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ARE STORM-TIME SUBSTORMS TRIGGERED OR SPONTANEOUS?

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ABSTRACT

Magnetic storms are almost always accompanied with substorms or substorm-like disturbances. Understanding the nature of the storm-time substorm is important for the currently critical issue of the storm-substorm relation. In this work we have done a statistical analysis in a straightforward way to see whether the storm-time substorms are preferably spontaneous or triggered. On the basis of 301 storm-time substorms selected for this work, we have found that the occurrence of about 28% of them was spontaneous while only 6.5% were associated with a clear trigger(s). The rest of the events were mostly associated with complex variations of IMF. The significant percentage for the spontaneous substorms implies that the possibility of finding a storm without a substorm is greatly reduced due to the spontaneous occurrence of the substorm even when the solar wind and IMF condition remains completely steady during the storm time.

Keywords: storm, substorm, IMF

1. INTRODUCTION

Magnetic storms are a major cause of the disturbances in space near Earth. It is conveniently characterized by a depression of several hours in the horizontal component of the low latitude geomagnetic field. The depression is believed to be caused mainly by an enhancement of the ring current which flows in the westward direction encircling the Earth. Then the decay of the ring current follows that typically lasts up to several days.

The standard paradigm for the ring current enhancement, namely, the cause of magnetic storms, is that a storm would simply be a collection of several intense substorms (e.g., Gonzalez et al. 1994, Kamide et al. 1998). A number of recent observations, however, suggest that the buildup of the ring current can be done by global, enhanced convection rather than substorm expansion (e.g., Russell et al. 2000). Others have suggested that both substorms and convection can contribute to the storm development (e.g., Lui et al. 2001).

It is crucial to understand the basic nature of the storm-time substorms in order to firmly establish the storm-substorm relation. Recently, Lee & Min (2002) examined the storm-time substorm features in terms of magnetic dipolarization and energetic particle injection. They reported similarities and differences between normal substorms and storm-time substorms, including the new feature

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that the storm-time substorm onset sector can be quite away from the midnight in contrast to being limited to local midnight for normal substorms. Reeves & Henderson (2001) reported that the storm-time injection differs in that the injected flux level remains elevated for 2-3 hours in contrast to a few tens of minutes for normal substorm injections. Lee et al. (2004) have found that the flux enhancement of proton injections increases with energy while that of the electrons shows an opposite trend. They further argued that this feature is unique only for the storm time, but not seen for normal substorm injections. Our understanding on the nature of the storm-time substorm is yet incomplete in many aspects.

The purpose of the present paper is to suggest some idea on whether the storm-time substorm is preferably triggered by IMF turnings or can be spontaneous. By the term "triggered" we mean that the cause of the substorm is a sudden turning of IMF B_y and/or B_z. The term "spontaneous" is used to mean the case that the substorm occurs by an instability when the magnetosphere-ionosphere system reaches some critical point (beyond which the instability is triggered) after a period of solar wind energy input. This question is crucial for the issue of the storm-substorm relation. Kamide (2001) has suggested that the storm is driven by a steady-component of the solar wind electric field (so steady-component of the IMF B_z) while substorms during the storm occurs due to varying component of the IMF. The idea is based on the assumption that the substorm is triggered by a northward turning of IMF B_z and/or a IMF B_y turning (Lyons et al. 1997, Bae et al. 2001). The Kamide's proposal implies, if correct, that a storm may be possible even without a substorm if the IMF stays completely steady. In order to see how plausible this scenario is, we examine in this work how often, if not always, substorms during the storm are triggered by the IMF changes and how often they occur spontaneously. In this work we do not aim to resolve the difficult issue of the storm-substorm relation, but rather limit our goal to providing a set of useful statistics that can shed some light on the issue.

2. DATA AND METHODOLOGY

First we have selected a total of 35 storms that meet the selection criteria: (i) $Dst_{min} < -50$nT, and (ii) the Dst curve is sufficiently smooth and well divided into three phases, namely, main phase, early recovery phase and late recovery phase. These were obtained from the period 1996-1998, and more details are described in the paper by Lee & Min (2002).

For each of the selected storms, substorms are identified using the data of ground geomagnetic field, geosynchronous magnetic field and geosynchronous energetic particle. Onset timing of each substorm is then determined by earliest one out of the three indicators: positive and/or negative geomagnetic bay, magnetic dipolarization, dispersionless injection of energetic particles (Other indicators such as Pi 2 pulsation might have been used, but it would lead to 2-3 min corrections at the most which is not critical for the purpose of the present work). Each substorm is considered to be independent when separated by 30 min or longer. Also, for the late recovery phase, we have considered only the interval of 1-8 days, depending on individual storm, around middle of late recovery phase. For the main and early recovery phases, however, the full interval has been taken into account. For more details of the substorm identification procedure, the reader is referred to the paper by Lee & Min (2002).

For each identified substorm, the availability of the IMF data is then checked from the spacecraft, WIND, IMP 8, and Geotail. We have limited to the cases only where the spacecraft distance from the Sun-Earth line is less than 30 R_E for at least one spacecraft. Otherwise, it is required that at least one spacecraft is located on the opposite side to another one. These requirements are necessary to increase the probability that the IMF information measured by the spacecraft is indeed the one that actually interacts with the magnetosphere. Given each substorm onset time $t_{substorm}$, the responsible IMF condition is determined by the one at the time t_{IMF} which is defined to be $t_{substorm} - 9min - t_{MP} \pm \Delta t_{error}$. Here t_{MP} is the traversal time of the measured IMF condition from the spacecraft location to the subsolar magnetopause on the basis of the Parker's spiral angle for the IMF direction and using the measured solar wind velocity. Estimation of this traversal time is limited by the error Δt_{error} that was suggested by Ridley et al. (1998). The 9 min refers to the potential interaction time between the magnetopause arrival of the corresponding IMF condition and the substorm occurrence, according to the suggestion by Lyons et al. (1997) and Bae et al. (2001). For more details of all these matters, the reader is referred to the paper by Bae et al. (2001) and references therein.

On the basis of the procedure above, we were able to obtain a total of 115, 65, and 121 substorms (and the corresponding IMF conditions) for the main, early recovery and late recovery phases, respectively. Our purpose was then to analyze the IMF condition responsible for each substorm.

The IMF condition is first distinguished by the polarity of B_z, namely, north or south, at and prior to the t_{IMF}. We define the 30 min interval prior to t_{IMF} as the growth phase. If it is positive continuously during the growth phase, then it is regarded as the north IMF condition. Otherwise, it is considered as the south IMF case. For south IMF condition, time derivatives of B_y and B_z at t_{IMF} are estimated to see the degree of the IMF variability and to determine if it can be a trigger.

3. RESULTS

Figure 1 shows an example of substorm events that occurred during the storm main phase. The top panel displays the Dst index for a moderate strength storm. The vertical line indicates where we identified the substorm, the data of which are shown in the rest of the panels (b)-(h). In panel (b), the typical magnetic dipolarization is seen starting at $\sim$ 0923 UT by geosynchronous GOES 9 spacecraft located at $\sim$ 0.3 MLT. Panels (c) to (g) show the typical positive and negative geomagnetic H-bays at selected stations of middle (VIC, BOU, FRD) and high (YKC, HCH) latitudes starting at $\sim$ 0923 UT and later (We have checked a number of other stations as well, but we only show a few here). In the last panel (h), we show the energetic proton flux measured by LANL geosynchronous spacecraft at five energy channels (50-75 keV, the uppermost curve, through 250-400 keV). The flux increase starts a few minutes later than 0923 UT, and is dispersed with respect to energy, the increase being seen earlier at higher energies. This is what is expected from a typical substorm injection when measured from a spacecraft away from the injection zone (Note that the LANL 1994-084 was located in the afternoon sector at the time of flux increase). We have also confirmed the occurrence of the auroral brightening from the POLAR spacecraft near 0923 UT (data not shown here). The onset time of this substorm is determined to be around 0923 UT.

The IMF condition responsible for the substorm event in Figure 1 is shown in panel (a) of Figure 2, IMF B_y in dashed line and B_z in solid line. The onset time of the substorm $t_{substorm}$ is indicated by the solid vertical line. The two short-dahsed vertical lines refer to the time interval t_{IMF} where the responsible IMF condition is identified according to the description in the previous section: For this event, the estimated travel time from WIND to the magnetopause t_{MP} is 67.3 min, and Δt_{error} is 7 min, which gives $t_{IMF} =\sim$ 0807 $\pm$ 0007 UT. We see that both B_z and B_y show significant turnings. We regard this as the trigger of the substorm presented in Figure 1. Figure 2 also shows another example in panel (b). The event shown in panel (b) is the case where the substorm is associated with the condition that both B_y and B_z remain fairly steady at t_{IMF} (here some turning of B_y is seen, but its turning rate is too small to be considered significant). The data of this substorm together with Dst are shown in Figure 3. The H-component negative and positive bays

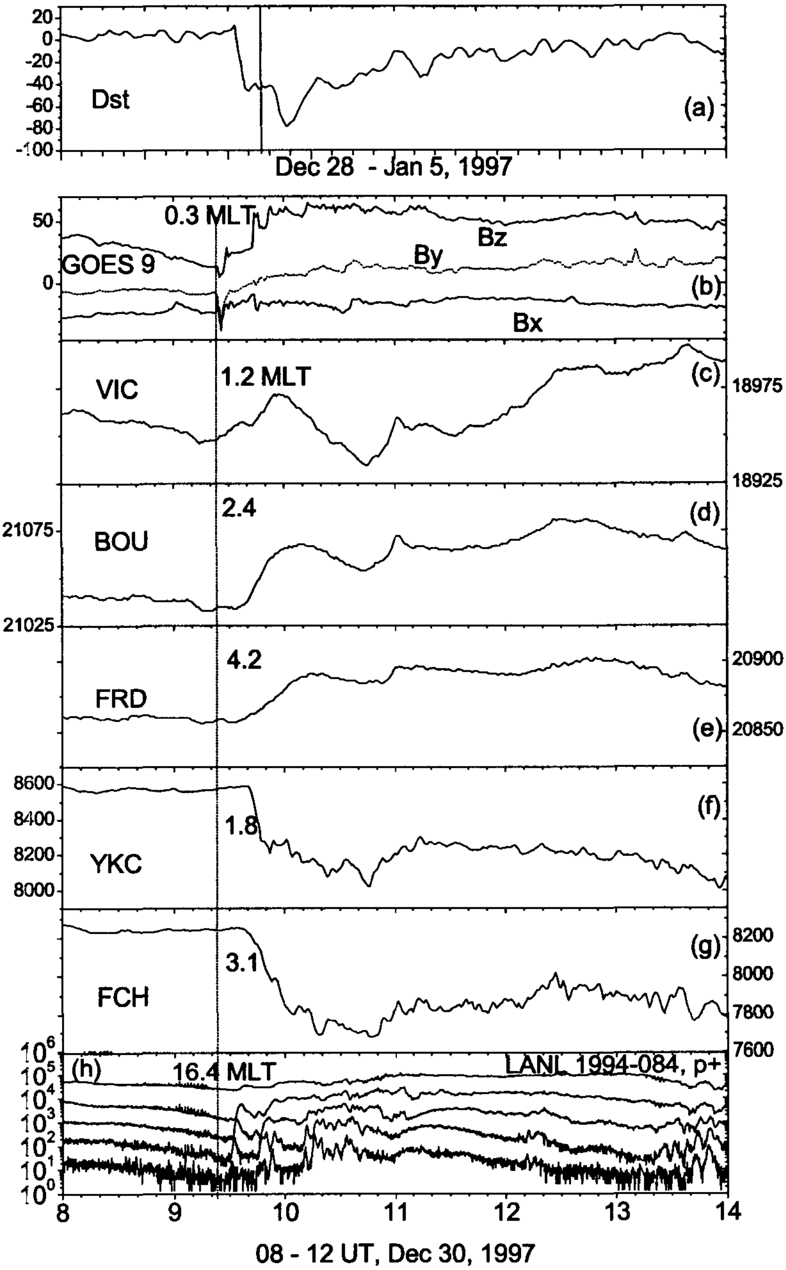

Figure 1. An example of substorm that occurred during the storm main phase.

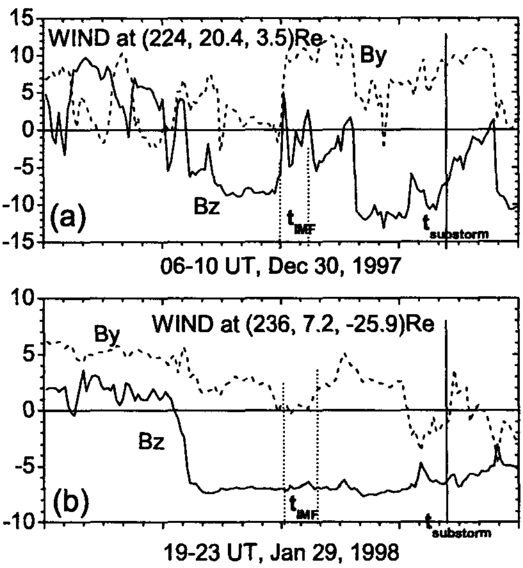

Figure 2. IMF conditions responsible for two substorms found during the storm main phase.

were clearly identified, the data at two stations being shown in panels (b) and (c). The onset appears to be around 2222 UT. The LANL energetic particle flux data shown in panels (d) to (g) show the typical dispersionless injection, dispersed echoes, and growth phase dropouts. It was found that t_{MP} = 63.5 min, and Δt_{error} = 8 min, which leads to t_{IMF} =~ 2110 ± 0008 UT as indicated by dotted vertical lines in panel (b) in Figure 2. It should be remarked that, in both of the two events in Figure 2, the IMF B_z during the growth phase is sustained southward and quasi-steady, and that the solar wind dynamic pressure at t_{IMF} did not show any significant change.

We have repeated the above procedure for the rest of the selected substorms. The statistical result is summarized in Table 1 which shows the number of events (and percentages) for different classes of IMF conditions and separately for three storm phases. The IMF condition is first divided into three classes, north, south, and undetermined. The south IMF case is further divided into two subclasses (steady B_y and B_z, and turning B_y and/or B_z). First, it is seen that the north IMF condition is very rare for the main phase of the storm. This is not surprising as it has been well known that the storm main phase typically corresponds to the southward IMF. However, the percentage for the north IMF condition becomes larger for the two recovery phases, 16.9 and 9.9%, respectively. This reflects the well-known fact that the IMF becomes much less southward, even northward, as the storm recovers.

Table 1 shows that 39.1 % of the main phase substorms were associated with the steady IMF B_y and B_z. Here the term "steady" is defined to be the case where the time variation of both components is, in its magnitude, less than 1 nT/min at t_{IMF} (This is a condition that is well below the turning rate suggested by Blanchard et al. (2000) to define a trigger). Thus, the occurrence of these 39.1 % of the main phase substorms may be considered to be spontaneous. In comparison with that, only 7.8 % of the main phase substorms are associated with a clear turning(s) of IMF B_y and/or B_z. This includes

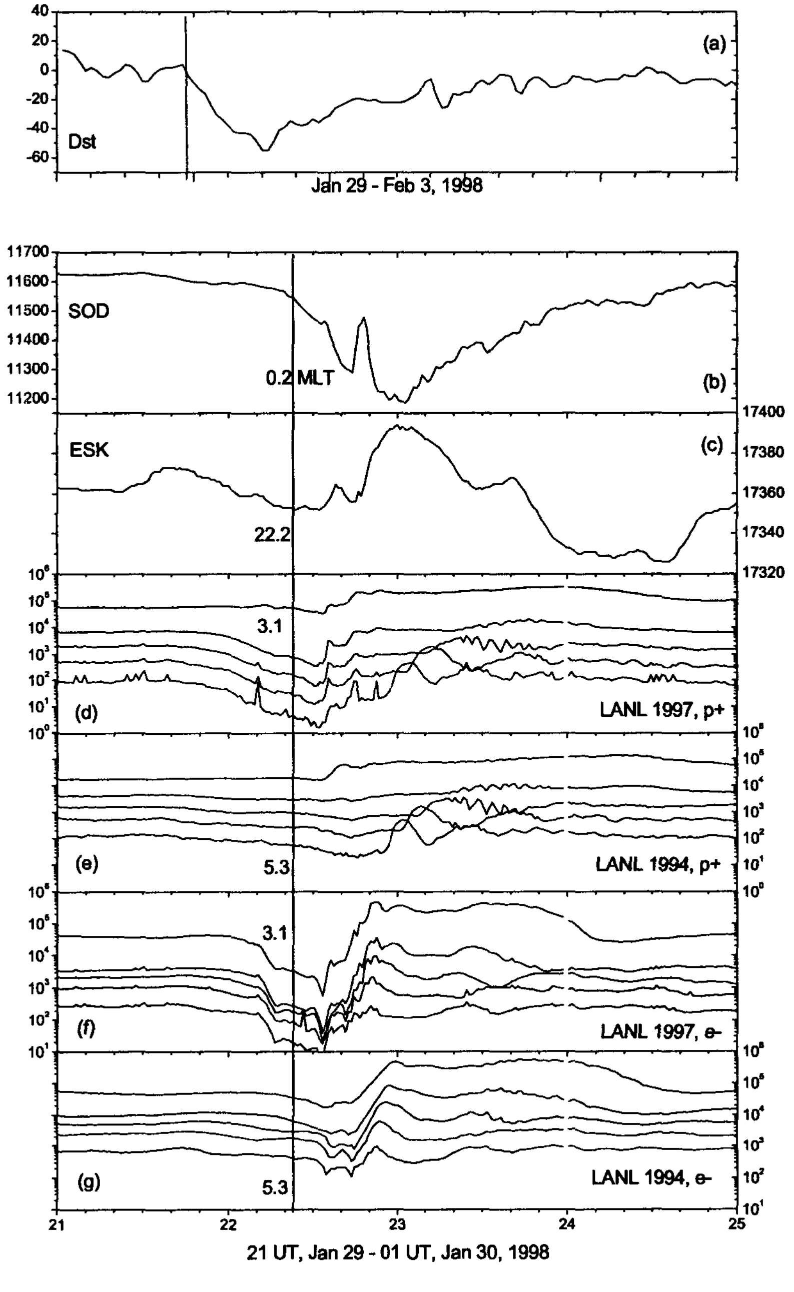

Figure 3. Another example of substorm that occurred during the storm main phase.

Table 1. Statistics on IMF conditions for storm time substorms.

	north B_z [a]	south B_z steady B_y, B_z [b]	south B_z turning B_y, B_z	undetermined fluctuations	total
main phase	1 (0.9%)	45 (39.1%)	9 (7.8%)	60 (52.2%)	115
early recv ph	11 (16.9%)	13 (20%)	5 (7.7%)	36 (55.4%)	65
late recv ph	12 (9.9%)	30 (24.8%)	5 (4.1%)	74 (61.2%)	121
average [c]	9.2%	28%	6.5%	56.3%	301

[a] IMF B_z is primarily northward for 30 min prior to t_{IMF}
[b] time derivative of B_y, B_z less than 1nT/min
[c] percentage averaged over three phases

only the case where the IMF turning is sufficiently unambiguous to be considered as a trigger. For the rest of the main phase substorms, 52.2%, the corresponding IMF conditions were found to be ambiguous due to short-time scale fluctuations, complex multiple turnings, and the growth phase characterized by both south and (non-negligible) north intervals, etc. For these events, it appears to be impractical to determine whether there was a trigger or not.

For the early recovery phase, the occurrence percentage of spontaneous substorms is 20 % while the percentage for the substorms associated with a clear IMF turning(s) is only 7.7 %. Again for the other 55.4% events, the IMF condition was found to be ambiguous. We obtain similar results for the late recovery phase substorms, 24.8 %, 4.1 %, 61.2% for the steady IMF, the clearly turning IMF, and the ambiguously varying IMF, respectively. When averaged over all three phases of the storm, we find that 28 % of the total substorm events appear to be spontaneous, only 6.5% are associated with a clear IMF trigger(s), and 56.3% are associated with IMF variations in a complex pattern.

4. DISCUSSION AND CONCLUSION

The major point in the statistics above is that the occurrence percentage of the spontaneous substorms is significant, being 28% of the total storm-time substorms selected for this study. It is interesting to note that this is in good agreement with the number, 29%, previously reported by McPherron et al. (1986) though their work did not distinguish between storm time and nonstorm time. The significant percentage for the storm-time substorm occurrence is an important finding, considering that if no storm-time substorm were spontaneous, a storm without a substorm would be possible under a steady solar wind and IMF condition as Kamide (2001) has proposed, implying that the storm would basically be a phenomenon independent of substorms. However our statistics does not support the Kamide's proposal (2001) because of the significant percentage of spontaneous substorms. The main problem with the Kamide's idea seems to lie in the assumption that all storm-time substorms would be triggered by IMF turnings. According to what we have found in this work, storm-time substorms can be spontaneous as well as triggered externally. Therefore, it is unlikely to have a storm without a substorm even when the solar wind/IMF condition remains completely steady, unless the storm main phase is too short to allow a substorm.

For the steady IMF, one might expect a steady magnetospheric convection without a "spontaneous" substorm, but this is possible only when the Erickson-Wolf pressure crisis (1980) can be resolved. This is however normally very difficult to occur, and most likely the reason for the significant occurrence percentage, 28%, for spontaneous substorms under steady IMF condition. Thus, a storm under steady IMF will likely still accompany a substorm(s) due to the pressure crisis. How much this substorm can contribute to the storm evolution is currently a controversial issue and so beyond the scope of the present work.

Rigorously the steady solar wind condition refers to no significant change in both the IMF and the dynamic pressure. The recent work by Lee & Lyons (2004), Lee, Lyons, & Yumoto (2004), and our new preliminary work (Baek & Lee 2004) showed that the effect of the dynamic pressure sometimes appears to be very similar to that of substorm, in particular, when the IMF remains strongly southward just like in the storm main phase: It sometimes shows nightside dipolarization, energetic particle injections, and auroral brightening in the Harang discontinuity region. Thus the effect of the dynamic pressure may increase the chance that the substorm or substorm-like event is triggered even under a steady IMF condition, very similar to what IMF turnings do. However, we find in this work that a pressure pulse associated with a steady IMF is seldom observed, but instead most of the pressure pulses are accompanied with an IMF change.

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