Chapter 1

Nonequilibrium Phenomena in the Magnetosphere:

Phase Transition, Self-organized Criticality and Turbulence

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Abstract: The magnetosphere is a large scale natural system powered by the solar wind that exhibits many nonequilibrium phenomena. A wide range of these phenomena are driven directly by the solar wind or arise from the storage-release processes internal to the magnetosphere. Under the influnce by the turbulent solar wind, the magnetosphere during geomagnetically active periods is far from equilibrium and storms and substorms are essentially non-equilibrium phenomena. In spite of the distributed nature of the physical processes and the apparent irregular behavior, there is a remarkable coherence in the magnetospheric response during substorms and the entire magnetosphere behaves as a global dynamical system. Alongwith the global features, the magnetosphere exhibits many multi-scale and intermittent characteristics. These features of the magnetosphere have been studied in terms of phase transitions, self-organized criticality and turbulence. In the phase transition scenario the global features are modeled as first-order transitions and the multi-scale behavior is interpreted as a manifestation of the scale-free nature of criticality in second order phase transitions. In the self-organized criticality framework substorms are considered as avalanches in the system when criticality is reached. Many features of the magnetosphere, in particular the power law dependence of scale sizes, can be viewed as a feature of a turbulent system.The common theme underlying these approaches is the recognition that the nonequilibrium phenomena in the magnetosphere could be understood in terms of processes generic to such systems. In many cases the power-law behavior of the magnetosphere seen in many observations is the starting point for these studies. This chapter is an overview of the recent understanding achieved using these different approaches, and identifies the common issues and differences.

Key words: magnetosphere, solar wind, storms, substorms, complexity, phase transitions, self-organized criticality, turbulence, intermittency

1. INTRODUCTION

Earth's magnetosphere is a magnetic cavity formed by the interaction of the solar wind with the geoplasma in the dipole magnetic field. It is a large scale natural system which exhibits complex behavior originating from the turbulence in the solar wind as well as its internal processes. The time evolution of such systems is essentially determined by the interactions between its different components or subsystems, and by the characteristics of its driver, the solar wind. Underlying this behavior is the nonlinearity inherent in the magnetospheric plasma and fields.

The main dynamical features of the magnetosphere are storms and substorms, which are prevalent mainly when the solar wind is strongly coupled to the magnetosphere, e.g., due to enhanced magnetic reconnection at the magnetopause. Geospace storms and related processes have time scales of days and are associated with enhancements of the ring current in the inner magnetosphere. Substorms on the other hand have characteristic time scales of an hour or so and are associated mainly with the plasma processes in the magnetotail. While our understanding has advanced rapidly due to recent multi-spacecraft and ground-based measurements, and theory and modeling, many outstanding questions due to the complexity of the magnetosphere arising from the interactions among its components and the driving by the turbulent solar wind. Studies of the magnetosphere from the viewpoint of nonlinear dynamics and complexity provides a complementary framework for understanding the solar wind – magnetosphere coupling.

The dynamical behavior of the magnetosphere has been studied extensively using nonlinear dynamical techniques (see reviews: Sharma, 1995, 1997, 2003, 2004; Klimas et al., 1996). The evidence of large scale coherence in magnetospheric dynamics was first obtained in the form of low dimensional behavior using the time series data of auroral electrojet indices (Vassiliadis et al. al., 1990). This result is consistent with simplified dynamical models of the magnetosphere (Baker et al., 1990), its morphology derived from the observational data and theoretical understanding (Siscoe, 1991), and numerical simulations using global MHD codes (Lyon, 2000). The recognition of the effectively low dimensional dynamics of the magnetosphere has stimulated a new direction in the studies of the solar wind-magnetosphere coupling. Among the outcomes of this research is the capability of forecasting substorms (Vassiliadis et al., 1995; Ukhorskiy et al. 2004) and storms (Valdivia et al., 1996; Sharma et al., 2003) with high accuracy and reliability. Many models of the magnetosphere have been developed based on the low-dimensionality of its dynamics (Baker et al., 1990; Klimas et al., 1992; Horton et al., 1996).

The multiscale behavior of the magnetosphere, on the other hand, has been recognized in many different ways. An earlier recognition of the multiscale behavior in the magnetosphere is, albeit indirectly, in the analogy between the dynamics of the magnetotail to the turbulence generated by a fluid flow past an obstacle (Rostoker, 1984). Subsequently, the power law dependences of the observed time series data, e.g., in the AE index (Tsurutani et al., 1990) provided quantitative measures of the multi-scale behavior. Studies of the auroral electrojet indices using more sophisticated techniques such as the structure function showed features that could be reconciled only with multi-scale behavior (Takalo et al., 1993). It should be noted that the concept of criticality in magnetospheric dynamics (Chang, 1992) implies multiscale behavior.

The coexistence of the global coherence with multiscale behavior is a key feature of the magnetosphere and has been modeled using many approaches. In the phase transition approach the global features are considered as phase transitions of the first order, while the multiscale properties originate from the scale-free properties of second order phase transitions (Sitnov et al., 2000, 2001; Sharma et al., 2001; Ukhorskiy et al., 2002, 2003, 2004; Shao et al., 2003). The framework of self-organized criticality have used model magnetospheric dynamics (Consolini, 1997; Chapman et al., 1998; Watkins et al., 1999; Klimas et al., 2002; Uritsky et al., 2002, 2003). The power law behavior of multiscale phenomena is akin to such characteristics of turbulent systems and these properties have been studied using spacecraft and ground based measurements (Borovsky et al., 1993; Ohtani et al., 1995, 1998; Freeman et al., 2000). These three approaches and the inter-relationship are discussed in the following sections in the context of magnetospheric complexity.

2. PHASE TRANSITION-LIKE BEHAVIOR

The phenomenon of phase transition is well known, e.g., the change of state or phase from liquid to gas at the boiling point. Such transitions in which there is an abrupt change in the density, e.g., water-steam transition at 100 deg. C under normal pressure, are the first order phase transitions. The boiling temperature however depends on the pressure and at higher pressures the transition takes place at higher temperatures. Also the changes in the density at higher pressures become smaller compared to those at normal pressure. This trend of higher pressure yielding higher boiling point and smaller change in the density continues until characteristic values of the pressure and temperature are reached and at these values there is no change in the density. This is the critical point of the liquid and the transition is the second order phase transition. For example, the critical point for water-steam transition is 374 deg C and 218 atmospheres. The critical behavior is characterized by universality (being generic to a whole class of problems) and scale-invariance (the absence of a preferred scale length and the presence of all relevant scales). The study of the critical behavior (Stanley, 1971; Dixon et al., 1999) has been strongly motivated by these features and has led to new powerful theoretical techniques such as the renormalization group (Fisher, 1974; Wilson, 1983).

The correlated data of the coupled solar wind-magnetosphere compiled by Bargatze et al. (1985) has been used to study the phase transition-like behavior of substorms (Sitnov et al., 2000, 2001; Sharma et al., 2001, 2004). The data set consists of 34 intervals of correlated solar wind input and the magnetospheric response as an output. The solar wind input is the interplanetary electric field VB_s, where B_s is the southward component of the interplanetary magnetic field (IMF) and V is the component of the solar wind velocity along the Earth-Sun axis. The magnetospheric response to the solar wind is represented by the auroral electrojet index, AL.

The magnetospheric dynamics can be reconstructed from the time series data using time delay techniques (Abarbanel et al., 1993). Among these, the singular spectrum analysis is often used to reveal the main dynamical features inherent in the data. This techniques has been used earlier to reconstruct the autonomous dynamics of the magnetosphere from the auroral electrojet indices (Sharma, 1993; Sharma et al., 1993). The singular spectrum analysis is based on the singular value decomposition and uses the properties of the trajectory matrix constructed from the time series data by time delay embedding. The VBs-AL data can be used to construct the time delay vectors and consequently the trajectory matrix. Since the averaging time for this data set is 2.5 min the value of the embedding dimension m is chosen to be 32 to provide a time window of 80 min, appropriate for substorms. The singular value decomposition of this matrix provides orthogonal eigenfunctions corresponding to different eigenvalues. The original idea of the autonomous version of singular spectrum analysis (SSA) is that there should be a noise floor inherent in the data and the number of eigenvalues with magnitudes greater than the noise floor is an estimate of the effective dimension of the system. In many real systems the SSA spectrum has a clear power-law form, with no clear noise floor. In such cases, the projections of the data along the leading eigenvectors provide a good approximation of the system, similar to the so called mean-field or Landau approximation, often used in the phase transition theory as a zeroth-level approximation (Sitnov et al, 2000).

The first principal component obtained by singular spectrum analysis is a measure of the solar wind input averaged over the interval of about 80 min while the second principal component is of the similarly averaged AL index. The third component reflects the changes in the input with time (Sharma et al., 2001, Sitnov et al., 2000, 2001). The eigenvectors corresponding to these three components are shown in the right hand panel of Figure 1, whereas the structure of the three-dimensional space is shown in the left panel. The global dynamics of the magnetosphere derived from the Bargatze et al. (1985) data set are represented by the set of points representing the trajectory of the magnetospheric dynamics in this 3D space, and lie on a 2D surface (Sitnov et al., 2000; Ukhorskiy et al., 2004). Also shown in Figure 1 are the arrows indicating the circulation flows, which reflect the evolution of the system. The growth phase of substorms is reflected in Figure 1 by the lower right hand side of the surface, while the recovery phase corresponds to the left hand side. The substorm onset is located close to the middle.

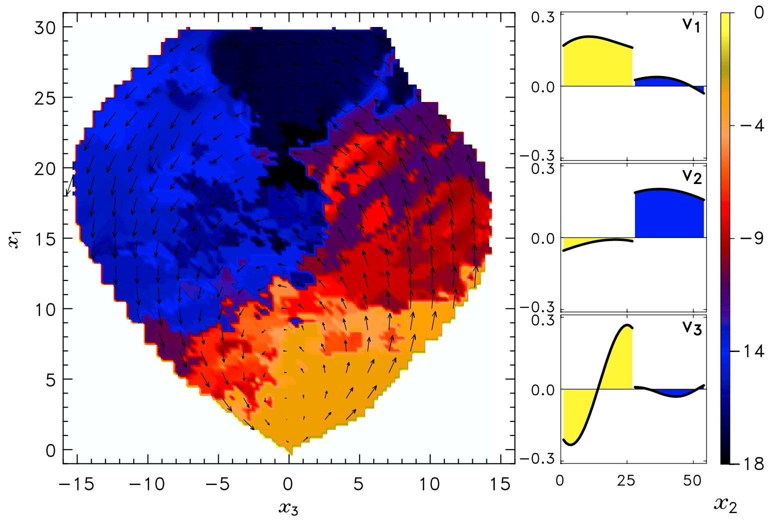

Figure 1. The global features of the magnetosphere obtained from the first three components of the dynamics computed from correlated solar wind-magnetosphere data (Bargatze et al., 1985). The eigenvectors corresponding to three largest eigenvalues are shown on the right panel. The first and second components are plotted along the y and x axes, respectively, and the color represents the third component (light color representing a higher elevationof the 3D surface. The circulation flows (arrows) represent the evolution of the solar wind parameters during the substorm cycle (Ukhorskiy et al., 2004).

The reconstructed surface shown in Figure 1 resembles the so-called temperature-pressure-density diagram typical for the well known first order phase transitions. The dynamical or nonequilibrium transitions exhibit hysteresis phenomenon in which different values of output parameter (AL index) may correspond to the same set of input parameters (VBs). Such features are important characteristics of the critical behavior or of the second order phase transition. However the surface shown in Figure 1 represent a mean-field feature obtained by averaging over the data set and thus the features of hysteresis are absent.

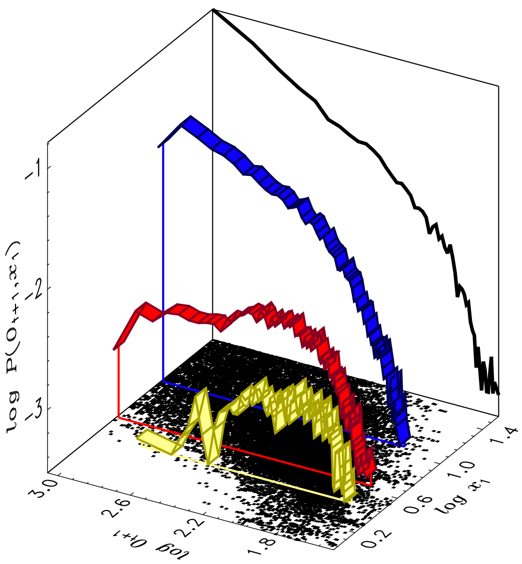

Figure 2. The conditional probabilities of AL as functions of solar wind conditions. The yellow, red and blue curves correspond to strong (vBs > 9 mV), medium (0.6 < vBs < 9 mV) and low (vBs , 0.6 mV) solar wind activity levels, respectively. The floor shows all the points in the data base, corresponding to the marginal probability distribution function shown in the back panel (Ukhorskiy et al., 2004).

The multi-scale behavior of the magnetosphere is evident from the singular spectra of the ground-based data (Sitnov et al., 2001) as well as global MHD simulations (Shao et al., 2003). The eigenvalue spectrum in these cases are close to the 1/f spectrum. In the reconstructed phase space the multi-scale portion of magnetospheric dynamics, averaged out in the mean-field model, is naturally coupled to the large-scale coherent component. It appears as fluctuations of data around the smooth manifold containing the trajectories of averaged system and thus it can be described in terms of conditional probability $P(O_{t+1} \mid \mathbf{x}_t)$ defined in the embedding space $\mathbf{x_i}$ for the predicted output O_{i+1} (Ukhorskiy et al., 2004). To investigate the role of the solar wind driver in the generation of the multi-scale dynamical features of substorms the evolution of conditional probability was considered as a function of input parameters. For this purpose $P(O_{t+1} \mid \mathbf{x}_t)$ was calculated in one and two-dimensional subspaces spanned by the first

$\mathbf{v}_1$ and the third $\mathbf{v}_3$ principle components of vB_S-AL time series which characterize the input in the system. Distribution functions $P(O_t, x_1)$ calculated for different levels of solar wind activity are show in Figure 2 in blue, red and yellow colors. Their sum yields the cumulative distribution $P(O_t)$ shown in the back panel of the plot. It has a power-law shape with a break corresponding to –*AL*~500 nT. The distribution functions corresponding to the medium and high activity have well distinguished maxima and do not exhibit scale-invariance. At the same time, the distribution function corresponding to the low solar wind activity has a broad-band structure similar to the scale-invariant cumulative distribution which is often interpreted as an indication of complexity in magnetospheric dynamics. However, if the input space is expanded from one to two dimensions, then this broad-band portion of $P(O_t \mid x_1)$ breaks into a number of distribution functions $P(O_t \mid x_1, x_3)$ with the pronounced peaks which width and position depend on both input parameters (Ukhorskiy et al., 2004). The conditional probability functions $P(O_{t+1} \mid \mathbf{x}_t)$ calculated in a space with dimension as low as two do not have a power-law shape. This indicates that a large portion of the scale-free distribution of *AL* is directly induced by the scale-invariance of the solar wind driver rather than been a result of the inherent complexity of magnetospheric dynamics. With increase in the phase space dimension the width of the corresponding distribution functions keeps decreasing until it saturates when the dimensionality of the mean-field model is reached.

3. SELF-ORGANIZED CRITICALITY

The multiscale characteristics of the magnetosphere have been studied in many ways. The power spectrum of the AE index was studied using 5-min averaged data from 1967 to 1980 (Tsurutani et al., 1990). The power spectrum is found to have a break at about 5 hrs, and at frequencies less than that corresponding to this time scale, the spectrum is close to 1/f and at higher frequencies the spectral index is -2.2, while that of the solar wind VBs is -1.42.

The power spectral nature of the magnetospheric response has been studied using the structure function, which characterizes the fractal nature, and the break in the spectrum was interpreted in terms of bicolored noise (Takalo et al., 1993). These results have shown that the fractal nature, and hence the self-similarity and scale in invariance, are indications that the dynamics may depart from that of a low-dimensional system. The multi-scale and intermittent behavior of the magnetosphere were investigated by Consolini (1996) using the multi-fractal approach. This result, based on the probability scale distribution computed from the AE index data, further emphasized the presence of the multi-scale behavior in the magnetospheric dynamics. This has motivated a view of the magnetosphere as a complex system and self-organized criticality (SOC) has been introduced as a new way to understand its complexity and multi-scale nature.

The framework of self-organized criticality was introduced as a way to describe the behavior of complex systems which exhibit 1/f spectrum (Bak et al., 1987). Such systems can naturally evolve into what is called a self-organized critical state, which is far from equilibrium and barely stable. In this delicately balanced state the system is on the edge of collapse and yet responds resiliently to external driving by returning to a critical state. The simplest way to visualize such a dynamical behavior of systems made up of large number of interacting parts is the behavior of avalanches on sandpile surfaces. A sandpile can be built on a table by slowly adding grains of sand. From the initially flat state the sandpile gradually gets steeper and avalanches begin to occur, becoming bigger as the pile grows. The sandpile eventually reaches a critical state and the system regulates itself by balancing the accumulated amount of sand by that carried away by avalanches. This concept has been readily applied to so many diverse areas and a variety of computer models have been developed to study such systems (Creutz, 1997; Jensen, 1998).

The avalanche phenomenon exhibited by model sandpiles have motivated many models of the dynamics in the magnetosphere. These models are essentially cellular automaton models with the simplified rules chosen from considerations of the known properties of the system. They can be put into the categories of sandpile models (Chapman et al., 1998; Uritsky and Pudovkin, 2000), coupled-map lattice models (Takalo et al., 1999a, 1999b) and simulations based on simplified models (Klimas et al., 2000). Many studies have used observational data to identify the leading features of SOC, viz., power spectral distribution of scale sizes in satellite images of the aurora (Lui et al., 2002, Uritsky et al., 2001, 2002). The probability distributions computed from the Polar UVI images show a broad range of scale-free power law distributions, shown in Figure 3. The power distributions cover the entire range from the size of the bright auroral region to the smallest size determined by the pointing accuracy of the spacecraft (Uritsky et al., 2002).

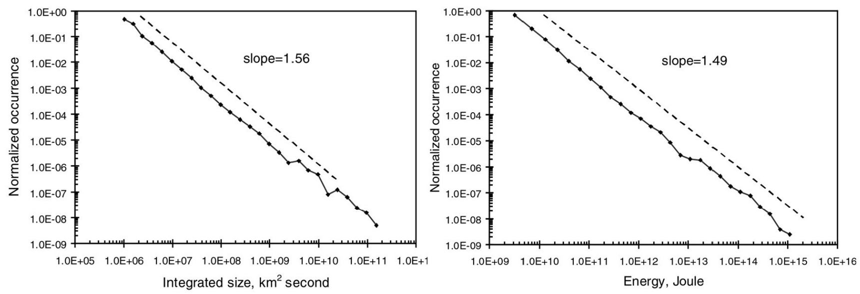

Figure 3. Normalized probability distributions for (left) size and (right) energy for the UVI measurements aboard Polar spacecraft (taken from Uritsky et al. (2002))

The idea of self-organized criticality has been extended to include the forcing in the system and such a system may then exhibit forced and/or self-organized criticality (FSOC). An application of the renormalization group approach to FSOC has given the power law index for the avalanches in the sandpile model of the magnetosphere (Tam et al., 2000). The renormalization group technique, developed in the study of critical phenomena (Fisher, 1974, 1998; Wilson, 1983), is based on searching for scale invariance by continued coarse-graining and rescaling of the system. The main purpose for the applications of this technique is to obtain the critical exponents characterizing the critical state, and thus this technique has the promise of yielding deeper insight into the criticality in the solar wind-magnetospheric coupling.

The recognition of the role of criticality in magnetospheric dynamics has motivated the development of models based on simplified physics considerations. While these models are not fully self-consistent they provide a means to study the relative roles of different physical processes known to be important in the magnetosphere. The WINDMI model (Horton et al., 1999) is based on the physical processes relevant to the coupled solar wind-magnetosphere-ionosphere system and describes many global and multi-scale features. This low dimemsional model naturally describes the global dynamics and the multiscale features arise due to the sequence of inverse bifurcations. A model of localized reconnection in the magnetotail based on resistive MHD considerations (Klimas et al., 2000, 2004) yields a power-law spectra and different features of internal and global dynamics. The model consists of simple equations of the type of a forced nonlinear diffusion equation, and the characteristics of the system under different forcing conditions are studied. The stregnth and nature of the forcing naturally plays an important role and the model yields avalanche phenomenon, which is consistent with SOC.

The SOC scenario has been used extensively to study the multiscale behavior of the magnetosphere. These models are inspired by the observational features such as the power law spectra of AE index and are based on simplified physics considerations. In this sense they are essentially like model sandpiles, and like most such cellular automaton models (Jensen, 1998) characterize the system in terms of the local slope, which is updated using a chosen rule, which to a large extent may be arbitrary. The distribution of the avalanches in such models and its comparison with the data of the physical systems usually yields a measure of the SOC model. The first such model (Chapman et al., 1998) showed two types of avalanches, corresponding to internal reorganization, with power distribution and SOC behavior, and to systemwide discharges which do not exhibit SOC.

The UVI images from Polar spacecraft was used to study the nature of the dynamics during global auroral energy deposition events (Lui et al., 2000). In this study using more than 9,000 frames of auroral images the internal scales of the magnetosphere were found to have the same power law in both quiet and active periods. The global energy dissipation during active periods however had a different scale. These features were interpreted as consistent with an avalanching system that exhibts criticality. More detailed studies of these spacecraft images have shown a wide range of the power spectral distribution (Uritsky et al., 2001, 2002).

While the SOC models of substorms have given many interesting results, it should be noted that real sandpiles may behave in a manner more reminiscent of a first-order transition similar to the fold catastrophe than a second order one (Nagel, 1992). In the case of substorms similar deviations from the simplest SOC picture are evident in the form of the statistics of chorus events (Borovsky et al., 1993; Pritchard et al., 1996; Smith et al., 1996), which showed that the intensity and occurrence rate of substorms have a probability distribution with a well-defined mean. Independent studies of SOC models have shown that the critical points in some of them are not attractive. Also typical SOC models imply some specific tuning of either the state (Gil and Sornette, 1996) or control (Vespignani and Zapperi, 1998) parameters. An SOC model consistent with the above sandpile experiments has been proposed recently by Gil and Sornette (1996) within the framework of Landau-Gizburg theory of self-organized criticality.

The power law nature of auroral index AE however may not be due entirely to the internal magnetospheric dynamics. Studies of the solar wind induced electric field field VBs and the energy input into the magnetosphere have recently been found to have power law dependences (Freeman et al., 2000). This result has interesting implications for magnetospheric dynamics, especially the interpretation in terms of SOC phenomenon. The analysis of the probabilty density functions of the solar wind variables also show power law dependences. The power law form of the inter-burst intervals in the solar wind was found to be distinct from that of ideal SOC but not from SOC-like sandpile models. This result has a wider implication on the signatures of SOC.

4. TURBULENCE IN THE MAGNETOSPHERE

The turbulent aspects of the magnetosphere have been studied extensively. The statistics of chorus events seen in the groundbased data and spacecraft data of particle injections in the near-Earth magnetosphere (Borovsky et al., 1993; Pritchard et al., 1996; Smith et al., 1996) show that the intensity and occurrence rate of substorms have a probability distribution with a well-defined mean. While many studies have been based on the auroral indices data, many other studies have used the spacecraft data, notably from the fleet of ISTP spacecraft. Studies of the magnetic field fluctuations during the disruption of the magnetotail current have shown power spectrum dependence (Ohtani et al., 1995; 1998). The plasma flow in the inner plasma sheet measured by Geotail and Wind spacecraft have been used to study the nature of the intermittency in the magnetosphere (Angelopoulos et al., 1999). The probability density of the magnitudes of the bursty bulk flows show power law dependence in time and their distribution is non-Gaussian.

Because the dissipation of vorticity is so weak in the collisionless, high-β plasma of the magnetotail, any flow there will have an extremely high Reynolds number and is expected to be MHD turbulent (Montgomery, 1989). Only recently have MHD computer simulations of the solar-wind-driven magnetosphere attained Reynolds numbers high enough see the turbulent flows of the magnetotail (White et al., 2001). For years there has been a theoretical analysis of MHD turbulent plasma-sheet flows by Antonova (e.g. Antonova 1985, 1987, 2000; Antonova and Ovchinnikov, 1998, 1999a,b, 2000, 2002).

The turbulent flow of the magnetotail plasma sheet has been studied with spacecraft measurements (Borovsky et al., 1997; Yermolaev et al., 2000; 2002; Ovchinnikov et al., 2000, 2002; Petrukovich , 2004; Petrukovich and Yermolaev, 2002; Borovsky and Funsten, 2003; Borovsky, 2004, Petrukovich, 2004). The data analysis of the turbulence has not been motivated by substorm dynamics, geomagnetic indices, or solar-wind driving of the magnetosphere; rather it has been motivated by questions about the physics of mass transport in the magnetosphere, the enabling of small-scale reconnection events in the magnetotail, and the magnetic-field structure of the magnetotail. Most of the data analysis examined the flow and field fluctuations to discern the dynamical nature of the MHD turbulence in the plasma sheet: i.e. whether it is an eddy turbulence of an Alfven-wave turbulence. The arguments favor a turbulence of eddies. Boundaries and time-dependent magnetosphere-ionosphere coupling (Borovsky and Bonnell, 2001) greatly complicate the analysis of the turbulence. The MHD turbulent fluctuations have $\delta v/v_o >>1$, $\delta B/B_o \sim 1$, and an Alfven ratio $R_A < 1$. The correlation times of the MHD fluctuations are a few minutes. The integral scale of the turbulence is ~ 1.5 R_E, meaning large eddy scale sizes are about 1.5 R_E and magnetic-field domain sizes are about 1.5 R_E. Adding magnetic-field fluctuations with the statistical properties observed for fluctuations in the magnetotail plasma sheet to data-based models of the magnetospheric magnetic field (see Figure 4) results in a depiction of a "spaghetti plasma sheet" with a highly tangled magnetotail field. The MHD fluctuations of the turbulence show power-law frequency spectra. Statistics of the turbulent flows are non-Gaussian, but interpretation of those statistics are problematic. The range of MHD spatial scales in the plasma sheet available for the turbulence is very limited: ~35,000 km is the thickness of the plasma sheet (largest scalesize) and ~700 km is the ion gyroradius (smallest scalesize). With less than two decades of scalesizes available for the MHD turbulence, a "turbulence-in-a-box" picture has been put forth, with magnetosphere-ionosphere coupling having a major influence on the turbulence.

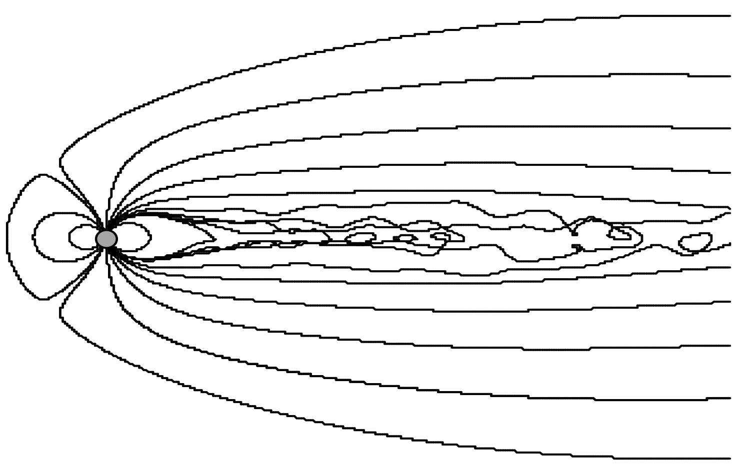

Figure 4. Magnetic-field fluctuations are added to the plasma-sheet region of T96 magnetic-field model (Tysaganenko, 1996) and magnetic-field lines are traced. The statistics of the added field fluctuations match the statistics of the MHD turbulence see by spacecraft in this region. See also Fig. 4 of Hruska (1973).

The multiscale turbulence in the magnetotail with external forcing is the motivation of another model based on percolation theory, which is intimately connected with the fractal structure and multiscale behavior. Substorms have been modeled in terms of a percolating network of cross-tail currents (Milovanov et al., 2001). In this scenario the network has different levels of fractal measures and at a critical level the structural stability breaks down and the onset corresponds to a topological phase transition. In a related approach, the plasma turbulence in the distant magnetotail has been found to have self-organizing properties and these have been described in terms of the fractal properties (Zelenyi et al., 1998).

5. DISCUSSION

The main efforts in the study of the coupled solar wind -magnetosphere system has been to interpret and understand the extensive ground and spacecraft based data in terms of the interactions between plasmas and electric and magnetic fields. However the understanding of the complex magnetospheric dynamics apparent in the observational data of substorms continue to be a challenge. Recent advances to the study of complexity, in terms of low dimensional dynamics, phase transitions, self-organized criticality and turbulence, present new approaches to the modeling of the magnetospheric activity.

The substorms are consequences of the solar wind energy and momentum input into the magnetosphere and are essentially non-equilibrium processes. The main framework for understanding substorms is the formation of plasmoids in the magnetotail accompanied by the reconfiguration of the magnetosphere (Hones et al., 1983). The properties of the magnetosphere derived from the observational data as well as models, show that magnetospheric behavior during substorms are more akin to a combination of such large scale features with the multiscale properties, such as due to a flow past an obstacle (Rostoker, 1984).

The SOC concept has stimulated a large number of applications in many areas (Jensen, 1999). Although its claims have been somewhat ambitious, it has made important contributions to the study of non-equilibrium phenomena. The current interest in granular matter (de Gennes, 1999) has been partly stimulated by SOC ideas. The transition between fluid and frozen phases of granular matter may in fact have features of phase transition and critical behavior. While the theory of SOC is not fully developed, a dynamic mean-field theory description in terms of transition probabilities (Vespignani and Zapperi, 1998) has been used to determine its relationship to other non-equilibrium phenomena. This approach describes

SOC models as non-equilibrium systems which reach criticality by the fine tuning of the control parameters. The original SOC idea is based on the absence of fine tuning and the mean field theory of SOC brings it closer to conventional critical phenomena, rather than the non-equilibrium case. However it should be noted that there are subtle differences in the nature of tuning in the two cases.

Phase transitions as a framework for the solar wind-magnetosphere coupling is attractive because of its input-output nature. The phase transition picture provides a number of relationships between the control (input) and order (output) parameters in terms of critical exponents (Stanley, 1971; Dixon et al., 1999). These relationships provide a new way of understanding the solar wind-magnetosphere coupling. On the other hand the studies of SOC have emphasized the power spectral index as the main characteristics of the phenomenon. However, the phase transition picture of the global and multi-scale manifestations of the dynamics is not fully developed as yet. The next step in this direction would be to obtain analogues of the power-law spectra discussed above, where the state parameter of the system would be related not to scale or frequency but to some input (control) parameter of the system as it takes place in actual second order phase transitions or some advanced SOC models (Gil and Sornette, 1996), i.e., in terms of the critical exponents of the system. This is however a complicated task due to the non-equilibrium nature of the phase transition. One of the critical exponents for the solar wind-magnetosphere system has been computed from the VBs-AL data (Sitnov et al., 2001) and the conditional probabilities of the solar wind – magnetosphere system (Ukhorskiy et al., 2004) support such relationships. The global coherence of the magnetosphere during substorms can be viewed as a catastrophe (Lewis, 1991), akin to the phase transition behavior (Sitnov et al., 200). A minimal substorm model based on similar considerations (Freeman and Morley, 2004) yields good agreement with the probability distribution of substorm occurrence. Further, the peaked conditional probability distributions shown in Figure 2 are in agreement with the correlation between the variabilities of the solar wind and the substoms (Freeman and Morley, 2004).

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