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No evidence for externally triggered substorms based on superposed epoch analysis of IMF B_z

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[1] Superposed epoch analyses have shown that, on average, the interplanetary magnetic field (IMF) turns northward close to substorm onset. This has been commonly accepted as evidence for the substorm onset being triggered by a rapid northward turning of the IMF. Here we show that the tendency arises in any superposed epoch analysis of the IMF in which event onset is biased to occur for southward IMF, irrespective of a coincident rapid northward turning of the IMF. The overall IMF variation found in the largest superposed epoch analysis of this kind is also well reproduced using a Minimal Substorm Model in which substorm onsets are determined without the requirement of a northward IMF turning trigger. We discuss the explanation underlying these results and conclude that there is no conclusive evidence in favour of the hypothesis that substorm onsets are triggered by a rapid northward turning of the IMF. **Citation:** Freeman, M. P., and S. K. Morley (2009), No evidence for externally triggered substorms based on superposed epoch analysis of IMF B_z, *Geophys. Res. Lett.*, *36*, L21101, doi:10.1029/2009GL040621.

1. Introduction

[2] The substorm is an intermittent, system-scale energy release event that occurs in the magnetosphere of the Earth and probably of other planets also [e.g., *McPherron et al.*, 1973; *Kronberg et al.*, 2007; *Russell et al.*, 2008]. Since its discovery over forty years ago [*Akasofu*, 1964], scientists have been intrigued and challenged by what causes its intermittency. The debate centres on whether, or in what proportions, onsets are endogenous (generated from within) or exogenous (generated from outside).

[3] In one sense all substorm onsets are exogenous in that it was recognised early on that a necessary condition for the onset of a substorm is a preceding interval of southward interplanetary magnetic field (IMF), known as the growth phase, during which energy from the solar wind is accumulated in the magnetotail [*McPherron et al.*, 1973]. In the context of the current debate, exogenous refers to whether an additional influence from the solar wind is required for substorm onset. This additional influence, called an external trigger, is usually postulated to be a northward turning of the IMF vector on a time scale very much shorter than the growth phase duration that coincides with, and is causally related to, the substorm onset [*Caan et al.*, 1977]. Other types of external trigger have also been suggested related to rapid changes in the east-west component of the IMF [*Troshichev et al.*, 1986] and solar wind dynamic pressure [*Kokubun et al.*, 1977]. Various physical models that accommodate these triggers have been proposed [e.g., *Lyons*, 1995; *Russell*, 2000; *Lui*, 2001].

[4] Besides numerous anecdotal reports of individual substorm onsets coinciding with a rapid northward turning of the IMF [e.g., *Caan et al.*, 1977; *Rostoker*, 1983; *Blanchard et al.*, 2000; *Lee et al.*, 2006, and references therein], the most objective evidence in favour of exogenous/externally triggered substorms is based on results from two types of statistical analysis.

[5] Firstly, statistical analyses of the relative timings of candidate external triggers and substorm onsets have revealed that they coincide significantly more frequently than expected by random chance [*Lyons et al.*, 1997; *Hsu and McPherron*, 2002]. However, it has been demonstrated recently that this does not provide conclusive evidence that the substorm onset is causally related to, or even statistically associated with, a rapid northward turning of the IMF [*Morley and Freeman*, 2007]. This is because the definition of an external trigger included not only the requirement of a rapid northward turning of the IMF but also a prior interval of southward IMF, which is sufficient on its own to give the statistical association; the additional requirement of a rapid northward turning of the IMF is not necessary. Indeed, it was further shown that the statistical association is reproduced well by a simple toy model of the substorm, known as the Minimal Substorm Model (MSM) [*Freeman and Morley*, 2004], in which substorm onsets are endogenous by construction.

[6] Secondly, superposed epoch analysis has shown that, on average, the IMF turns northward close to substorm onset [*Caan et al.*, 1978, hereafter CMR78]. This has been commonly accepted as evidence of the association and causal connection of a rapid northward turning of the IMF and substorm onset [e.g., *McPherron*, 1979; *Baker et al.*, 1996; *Blanchard et al.*, 2000]. However, in this paper, we shall show that, similarly to the first case above, the average tendency of the IMF to become more northward close to substorm onset is due to the average tendency of substorm onset to occur under southward IMF; the additional requirement of a rapid northward turning of the IMF is not necessary.

2. Method and Results

[7] We use a superposed epoch analysis to make two tests of the null hypothesis:

[8] H_0 – The average tendency of the IMF to turn northward close to substorm onset is independent of a rapid northward turning of the IMF at onset.

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[9] Acceptance of H_0 implies rejection of the hitherto accepted alternative hypothesis:

[10] H_1 – The average tendency of the IMF to turn northward close to substorm onset requires a rapid northward turning of the IMF at onset.

[11] The first test is designed to test whether H_0 can be satisfied purely by the bias of substorm onset to occur during southward IMF, irrespective of a rapid northward turning of the IMF. The second test then extends this using the MSM to investigate the influence of other plausible factors affecting substorm onset, including the time history of the IMF and a magnetotail energy threshold but not the rapid northward turning of the IMF.

[12] The IMF data set used in these tests comprises 1-min-averaged measurements made by the MAG instrument on the NASA Advanced Composition Explorer (ACE) spacecraft from 5 February 1998 to 7 May 2002. Data gaps of less than 5 min were filled by linear interpolation. To avoid larger data gaps, we only used intervals of data that were unbroken for 100 h or more.

[13] The date range covers the ascending phase and maximum of solar cycle 23, thereby including the equivalent phase of the solar cycle in 1967–8 during which the Explorer 33 and 35 spacecraft data used by CMR78 were recorded. To make a direct comparison with their results, data points were measured from the published superposed epoch analysis curve (the top trace from *Caan et al.* [1978, Figure 4]). The gross variation was captured by sampling at 30 min resolution, with the shape of the peak requiring coordinates to be noted at 10 min resolution. These data have then been lagged by 35 min with respect to those shown by CMR78 to account for the delay between measurements of the IMF by the Explorer spacecraft and their possible influence on substorm onset in the magnetotail and subsequent detection on the ground.

[14] The lag places the minimum of the CMR78 superposed epoch analysis curve approximately at the substorm onset time $t = t_i$, and may be justified as follows: The delay can be broken down into three parts $T = T_1 + T_2 + T_3$. $T_1 = (X_s - X_o)/V$ takes into account advection in the solar wind at speed V of a phase front orthogonal to the Sun-Earth line from a spacecraft at $X = X_s$ to a position on the magnetopause at $X = X_o$, where X is the position coordinate on the Earth-Sun line. $T_2 = R_o/c$ is the time for the effect of the IMF at the magnetopause at $X = X_o$ to affect the central magnetotail and possibly trigger substorm onset, where R_o is the effective radius of the magnetotail and c is the characteristic propagation speed, which we take to be the Alfvén speed. T_3 is the time delay between the substorm onset in the magnetotail and its detection on the ground. Choosing $X_o = 11\ R_E$, corresponding to the subsolar magnetopause, $v = 400$ km/s, and $25 < X_s < 75\ R_E$, appropriate to the part of the solar wind in which the Explorer spacecraft spent most of their time [e.g., *Taylor et al.*, 1968], we find $4 < T_1 < 17$ min, consistent with the estimate by CMR78 of about a 10 min delay between spacecraft and subsolar magnetopause. However, we estimate T_1 to be greater than this because we expect that X_o should correspond to a magnetopause position anti-sunward of the location of substorm onset. Assuming $R_o = 25\ R_E$ and $c = 500$ km/s appropriate to the mid-tail ($-10 > X > -20\ R_E$) [*Mazur and Leonovich*, 2006] gives $T_2 \approx 5$ min, and also assuming $T_3 = 2$ min [*Samson*, 1995] we find the T = 35 min delay corresponds to $X_o \leq -30\ R_E$ – at or beyond the expected location of the near-earth neutral line [*Baumjohann et al.*, 2000].

2.1. Test 1

[15] We define a set of times $\{t_i\}$ ($i = 1, 2, 3, \ldots, N$), selected randomly from the set of all times in the unbroken ACE time intervals for which the north-south component of the IMF is below some threshold: $B_z(t_i) \leq 0.7$ nT. This criterion reflects the expected tendency of substorm onsets to occur during southward IMF, but without regard to a requirement for a coincident rapid northward turning of the IMF. (The value of 0.7 nT rather than simply zero nT is chosen such that the average value of $B_z(t_i)$ is approximately equal to that in CMR78's study; see Figure 1b.) Whilst most, if not all, of the times will not correspond to actual substorm onsets, the purpose of this test is to see whether the average tendency of the IMF to turn northward immediately after substorm onset arises generally from any set of events that are biased to occur for southward IMF, irrespective of a rapid northward turning of the IMF at event onset.

[16] Figure 1a shows the resulting superposed epoch analysis of the variation of IMF B_z with respect to the event times t_i for N = 10,000. The heavy solid line shows the ensemble mean. The upper and lower dotted lines show the upper and lower quartiles of the ensemble, respectively. The median is shown by a dashed line and can be seen to be very similar to the mean. Figure 1a clearly shows an average tendency of the IMF to become more northward immediately after event onset, qualitatively similar to the results of CMR78. This suggests acceptance of the null hypothesis H_0 because it shows that this tendency could be explained purely by the bias of substorm onset to occur during southward IMF, independent of a rapid northward turning of the IMF at substorm onset.

[17] Figure 1b presents a more direct comparison with the superposed epoch analysis results of CMR78. The diamonds show the data points measured by us from the published superposed epoch analysis curve, as described above, and the dashed curve is a cubic spline interpolation of these points. The heavy solid line shows the mean variation of IMF B_z with respect to the 10,000 event times used in Figure 1a, but with a random time lag added to the event times, drawn from a normal distribution with a standard deviation of 8 min. This lag simulates the effect of observational uncertainty in the timing of the substorm onset with respect to the IMF signal in CMR78's study. The 8 min value approximately optimizes the agreement between the test curve and CMR78's results and seems plausible given the various sources of random error in the satellite to ground delay T calculated above. For example, the variation in X_s quoted above alone causes T to vary by 13 min. The light solid line shows the mean variation of IMF B_z for a subset of 1153 event times randomly selected from those that yielded the heavy line. This is the same number of event times as in CMR78's study, and thus illustrates the likely statistical variability.

[18] Comparing the superposed epoch analysis curves of Test 1 with that from CMR78, we see that the average variation of IMF B_z with respect to substorm onset, and

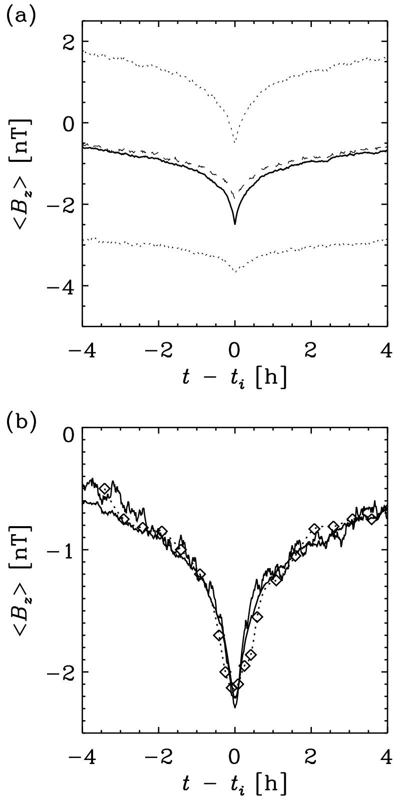

Figure 1. (a) Superposed epoch analysis of IMF B_z with respect to events defined by times t_i where $B_z(t_i) \leq 0.7$ nT. The curves show the ensemble mean (heavy solid), upper and lower quartiles (dotted), and median (dashed). (b) Comparison of this superposed epoch analysis (heavy solid line) with that derived from the observational study of CMR78 (diamonds and dashed line), taking into account a systematic correction and random errors in the propagation of effects from the spacecraft to ground. Also shown is the corresponding curve (light solid) for a subset of events equal to the number used by CMR78.

especially the tendency of the IMF to begin a northward trend at substorm onset, is reproduced closely and likely within statistical uncertainty. Consequently we conclude that there is no reason to reject the null hypothesis H_0 that the average tendency of the IMF to turn northward close to substorm onset is independent of a rapid northward turning of the IMF at onset.

2.2. Test 2

[19] We define a set of times $\{t_i\}$ (i = 1, 2, 3, ..., N) corresponding to substorm onset times generated by the MSM, in which (by design) there is no requirement for a northward IMF turning to trigger substorm onset. Instead, substorm onset occurs when solar wind energy input reaches a constant critical energy threshold following a prior substorm in which an amount of energy is lost that is proportional to the solar wind power input at the time of that substorm onset. (Note that, in this case, the actual value of the energy threshold is arbitrary; see *Freeman and Morley* [2004, section 2].)

[20] The MSM is driven by the time series of the solar wind epsilon function, derived from actual measurements of the solar wind speed and IMF made by the SWEPAM and MAG instruments, respectively, on the ACE spacecraft (the same IMF data set as used in Test 1 above). The resultant probability distribution of waiting times between substorm onsets is the same as that found from observations by *Borovsky et al.* [1993] (see *Freeman and Morley* [2004] for more details). Selecting the date range 22 January 1999 to 12 December 2000 in order to closely match the overall duration and solar cycle phase of CMR78's study yields N = 1290 substorm onsets, which is also conveniently similar to the number of onsets in CMR78's study (N = 1153).

[21] The average variation of IMF B_z with respect to the MSM substorm onset times, in the same format as Figure 1 (but omitting the curve equivalent to the light solid line in Figure 1b because the total number of MSM substorm onsets is already similar to that of CMR78's study). In this case, a random normally-distributed lag with a standard deviation of 20 min has been added to the MSM times to approximately optimize the agreement between the test curve and CMR78's results in Figure 2b.

[22] As in Test 1, the results suggest acceptance of the null hypothesis H_0 because they reproduce the average tendency of the IMF to begin a northward trend at substorm

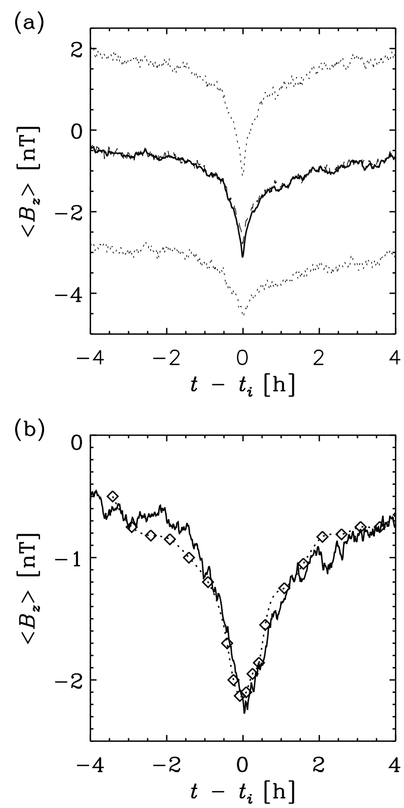

Figure 2. (a) Superposed epoch analysis of IMF B_z with respect to substorm onset times derived from the MSM. The curves show the ensemble mean (heavy solid), upper and lower quartiles (dotted), and median (dashed). (b) Comparison of this superposed epoch analysis (solid) with that derived from the observational study of CMR78 (diamonds and dashed line), taking into account a systematic correction and random errors in the propagation of effects from the spacecraft to ground.

onsets that are defined without the requirement of a rapid northward turning of the IMF at onset.

3. Discussion and Conclusions

[23] Contrary to what is commonly thought, we have shown that the superposed epoch analysis of CMR78 does not provide empirical support for the hypothesis that substorm onsets are externally triggered by a rapid northward turning of the IMF.

[24] Instead, the average tendency of the IMF to begin a northward trend at substorm onset can be explained purely by the known bias of substorms to occur during southward IMF, e.g., when $B_z \leq c$, a constant ~ 0. In this case – our test 1 – the superposed epoch analysis curve is constrained to be less than c at $t = t_i$ by definition (and c was chosen such that the mean of $B_z(t_i)$ is approximately equal to the minimum value of the Caan et al. curve). However, at sufficiently large lags, the memory of this constraint is lost and the curve must approach the long-term average $B_z \approx 0$. Consequently, it is inevitable that the superposed epoch analysis curve will turn systematically northward after any event onset that is biased to southward IMF.

[25] More realistically, the requirement of a growth phase means that substorm onsets occur when the IMF has been southward for some time ($\sim$1 h). Comparison of Test 2 (Figure 2a) with Test 1 (Figure 1a) shows the effect of this additional requirement in that the average B_z is more negative from about 25 min prior to event onset (and $\approx$0.5 nT lower at $t = t_i$), but beyond about 25 min on either side of event onset the average variation in B_z is very similar.

[26] After taking into account various observational considerations (Figures 1b and 2b), the growth phase alone is a necessary and sufficient substorm condition to reproduce closely the superposed epoch analysis results of CMR78. The additional requirement of a rapid northward IMF turning at substorm onset is unnecessary. The same equivalent conclusion has also been reached from a different analysis method – the statistical association of substorm onsets with rapid northward turnings of the IMF [*Morley and Freeman*, 2007]. Thus, whilst the hypothesis of exogenous/externally triggered substorms seems physically plausible and is still possible, the two main statistical analyses purported to support the hypothesis have been shown to be inconclusive. Instead, in the absence of other evidence, parsimony favours the simpler null hypothesis of endogenous substorms.

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