The statistical characteristics of IMF triggered substorms

T.-S. Hsu and R.L. McPherron

Abstract: To understand the magnetospheric substorm it is necessary to determine whether substorm onset is always externally triggered by the interplanetary magnetic field (IMF) or whether substorm onset sometimes occurs spontaneously as a result of internal processes. One of the proposed mechanisms for substorm onsets requires that every substorm be triggered by a northward turning of the interplanetary magnetic field (IMF) [8, 9, 10]. A statistical study performed by [7] has demonstrated that the association between IMF triggers and substorm onsets is a real physical phenomenon. However, this result was recently challenged. It is suggested that the high confidence level in the association between IMF triggers and substorm may be due to the condition of substorm growth phase. In essence, the argument is that "after 20 minutes of southward IMF, there ought to be a very high probability of a northward turning of the IMF". In this study, we examine the probability of association after 20 minutes of southward IMF and found that the probability of northward turning is not as high as expected.

Key words: Substorms, IMF triggering.

1. Introduction

Twenty-five years ago [1] used superposed epoch analysis to demonstrate that a maximum in the tail lobe field is associated with the onset of the expansion phase of a magnetospheric substorm as measured by midlatitude positive bays. Quite by accident they also found that this maximum, and hence the substorm onset, is also associated with an apparent northward turning of the interplanetary magnetic field (IMF). [1] pointed out that a similar statistical association could be seen in an earlier study of isolated substorms [4]. In a subsequent study [2] demonstrated that this same association was present in time series of IMF Bz and traces of auroral zone magnetometers. Sudden decreases in the horizontal component of the magnetic field occurring at the time of a brightening of the aurora appeared to be associated with northward turnings of the IMF. They concluded that the change in the orientation of the IMF was somehow "triggering" the onset of the magnetospheric substorm.

These results did not receive much attention until [14]and [15] published several particularly clear examples of apparent triggering. [3] and [17] also suggested that the explosive phase of isolated substorms could begin under the influence of a change in the IMF Bz component. Shortly thereafter [16] used the technique of generalized superposed epoch analysis to again demonstrate a statistical association between substorm onset as defined by ground magnetograms from former U.S.S.R stations and northward turnings of the z component of the IMF. Most researchers at this time dismissed this apparent relation as simply coincidence. The Bz component of the IMF is constantly changing from positive to negative. Substorm expansions occur frequently when the IMF has been southward for about an hour. This is close to what is thought to be the typical time that the IMF remains southward so it is inevitable that some onsets will appear to occur about the time of a northward turning. To counter this view [13] performed a statistical examination of all substorms occurring in a six-month interval. They found that nearly half of all substorms could be associated with northward turnings of the IMF.

These results were again ignored until [8] proposed a substorm model ultimately requiring that all substorm expansions are triggered by northward turnings of the IMF or changes in IMF By. This view was so extreme that it immediately drew criticism from numerous researchers. [6] and [13]had published several examples of substorm onsets that occurred when there was no apparent change in IMF Bz. [9] dismissed these examples as either not being substorms or as having been triggered by changes in the IMF By component. However, [5] immediately published examples that were unambiguously substorms (as determined by synchronous particle injection), yet there were no changes in any component of the IMF. The conclusion appeared to be that triggering of substorm expansion by the IMF is not necessary. Many researchers continued to believe that those events that appeared to be triggered were simply a matter of coincidence.

In an attempt to examine the probability of association between IMF triggers and substorm onsets, [7] used a point process technique to examine the chance association between IMF triggers and substorm onsets. They found that the association between IMF triggers and substorm onsets is a real physical phenomenon. However, this result was recently challenged. They suggested that the high confidence level in the association between IMF triggers and substorm may be due to the condition of substorm growth phase. In essence, the argument is that "after 20 minutes of southward IMF, there ought to be a very high probability of a northward turning of the IMF". In this study, we examine the probability of occurrence of IMF triggers after 20 minutes.

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2. Probability of Northward IMF Turning from Southward IMF

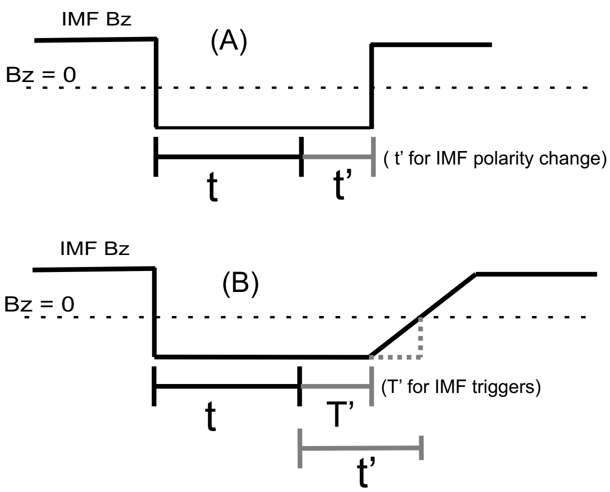

Fig. 1. Schematic explanation of IMF northward turning, where *t'* is the IMF polarity change time and *T'* is the IMF triggers time after some waiting time *t*. Panel (A) is an schematic example of a south to north IMF can be a IMF trigger. Panel (B) is a more general case for IMF triggers. In this schematic example, it is obvious that some additional time *t'*-*T'* has been calculated in the previous analysis [7].

In the statistical study done by [7], they found that the probability of their chance association between two point processes appears to be extremely low. However, it might be suggested that the high probability of association is a consequence of the natural tendency of the IMF to turn northward after an interval of southward IMF. If it were the case that all intervals of southward IMF were exactly one hour long, and all substorm growth phases were as well, then every onset would be correlated with a northward turning. Such a circumstance is unlikely to occur because of the power law spectrum of the IMF, and because the duration of the growth phase of substorms varies over a range of 20-200 minutes, with 55 minutes most typical [e.g. [12]]. None-the-less we are led to consider the question "what is the probability for a northward turning of the IMF after some extended interval of southward IMF?" If the probability of an IMF polarity change after some specified interval of southward IMF Bz is extremely high, then the association between IMF Bz northward turnings and substorm onsets may still be coincidental rather than physical. In our case our trigger criteria requires that the IMF have been southward for at least 20 of the 30 preceding minutes.

[7] used a procedure developed by [18] to examine the probability of IMF polarity change after a certain amount of time. In essence, the question is whether "the longer there has been southward IMF, the shorter the expected time till a northward turning"? A detailed theoretical argument can be found in [7]. The argument is focused on a determination of the sign of $\frac{d<t'>}{dt}$ in which *t'* is an additional time we must wait until the northward turning IMF Bz, given the time *t* since the southward turning (Figure 1).

It should be pointed out that [7] only estimated the probability of IMF polarity change in their paper, i.e., from southward IMF to northward IMF. In Figure 1, we have plotted two schematic examples for the analysis. The panel (A) is an example which has a sharp change of IMF sign. Panel (B) is a more general case for IMF triggers. In the previous analysis, the waiting time is *t'* [7]. If we use a more general case for the IMF triggers (Figure 1, panel B) and assume the waiting time is *T'*, we can see that there is an additional *t'*-*T'* waiting time for the polarity change (panel B). Figure 2 shows an example of automatic identified IMF triggers by [11] criteria]. It is clear that case (a) and (c) are more general examples of IMF triggers while the case (b) is a classic change in sign of the IMF. Nevertheless, both cases satisfy the criteria [11] and should be consider in the same group.

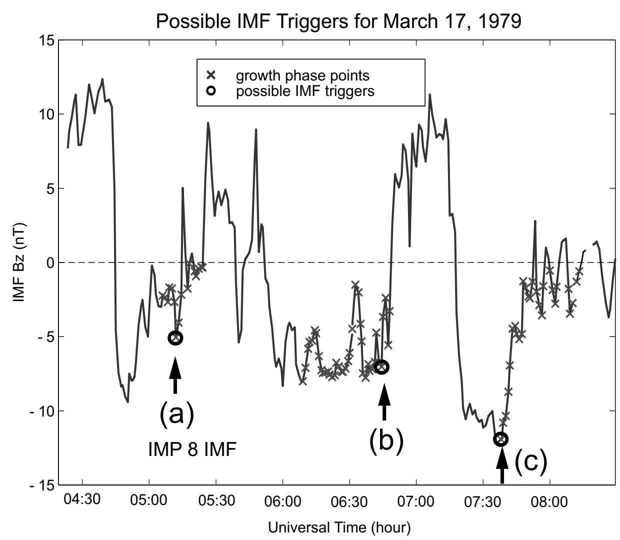

Fig. 2. An example of automatic identified IMF triggers by [11] criteria. IMF triggers (a) and (c) are a more general example of IMF triggers while trigger (b) is more likely the sharp change of IMF sign. In this figure, x means point satisfies the groth phase criteria and O is the selected IMF triggers.

The estimation the probability distribution between southward and northward turnings of IMF Bz is obtained by using six continuous months of 5-minute resolution ISEE-3 data (January to June 1979) [7]. The duration of southward IMF Bz intervals was calculated and used to construct the probability distribution. In Figure 3, this complementary cumulative probability distribution is plotted for IMF polarity change and IMF triggers. Using a least square fit we find that this distribution, P¿ can be represented as $P_{>} = 1.4e^{(-\sqrt{t/33.1})}$ for IMF polarity change (Bs to Bn) and $P_{>} = 1.7e^{(-\sqrt{t/23.5})}$ for IMF triggers, in which *t* is the time duration of the southward IMF Bz. It should be noticed that $P_{>}(t)$ is actually $f'(t)$, the cumulative integral of *p(u)* [7]. In essence, this distribution is a Weibull distribution with an exponent less than 1 [see also Chapter 6 in *Sornette*, 2000; [18]], a stretched exponential distribution. A particular characteristic of this distribution is that "the longer we have waited since the last event, the longer the time to the next event". This has been demonstrated in the [7] which is shown briefly here.

Given that $f'(t) = ce^{-\sqrt{t/\tau}}$, we have
$f(t) = -2c\tau[\sqrt{t/\tau}e^{-\sqrt{t/\tau}} + e^{-\sqrt{t/\tau}}]$ and
$f"(t) = \frac{-c}{2\sqrt{t\tau}}e^{-\sqrt{t/\tau}}$ in which we have set c = 1.4 , τ =33.1 (IMF Bs to Bn, polarity change) and c =1.7 ,τ =23.5 (IMF triggers) for simplicity. After substituting these formulas into equation (20) of [7], we have

$$f(t)f'(t) - [f'(t)]^2 = \frac{c^2 e^{-2\sqrt{t/\tau}}}{\sqrt{t/\tau}} \quad (1)$$

It is apparent that this equation has $\frac{d<t'>}{dt} > 0$ for finite t. If $t \to \infty$, $\frac{d<t'>}{dt} \to 0$. However, this would imply that IMF Bz can remain southward forever, a nearly impossible situation for IMF Bz. Thus, this result suggests that the hypothesis Q, "the longer it has been since the last southward turning of IMF, the shorter the time expected till the northward turning" is not correct. Instead, the opposite hypothesis that, "the longer it has been since the last southward turning of IMF Bz, the longer the time expected till the northward turning" is true. While the previous estimation of [7] has only estimated the Bs to Bn (polarity change, Figure 2 (A)), it is shown here that the consideration of more general IMF trigger cases (Figure 2 does not significantly change the probability distribution. This implies that the probability of a northward turning of IMF Bz (either for polarity change or IMF triggers) after our "pre-selected" southward IMF Bz period of 20 minutes used in determining a trigger may not be "extremely" high as has been suggested.

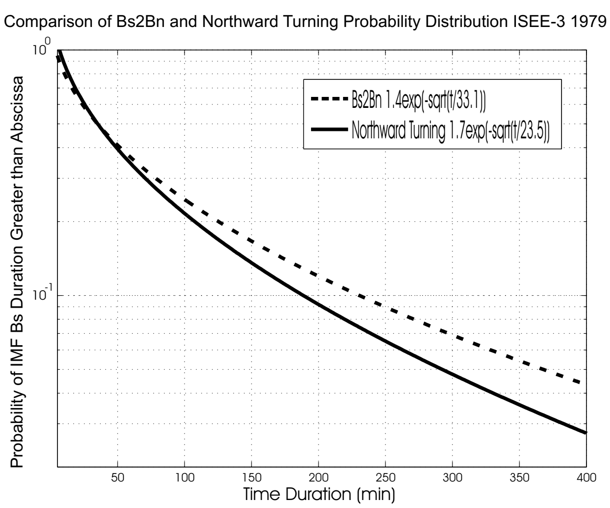

Fig. 3. Probability of southward IMF duration for Bs to Bn (polarity change, dashed line) and IMF triggers (solid line).

A study done by [14] examining the duration of intervals of IMF polarity obtained a similar result. Their study found that 65.7% of the IMF Bz data do not change their polarity in a one-hour time interval. This is consistent with our finding, i.e., the polarity change from southward IMF to northward IMF occurred in a time frame much longer the 20 minutes used in our trigger selection.

From the complementary cumulative probability distribution, we can estimate the probability that a northward turning will have occurred within some specified time after the southward turning by using the cumulative probability distribution. Now the problem is to find the northward turning probability Pnorth at t' after a time t. In Figure 3 we have the cumulative probability that the duration of southward IMF Bz exceeds a time T. Thus the probability that Bz will have turned northward within an additional time t' can be estimated by the difference in cumulative probabilities at t and t+t', which is $P_>(t \geq T) - P_>(t \geq T + t')$. Thus,

$$\begin{aligned} P_{north}(t') &= \frac{P_>(t \geq T) - P_>(t \geq T + t')}{P_>(t \geq T)} \\ &= 1 - \frac{e^{-\sqrt{(T+t'/\tau)}}}{e^{-\sqrt{(T/\tau)}}} \end{aligned} \quad (2)$$

Which is normalized because $P_{north} = 0$ at $t' = 0$ and $P_{north} = 1$ as $t' \to \infty$.

In our case, we can set $T = 20$ minutes because this is the growth phase requirement in the "IMF trigger" selection procedure [11]. The result presented in Figure 4 shows that the probability of a northward turning within the first 10 minutes after 20 minutes of southward IMF is about 15$\%$ (for polarity change) and 18 $\%$ for IMF triggers. It is thus not correct to say that there is an extremely high probability of a northward turning within our $\pm$10-minuteassociation window if the field has been southward for 20 minutes. Based on this result, it does not seem likely that the occurrence of northward IMF after 20 minutes of southward IMF is highly probable in the next 10$\sim$20 minutes. On the contrary, there is only a 50$\%$ (polarity change) and 54$\%$ (IMF triggers) of chance occurred 50 minutes beyond the end of our trigger selection window.

The preceding argument can be extended to estimate the number of substorm onsets that will appear to be associated with a trigger as a result of our selection criterion that the IMF must have been southward for longer than 20 minutes before the northward turning. If we assume that all of the substorms in our list had a growth phase with duration 60 minutes, i.e. that the time of the substorm onset was actually 60 minutes after the southward turning. We can estimate the probability of a northward turning (polarity changes or IMF triggers) within a 20-minute interval centered at 60 minutes. Let $T = T_0 - h$ and $t = 2h$ in Equation 2 so that we obtain

$$P_{north}(T_0 \pm h) = 1 - \frac{e^{-\sqrt{(T_0+h)/\tau}}}{e^{-\sqrt{(T_0-h)/\tau}}} \quad (3)$$

For the chosen values this reduces to P_{north} = 0.2019 (polarity change)and 0.2345 (IMF triggers). If the typical growth phase were either 30 min or 90 min the corresponding probabilities would be 0.2756 and 0.1679 for polarity change and 0.3176 and 0.1957 for IMF triggers. Note that the probability of a chance association decreases with increasing duration of the growth phase because of the likelihood that the IMF has already turned northward at an earlier time. Since the most probable duration of substorms in our list was 55 minutes (data not shown) it is apparent that the probability of a chance association will be about 20% (for polarity change) and 23% (for

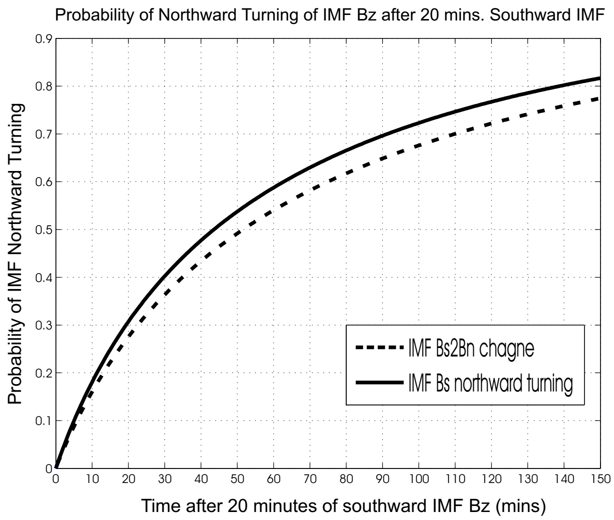

Fig. 4. The estimated probability for a northward IMF polarity change and IMF triggers as a function of time after a 20 minutes interval of southward IMF Bz is plotted. The probability of northward IMF polarity change increases very slowly with the time *t'* beyond the end of the IMF trigger criterion. The probability of a northward IMF polarity change soon after the end of the 20-minute interval is very low. The same thing applies to IMF triggers probability.

IMF triggers). If we multiply the 145 observed substorm onsets by this fraction we obtain 29 events (for polarity change) and 32 events (for IMF triggers) that were possibly a result of chance. This number should be compared to the observation of 15 chance associations at times far from the expected arrival at the Earth of the IMF trigger [7]. The number of associations is clearly larger than what we would expect if the two events were independent, but is still much smaller than the 52 associations actually observed at zero lag from [7]. The difference divided by the standard deviation is (52-29)/4.5 or 5.11 standard deviations from the background level for polarity change. Similarly, it is (52-32)/4.5=4.44 standard deviation above the background level for IMF triggers. For a normal distribution the probability of obtaining this difference by chance is about 1.6×10^{-7} (for polarity change) and 4.5×10^{-6} (for IMF triggers). This number is somewhat larger than the earlier estimate from [7] for independent processes, but still represents an exceedingly unlikely coincidence. Even so, an important result from this estimation is that the previous estimation of IMF probability [7] after some certain time ($\sim$20-30 minutes) is confirmed even when we consider a more general IMF trigger criteria. It is thus very unlikely that the IMF triggered substorm is a chance association.

A more accurate estimate of the associations resulting from our growth phase criterion would require knowledge of the actual duration of every substorm growth phase in our list of substorms. This list could then be used to weight the probabilities of chance association for different durations. If this distribution were skewed it could either increase of decrease our estimate somewhat. Unfortunately this information was not retained in our survey of the data because our null hypothesis viewed the two processes as completely independent. However, since most substorms have about an hour-long growth phase we are confident that our estimate is reasonably correct, and that our primary conclusion remains unchanged.

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