the solar wind flow and the Parker spiral. Richardson and Paularena [2001] use much more data and find that the transverse scale for a decrease in density correlation by 0.1 is 120 $R_e$ and for velocity about 70 $R_e$. In contrast the transverse scales for the components of the IMF are about 50 $R_e$. They quote a scale parallel to the solar wind flow as 280 $R_e$. In general, all of the correlation coefficients rise with increasing density (or its variability), increasing $|B|$ (or its variability), increasing cone angle, and increasing $|B_z|$. No dependence on solar cycle could be found in this comprehensive data set. Again the authors find that a corotation delay must be added to the solar wind convection delay, but this delay should be based on an average alignment of both IMF and plasma structures intermediate between the $x$ axis and the Parker spiral.

The Lyons hypothesis is that all substorms are triggered, but some triggers are too localized to hit both the solar wind monitor and the Earth. Thus a substorm without a trigger is an artifact of the distribution of scales of triggering structures. This hypothesis can only be disproved by a careful statistical study that shows that the probability that a trigger misses the monitor is large enough to explain the number of substorms for which no triggers are seen. One way to study this problem is to examine how often interplanetary shocks can trigger substorms. Given that the interplanetary shock has a significant spatial scale (0.5 ~ 1.0 AU), it is very unlikely that a solar wind monitor will miss a shock. The results shows that only 44% of the interplanetary shocks can trigger substorms [Zhou and Tsurutani, 2001]. In other word, sometimes substorms can be triggered and sometimes not. Another way to examine this problem is to use multi solar wind monitor to examine how often do we miss IMF $B_z$ triggers. Some work has been done on the problem of scale size of solar wind structures, but this work has not specifically addressed the question of the size of substorm triggers. Because of the manner in which the previous studies were done, mainly cross correlation of time series, it is nearly impossible to determine whether they support or invalidate the Lyons hypothesis. This difficulty is the primary motivation for the work presented in this paper.

Another interesting question is what produces the IMF structures we have identified as substorm triggers. One of the fundamental structures present in the solar wind plasma is directional discontinuities (DDs) in which the magnetic field direction changes sharply on time scales of seconds [e.g., Tsurutani et al., 2005]. There are several different types of directional discontinuities: rotational discontinuities, tangential discontinuities, shocks (fast, intermediate, and slow), and contact discontinuities [see Tsurutani et al., 2005, and references therein]. While our selection criterion requires a sharp change of IMF $B_z$, it is not clear whether the abrupt change of IMF $B_z$ can be attributed/identified as a directional discontinuity [Smith, 1973; Tsurutani et al., 1999; Winterhalter et al., 1994]. The occurrence frequency of DDs is about 1–2 times per hour [e.g., Tsurutani et al., 2002] which is approximately the same occurrence rate of IMF triggers (~1 per hour) [Hsu and McPherron, 2002]. It is thus reasonable to speculate that the cause of these IMF triggers is DDs. However, we emphasize that the purpose of this paper is to examine the spatial scale of the changes identifies as IMF triggers and is
not a study of phenomena in the solar wind that produce these changes. It would be interesting to examine the relationship between DDs and IMF triggers in a future study.

[14] In following sections we examine the dependence of triggering on the location of the monitor, and the dependence of simultaneous triggers on the separation of two monitors in the solar wind. Also we consider the dependence of the association of onsets and triggers with solar cycle to see if this is important. Finally, we examine the auroral response to the different scale of IMF triggers.

2. Data Analysis

2.1. IMP 8 and ISEE 2 Data Sets

[15] In this study, we use two satellites whose orbits are very close to the Earth: IMP 8 and ISEE 1/2. The IMP 8 satellite has a nearly circular orbit with a radius of about 35 $R_e$. However, the IMP 8 orbit is inclined with respect to the ecliptic plane so that in spring it is above the ecliptic when it crosses the Earth-Sun line. Because of this in spring and fall the satellite seldom observed the region with radius 5–10 $R_e$ from the Earth-Sun line [Hsu and McPherron, 2003]. Figure 1 shows that IMP 8 has a near circular orbit around the Earth while ISEE 2 has a very eccentric orbit. As illustrated, the perigee of ISEE 2 shifts to the dayside during the fall season providing an opportunity to examine the small-scale hypothesis of Lyons et al. [1997].

[16] All of the solar wind observations have been time propagated to the subsolar region using simple advection for comparison between IMP 8 and ISEE 2. Since ISEE 2 is very close to the subsolar region (Figure 1) we have used ISEE 2 solar wind as our comparison base. This means that we have assumed that all of the solar wind parcels measured by ISEE 2 actually arrive at the Earth. The magnetic field data on ISEE 2 were obtained with the UCLA fluxgate magnetometers [Russell, 1978]. These magnetometers utilized three ring core sensors from the Naval Ordnance Laboratory [Russell, 1978]. One minute average magnetic data are used in this study. The ISEE 2 Fast Plasma Experiment plasma data were only available for 1978 and 1979 tail passage. Therefore, we have to estimate the solar wind speed in order to time propagate the solar wind observations to the subsolar position. Fortunately, since ISEE 2 is only a few $R_e$ away from the Earth-Sun line and a few $R_e$ upstream from the nominal bow shock location, the error in time delay is almost negligible [Hsu and McPherron, 2003]. Similarly, 1-min magnetic data from IMP 8 are used in this study. IMP 8 orbit has a more circular orbit than ISEE 2 with a radius of about 35 $R_e$. The IMP 8 plasma data is available about half the time throughout the ISEE mission and is used for the time propagation to the subsolar region. However, because of the inclination of the IMP 8 orbit, IMP 8 seldom crosses the subsolar region (Figure 1). This is another reason why we chose ISEE 2 as our comparison base in this study.

[17] For this study, we examined a fall database that covered the period of August to November from 1978 to 1986 because this is the ISEE 2 operational time span. Out of this 8 years of data, ISEE 2 was available for 502 d and IMP 8 for 399 d. This corresponds to about 49.9 d of IMF data per year (Aug–Nov) for IMP 8 and 62.8 d IMF data per year (Aug–Nov) for ISEE 2. One reason that IMP 8 has less data is that the quality of IMP 8 data is not as good as that from ISEE 2.

2.2. Definition of an IMF Trigger

[18] There are three suspected triggers of substorm onset: northward turnings of $B_z$, reductions in IMF $|B_z|$, changes in dynamic pressure. Often, all occur simultaneously. Each of these triggering phenomena requires that the magnetosphere be preconditioned. There exists no precise characterization of these triggers, although Lyons et al. [1997] developed a set of criteria they used to automatically detect northward turnings of the IMF. These criteria have been used in several studies and seem satisfactory for solar wind triggering studies [Hsu and McPherron, 2003; Hsu and McPherron, 2004]. However, the criteria are apparently not optimized since we find the program generates approximately three times as many IMF triggers as there are substorm onsets. No doubt there are many more rotations of the IMF or changes in pressure than substorm onsets [e.g., Tsurutani and Ho, 1999; Tsurutani et al., 2005], but a proper set of criteria should take into account the state of the magnetosphere and not identify a particular feature as a trigger if the magnetosphere is unable to produce a substorm. For example, a trigger after only 10 min of southward $B_z$ is extremely unlikely to initiate a substorm. Similarly, if a substorm expansion has just begun we would not expect a second substorm to be triggered.

[19] A pattern for trigger detection can be expressed as a set of rules quantified by model parameters. In Table 1 these parameters are the various numbers in the right hand column. The point $t_0$ is advanced one point at a time through the IMF time series. An example is given by Hsu and McPherron [2003].

2.3. Propagation of Solar Wind Data

[20] For the present study the ideal position to observe solar wind conditions is at a point just upstream of the merging region where energy enters the magnetosphere.
from the solar wind. Unfortunately, this situation never occurs with IMP 8. Consequently, we have to modify the solar wind time series to account for the change in time delay between corresponding events occurring at IMP 8 (or ISEE 2) and the coupling region. To do this, we have estimated the actual time delay using a formula developed by Baker et al. [1983]. Here, the formula has been expressed ignoring the orbital motion of the Earth and using a small-angle approximation:

\[ T_{\text{solar\ wind}} = \frac{(X - X_0)}{V_{sw}} + \frac{(Y - Y_0) \cdot T_0}{2\pi a} \]  

(1)

where \( T_{\text{solar\ wind}} \) is the solar wind time delay; \( X \) and \( Y \) are the location of the spacecraft in GSM coordinates; \( X_0 \) and \( Y_0 \) are the coordinates of the subsolar point on the bow shock, \( T_0 \) is the mean solar rotation period, \( a \) is the mean radial distance from the Sun to the Earth, \( V_{sw} \) is the instantaneous solar wind bulk speed. Using the average position of the subsolar bow shock \( (X_0 = 15, Y_0 = 0) \) as a fixed reference point we can approximately eliminate effects of solar wind advection. In this approximation we have assumed that discontinuities in solar wind properties are aligned along the average spiral angle of the solar wind, and are not propagating.

We estimate the time propagation error from the solar wind monitor (ISEE 2) to the subsolar magnetopause as less than a minute. The largest part of this error is a consequence of the ISEE 2 plasma instruments failure in June 1978. This failure means it was not possible to use solar wind velocity measured by the ISEE 2 plasma instrument. However, plasma data are available from the IMP 8 spacecraft. An examination of the measured IMP 8 values of speed during the study interval gave 295, 390 and 485 km/s for the median and quartiles of speed. Thus, we used a solar wind speed of 400 km/s to propagate the solar wind to the magnetopause in the ISEE data. The difference in velocity between the upper and lower quartiles and the median causes about 30 s difference in time delays. Since the time resolution of the data is 1 min the errors caused by using the median solar wind speed to time propagate the ISEE data are negligible.

The IMP 8 spacecraft was in circular orbit and depending on the location of ISEE 2 could be as much as 40 \( R_E \) away from ISEE 2 transverse to the Earth-Sun line. Estimates of the average error in propagation delays by Ridley [2000] are about 8 min for IMP 8.

### 2.4. Spatial Distribution of IMF Triggers

Our approach uses one spacecraft, ISEE 2, immediately upstream of the bow shock as a reference monitor of the IMF. At this location the time delays between measurement of a change in the field and its arrival at the magnetopause are typically 3~4 min. Propagation delay errors are a small fraction of this number. Most of the time delay is a consequence of transport across the magnetosheath and along field lines to the ionosphere.

[24] For each spacecraft we applied the rules devised by Lyons et al. [1997] to the IMF GSM \( B_z \) time series identifying the times of potential substorm triggers. This time was corrected using a time delay calculated under the assumption that discontinuities in the solar wind are aligned with the Parker spiral. The cylindrical distance of each spacecraft from the Earth-Sun line at the time of the observations was also calculated. This distance was divided into bins of width 1.0 \( R_E \) and the number of occurrences of a trigger in each bin was determined. Since the time spent in different bins depends on the orientation of the orbit relative to the Earth-Sun line we also determined the total number of good observations made by each spacecraft in each bin. Dividing the number of triggers in a given bin by the total number of triggers gives the frequency of observing a trigger at a given distance. Similarly dividing the number of observations in a given bin by the total number of observations in all bins gives the frequency of having data in a particular bin. Since the frequency of having data in a particular bin is not uniform we must weight the number of events observed in each bin by the reciprocal of the fraction of time it spends in a given bin. This “time normalized ratio” for both classes of events is defined as follows:

\[ f_p = \frac{n_p}{N_{tot}} \]  

(2)

\[ f_{fr} = \frac{t_p}{T_{tot}} \]  

(3)

\[ R_{ot} = \frac{f_p}{f_{fr}} = \frac{n_p}{N_{tot}} \cdot \frac{T_{tot}}{t_p} \]  

(4)

where \( \rho \) is the distance from IMP 8/ISEE 2 to the Earth-Sun line, \( n_p \) is the number of triggered or nontriggered substorms for each \( \rho \) bin, \( N_{tot} \) is the total number of triggered or nontriggered substorms in this analysis, \( t_p \) is the time IMP 8/ISEE 2 spent in each \( \rho \) bin, and \( T_{tot} \) is the total time of solar wind observation in this analysis, \( f_p \) is the occurrence probability for triggered or nontriggered substorms in each \( \rho \) bin, \( f_{fr} \) is the fraction of time IMP 8/ISEE 2 spent in each \( \rho \) bin. \( R_{ot} \) is the time normalized ratio for each \( \rho \) bin for triggered or nontriggered events. It should be noticed that
the time-normalized ratio is not a probability function. A change in this ratio as a function of distance would be an indication that triggers are more probable at some locations than others. Note that the sum over all bins of either the numerator or the denominator gives 1.0 so that we expect the ratio to be close to 1.0.

[25] For the years 1978 through 1986 the selection criteria identified 2898 IMF triggers at ISEE 2 and 2149 triggers at IMP 8. Because both spacecraft spend about half their orbits inside the bow shock and magnetosphere only 1602 of the ISEE 2 events were seen during times when some IMF data were available at IMP 8. In this list only 975 triggers were identified at IMP 8. If in addition we require that IMP 8 actually have good data within ±30 min of an ISEE 2 trigger the total number of simultaneous ISEE trigger events with good IMP data is reduced to 833. Figure 2 summarizes the results of our analysis of all 2898 events at ISEE and 2149 events at IMP 8. The top left plot shows the probability that a spacecraft will occupy a particular bin of width 1.0 $R_e$ in cylindrical distance. Note that neither IMP 8 nor ISEE 2 spent much time in the bin closest to the Earth-Sun line because of the tilt of their orbits. Also ISEE 2 could only monitor the IMF when it was close to the Earth-Sun line since at other times it was inside the bow shock. The top right and bottom left plots show the frequencies of trigger observations in each bin. The bottom right plot shows the time normalized ratio of these two probabilities.

Figure 2. The information used to calculate the probability of either spacecraft alone observing an IMF trigger as a function of distance from the Earth-Sun line. The top left plot shows fraction of time spent in radial bins. The top right and bottom left plots show the frequency of trigger observations in each bin. The bottom right plot shows the time normalized ratio of these two probabilities.

[26] Figure 3 presents the aggregate observations from the two spacecraft with estimates of the error in the normalized ratio. The error was estimated by the bootstrap method. The bootstrap is a procedure that involves choosing random samples with replacement from a data set and analyzing each sample the same way. Sampling with replacement means that every sample is returned to the data set after sampling. So a particular data point from the original data set could appear multiple times in a given bootstrap sample. The number of elements in each bootstrap sample equals the number of elements in the original data set. The range of sample estimates you obtain enables you to establish the uncertainty of the quantity you are estimating [Press et al., 1986]. In this particular case, the positions of identified IMF triggers are the random sample and we have repeated the bootstrap procedure 10,000 times. For
most of the range of radial distance the normalized ratio
does not deviate significantly from 1.0. There is, however, a
slight bias toward observing more trigger pulses on the
dawn side (negative $r$). This may indicate that the foreshock
creates some trigger pulses not present in the solar wind
measured near the Earth-Sun line.

2.5. Simultaneity of IMF Triggers

It was mentioned above that there were only 833
ISEE trigger events for which there were simultaneous IMP
magnetic data. The next step is to choose the width of the
time association window. We choose ±10 min because Hsu
and McPherron [2002] determined this is an optimal choice
of time association window between IMF triggers and
substorm onsets. For this subset we initially found an
associated trigger at IMP within ±10 min for only 491
triggers or 59% of the ISEE triggers. This probability is
coincidently the same as the probability of a substorm onset
being correlated with an IMF trigger measured at a single
spacecraft [Hsu and McPherron, 2000, 2004]. Lyons (per-
sonal communication, 2005) argues that this number con-
stitutes proof of his "small-scale structure" hypothesis
discussed in the introduction. As we will show next this
result appears to be a consequence of errors in the solar
wind propagation delay and our procedure for determining
association.

Figure 4 shows six examples of IMF triggers
detected simultaneously at both spacecraft for which the
cross correlation of the two $B_z$ traces was greater than 0.8.
Each plot displays one hour of data centered on the ISEE
trigger time. In every case the data from the two spacecraft
have essentially the same waveforms with small differences
due to propagation errors and high-frequency components.
Six additional examples of simultaneous triggers, but with
low cross correlation coefficients between the $B_z$ traces are
plotted in Figure 5. Typically the poor correlation is a
consequence of missing data in one of the two traces. Such
events were included in the subset of 59% of the events
classified as simultaneous triggers.

Examples of events with a high cross correlation that
were not automatically classified as associated triggers are
presented in Figure 6. In each plot the IMP $B_z$ traces have
been offset by the delays calculated for each spacecraft at
the time of the ISEE trigger. A visual inspection revealed
that triggers were present in both waveforms but the calcu-
lated propagation delay was obviously wrong. To compen-
sate for such errors we reanalyzed the entire subset of 833
intervals using the time lag of optimum cross correlation as
a correction to the IMP $B_z$ time delay. This correction
forces the waveforms to correspond as well as possible. If
triggers were present in both traces then the events were
classified as "associated." This procedure showed that 717
ISEE events (87%) had an associated IMP 8 trigger.

The forgoing procedure left 116 or 14% of the ISEE
2 triggers without an associated IMP 8 trigger. Of these, 63
events (8% of total) had highly correlated wave forms

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**Figure 3.** Combined observations from both spacecraft show ratio of probability of observing a trigger
to the probability of having good data. The shaded bands show a bootstrap determination of the 99%
confidence interval. A ratio close to 1.0 implies that the number of observed triggers depends only on the
time a spacecraft acquired data in a particular bin.
similar to those shown in Figure 7. An examination of these traces suggests that roughly half of these events were misclassified. The most common reason for misclassification appears to be a bad data point in one of the traces that caused the algorithm to either miss a trigger, or identify a trigger when none was present. An examination of the 53 (6%) of the events that had both low cross correlation and no simultaneous trigger at IMP 8 suggests that there does exist a set of small structures that differ substantially between the two spacecraft. Figure 8 displays six of these.
Figure 5. Examples of simultaneous triggers with low cross correlation of $B_z$ waveforms (see Figure 4 for explanation).
Figure 6. Six examples of events seen at both spacecraft that were not automatically classified as simultaneous triggers are displayed. Both traces have been offset to the subsolar magnetopause by the time delay calculated with the corotation delay model. The traces are highly correlated but at a delay greater than the ±10 min association window assumed in our initial analysis.
Figure 7. Six examples of $B_z$ waveforms containing an ISEE 2 trigger without IMP 8 trigger that exhibit a high cross correlation ($r > 0.8$) between the two traces.
Figure 8. Six examples of poorly correlated $B_z$ waveforms containing a trigger at ISEE 2 but none at IMP 8.
cases. In several of the cases it appears that the waveform seen at ISEE 2 has been so altered by propagation that it is not recognizable at IMP 8 as an IMF trigger. Furthermore, the statistics do not seem to change with solar cycle. The dependence of the probability of a small-scale structure on the solar cycle is shown in Figure 9. There is no indication that the probability of observation of small-scale IMF structure depends on the time in the solar cycle.

In summary we have shown that most of the time (59%) of the IMF triggers seen just upstream of the bow shock are also seen at IMP 8 within ±10 min somewhere in its ∼35 R_e circular orbit. If in addition we take into account the possibility of large errors in propagation delays we find that about 86% of the ISEE 2 triggers are associated with an IMP 8 trigger. For the remaining 14% of the events we believe that about 8% are misclassified at one or the other spacecraft due to bad data points in one of the traces. Thus we believe that less than 10% of all IMF triggers correspond to small-scale structures that might be missed by a single spacecraft. This number is insufficient to explain the 40% of all substorms that do not appear to have an IMF trigger [Hsu and McPherron, 2003].

2.6. Magnetic Activity Produced by Large- and Small-Scale Structures

To test whether small-scale structures are important in triggering substorms we performed a superposed epoch analysis of the AL index for both the large-scale (simultaneous trigger at both spacecraft) and small-scale events (trigger seen only at ISEE 2). The results are plotted in Figure 10. The left plot shows quartiles of the ensemble of events organized by the time of IMF triggers seen at both spacecraft. It is apparent that these triggers are associated with an auroral zone response. Furthermore, the median curve shows a sharp break in slope characteristic of a substorm expansion within minutes of the time of the trigger. Since no information concerning the presence or absence of substorms was used in selecting the IMF triggers this result provides confirmation of the hypothesis that northward turnings can trigger substorm expansions. The right plot shows a similar analysis of the small-scale events in which only ISEE 2 observed the IMF trigger. The median AL index curve is much less disturbed than in the previous case and the change seen after the time of the small-scale trigger is much smaller and hardly significant. Whether the slight reduction indicates a weak substorm is occasionally triggered by these events would require further study.

3. Discussion

A preliminary attempt to associate two sets of IMF triggers (ISEE 2 and IMP 8) showed initially that only 59% of ISEE 2 triggers have simultaneous IMP 8 triggers. However, most of the 41% of events classified as unassociated did not actually observe different solar wind structures. Further examination shows that only 14% of the nonassociated events can be attributed to different solar wind. A majority of the nonassociated events appear to be a consequence of propagation errors as was suggested by Hsu and McPherron [2002]. A more accurate solar wind time propagation method should be used such as the algorithm developed by Weimer et al., 2003. Nevertheless, even with a crude solar wind time propagation method, we did not find evidence that small-scale solar wind structures occur frequently. Overall, only
14% of the simultaneous triggers could not be associated at the two spacecraft. The low probability (14%) does not match the occurrence frequency of 40% of substorm onsets that appear to be nontriggered. It is thus unlikely that all of the nontriggered substorms can be attributed to the monitor missing small-scale IMF triggers.

Another interesting result is the magnetic response to the IMF triggers. In a recent study, Morley and Freeman [2007] suggest that the association between IMF triggers and substorms is random. According to these authors the high statistical significance between IMF triggers and substorms reported by Hsu and McPherron [2002] arises from the growth phase requirement in criterion 1 of Table 1. It is thus reasonable to question whether the association between IMF triggers and substorms is a real phenomenon. As a matter of fact, Morley and Freeman [2007] suggest that the association between IMF triggers and substorms should be a random relation instead of a causal relation. If their suggestion is true, then if we superpose the magnetic response in the auroral zone, i.e., the AL index, we ought to see a flat line as the small IMF structure does. On the contrary, we see a significant decrease of AL index after the arrival of IMF triggers. This strongly suggests that IMF triggers play a role in substorm initiation. It is not easy to explain how the typical break in slope of the AL index expected at substorm onset should occur at the time of an IMF trigger. It is noted, however, we need a substorm list to do a conditional probability estimation in order to assess the association probability similar to Hsu and McPherron [2002]. Since such a substorm list needs to cover the data from 1978 to 1986, it is beyond the scope of this study and will be a future topic for study.

Figure 10. A superposed epoch analysis of the AL index for the subset of large- and small-scale structures detected by the ISEE 2 and IMP 8 monitors in the solar wind. The left plot (blue lines) shows quartiles of AL response to triggers detected by both spacecraft. The right plot (green lines) shows quartiles for a small subset seen by ISEE but not by IMP.
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