An Avalanche Model of Magnetospheric Substorms Based on Cross-Scale Coupling in the Central Plasma Sheet

William Liu, Paul Charbonneau, Eric Donovan, and John Manuel

Abstract: TBD

Key words: Complexity, SOC, Cross-Scale Coupling.

1. Introduction

Chang [6] speculated the applicability of self-organized criticality to magnetospheric physics. Recent observational evidence has established that the magnetosphere exhibits a range of scale-free distributions suggestive of SOC [9, 23, 32, 33, 10]. It is generally suggested that SOC is a state of dynamical systems significantly removed from a minimum-energy equilibrium; sometimes, the system is referred to as being metastable. Intermittently, global, avalanching instabilities occur in what is called a systemwide discharge. Although the extension of SOC from abstract mathematical models to a multiscale, multispecie magnetized plasma is not trivial, the concept offers a new perspective to look at magnetospheric dynamics, particularly those aspects associated with the onset of magnetospheric substorms.

Bargatze et al. [3] showed that the magnetosphere is a nonlinear system, as its response function to the solar wind depends on the level of activity. Vassiliadis et al. [34] developed a mathematical model of nonlinear filters to explain the observed behavior. Complementary to time-series analysis, intermittencies in the spatiotemporal domain such as the bursty-bulk flows have been interpreted as another manifestation of a magnetosphere in SOC. A related, but not identical observation is due to Borovosky et al. [5] who showed that the current sheet exists in a permanent state of turbulence without a well-ordered velocity.

Although there is no widely accepted definition of SOC in relation to the magnetosphere, many believe that it is different from a mere turbulent state in that a SOC state is capable of a system-wide discharge or avalanche. Chapman et al. [7] constructed a sandpile model to elucidate such behaviors, but the model itself is quite abstract, and its relevance to the actual magnetospheric physics is metaphorical.

One avenue to further advance the SOC model is to couple its universalist perspective with details of magnetospheric physics, that is, to construct magnetospheric models wherein dynamics are globally connected on all scales. Klimas et al. [15, 16] adapted the reduced MHD theory of Lu [20] to the magnetotail and found that an anomalous resistivity following a hysteretic cycle can reproduce a number of intermittent phenemena observed in the magnetosphere, including the power-law distributions suggested by empirical studies.

Although the comparison between the hysteretic MHD and SOC-inspired data analyses has been encouraging, there remains some doubt whether scale-free distributions observed in POLAR auroral images and of geomagnetic indices such as AE can be directly attributed to the hysteretic MHD. Statistically, magnetic reconnection occurs tailward of 20 Re in the magnetotail [25], whereas the auroral substorm expansion typically maps to a distance of 10 Re or less [28]. Bursty bulk flows have been invoked to link the near-Earth neutral line (NENL) to aurora intensification [30], but this proposal is unsettled and controversial. Many researchers support a point of view that posits a different causal relationship.

In this paper we give the essential outline of a model describing multiscale energy transport and release in the central plasma sheet Earthward of 15 Re. Our survey of the literature indicates a near-consensus that releasing excessive energy and mass stored in this region is an essential aspect of substorm expansion. Substorm phenomenology from the beginning has shown that the expansion starts from an equatorward auroral arc and progresses in ways mimicking an avalanche [1]. The current controversy is centered on the question of substorm trigger. Our objective in this paper is to construct a model of energy transport and release, taking into account of the basic physics while taking care to instill into the model a propensity for avalanche. The model admits, in principle, different triggers of energy release and does not have a built-in preference to any. We shall argue that most proposed substorm triggers can set off an avalanche in the confine of the model; which triggering mechanism is dominant depends on how the balance of energy inflow and outflow through this region is affected by boundary conditions in the magnetotail, dayside magnetopause, and ionosphere. In this sense, the proposed model can be used to test various substorm triggering theories in the context of global solar wind-magnetosphere interaction.

2. Physics of Energy Transport and Release in the Central Plasma Sheet

It is generally agreed that the substorm is a result of coupling among processes on the global, meso, and microscopic

Received 15 May 2005.

William Liu and John Manuel. Space Science Branch, Canadian Space Agency.
Paul Charbonneau. Dèpartment de Physique, Université de Montréal
Eric Donovan. Department of Physics and Astronomy, University of Calgary

DOI: 10.1139/*Zxx-xxx*

scales. However, relatively few attempts have been made to address quantitatively the cross-scale coupling problem. Part of the problem has to do with the limitation of the prevalent MHD theory; the rest may be attributed to mental inertia - an established point of view takes years to form and a lifetime to abandon. Yet, it has become clear to many that, in order to advance the substorm research, the traditional methodology of correlation, be them event- or statistically based, must be complemented by a mathematically more sophisticated view and methodology so that deeper relationships can be probed and revealed. It is further necessary that borrowed concepts such as SOC not become an end in itself but be a device to help develop higher-level physical models. Our objective in this paper is to couple certain known aspects of magnetospheric physics with several attractive aspects of SOC, in an attempt to form a new perspective of substorm physics.

2.1. Global Physics

Our model region spans the part of the equatorial plane that coincides with the central plasma sheet active in the substorm. The plane is divided into a two-dimensional grid, shown in Figure 1; each grid point represents a magnetic flux tube that crosses the equatorial plane at that point.

The global physics of our model concerns the energy transport through the grid and is described quantitatively by the Rice Convection Model. The energy inflow into the grid is controlled by the outer boundary condition (B1). Energy outflow from the grid, on the other hand, is determined by three factors: A) return flow to the dayside magnetosphere (B2); B) Poynting flux into the ionosphere (B3), and C) Particle injection into the ring current (B4). The balance between B1, B2, B3, and B4 determines the state of the central plasma sheet. Since the magnetosphere is perpetually interacting with the solar wind, none of the boundary conditions is nil at any given time. The claim that the central plasma sheet is in a SOC state implies that the energy sources and sinks controlling the boundaries keep the energy distribution on the grid always near the “boiling point”. While the studies cited in the introduction give some evidence that this might indeed be the case, the proof is not yet conclusive. The model proposed here provides a theoretical means to verify this assertion.

The model depicted in Figure 1 is rich in potential behaviors. Taking the very simplistic view that each of the 4 boundary conditions can have only two modes of variation, up (↑) and down (↓), one can see that energy accumulation on the grid will exhibit 16 different modes, more than the number of distinct substorm triggering theories!

The latest development of RCM is described by Lemon et al. [17]. In essence, the plasma energy distribution, expressed in terms of the plasma pressure, can be calculated at each grid point, subject to the boundary conditions. An array $p(i, j, t)$, as an output of the RCM, gives the internal energy accumulation as a function of time, at the grid point (i, j). During the growth phase, convection intensifies, and we can compute in detail how $p(i, j, t)$ increases with time.

2.2. Micro-scale physics

During periods of the growth phase of the substorm (corresponding to an ↑ state of B1 in Figure 1), energy increases over the entire grid. Recalling that each grid point represents a flux tube, the energy increases generally leads to a tailward stretching of the flux tube. Because the central plasma sheet is an open system (i.e., $Bn \neq 0$), this increase of internal energy does not provoke an immediate relaxation to a lower-energy state. As a gendanken experiment, let us assume only $B1 \neq 0$ in Figure 1, i.e., energy is accumulated on the grid without sinks. An instability (or substorm) is foreordained in this case. With respect to an individual flux tube, the above situation corresponds to an indefinite stretching, which leads to an indefinite increase of two parameters, the plasma β and the current density j volume-averaged over the flux tube. Eventually one or both quantitities will exceed the threshold of local instability. The β-critical instability belongs to the family of ballooning modes [12, 27, 19] and is generally MHD in character. The j-critical instability belongs to the family of current-driven modes [21, 22] and is generally non-MHD in character.

Let the threshold values for the above two local criticalities be β_h and j_h, respectively. Whether β_h or j_h dominates depends on the detail of the stretching and which instabilities is excited first. It is quite possible that one of the two will dominate some regions on the grid, while the other will dominate the rest; this aspect will be studied in future simulations. An important aspect of plasma instability is its hysteretic nature, a point emphasized by Klimas et al. [**?**, 16] in regard to the formation of SOC. The hysteresis consists in the high thresholds of onset (β_h and j_h) and the lower thresholds of settlement (β_l and j_l). A rudimentary example is a mass resting on an inclined plane. Initially, the mass stays stationary even though the plane is raised. This lasts until a high threshold height H_h at which the static friction is equal to the pull of gravity along the plane. Once the mass starts moving, it will settle on a low threshold $H_l = 0$, releasing the potential energy into heat and kinetic energy.

In the present case, the high threshold values can be determined by a detailed analysis of the unstable mode in question. For example, Liu [19] showed that the ballooning mode will become unstable when the threshold $\beta_h = k_{\|}^2/(\kappa_p \kappa_c)$ is crossed, where $k_{\|}$ is the parallel wavenumber of the perturbation, and κ_p and κ_c are the pressure scale factor and field line curvature, respectively. Similar thresholds can be established for current-driven instabilities. The lower thresholds, on the other hand, are subject to some indeterminancy because they are not instability criteria but some “typical” relaxed states a flux tube is wont to settle in. There are different ways to handle this problem. In the case where the high threshold is much greater than the low threshold, setting the latter to zero is often acceptable. Alternatively, we can adopt a scheme where the system always strives to return to its original state, i.e., $\beta_l(i, j) = \beta(I, j, t = 0)$. We will investigate other possible ways in later studies, but the essential point at present is that, once destabilized a flux tube will release a finite amount of energy proporation to the difference of the high and low thresholds ($\beta_h - \beta_l$ or $j_h - j_l$) .

2.3. Mesoscale Physics

The above discussion established that energy transport on the global scale can drive individual flux tubes to instability and release part of the potential energy stored therein. This has the classical direction of a cascade where inputs from the large-scale end drive small-scale activities. There is also a possibility of a backward propagation, namely, small-scale release causes an avalanche of collapses and a systemwide discharge. This is our main motivation in this paper.

Suppose that, through a local destabilization of a flux tube, a certain quantity of energy $\propto \Delta\beta = \beta_h - \beta_l$ is released. This energy is propagated in space and perturbs neighboring flux tubes. An essential factor governing the behavior of the cellular automaton in Figure 1 is how the released energy is distributed over the grid.

Without loss of generality, assume that $\kappa\Delta\beta$ of the released energy goes into the Alfvén mode, which carries the energy to the ionosphere and creates little disturbance to the neighbors. The rest, $(1-\kappa)\Delta\beta$, is in the cross-field propagating compressive mode, and changes the state of neighboring flux tubes; we call this latter release the effective energy. The partition of energy among the shear and compressional mode can be done randomly in each individual case, with a statistical mean $<\kappa>$, which can be a global parameter controlling the avalanche.

Since the central plasma sheet is an inhomogenuous medium, a fast-mode wave will experience any combination of reflection, mode-conversion, and absorption. There are two possible ways to write the redistributive rule of the effective energy. In a system that is globally smooth and locally uniform (i.e., one-scale global distribution), the effective energy propagates as classical MHD fast modes. There is a long series of theoretical works dedicated to this subject [8, 31, 11, 18]. The general conclusion from this body of works is that the effective energy will either be spent or escape the system after a distance R comparable to the scale length of global distributions. In this scenario, the cellular automaton in Figure 1 would be maximally connected. In the alternative possibility that the central plasma sheet is globally smooth and locally granulated (i.e., two-scale distribution, which is consistent with the observation of Borovsky et al. [5]), the effective energy is likely to be dissipated before the fast mode has a chance to travel far. In this case, the cellular automaton would be minimally connected. We believe that the second scenario is more realistic, both because of the extreme implausibility for the central plasma sheet not to have any localized graininess and of the logic of the cellular automaton model: the very fact that a flux tube is treated as an energy storing unit means that two flux tubes are considered different.

3. Relationship With Existing Substorm Theories

We stress that our model is not a microscopic substorm triggering theory per se. Rather, it represents a different perspective to view the substorm as a global systemic behavior facilitated by two-way cross-scale coupling. In the forward direction, the enhanced global transport leads to localized release of energy by way of small-scale instabilities. In the backward direction, the localized releases can, under certain conditions, self-organize into an avalanche and trigger a systemwide discharge, namely substorm.

A salient point to emphasize, precedent to any specific computation, is that for fixed energy redistribution rules and global transport physics, the behavior of substorm onset is controlled by the four boundary conditions indicated in Figure 1. In fact, we believe most substorm triggering theories are consistent with at least one way to change the boundary conditions. In this sense, the present model can be used as a quantitative test to arbitrate which possible trigger has the lowest onset threshold, hence becoming *the* trigger, for a given condition. Here we discuss some of the most discussed onset scenarios and substorm features to establish a context for future numerical studies.

3.1. “Internally Driven” Onset: $|\mathbf{B1}|>|\mathbf{B2}|+|\mathbf{B3}|+|\mathbf{B4}|$

This corresponds roughly to the situation where the IMF persists in the southward direction, and the energy inflow from the tail exceeds the combined outflow for a sufficiently long time so that the overall energy distribution on the grid is driven to the critical avalanche point. The term “internally driven” suggests that the onset is independent of a reconnection-related trigger and that the onset is owing to an instability (either β- or j-critical) internal to the region of energy storage. The likely path to this instability is that a localized region of the central plasma sheet goes unstable, and the instability avalanches in space, as the effective energy releases set off a chain reaction.

3.2. BBF Onset: $|\mathbf{B1}|$ = Output of Hysteretic MHD Module

While we believe that the hysteretic MHD model of Klimas et al. [**?**, 16] is not spatially conjugate to dominant auroral substorm features, it is possible, however, to connect the model to SOC-like behavior in auroral substorms by way of bursty bulk flows as described by Shiokawa et al. [30]. Effectively, it is asserted that bursty-bulk flows from intermittent and spatially localized reconnections in the midtail inject large quantities of mass and flux to the central plasma sheet; the slowdown of the BBFs results in a reduction of cross-tail current. In our present model, we can use the output of the hysteretic MHD, which exhibits intermittent behavior reminiscent of BBF, as B1. As the BBFs interact with the internal grid points (flux tubes), an avalanche may result.

3.3. Northward IMF Trigger: $\partial|\mathrm{B2}|/\partial t < 0$

Lyons et al. [24] argued that a northward trending of the IMF precedes many substorms, and suggested that the substorm is essentially a solar-wind triggered event. This possibility can be incorporated into the present model. As the IMF turns northward, the return flow to the dayside is temporarily suppressed. During this interval, the net energy accumulation on the grid increases, and an avalanche again may result.

3.4. Ionospheric Trigger: $\partial|\mathrm{B3}|/\partial t < 0$

Some authors (see eg., [14]) suggested that the ionosphere can play a role in triggering a substorm. The basic idea is that during periods of enhanced magnetospheric convection, the increase in the ionospheric conductance can result in a positive feedback, which has the sense to disrupt the near-Earth current sheet. In our present model, an increase in ionospheric conductivity will temporarily reduce the Joule heating rate for a given magnetospheric current (i.e., $\propto J^2/\sum$). Choking off the ionospheric channel of outflow will lead to an enhanced energy accumulation on the grid.

3.5. SMC and Sawtooth events: <B1>=<B2+B3+B4>

Steady magnetospheric convection (SMC) [29] refers to a period of prolonged southward IMF (several hours) during which no substorm expansion is observed. Rather, the convection is more intense and moves to more equatorward latitudes. The sawtooth events corresponds roughly to the same solar wind condition, but the magnetosphere is marked by a periodic oscillation of injected particle fluxes (see eg. [13]). Many associate sawtooth events with quasi-periodic recurrence of substorms. Since the solar wind driver is the same for the two classes, it is not illogical to suppose that they are two solutions of the same problem, under different boundary conditions. We propose that SMC and sawtooth events correspond to a condition where the energy inflow and outflow on the grid are balanced in a time-averaged sense. The phasing among the four conditions, however, determines whether the solution on the grid is steady-state or quasiperiodic.

The above discussion is not exhaustive, only to underscore our principal argument that the route to substorm is not a one-lane highway, but a manifold of possibilities. The chief controlling factor is the boundary conditions governing energy inflow and outflow out of the expansion onset region, the central plasma sheet. Some of the phenomena such as pseudo-breakup, poleward boundary intensification, and the boundary-layer model [26] can all be incorporated as part of the model, with proper adjustment of the boundary conditions.

We remind the reader that some of our descriptions of the path to avalanche is different from the view originally associated with a particular boundary-condition trigger. For example, the ionospheric trigger theory of Kan et al. [14] involves more than just choking off energy outflow to the ionosphere. A more accurate characterization is a redistribution of energy flow pattern so that the ionosphere actually sends an inflowing flux (reflected Alfvén waves) to trigger the substorm in the central plasma sheet.

4. Summary

We have developed a model whereby energy transport and release in the central plasma sheet can be studied as a cellular automaton problem. We have focused on the conceptual aspect of the development, leaving a number of details and the numerical implementation to the future. We believe that the conceptual underpinning of the model represents a potentially new and fruitful approach to substorm research and warrants a report in this proceeding, notwithstanding a certain lack of details.

We believe that recent evidence and theoretical argument for self-organized criticality in the magnetosphere are not merely an importation of faddish terms from another field but reveal a deep order in what is now commonly accepted as a very nonliear magnetosphere; the substorm problem, as a "going concern", can be most profitably studied by treating the magnetosphere holistically. According to this dictum, our model is guided by the following principles:

1. The substorm problem must be studied by treating the entire region implicated in the process as a whole;
2. We subscribe to the view that most of the energy release during a substorm takes place in the central plasma sheet, and that, based on statistical evidence, reconnection is not directly involved in tapping the free energy stored in this region;
3. Partly in response to the recent evidence suggestive of a magnetosphere in SOC, we develop the model with a view to a potential for avalanche behavior;
4. We believe, despite the opinion which the elephant may hold of the blind man, the latter has gotten a part of the elephant that is real. In other words, a "higher-level" substorm theory should ideally be "backward-adaptable" to accommodate more elemental theories, unless there are good reasons not to include some.

The conceptual model developed in this paper has the following principal features:

1. Magnetic flux tubes in the central plasma sheet are treated as the unit of energy sotrage, and a cellular automaton comprised of the equator-crossing points of the flux tubes form the basis of our model;
2. The model is driven by known magnetospheric physics on the global, meso, and microscale;
3. Energy deposit on each grid point (flux tube) is determined quantitatively by the Rice Convection Model or an equivalent computational model;
4. Each flux tube has an energy-containing threshold above which a localize energy release takes place;
5. The local release is hysteretic, whereby the flux tube settles on to an energy state lower than the threshold; the threshold physics depends on the nature of the instability incorporated; both MHD (ballooning-type) and non-MHD (current-driven type) can be included;
6. Grid points near a local release are coupled through a redistributive rule, whose exact form depends on the assumption of propagation physics of waves in the magnetosphere. We favor a minimally-connected grid, on the assumption that the central plasma sheet is grainy on a local scale, but will consider redistributive rules with longer-range connections;
7. The behavior of the cellular automaton is determined by four boundary conditions: a) the energy inflow into the grid from the tailward boundary; b) the energy outflow through the flanks to the dayside magnetosphere; c) the energy outflow into the ionosphere; and d) the energy outflow through the inner edge of the plasma sheet into the ring current; we believe that the balance of energy flows at the boundary determines whether or how a substorm as a global avalanche will occur, and which subtorm trigger mechanism prevails.

We discussed some examples how the model can be triggered to produce substorms by boundary condition changes. It appears that the model is general enough to accommodate different trigger theories proposed in the past and, more importantly, provide a quantitative means to test under which condition(s) each can set off energy avalanches in the central plasma sheet.

As a moral of sort, self-organized criticality offers a new perspective to studying magnetospheric physics in a rather profond way: The magnetosphere is an open system subject to changing energy fluxes across its boundary. In contrast to the classical energy principle analysis appropriate for closed systems, the substorm problem is controlled by the balance of energy flows into and out of the system, not free energy measured against a global minimum. Although this point may sound obvious, it is not universally realized; SOC and sandpile models provide an initial glimpse to how a changed perspective can lead to new insights and a drastic departure from established expectations.

Acknowledgements

The authors thank V. Uritsky, A. T. Y. Lui, and A. Crouch for illuminating discussions. This work was supported by the Canadian Space Agency and Natural Sciences and Engineering Research Council of Canada.

References

1. Akasofu, S.-I., The development of the auroral substorm, *Planet. Space Sci., 12*, 273, 1964.
2. Angelopoulos, V., W. Baumjohann, C. F. Kennel, F. V. Coroniti, M. G. Kivelson, R. Pellat, R. J. Walker, H. Luhr, and G. Paschmann, Bursty bulk flows in the inner central plasma sheet, *J. Geophys. Res., 97*, 4027, 1992.
3. Bargatze, L. F., D. N. Baker, R. L. McPherron, and E. W. Hones, Jr., Magnetospheric impulse-responnse for many levels of geomagneticv activity, *J. Geophys. Res., 90*, 6387, 1985.
4. Baumjohann, W., G. Paschmann, and H. Luhr, Characteristics of high-speed ion flows in the plasma sheet, *J. Geophys. Res., 95*, 3801, 1990.
5. Borovsky, J. E., R. C. Elphic, H. O. Funsten, and M. F. Thomsen, The Earth's plasma sheet as a laboratory for flow turbulence in high-beta MHD, *J. Plasma Phys., 57*, 1-34, 1997.
6. Chang, T., Low-dimensional behavior and symmetry-breaking of stochastic systems near criticality: Can these effects be observed in space and in the laboratory, *IEEE Trans. Plasma Sci., 20*, 691, 1992.
7. Chapman, S. C., N. W. Watkins, R. O. Dendy, P. Herlander, and G. Rowlands, A simple avalanche model as an analogue for magnetospheric activity, *Geophys. Res. Lett., 25*, 2397, 1998.
8. Chen, L., and A. Hasegawa, A theory of long-period magnetic pulsations, 1: Steady-state excitation of field-line resonances, *J. Geophys. Res., 79*, 1024, 1974.
9. Consolini, G., Sandpile cellular automata and magnetospheric dynamics, in *Cosmic Physics in the Year 2000*, edited by S. Aiello et al., p. 123, Soc. Ital. Di Fis, Bolgna, Italy, 1997.
10. Freeman, M. P., and N. W. Watkins, The heavens in a pile of sand, *Science, 298*, 979, 2002.
11. Goertz, C. K., and R. A. Smith, The thermal catastrophe model of substorms, *J. Geophys. Res., 94*, 6581, 1989.
12. Hameiri, E., P. Laurent, and M. Mond, The ballooning instability in space plasmas, *J. Geophys. Res., 96*, 1513, 1991.
13. Henderson, M. G., The May 2-3, 1986 CDAW-9C interval, A sawtooth event, *Geophys. Res. Lett., 31*, L11804, doi:10.1029/2004GL019941, 2004.
14. Kan, J. R., L. Zhu, and S.-I. Akasofu, A theory of substorms, Onset and subsidence, *J. Geophys. Res., 93*, 5624, 1988.
15. Klimas, A. J., J. A. Valdivia, D. Vassiliadis, D. N. Baker, M. Hesse, and J. Takalo, Self-organized criticality in the substorm phenomenon and its relation to localized reconnection in the magnetospheric plasma sheet, *J. Geophys. Res., 105*, 18765, 2000.
16. Klimas, A. J., V. M. Uritsky, D. Vassiliadis, and D. N. Baker, Reconnection and scale-free avalanching in a driven current sheet model, *J. Geophys. Res., 109*, A02218, doi:10.1029/2003JA010036, 2004.
17. Lemon, C., R. A. Wolf, T. W. Hill, S. Sazykin, R. W. Spiro, F. R. Toffoletto, J. Birn, and M. Hesse, Magnetic storm ring current injection modeled with Rice Convection Model and a self-consistent magnetic field, *Geophys. Res. Lett., 31*, L21801, doi:10.1029/2004GL020914, 2004.
18. Liu, W. W., B. L. Xu, J. C. Samson, and G. Rostoker, Theory and observation of auroral substorms: A magnetohydrodynamic approach, *J. Geophys. Res., 100*, 79, 1995.
19. Liu, W. W., Physics of the explosive growth phase: Ballooning instability revisited, *J. Geophys. Res., 102*, 4927, 1997.
20. Lu, E. T., Avalanche in continuum driven dissipative systems, *Phys. Rev. Lett., 74*, 2511, 1995.
21. Lui, A. T. Y., A. Mankovsky, C. L. Chang, K. Papadopoulos, and C. S. Wu, A current disruption mechanism in the neutral sheet - a possible trigger for substorm expansion, *Geophys. Res. Lett., 17*, 745, 1990.
22. Lui, A. T. Y., T. Chang, and P. H. Yoon, Preliminary nonlocal analysis of cross-field current instability for substorm expansion onset, *J. Geophys. Res., 100*, 19147, 1995.
23. Lui, A. T. Y., S. C. Chapman, K. Liou, P. T. Newell, C. I. Meng, M. Brittnacher, and G. K. Parks, Is the dynamic magnetosphere an avalanching system, *Geophys. Res. Lett., 27*, 911, 2000.
24. Lyons, L. T., G. T. Blanchard, J. C. Samson, R. P. Lepping, T. Yamamoto, and T. Moretto, Coordinated observation demonstrating external substorm triggering, *J. Geophys. Res., 102*, 27039, 1997.
25. Nagai, T., M. Fujimoto, Y. Saito, S. Machida, T. Terasawa, R. Nakamura, T. Yamamoto, T. Mukai, A. Nishida, and S. Kokubun, Structure and dynamics of magnetic reconnection for substorm onsets with Geotail observations, *J. Geophys. Res., 103*, 4419, 1998.
26. Rostoker, G. and T. Eastman, A boundary layer model for magnetospheric substorms, *J. Geophys. Res.*, *92*, 12187, 1987.
27. Roux, A., S. Perrault, P. Robert, A, Morane, A. Pedersen, A. Korth, G. Kremser, B. Aparicio, and R. Pellinen, Plasma sheet instability related to the westward traveling surge, *J. Geophys. Res., 96*, 17697, 1991.
28. Samson, J. C., Samson, L. R. Lyons, P. T. Newell, F. Creutzberg, and B. Xu, Proton aurora and substorm intensifications, *Geophys. Res. Lett., 19*, 2167, 1992.
29. Sergeev, V. A., On the state of the magnetosphere during prolonged southward oriented IMF, *Phys. Solarterr., 5.*, 39, 1977.
30. Shiokawa, K., W. Baumjohann, G. Harendel, G. Paschmann, J. F. Fennel, E. Friis-Christensen, H. Luhr, G. D. Reeves, C. T. Russell, P. R. Sutcliff, and K. Takahashi, High-speed ion flow, substorm current wedge, and multiple Pi 2 pulsations, *J. Geophys. Res., 103*, 4491, 1998.
31. Southwood, D. J., Some features of field-line resonances in the magnetosphere, *Planet. Space Sci., 22*, 483, 1974.

32. Uritsky, V. M., A. J. Klimas, and D. Vassiliadis, Comparative study of dynamical critical scaling in the auroral electrojet index versus solar wind fluctuations, *Geophys. Res. Lett., 28*, 3809, 2001.
33. Uritsky, V. M. A. J. Klimas, D. Vassiliadis, D. Chua, and G. Parks, Scale-free statistics of spatiotemporal auroral emissions as depicted by POLAR UVI images: Dynamic magnetosphere is an avalanching system, *J. Geophys. Res., 107*, 1426, doi:10.1029/2001JA000281, 2002.
34. Vassiliadis, D. A. J. Klimas, D. N. Baker, and D. A. Roberts, A description of the solar-wind magnetosphere coupling based on nonlinear filters, *J. Geophys. Res., 100*, 3495, 1995.